TABLE OF CONTENTS

MANUFACTURING PROCESSES

PUNCHES, DIES, AND PRESS WORK

1301 Punches and Dies
1301 Clearance
1302 Lubricants for Press Work
1302 Annealing Drawn Shells
1302 Drawing Rectangular Shapes
1302 Speeds and Pressures for Presses
1303 Pressure Required for Punching
1303 Shut Height of Press
1303 Diameters of Shell Blanks
1305 Drawn Cylindrical Shells
1306 Depth and Diameter Reductions
1307 Bending Sheet Metal
1308 Lengths of Straight Stock
1311 Bending Allowance Formulas
1311 Bending Sheet Metal
1312 Fine Blanking
1314 V-projections
1315 Steel Rule Dies
1316 Making Steel Rule Dies

ELECTRICAL DISCHARGE MACHINING

1319 EDM Terms
1321 EDM Process
1324 Electrical Control Adjustments
1324 Workpiece Materials
1324 Characteristics of Materials
1325 Electrode Materials
1326 Types of Electrodes
1327 Making Electrodes
1328 Wire EDM

IRON AND STEEL CASTINGS

1330 Gray Cast Iron
1330 White Cast Iron
1330 Chilled Cast Iron
1330 Alloy Cast Iron
1331 Malleable-iron Castings
1332 Ductile Cast Iron
1332 Steel Castings
1333 Carbon Steel Castings
1334 Alloy Steel Castings
1336 Casting of Metals
1338 Removal of Gates and Risers
1338 Blast Cleaning of Castings
1339 Heat Treatment of Steel Castings
1339 Estimating Casting Weight

IRON AND STEEL CASTINGS (Cont.)

1339 Woods for Patterns
1339 Selection of Wood
1340 Pattern Varnish
1340 Shrinkage Allowances
1340 Metal Patterns
1340 Weight of Casting
1341 Die Casting
1342 Porosity
1342 Designing Die Castings
1342 Alloys Used for Die Casting
1342 Aluminum-Base Alloys
1343 Zinc-Base Alloys
1343 Copper-Base Alloys
1343 Magnesium-Base Alloys
1343 Tin-Base Alloys
1344 Lead-Base Alloys
1344 Dies for Die-Casting Machines
1344 Die-Casting Bearing Metal
1344 Injection Molding of Metal
1345 Precision Investment Casting
1345 Casting Materials
1345 General Procedure
1346 Master Mold
1346 Shrinkage Allowances
1346 Casting Dimensions
1346 Investment Materials
1347 Casting Operations
1347 Investment Removal
1347 Investment Castings
1347 Casting Weights and Sizes
1347 Design for Investment Casting
1347 Casting Milling Cutters
1348 Extrusion of Metals
1348 Basic Process
1350 Powder Metallurgy
1350 Advantages of Powder Metallurgy
1350 Limiting Factors
1350 Design of Briquetting Tools
1351 Flame Spraying Process

METAL JOINING, CUTTING, AND SURFACING

1352 Soldering
1352 Forms Available
1352 Fluxes for Soldering
1352 Methods of Application
1354 Ultrasonic Fluxless Soldering

TABLE OF CONTENTS

METAL JOINING, CUTTING, AND SURFACING (Cont.)

1355 Brazing
1355 Filler Metals
1355 Fluxes for Brazing
1356 Brazing Filler Metals
1359 Selection of Filler Metals
1360 Steadying Work
1360 Supplying Heat
1360 Symbol Application

WELDING

1362 Welding Electrodes and Fluxes
1362 Processes
1363 Gas Metal Arc Welding (GMAW)
1363 Electrode Diameters
1364 Maximum Deposition Rates
1364 GMAW Welding of Sheet Steel
1364 Application of Shielding Gases
1366 Welding Controls
1368 GMAW Spray Transfer
1368 Deposition Rates of Electrodes
1370 Optimum Settings for GMAW
1371 Spray Transfer Voltage
1371 Flux-Cored Arc Welding
1371 Flux-Cored Welding Electrodes
1372 Gas-Shielded Electrodes
1372 Settings for FCAW Electrodes
1372 Weld Requirements
1373 Selecting an FCAW Electrode
1373 FCAW Electrodes
1374 Contact Tip Recess
1374 Porosity and Worm Tracks
1374 Welding with Various Diameter
1375 High-Deposition Electrodes
1376 Deposition Rates for Vertical Up Welding
1376 Deposition Rates of Flat and Horizontal Welds
1376 Electrode Diameters and Deposition Rates
1378 Shielding Gases and FCAW Electrodes
1378 Shielded Metal Arc Welding
1379 ANSI/AWS Standard
1380 AWS E60XX Electrodes
1381 AWS E70XX Electrodes
1382 Gas Tungsten Arc Welding
1383 GTAW Welding Current

WELDING (Cont.)

1385 Tungsten Electrode Type
1385 Selection of GTAW
1385 Tungsten Electrode Compositions
1386 Electrode and Current Selection
1386 Current Ranges for GTAW Electrodes
1386 Current Ranges for EWP and EWZ and GTAW Electrodes
1387 Filler Metals
1387 Shielding Gases
1387 Plasma Arc Welding (PAW)
1388 Welding Gases
1388 Shielding Gases
1389 PAW Welding Equipment
1389 Applications
1390 Welding Aluminum
1390 Plasma Arc Surface Coating
1391 Plasma Arc Cutting
1391 Precision Plasma Arc Cutting
1392 Electron-Beam (EB) Welding
1393 Weld and Welding Symbols
1393 ANSI Weld and Welding Symbols
1394 Basic Weld Symbols
1394 Supplementary Weld Symbols
1395 Welding Codes, Rules, Regulations, and Specifications
1396 Letter Designations for Welding
1397 ANSI Welding Symbols
1402 Pipe Welding
1404 Use of Flux-cored Electrodes
1405 Complete Weld Fusion
1405 Other Methods
1405 Pipe Welding Procedure
1405 Thick-walled, Carbon-steel Pipes, Root Welding
1407 Thin-walled Carbon Steel Pipes, Root, Fill and Cover Pass
1408 Nondestructive Testing
1408 Symbols

TABLE OF CONTENTS

LASERS

1410 Laser Light
1410 Laser Beams
1411 Beam Focusing
1412 Types of Industrial Lasers
1413 Industrial Laser Systems
1413 Safety
1413 Laser Beam/Material Interaction
1414 Thermal Properties of Workpieces
1415 Cutting Metal with Lasers
1415 Beam Assistance Techniques
1416 Cut Edge Roughness
1416 Heat-Affected Zones
1417 Cutting of Nonmetals
1419 Welding with Lasers
1419 Laser Welding Theory
1420 Welded Joint Design
1420 Welding Rates
1420 Processing Gas
1421 Drilling with Lasers
1421 Laser Drilling Theory
1421 Direct Drilling
1421 Percussive Drilling
1421 Trepanning
1421 Drilling Rates
1421 Heat Treatment with Lasers
1422 Materials Applicability
1422 Hardening Rates
1422 Cladding with Lasers
1422 Marking with Lasers
1422 Mask Marking
1423 Scanned-Beam Marking

HARD FACING

1423 Hard-Facing Materials
1423 High-Speed Steels
1424 Austenitic Manganese Steels
1424 Austenitic High-Chromium Irons
1425 Cobalt-Base Alloys
1425 Copper-Base Alloys
1426 Nickel-Chromium-Boron Alloys
1427 Chromium Plating

CUTTING METALS

1428 The Cutting Torch
1428 Adjustment of Cutting Torch
1428 Metals That Can Be Cut
1428 Cutting Stainless Steel
1428 Cutting Cast Iron

CUTTING METALS (Cont.)

1429 Mechanically Guided Torches
1429 Cutting Steel Castings
1429 Thickness of Metal
1429 Arc Cutting of Metals
1429 Arc Cutting
1429 Plasma Cutting of Metals

FILES AND BURS

1430 Definitions of File Terms
1431 File Characteristics
1431 Classes of Files
1433 Effectiveness of Rotary Files and Burs
1434 Speeds of Rotary Files and Burs
1435 Power Brush Finishing
1435 Description of Brushes
1435 Use of Brushes
1435 Deburring and Producing a Radius
1436 Eliminating Undesirable Conditions
1437 Characteristics in Power Brush
1439 Polishing and Buffing
1439 Polishing Wheels
1439 Polishing Operations and Abrasives
1440 Buffing Wheels
1440 Speed of Polishing Wheels
1440 Grain Numbers of Emery
1440 Grades of Emery Cloth

SURFACE TREATMENTS FOR METALS

1440 Etching and Etching Fluids
1440 Etching Fluids
1441 Conversion Coatings and the Coloring of Metals
1441 Passivation of Copper
1442 Coloring of Copper Alloys
1442 Coloring of Iron and Steel
1443 Anodizing Aluminum Alloys
1443 Magnesium Alloys
1443 Titanium Alloys
1444 Plating
1444 Surface Coatings

PUNCHES, DIES, AND PRESS WORK

Clearance between Punches and Dies.—The amount of clearance between a punch and die for blanking and perforating is governed by the thickness and kind of stock to be operated upon. For thin material, the punch should be a close sliding fit to prevent ragged edges, but for heavier stock, there should be some clearance. The clearance between the punch and die in cutting heavy material reduces the pressure required for the punching operation and the danger of breaking the punch.

Meaning of the Term "Clearance".—There is a difference of opinion among diemakers as to the method of designating clearance. The prevailing practice of fifteen firms specializing in die work is as follows: Ten of these firms define clearance as the space between the punch and die on *one side,* or one-half the difference between the punch and die sizes. The remaining five firms consider clearance as the total difference between the punch and die sizes; for example, if the die is round, clearance equals die diameter minus punch diameter. The advantage of designating clearance as the space on each side is particularly evident with dies of irregular form or of angular shape. Although the practice of designating clearance as the difference between the punch and die diameters may be satisfactory for round dies, it leads to confusion when the dies are of unsymmetrical forms. The term "clearance" should not be used in specifications without indicating clearly just what it means. According to one die manufacturer, the term "cutting clearance" is used to indicate the space between the punch and die on each side, and the term "die clearance" refers to the angular clearance provided below the cutting edge so that the parts will fall easily through the die. The term "clearance" as here used means the space on one side only; hence, for round dies, clearance equals die radius minus punch radius.

Clearances Generally Allowed.—For brass and soft steel, most dies are given a clearance on one side equal to the stock thickness multiplied by 0.05 or 0.06; but one-half of this clearance is preferred for some classes of work, and a clearance equal to the stock thickness multiplied by 0.10 may give the cleanest fracture for certain other operations such as punching holes in ductile steel boiler plate.

Where Clearance Is Applied.—Whether clearance is deducted from the diameter of the punch or added to the diameter of the die depends upon the nature of the work. If a blank of given size is required, the die is made to that size and the punch is made smaller. Inversely, when holes of a given size are required, the punch is made to the diameter wanted and the die is made larger. Therefore, for blanking to a given size, the clearance is deducted from the size of the punch, and for perforating, the clearance is added to the size of the die.

Effect of Clearance on Working Pressure.—Clearance affects not only the smoothness of the fracture, but also the pressure required for punching or blanking. This pressure is greatest when the punch diameter is small compared to the thickness of the stock. In one test, for example, a punching pressure of about 32,000 pounds was required to punch $\frac{3}{4}$-inch holes into $\frac{5}{16}$-inch mild steel plate when the clearance was about 10 per cent. With a clearance of about 4.5 per cent, the pressure increased to 33,000 pounds and a clearance of 2.75 per cent resulted in a pressure of 34,500 pounds.

Soft ductile metal requires more clearance than hard metal, although it has been common practice to increase the clearance for harder metals. In punching holes in fairly hard steel, a clean fracture was obtained with a clearance of only 0.03 times stock thickness.

Angular Clearance for Dies.—The angular clearance ordinarily used in a blanking die varies from 1 to 2 degrees, although dies intended for producing a comparatively small number of blanks are sometimes given a clearance angle of 4 or 5 degrees to facilitate making the die quickly. When large numbers of blanks are required, a clearance of about 1 degree is used.

There are two methods of giving clearance to dies: In one method, the clearance extends to the top face of the die; and in the other, there is a space about $\frac{1}{8}$ inch below the cutting edge that is left practically straight, or having a very small amount of clearance.

For very soft metal, such as soft, thin brass, the first method is employed, but for harder material, such as hard brass, steel, etc., it is better to have a very small clearance for a short distance below the cutting edge. When a die is made in this way, thousands of blanks can be cut with little variation in their size, as grinding the die face will not enlarge the hole to any appreciable extent.

Lubricants for Press Work.—Blanking dies used for carbon and low-alloy steels are often run with only residual mill lubricant, but will last longer if lightly oiled. Higher alloy and stainless steels require thicker lubricants. Kerosene is usually used with aluminum. Lubricant thickness needs to be about 0.0001 in. and can be obtained with about 1 pint of fluid to cover 500 sq. ft of material. During successive strokes, metal debris adheres to the punch and may accelerate wear, but damage may be reduced by application of the lubricant to the sheet or strip by means of rollers or spray. High-speed blanking may require heavier applications or a continuous airless spraying of oil. For sheet thicker than $\frac{1}{8}$ in. and for stainless steel, high-pressure lubricants containing sulfurs and chlorines are often used.

Shallow drawing and forming of steel can be done with low-viscosity oils and soap solutions, but deeper draws require light- to medium-viscosity oils containing fats and such active elements as sulfur or phosphorus, and mineral fillers such as chalk or mica. Deep drawing often involves ironing or thinning of the walls by up to 35 per cent, and thick oils containing high proportions of chemically active compounds are used. Additives used in drawing compounds are selected for their ability to maintain a physical barrier between the tool surfaces and the metal being shaped. Dry soaps and polymer films are frequently used for these purposes. Aluminum can be shallow drawn with oils of low to medium viscosity, and for deep drawing, tallow may be added, also wax or soap suspensions for very large reductions.

Annealing Drawn Shells.—When drawing steel, iron, brass, or copper, annealing is necessary after two or three draws have been made, because the metal is hardened by the drawing process. For steel and brass, anneal between alternate reductions, at least. Tin plate or stock that cannot be annealed without spoiling the finish must ordinarily be drawn to size in one or two operations. Aluminum can be drawn deeper and with less annealing than the other commercial metals, provided the proper grade is used. If it is necessary to anneal aluminum, it should be heated in a muffle furnace, care being taken to see that the temperature does not exceed 700 degrees F.

Drawing Brass.—When drawing brass shells or cup-shaped articles, it is usually possible to make the depth of the first draw equal to the diameter of the shell. By heating brass to a temperature just below what would show a dull red in a dark room, it is possible to draw difficult shapes, otherwise almost impossible, and to produce shapes with square corners.

Drawing Rectangular Shapes.—When square or rectangular shapes are to be drawn, the radius of the corners should be as large as possible, because defects usually occur in the corners when drawing. Moreover, the smaller the radius, the less the depth that can be obtained in the first draw.

The maximum depths that can be drawn with corners of a given radii are approximately as follows: With a radius of $\frac{3}{32}$ to $\frac{3}{16}$ inch, depth of draw, 1 inch; radius $\frac{3}{16}$ to $\frac{3}{8}$ inch, depth $1\frac{1}{2}$ inches; radius $\frac{3}{8}$ to $\frac{1}{2}$ inch, depth 2 inches; and radius $\frac{1}{2}$ to $\frac{3}{4}$ inch, depth 3 inches.

These figures are taken from actual practice and can doubtless be exceeded slightly when using metal prepared for the process. If the box needs to be quite deep and the radius is quite small, two or more drawing operations will be necessary.

Speeds and Pressures for Presses.—The speeds for presses equipped with cutting dies depend largely upon the kind of material being worked, and its thickness. For punching and shearing ordinary metals not over $\frac{1}{4}$ inch thick, the speeds usually range between 50 and 200 strokes per minute, 100 strokes per minute being a fair average. For punching metal over $\frac{1}{4}$ inch thick, geared presses with speeds ranging from 25 to 75 strokes per minute are commonly employed.

The cutting pressures required depend upon the shearing strength of the material, and the actual area of the surface being severed. For round holes, the pressure required equals the circumference of the hole × the thickness of the stock × the shearing strength.

To allow for some excess pressure, the tensile strength may be substituted for the shearing strength; the tensile strength for these calculations may be roughly assumed as follows: Mild steel, 60,000; wrought iron, 50,000; bronze, 40,000; copper, 30,000; aluminum, 20,000; zinc, 10,000; and tin and lead, 5,000 pounds per square inch.

Pressure Required for Punching.—The formula for the force in tons required to punch a circular hole in sheet steel is $\pi DST/2000$, where S = the shearing strength of the material in lb/in.^{2}, T = thickness of the steel in inches, and 2000 is the number of lb in 1 ton. An approximate formula is $DT \times 80$, where D and T are the diameter of the hole and the thickness of the steel, respectively, both in inches, and 80 is a factor for steel. The result is the force in tons.

Example: Find the pressure required to punch a hole, 2 inches in diameter, through $\frac{1}{4}$-in. thick steel. By applying the approximate formula, $2 \times \frac{1}{4} \times 80 = 40$ tons.

If the hole is not circular, replace the hole diameter with the value of one-third of the perimeter of the hole to be punched.

Example: Find the pressure required to punch a 1-inch square hole in $\frac{1}{4}$-in. thick steel. The total length of the hole perimeter is 4 in. and one-third of 4 in. is $1\frac{1}{3}$ in., so the force is $1\frac{1}{3} \times \frac{1}{4} \times 80 = 26\frac{2}{3}$ tons.

The corresponding factor for punching holes in brass is 65 instead of 80. So, to punch a hole measuring 1 by 2 inches in $\frac{1}{4}$-in. thick brass sheet, the factor for hole size is the perimeter length $6 \div 3 = 2$, and the formula is $2 \times \frac{1}{4} \times 65 = 32\frac{1}{2}$ tons.

Shut Height of Press.—The term “shut height,” as applied to power presses, indicates the die space when the slide is at the bottom of its stroke and the slide connection has been adjusted upward as far as possible. The “shut height” is the distance from the lower face of the slide, either to the top of the bed or to the top of the bolster plate, there being two methods of determining it; hence, this term should always be accompanied by a definition explaining its meaning. According to one press manufacturer, the safest plan is to define “shut height” as the distance from the top of the bolster to the bottom of the slide, with the stroke down and the adjustment up, because most dies are mounted on bolster plates of standard thickness, and a misunderstanding that results in providing too much die space is less serious than having insufficient die space. It is believed that the expression “shut height” was applied first to dies rather than to presses, the shut height of a die being the distance from the bottom of the lower section to the top of the upper section or punch, excluding the shank, and measured when the punch is in the lowest working position.

Diameters of Shell Blanks.—The diameters of blanks for drawing plain cylindrical shells can be obtained from the table on the following pages, which gives a very close approximation for thin stock. The blank diameters given in this table are for sharp-cornered shells and are found by the following formula:

$$D = \sqrt{d^2 + 4dh} \qquad (1)$$

where D = diameter of flat blank; d = diameter of finished shell; and h = height of finished shell.

Example: If the diameter of the finished shell is to be 1.5 inches, and the height, 2 inches, the trial diameter of the blank would be found as follows:

$$D = \sqrt{1.5^2 + 4 \times 1.5 \times 2} = \sqrt{14.25} = 3.78 \text{ inches}$$

For a round-cornered cup, the following formula, in which r equals the radius of the corner, will give fairly accurate diameters, provided the radius does not exceed, say, $\frac{1}{4}$ the height of the shell:

$$D = \sqrt{d^2 + 4dh} - r \qquad (2)$$

These formulas are based on the assumption that the thickness of the drawn shell is the same as the original thickness of the stock, and that the blank is so proportioned that its area will equal the area of the drawn shell. This method of calculating the blank diameter is quite accurate for thin material, when there is only a slight reduction in the thickness of the metal incident to drawing; but when heavy stock is drawn and the thickness of the finished shell is much less than the original thickness of the stock, the blank diameter obtained from Formula (1) or (2) will be too large, because when the stock is drawn thinner, there is an increase in area. When an appreciable reduction in thickness is to be made, the blank diameter can be obtained by first determining the "mean height" of the drawn shell by the following formula. This formula is only approximately correct, but will give results sufficiently accurate for most work:

$$M = \frac{ht}{T} \qquad (3)$$

where M = approximate mean height of drawn shell; h = height of drawn shell; t = thickness of shell; and T = thickness of metal before drawing.

After determining the mean height, the blank diameter for the required shell diameter is obtained from the table previously referred to, the mean height being used instead of the actual height.

Example: Suppose a shell 2 inches in diameter and 3 $\frac{3}{4}$ inches high is to be drawn, and that the original thickness of the stock is 0.050 inch, and the thickness of drawn shell, 0.040 inch. To what diameter should the blank be cut? By using Formula (3) to obtain the mean height:

$$M = \frac{ht}{T} = \frac{3.75 \times 0.040}{0.050} = 3 \text{ inches}$$

According to the table, the blank diameter for a shell 2 inches in diameter and 3 inches high is 5.29 inches. Formula (3) is accurate enough for all practical purposes, unless the reduction in the thickness of the metal is greater than about one-fifth the original thickness. When there is considerable reduction, a blank calculated by this formula produces a shell that is too long. However, the error is in the right direction, as the edges of drawn shells are ordinarily trimmed.

If the shell has a rounded corner, the radius of the corner should be deducted from the figures given in the table. For example, if the shell referred to in the foregoing example had a corner of $\frac{1}{4}$-inch radius, the blank diameter would equal 5.29 – 0.25 = 5.04 inches.

Another formula that is sometimes used for obtaining blank diameters for shells, when there is a reduction in the thickness of the stock, is as follows:

$$D = \sqrt{a^2 + (a^2 - b^2)\frac{h}{t}} \qquad (4)$$

Diameters of Blanks for Drawn Cylindrical Shells

Diam. of Shell	Height of Shell																			
	¼	½	¾	1	1 ¼	1 ½	1 ¾	2	2 ¼	2 ½	2 ¾	3	3 ¼	3 ½	3 ¾	4	4 ½	5	5 ½	6
¼	0.56	0.75	0.90	1.03	1.14	1.25	1.35	1.44	1.52	1.60	1.68	1.75	1.82	1.89	1.95	2.01	2.14	2.25	2.36	2.46
½	0.87	1.12	1.32	1.50	1.66	1.80	1.94	2.06	2.18	2.29	2.40	2.50	2.60	2.69	2.78	2.87	3.04	3.21	3.36	3.50
¾	1.14	1.44	1.68	1.89	2.08	2.25	2.41	2.56	2.70	2.84	2.97	3.09	3.21	3.33	3.44	3.54	3.75	3.95	4.13	4.31
1	1.41	1.73	2.00	2.24	2.45	2.65	2.83	3.00	3.16	3.32	3.46	3.61	3.74	3.87	4.00	4.12	4.36	4.58	4.80	5.00
1 ¼	1.68	2.01	2.30	2.56	2.79	3.01	3.21	3.40	3.58	3.75	3.91	4.07	4.22	4.37	4.51	4.64	4.91	5.15	5.39	5.62
1 ½	1.94	2.29	2.60	2.87	3.12	3.36	3.57	3.78	3.97	4.15	4.33	4.50	4.66	4.82	4.98	5.12	5.41	5.68	5.94	6.18
1 ¾	2.19	2.56	2.88	3.17	3.44	3.68	3.91	4.13	4.34	4.53	4.72	4.91	5.08	5.26	5.41	5.58	5.88	6.17	6.45	6.71
2	2.45	2.83	3.16	3.46	3.74	4.00	4.24	4.47	4.69	4.90	5.10	5.29	5.48	5.66	5.83	6.00	6.32	6.63	6.93	7.21
2 ¼	2.70	3.09	3.44	3.75	4.04	4.31	4.56	4.80	5.03	5.25	5.46	5.66	5.86	6.05	6.23	6.41	6.75	7.07	7.39	7.69
2 ½	2.96	3.36	3.71	4.03	4.33	4.61	4.87	5.12	5.36	5.59	5.81	6.02	6.22	6.42	6.61	6.80	7.16	7.50	7.82	8.14
2 ¾	3.21	3.61	3.98	4.31	4.62	4.91	5.18	5.44	5.68	5.92	6.15	6.37	6.58	6.79	6.99	7.18	7.55	7.91	8.25	8.58
3	3.46	3.87	4.24	4.58	4.90	5.20	5.48	5.74	6.00	6.25	6.48	6.71	6.93	7.14	7.35	7.55	7.94	8.31	8.66	9.00
3 ¼	3.71	4.13	4.51	4.85	5.18	5.48	5.77	6.04	6.31	6.56	6.80	7.04	7.27	7.49	7.70	7.91	8.31	8.69	9.06	9.41
3 ½	3.97	4.39	4.77	5.12	5.45	5.77	6.06	6.34	6.61	6.87	7.12	7.36	7.60	7.83	8.05	8.26	8.67	9.07	9.45	9.81
3 ¾	4.22	4.64	5.03	5.39	5.73	6.05	6.35	6.64	6.91	7.18	7.44	7.69	7.92	8.16	8.38	8.61	9.03	9.44	9.83	10.20
4	4.47	4.90	5.29	5.66	6.00	6.32	6.63	6.93	7.21	7.48	7.75	8.00	8.25	8.49	8.72	8.94	9.38	9.80	10.20	10.58
4 ¼	4.72	5.15	5.55	5.92	6.27	6.60	6.91	7.22	7.50	7.78	8.05	8.31	8.56	8.81	9.04	9.28	9.72	10.15	10.56	10.96
4 ½	4.98	5.41	5.81	6.19	6.54	6.87	7.19	7.50	7.79	8.08	8.35	8.62	8.87	9.12	9.37	9.60	10.06	10.50	10.92	11.32
4 ¾	5.22	5.66	6.07	6.45	6.80	7.15	7.47	7.78	8.08	8.37	8.65	8.92	9.18	9.44	9.69	9.93	10.40	10.84	11.27	11.69
5	5.48	5.92	6.32	6.71	7.07	7.42	7.75	8.06	8.37	8.66	8.94	9.22	9.49	9.75	10.00	10.25	10.72	11.18	11.62	12.04
5 ¼	5.73	6.17	6.58	6.97	7.33	7.68	8.02	8.34	8.65	8.95	9.24	9.52	9.79	10.05	10.31	10.56	11.05	11.51	11.96	12.39
5 ½	5.98	6.42	6.84	7.23	7.60	7.95	8.29	8.62	8.93	9.23	9.53	9.81	10.08	10.36	10.62	10.87	11.37	11.84	12.30	12.74
5 ¾	6.23	6.68	7.09	7.49	7.86	8.22	8.56	8.89	9.21	9.52	9.81	10.10	10.38	10.66	10.92	11.18	11.69	12.17	12.63	13.08
6	6.48	6.93	7.35	7.75	8.12	8.49	8.83	9.17	9.49	9.80	10.10	10.39	10.68	10.95	11.23	11.49	12.00	12.49	12.96	13.42

In this formula, D = blank diameter; a = outside diameter; b = inside diameter; t = thickness of shell at bottom; and h = depth of shell. This formula is based on the volume of the metal in the drawn shell. It is assumed that the shells are cylindrical, and no allowance is made for a rounded corner at the bottom, or for trimming the shell after drawing. To allow for trimming, add the required amount to depth h. When a shell is of irregular cross-section, if its weight is known, the blank diameter can be determined by the following formula:

$$D = 1.1284\sqrt{\frac{W}{wt}} \qquad (5)$$

where D = blank diameter in inches; W = weight of shell; w = weight of metal per cubic inch; and t = thickness of the shell.

In the construction of dies for producing shells, especially of irregular form, a common method to be used is to make the drawing tool first. The actual blank diameter then can be determined by trial. One method is to cut a trial blank as near to size and shape as can be estimated. The outline of this blank is then scribed on a flat sheet, after which the blank is drawn. If the finished shell shows that the blank is not of the right diameter or shape, a new trial blank is cut either larger or smaller than the size indicated by the line previously scribed, this line acting as a guide. If a model shell is available, the blank diameter can also be determined as follows:

First, cut a blank somewhat large, and from the same material used for making the model; then, reduce the size of the blank until its weight equals the weight of the model.

Depth and Diameter Reductions of Drawn Cylindrical Shells.—The depth to which metal can be drawn in one operation depends upon the quality and kind of material, its thickness, the slant or angle of the dies, and the amount that the stock is thinned or "ironed" in drawing. A general rule for determining the depth to which cylindrical shells can be drawn in one operation is as follows: The depth or length of the first draw should never be greater than the diameter of the shell. If the shell is to have a flange at the top, it may not be practicable to draw as deeply as is indicated by this rule, unless the metal is extra good, because the stock is subjected to a higher tensile stress, owing to the larger blank needed to form the flange. According to another rule, the depth given the shell on the first draw should equal one-third the diameter of the blank. Ordinarily, it is possible to draw sheet steel of any thickness up to ¼ inch, so that the diameter of the first shell equals about six-tenths of the blank diameter. When drawing plain shells, the amount that the diameter is reduced for each draw must be governed by the quality of the metal and its susceptibility to drawing. The reduction for various thicknesses of metal is about as follows:

Approximate thickness of sheet steel	1⁄16	1⁄8	3⁄16	1⁄4	5⁄16
Possible reduction in diameter for each succeeding step, per cent	20	15	12	10	8

For example, if a shell made of 1⁄16-inch stock is 3 inches in diameter after the first draw, it can be reduced 20 per cent on the next draw, and so on until the required diameter is obtained. These figures are based upon the assumption that the shell is annealed after the first drawing operation, and at least between every two of the following operations. Necking operations—that is, the drawing out of a short portion of the lower part of the cup into a long neck—may be done without such frequent annealings. In double-action presses, where the inside of the cup is supported by a bushing during drawing, the reductions possible may be increased to 30, 24, 18, 15, and 12 per cent, respectively. (The latter figures may also be used for brass in single-action presses.)

When a hole is to be pierced at the bottom of a cup and the remaining metal is to be drawn after the hole has been pierced or punched, always pierce from the opposite direction to that in which the stock is to be drawn after piercing. It may be necessary to machine the metal around the pierced hole to prevent the starting of cracks or flaws in the subsequent drawing operations.

The foregoing figures represent conservative practice and it is often possible to make greater reductions than are indicated by these figures, especially when using a good drawing metal. Taper shells require smaller reductions than cylindrical shells, because the metal tends to wrinkle if the shell to be drawn is much larger than the punch. The amount that the stock is “ironed” or thinned out while being drawn must also be considered, because a reduction in gage or thickness means greater force will be exerted by the punch against the bottom of the shell; hence the amount that the shell diameter is reduced for each drawing operation must be smaller when much ironing is necessary. The extent to which a shell can be ironed in one drawing operation ranges between 0.002 and 0.004 inch per side, and should not exceed 0.001 inch on the final draw, if a good finish is required.

Allowances for Bending Sheet Metal.—In bending steel, brass, bronze, or other metals, the problem is to find the length of straight stock required for each bend; these lengths are added to the lengths of the straight sections to obtain the total length of the material before bending.

If L = length in inches, of straight stock required before bending; T = thickness in inches; and R = inside radius of bend in inches:

For 90-degree bends in soft brass and soft copper see Table 1 or:

$$L = (0.55 \times T) + (1.57 \times R) \qquad (1)$$

For 90-degree bends in half-hard copper and brass, soft steel, and aluminum see Table 2 or:

$$L = (0.64 \times T) + (1.57 \times R) \qquad (2)$$

For 90-degree bends in bronze, hard copper, cold-rolled steel, and spring steel see Table 3 or:

$$L = (0.71 \times T) + (1.57 \times R) \qquad (3)$$

Angle of Bend Other Than 90 Degrees: For angles other than 90 degrees, find length L, using tables or formulas, and multiply L by angle of bend, in degrees, divided by 90 to find length of stock before bending. In using this rule, note that *angle of bend* is the angle through which the material has actually been bent; hence, it is not always the angle as given on a drawing. To illustrate, in Fig. 1, the angle on the drawing is 60 degrees, but the angle of bend A is 120 degrees (180 – 60 = 120); in Fig. 2, the angle of bend A is 60 degrees; in Fig. 3, angle A is 90 – 30 = 60 degrees. Formulas (1), (2), and (3) are based on extensive experiments of the Westinghouse Electric Co. They apply to parts bent with simple tools or on the bench, where limits of $\pm \frac{1}{64}$ inch are specified. If a part has two or more bends of the same radius, it is, of course, only necessary to obtain the length required for one of the bends and then multiply by the number of bends, to obtain the total allowance for the bent sections.

Table 1. Lengths of Straight Stock Required for 90-Degree Bends in Soft Copper and Soft Brass

Radius *R* of Bend, Inches	Thickness *T* of Material, Inch												
	1/64	1/32	3/64	1/16	5/64	3/32	1/8	5/32	3/16	7/32	1/4	9/32	5/16
1/32	0.058	0.066	0.075	0.083	0.092	0.101	0.118	0.135	0.152	0.169	0.187	0.204	0.221
3/64	0.083	0.091	0.100	0.108	0.117	0.126	0.143	0.160	0.177	0.194	0.212	0.229	0.246
1/16	0.107	0.115	0.124	0.132	0.141	0.150	0.167	0.184	0.201	0.218	0.236	0.253	0.270
3/32	0.156	0.164	0.173	0.181	0.190	0.199	0.216	0.233	0.250	0.267	0.285	0.302	0.319
1/8	0.205	0.213	0.222	0.230	0.239	0.248	0.265	0.282	0.299	0.316	0.334	0.351	0.368
5/32	0.254	0.262	0.271	0.279	0.288	0.297	0.314	0.331	0.348	0.365	0.383	0.400	0.417
3/16	0.303	0.311	0.320	0.328	0.337	0.346	0.363	0.380	0.397	0.414	0.432	0.449	0.466
7/32	0.353	0.361	0.370	0.378	0.387	0.396	0.413	0.430	0.447	0.464	0.482	0.499	0.516
1/4	0.401	0.409	0.418	0.426	0.435	0.444	0.461	0.478	0.495	0.512	0.530	0.547	0.564
9/32	0.450	0.458	0.467	0.475	0.484	0.493	0.510	0.527	0.544	0.561	0.579	0.596	0.613
5/16	0.499	0.507	0.516	0.524	0.533	0.542	0.559	0.576	0.593	0.610	0.628	0.645	0.662
11/32	0.549	0.557	0.566	0.574	0.583	0.592	0.609	0.626	0.643	0.660	0.678	0.695	0.712
3/8	0.598	0.606	0.615	0.623	0.632	0.641	0.658	0.675	0.692	0.709	0.727	0.744	0.761
13/32	0.646	0.654	0.663	0.671	0.680	0.689	0.706	0.723	0.740	0.757	0.775	0.792	0.809
7/16	0.695	0.703	0.712	0.720	0.729	0.738	0.755	0.772	0.789	0.806	0.824	0.841	0.858
15/32	0.734	0.742	0.751	0.759	0.768	0.777	0.794	0.811	0.828	0.845	0.863	0.880	0.897
1/2	0.794	0.802	0.811	0.819	0.828	0.837	0.854	0.871	0.888	0.905	0.923	0.940	0.957
9/16	0.892	0.900	0.909	0.917	0.926	0.935	0.952	0.969	0.986	1.003	1.021	1.038	1.055
5/8	0.990	0.998	1.007	1.015	1.024	1.033	1.050	1.067	1.084	1.101	1.119	1.136	1.153
11/16	1.089	1.097	1.106	1.114	1.123	1.132	1.149	1.166	1.183	1.200	1.218	1.235	1.252
3/4	1.187	1.195	1.204	1.212	1.221	1.230	1.247	1.264	1.281	1.298	1.316	1.333	1.350
13/16	1.286	1.294	1.303	1.311	1.320	1.329	1.346	1.363	1.380	1.397	1.415	1.432	1.449
7/8	1.384	1.392	1.401	1.409	1.418	1.427	1.444	1.461	1.478	1.495	1.513	1.530	1.547
15/16	1.481	1.489	1.498	1.506	1.515	1.524	1.541	1.558	1.575	1.592	1.610	1.627	1.644
1	1.580	1.588	1.597	1.605	1.614	1.623	1.640	1.657	1.674	1.691	1.709	1.726	1.743
1 1/16	1.678	1.686	1.695	1.703	1.712	1.721	1.738	1.755	1.772	1.789	1.807	1.824	1.841
1 1/8	1.777	1.785	1.794	1.802	1.811	1.820	1.837	1.854	1.871	1.888	1.906	1.923	1.940
1 3/16	1.875	1.883	1.892	1.900	1.909	1.918	1.935	1.952	1.969	1.986	2.004	2.021	2.038
1 1/4	1.972	1.980	1.989	1.997	2.006	2.015	2.032	2.049	2.066	2.083	2.101	2.118	2.135

Table 2. Lengths of Straight Stock Required for 90-Degree Bends in Half-Hard Brass and Sheet Copper, Soft Steel, and Aluminum

Radius *R* of Bend, Inches	Thickness *T* of Material, Inch												
	1/64	1/32	3/64	1/16	5/64	3/32	1/8	5/32	3/16	7/32	1/4	9/32	5/16
1/32	0.059	0.069	0.079	0.089	0.099	0.109	0.129	0.149	0.169	0.189	0.209	0.229	0.249
3/64	0.084	0.094	0.104	0.114	0.124	0.134	0.154	0.174	0.194	0.214	0.234	0.254	0.274
1/16	0.108	0.118	0.128	0.138	0.148	0.158	0.178	0.198	0.218	0.238	0.258	0.278	0.298
3/32	0.157	0.167	0.177	0.187	0.197	0.207	0.227	0.247	0.267	0.287	0.307	0.327	0.347
1/8	0.206	0.216	0.226	0.236	0.246	0.256	0.276	0.296	0.316	0.336	0.356	0.376	0.396
5/32	0.255	0.265	0.275	0.285	0.295	0.305	0.325	0.345	0.365	0.385	0.405	0.425	0.445
3/16	0.305	0.315	0.325	0.335	0.345	0.355	0.375	0.395	0.415	0.435	0.455	0.475	0.495
7/32	0.354	0.364	0.374	0.384	0.394	0.404	0.424	0.444	0.464	0.484	0.504	0.524	0.544
1/4	0.403	0.413	0.423	0.433	0.443	0.453	0.473	0.493	0.513	0.533	0.553	0.573	0.593
9/32	0.452	0.462	0.472	0.482	0.492	0.502	0.522	0.542	0.562	0.582	0.602	0.622	0.642
5/16	0.501	0.511	0.521	0.531	0.541	0.551	0.571	0.591	0.611	0.631	0.651	0.671	0.691
11/32	0.550	0.560	0.570	0.580	0.590	0.600	0.620	0.640	0.660	0.680	0.700	0.720	0.740
3/8	0.599	0.609	0.619	0.629	0.639	0.649	0.669	0.689	0.709	0.729	0.749	0.769	0.789
13/32	0.648	0.658	0.668	0.678	0.688	0.698	0.718	0.738	0.758	0.778	0.798	0.818	0.838
7/16	0.697	0.707	0.717	0.727	0.737	0.747	0.767	0.787	0.807	0.827	0.847	0.867	0.887
15/32	0.746	0.756	0.766	0.776	0.786	0.796	0.816	0.836	0.856	0.876	0.896	0.916	0.936
1/2	0.795	0.805	0.815	0.825	0.835	0.845	0.865	0.885	0.905	0.925	0.945	0.965	0.985
17/32	0.844	0.854	0.864	0.874	0.884	0.894	0.914	0.934	0.954	0.974	0.994	1.014	1.034
9/16	0.894	0.904	0.914	0.924	0.934	0.944	0.964	0.984	1.004	1.024	1.044	1.064	1.084
5/8	0.992	1.002	1.012	1.022	1.032	1.042	1.062	1.082	1.102	1.122	1.42	1.162	1.182
11/16	1.090	1.100	1.110	1.120	1.130	1.140	1.160	1.180	1.200	1.220	1.240	1.260	1.280
3/4	1.188	1.198	1.208	1.218	1.228	1.238	1.258	1.278	1.298	1.318	1.338	1.358	1.378
13/16	1.286	1.296	1.306	1.316	1.326	1.336	1.356	1.376	1.396	1.416	1.436	1.456	1.476
7/8	1.384	1.394	1.404	1.414	1.424	1.434	1.454	1.474	1.494	1.514	1.534	1.554	1.574
15/16	1.483	1.493	1.503	1.513	1.523	1.553	1.553	1.573	1.693	1.613	1.633	1.653	1.673
1	1.581	1.591	1.601	1.611	1.621	1.631	1.651	1.671	1.691	1.711	1.731	1.751	1.771
1 1/16	1.697	1.689	1.699	1.709	1.719	1.729	1.749	1.769	1.789	1.809	1.829	1.849	1.869
1 1/8	1.777	1.787	1.797	1.807	1.817	1.827	1.847	1.867	1.887	1.907	1.927	1.947	1.967
1 3/16	1.875	1.885	1.895	1.905	1.915	1.925	1.945	1.965	1.985	1.005	2.025	2.045	2.065
1 1/4	1.973	1.983	1.993	1.003	2.013	2.023	2.043	2.063	2.083	2.103	2.123	2.143	2.163

Table 3. Lengths of Straight Stock Required for 90-Degree Bends in Hard Copper, Bronze, Cold-Rolled Steel, and Spring Steel

Radius *R* of Bend, Inches	Thickness *T* of Material, Inch												
	1⁄64	1⁄32	3⁄64	1⁄16	5⁄64	3⁄32	1⁄8	5⁄32	3⁄16	7⁄32	1⁄4	9⁄32	5⁄16
1⁄32	0.060	0.071	0.082	0.093	0.104	0.116	0.138	0.160	0.182	0.204	0.227	0.249	0.271
3⁄64	0.085	0.096	0.107	0.118	0.129	0.141	0.163	0.185	0.207	0.229	0.252	0.274	0.296
1⁄16	0.109	0.120	0.131	0.142	0.153	0.165	0.187	0.209	0.231	0.253	0.276	0.298	0.320
3⁄32	0.158	0.169	0.180	0.191	0.202	0.214	0.236	0.258	0.280	0.302	0.325	0.347	0.369
1⁄8	0.207	0.218	0.229	0.240	0.251	0.263	0.285	0.307	0.329	0.351	0.374	0.396	0.418
5⁄32	0.256	0.267	0.278	0.289	0.300	0.312	0.334	0.356	0.378	0.400	0.423	0.445	0.467
3⁄16	0.305	0.316	0.327	0.338	0.349	0.361	0.383	0.405	0.427	0.449	0.472	0.494	0.516
7⁄32	0.355	0.366	0.377	0.388	0.399	0.411	0.433	0.455	0.477	0.499	0.522	0.544	0.566
1⁄4	0.403	0.414	0.425	0.436	0.447	0.459	0.481	0.503	0.525	0.547	0.570	0.592	0.614
9⁄32	0.452	0.463	0.474	0.485	0.496	0.508	0.530	0.552	0.574	0.596	0.619	0.641	0.663
5⁄16	0.501	0.512	0.523	0.534	0.545	0.557	0.579	0.601	0.623	0.645	0.668	0.690	0.712
11⁄32	0.551	0.562	0.573	0.584	0.595	0.607	0.629	0.651	0.673	0.695	0.718	0.740	0.762
3⁄8	0.600	0.611	0.622	0.633	0.644	0.656	0.678	0.700	0.722	0.744	0.767	0.789	0.811
13⁄32	0.648	0.659	0.670	0.681	0.692	0.704	0.726	0.748	0.770	0.792	0.815	0.837	0.859
7⁄16	0.697	0.708	0.719	0.730	0.741	0.753	0.775	0.797	0.819	0.841	0.864	0.886	0.908
15⁄32	0.736	0.747	0.758	0.769	0.780	0.792	0.814	0.836	0.858	0.880	0.903	0.925	0.947
1⁄2	0.796	0.807	0.818	0.829	0.840	0.852	0.874	0.896	0.918	0.940	0.963	0.985	1.007
9⁄16	0.894	0.905	0.916	0.927	0.938	0.950	0.972	0.994	1.016	1.038	1.061	1.083	1.105
5⁄8	0.992	1.003	1.014	1.025	1.036	1.048	1.070	1.092	1.114	1.136	1.159	1.181	1.203
11⁄16	1.091	1.102	1.113	1.124	1.135	1.147	1.169	1.191	1.213	1.235	1.258	1.280	1.302
3⁄4	1.189	1.200	1.211	1.222	1.233	1.245	1.267	1.289	1.311	1.333	1.356	1.378	1.400
13⁄16	1.288	1.299	1.310	1.321	1.332	1.344	1.366	1.388	1.410	1.432	1.455	1.477	1.499
7⁄8	1.386	1.397	1.408	1.419	1.430	1.442	1.464	1.486	1.508	1.530	1.553	1.575	1.597
15⁄16	1.483	1.494	1.505	1.516	1.527	1.539	1.561	1.583	1.605	1.627	1.650	1.672	1.694
1	1.582	1.593	1.604	1.615	1.626	1.638	1.660	1.682	1.704	1.726	1.749	1.771	1.793
1 1⁄16	1.680	1.691	1.702	1.713	1.724	1.736	1.758	1.780	1.802	1.824	1.847	1.869	1.891
1 1⁄8	1.779	1.790	1.801	1.812	1.823	1.835	1.857	1.879	1.901	1.923	1.946	1.968	1.990
1 3⁄16	1.877	1.888	1.899	1.910	1.921	1.933	1.955	1.977	1.999	2.021	2.044	2.066	2.088
1 1⁄4	1.974	1.985	1.996	2.007	2.018	2.030	2.052	2.074	2.096	2.118	2.141	2.163	2.185

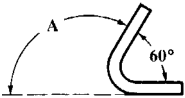


Fig. 1.

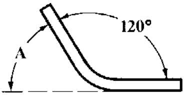


Fig. 2.

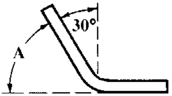


Fig. 3.

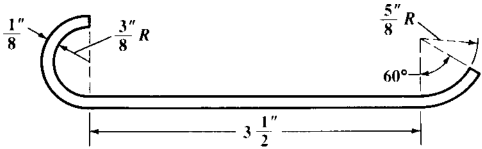


Fig. 4.

Example, Showing Application of Formulas: Find the length before bending of the part illustrated by Fig. 4. Soft steel is to be used.

For bend at left-hand end (180-degree bend)

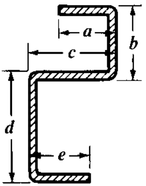
$$L = [(0.64 \times 0.125) + (1.57 \times 0.375)] \times \frac{180}{90} = 1.338$$

For bend at right-hand end (60-degree bend)

$$L = [(0.64 \times 0.125) + (1.57 \times 0.625)] \times \frac{60}{90} = 0.707$$

Total length before bending = 3.5 + 1.338 + 0.707 = 5.545 inches

Other Bending Allowance Formulas.—When bending sheet steel or brass, add from ⅓ to ½ of the thickness of the stock, for *each bend,* to the sum of the inside dimensions of the finished piece, to get the length of the straight blank. The harder the material the greater the allowance (⅓ of the thickness is added for soft stock and ½ of the thickness for hard material). The data given in the table, *Allowances for Bends in Sheet Metal,* refer more particularly to the bending of sheet metal for counters, bank fittings and general office fixtures, for which purpose it is not absolutely essential to have the sections of the bends within very close limits. Absolutely accurate data for this work cannot be deduced, as the stock varies considerably as to hardness, etc. The figures given apply to sheet steel, aluminum, brass and bronze. Experience has demonstrated that for the semisquare corners, such as are formed in a V-die, the amount to be deducted from the sum of the outside bend dimensions, as shown in the accompanying illustration by the sum of the letters from *a* to *e,* is as follows: $X = 1.67\ BG$, where X = the amount to be deducted; B = the number of bends; and G = the decimal equivalent of the gage. The values of X for different gages and numbers of bends are given in the table. Its application may be illustrated by an example: A strip having two bends is to have outside dimensions of 2, 1½ and 2 inches, and is made of stock 0.125 inch thick. The sum of the outside dimensions is thus 5½ inches, and from the table the amount to be deducted is found to be 0.416; hence the blank will be 5.5 − 0.416 = 5.084 inches long.



The lower part of the table applies to square bends which are either drawn through a block of steel made to the required shape, or else drawn through rollers in a drawbench. The pressure applied not only gives a much sharper corner, but it also elongates the material more than in the V-die process. In this case, the deduction is $X = 1.33\ BG$.

Allowances for Bends in Sheet Metal

Square Bends	Gage	Thickness Inches	Amount to be Deducted from the Sum of the Outside Bend Dimensions, Inches						
			1 Bend	2 Bends	3 Bends	4 Bends	5 Bends	6 Bends	7 Bends
Formed in a Press by a V-die	18	0.0500	0.083	0.166	0.250	0.333	0.416	0.500	0.583
	16	0.0625	0.104	0.208	0.312	0.416	0.520	0.625	0.729
	14	0.0781	0.130	0.260	0.390	0.520	0.651	0.781	0.911
	13	0.0937	0.156	0.312	0.468	0.625	0.781	0.937	1.093
	12	0.1093	0.182	0.364	0.546	0.729	0.911	1.093	1.276
	11	0.1250	0.208	0.416	0.625	0.833	1.041	1.250	1.458
	10	0.1406	0.234	0.468	0.703	0.937	1.171	1.406	1.643

Square Bends	Gage	Thickness Inches	Amount to be Deducted from the Sum of the Outside Bend Dimensions, Inches						
			1 Bend	2 Bends	3 Bends	4 Bends	5 Bends	6 Bends	7 Bends
Rolled or Drawn in a Draw-bench	18	0.0500	0.066	0.133	0.200	0.266	0.333	0.400	0.466
	16	0.0625	0.083	0.166	0.250	0.333	0.416	0.500	0.583
	14	0.0781	0.104	0.208	0.312	0.416	0.521	0.625	0.729
	13	0.0937	0.125	0.250	0.375	0.500	0.625	0.750	0.875
	12	0.1093	0.145	0.291	0.437	0.583	0.729	0.875	1.020
	11	0.1250	0.166	0.333	0.500	0.666	0.833	1.000	1.166
	10	0.1406	0.187	0.375	0.562	0.750	0.937	1.125	1.312

Fine Blanking

The process called fine blanking uses special presses and tooling to produce flat components from sheet metal or plate, with high dimensional accuracy. According to Hydrel A. G., Romanshorn, Switzerland, fine-blanking presses can be powered hydraulically or mechanically, or by a combination of these methods, but they must have three separate and distinct movements. These movements serve to clamp the work material, to perform the blanking operation, and to eject the finished part from the tool. Forces of 1.5–2.5 times those used in conventional stamping are needed for fine blanking, so machines and tools must be designed and constructed accordingly. In mechanical fine-blanking presses the clamping and ejection forces are exerted hydraulically. Such presses generally are of toggle-type design and are limited to total forces of up to about 280 tons. Higher forces generally require all-hydraulic designs. These presses are also suited to embossing, coining, and impact extrusion work.

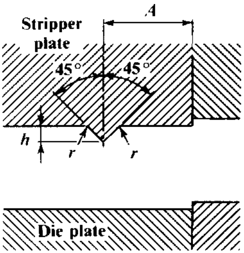
Cutting elements of tooling for fine blanking generally are made from 12 per cent chromium steel, although high speed steel and tungsten carbide also are used for long runs or improved quality. Cutting clearances between the intermediate punch and die are usually held between 0.0001 and 0.0003 in. The clamping elements are sharp projections of 90-degree V-section that follow the outline of the workpiece and that are incorporated into each tool as part of the stripper plate with thin material and also as part of the die plate when material thicker than 0.15 in. is to be blanked. Pressure applied to the elements containing the V-projections prior to the blanking operation causes the sharp edges to enter the material surface, preventing sideways movement of the blank. The pressure applied as the projections bite into the work surface near the contour edges also squeezes the material, causing it to flow toward the cutting edges, reducing the usual rounding effect at the cut edge. When small details such as gear teeth are to be produced, V-projections are often used on both sides of the work, even with thin materials, to enhance the flow effect. With suitable tooling, workpieces can be produced with edges that are perpendicular to top and bottom surfaces within 0.004 in. on thicknesses of 0.2 in., for instance. V-projection dimensions for various material thicknesses are shown in the table.

Fine-blanked edges are free from the fractures that result from conventional tooling, and can have surface finishes down to 80 μin. Ra with suitable tooling. Close tolerances can be held on inner and outer forms, and on hole center distances. Flatness of fine-blanked components is better than that of parts made by conventional methods, but distortion may occur with thin materials due to release of internal stresses. Widths must be slightly greater than are required for conventional press working. Generally, the strip width must be 2–3 times the thickness, plus the width of the part measured transverse to the feed direction. Other factors to be considered are shape, material quality, size and shape of the V-projection in relation to the die outline, and spacing between adjacent blanked parts. Holes and slots can be produced with ratios of width to material thickness down to 0.7, compared with the 1:1 ratio normally specified for conventional tooling. Operations such as countersinking, coining, and bending up to 60 degrees can be incorporated in fine-blanking tooling.

The cutting force in lb exerted in fine blanking is 0.9 times the length of the cut in inches times the material thickness in inches, times the tensile strength in $lb_f/in.^2$. Pressure in lb exerted by the clamping element(s) carrying the V-projections is calculated by multiplying the length of the V-projection, which depends on its shape, in inches by its height (h), times the material tensile strength in $lb_f/in.^2$, times an empirical factor f. Factor f has been determined to be 2.4–4.4 for a tensile strength of 28,000–113,000 $lb_f/in.^2$. The clamping pressure is approximately 30 per cent of the cutting force, calculated as above. Dimensions and positioning of the V-projection(s) are related to the material thickness, quality, and tensile strength. A small V-projection close to the line of cut has about the same effect as a large V-projection spaced away from the cut. However, if the V-projection is too close to the cut, it may move out of the material at the start of the cutting process, reducing its effectiveness.

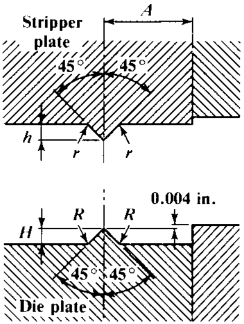
Positioning the V-projection at a distance from the line of cut increases both material and blanking force requirements. Location of the V-projection relative to the line of cut also affects tool life.

Dimensions for V-projections Used in Fine-Blanking Tools



V-Projections On Stripper Plate Only

Material Thickness	*A*	*h*	*r*
0.040-0.063	0.040	0.012	0.008
0.063-0.098	0.055	0.015	0.008
0.098-0.125	0.083	0.024	0.012
0.125-0.157	0.098	0.028	0.012
0.157-0.197	0.110	0.032	0.012



V-Projections On Both Stripper and Die Plate

Material Thickness	*A*	*H*	*R*	*h*	*r*
0.157–0.197	0.098	0.032	0.032	0.020	0.008
0.197–0.248	0.118	0.040	0.040	0.028	0.008
0.248–0.315	0.138	0.047	0.047	0.032	0.008
0.315–0.394	0.177	0.060	0.060	0.040	0.020
0.394–0.492	0.217	0.070	0.080	0.047	0.020
0.492–0.630	0.276	0.087	0.118	0.063	0.020

All units are in inches.

Steel Rule Dies

Steel rule dies (or knife dies) were patented by Robert Gair in 1879, and, as the name implies, have cutting edges made from steel strips of about the same proportions as the steel strips used in making graduated rules for measuring purposes. According to J. A. Richards, Sr., of the J. A. Richards Co., Kalamazoo, MI, a pioneer in the field, these dies were first used in the printing and shoemaking industries for cutting out shapes in paper, cardboard, leather, rubber, cork, felt, and similar soft materials. Steel rule dies were later adopted for cutting upholstery material for the automotive and other industries, and for cutting out simple to intricate shapes in sheet metal, including copper, brass, and aluminum. A typical steel rule die, partially cut away to show the construction, is shown in Fig. 1, and is designed for cutting a simple circular shape. Such dies generally cost 25 to 35 per cent of the cost of conventional blanking dies, and can be produced in much less time. The die shown also cuts a rectangular opening in the workpiece, and pierces four holes, all in one press stroke.

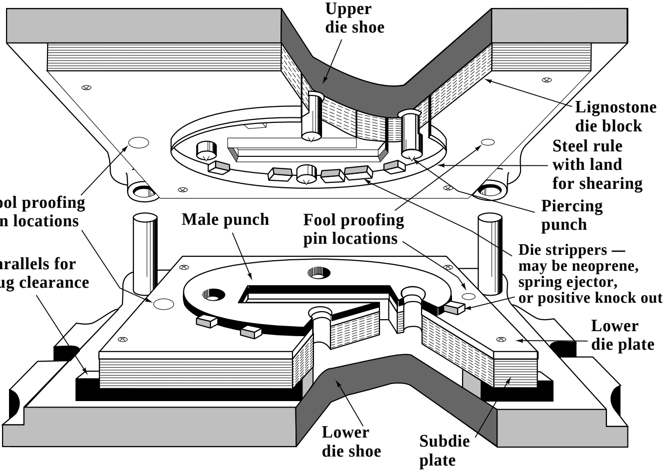


Fig. 1. Steel Rule Die for Cutting a Circular Shape, Sectioned to Show the Construction

The die blocks that hold the steel strips on edge on the press platen or in the die set may be made from plaster, hot lead or type metal, or epoxy resin, all of which can be poured to shape. However, the material most widely used for light work is $\frac{3}{4}$-in. thick, five- or seven-ply maple or birch wood. Narrow slots are cut in this wood with a jig saw to hold the strips vertically. Where greater forces are involved, as with operations on metal sheets, the blocks usually are made from Lignostone densified wood or from metal. In the $\frac{3}{4}$-in. thickness mostly used, medium- and high-density grades of Lignostone are available. The $\frac{3}{4}$-in. thickness is made from about 35 plies of highly compressed lignite wood, bonded with phenolformaldehyde resin, which imparts great density and strength. The material is made in thicknesses up to 6 in., and in various widths and lengths.

Steel rule die blocks can carry punches of various shapes to pierce holes in the stock, also projections designed to form strengthening ribs and other shapes in material such as aluminum, at the same time as the die cuts the component to shape. Several dies can be combined or nested, and operated together in a large press, to produce various shapes simultaneously from one sheet of material.

As shown in Fig. 1, the die steel is held in the die block slot on its edge, usually against the flat platen of a die set attached to the moving slide of the press. The sharp, free end of the rule faces toward the workpiece, which is supported by the face of the other die half. This other die half may be flat or may have a punch attached to it, as shown, and it withstands the pressure exerted in the cutting or forming action when the press is operated. The closed height of the die is adjusted to permit the cutting edge to penetrate into the material to the extent needed, or, if there is a punch, to carry the cutting edges just past the punch edges for the cutting operation. After the sharp edge has penetrated it, the material often clings to the sides of the knife. Ejector inserts made from rubber, combinations of cork and rubber, and specially compounded plastics material, or purpose-made ejectors, either spring- or positively actuated, are installed in various positions alongside the steel rules and the punch. These ejectors are compressed as the dies close, and when the dies open, they expand, pushing the material clear of the knives or the punch.

The cutting edges of the steel rules can be of several shapes, as shown in profile in Fig. 2, to suit the material to be cut, or the type of cutting operation. Shape *A* is used for shearing in the punch in making tools for blanking and piercing operations, the sharp edge later being modified to a flat, producing a 90° cutting edge, *B*. The other shapes in Fig. 2 are used for cutting various soft materials that are pressed against a flat surface for cutting. The shape at *C* is used for thin, and the shape at *D* for thicker materials.

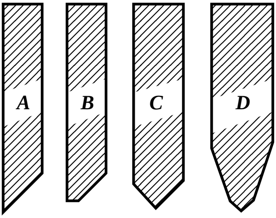


Fig. 2. Cutting Edges for Steel Rule Dies

Steel rule die steel is supplied in lengths of 30 and 50 in., or in coils of any length, with the edges ground to the desired shape, and heat treated, ready for use. The rule material width is usually referred to as the height, and material can be obtained in heights of 0.95, 1, $1\frac{1}{8}$, $1\frac{1}{4}$, and $1\frac{1}{2}$ in. Rules are available in thicknesses of 0.055, 0.083, 0.11, 0.138, 0.166, and 0.25 in. (4 to 18 points in printers' measure of 72 points = 1 in.). Generally, stock thicknesses of 0.138 or 0.166 in. (10 and 12 points) are preferred, the thinner rules being used mainly for dies requiring intricate outlines. The stock can be obtained in soft or hard temper. The standard edge bevel is 46°, but bevels of 40 to 50° can be used. Thinner rule stock is easiest to form to shape and is often used for short runs of 50 pieces or thereabouts. The thickness and hardness of the material to be blanked also must be considered when choosing rule thickness.

Making of Steel Rule Dies.—Die making begins with a drawing of the shape required. Saw cutting lines may be marked directly on the face of the die block in a conventional layout procedure using a height gage, or a paper drawing may be pasted to or drawn on the die board. Because paper stretches and shrinks, Mylar or other nonshrink plastics sheets may be preferred for the drawing. A hole is drilled off the line to allow a jig saw to be inserted, and jig saw or circular saw cuts are then made under manual control along the drawing lines to produce the slots for the rules. Jig saw blades are available in a range of sizes to suit various thicknesses of rule and for sawing medium-density Lignostone, a speed of 300 strokes/min is recommended, the saw having a stroke of about 2 in. To make sure the rule thickness to be used will be a tight fit in the slot, trials are usually carried out on scrap pieces of die block before cuts are made on a new block.

During slot cutting, the saw blade must always be maintained vertical to the board being cut, and magnifying lenses are often used to keep the blade close to the line. Carbide or carbide-tipped saw blades are recommended for clean cuts as well as for long life. To keep any "islands" (such as the center of a circle) in position, various places in the sawn line are cut to less than full depth for lengths of $\frac{1}{4}$ to $\frac{1}{2}$ in., and to heights of $\frac{5}{8}$ to $\frac{3}{4}$ in. to bridge the gaps. Slots of suitable proportions must be provided in the steel rules, on the sides away from the cutting edges, to accommodate these die block bridges.

Rules for steel rule dies are bent to shape to fit the contours called for on the drawing by means of small, purpose-built bending machines, fitted with suitable tooling. For bends of small radius, the tooling on these machines is arranged to perform a peening or hammering action to force the steel rule into close contact with the radius-forming component of the machine so that quite small radii, as required for jig saw puzzles, for instance, can be produced with good accuracy. Some forms are best made in two or more pieces, then joined by welding or brazing. The edges to be joined are mitered for a perfect fit, and are clamped securely in place for joining. Electrical resistance or a gas heating torch is used to heat the joint. Wet rags are applied to the steel at each side of the joint to keep the material cool and the hardness at the preset level, as long as possible.

When shapes are to be blanked from sheet metal, the steel rule die is arranged with flat, 90° edges (*B*, in Fig. 2), which cut by pushing the work past a close-fitting counter-punch. This counterpunch, shown in Fig. 1, may be simply a pad of steel or other material, and has an outline corresponding to the shape of the part to be cut. Sometimes the pad may be given a gradual, slight reduction in height to provide a shearing action as the moving tool pushes the work material past the pad edges. As shown in Fig. 1, punches can be incorporated in the die to pierce holes, cut slots, or form ribs and other details during the blanking operation. These punches are preferably made from high-carbon, high-vanadium, alloy steel, heat treated to Rc 61 to 63, with the head end tempered to Rc 45 to 50.

Heat treatment of the high-carbon-steel rules is designed to produce a hardness suited to the application. Rules in dies for cutting cartons and similar purposes, with mostly straight cuts, are hardened to Rc 51 to 58. For dies requiring many intricate bends, lower-carbon material is used, and is hardened to Rc 38 to 45. And for dies to cut very intricate shapes, a steel in dead-soft condition with hardness of about Rb 95 is recommended. After the intricate bends are made, this steel must be carburized before it is hardened and tempered. For this material, heat treatment uses an automatic cycle furnace, and consists of carburizing in a liquid compound heated to 1500°F and quenching in oil, followed by "tough" tempering at 550°F and cooling in the furnace.

After the hardened rule has been reinstalled in the die block, the tool is loaded into the press and the sharp die is used with care to shear the sides of the pad to match the die contours exactly. A close fit, with clearances of about half those used in conventional blanking dies, is thus ensured between the steel rule and the punch. Adjustments to the clearances can be made at this point by grinding the die steel or the punch. After the adjustment work is done, the sharp edges of the rule steel are ground flat to produce a land of about $\frac{1}{64}$ in. wide (*A* in Fig. 2), for the working edges of the die. Clearances for piercing punches should be similar to those used on conventional piercing dies.

ELECTRICAL DISCHARGE MACHINING

Generally called EDM, electrical discharge machining uses an electrode to remove metal from a workpiece by generating electric sparks between conducting surfaces. The two main types of EDM are termed sinker or plunge, used for making mold or die cavities, and wire, used to cut shapes such as are needed for stamping dies. For die sinking, the electrode usually is made from copper or graphite and is shaped as a positive replica of the shape to be formed on or in the workpiece. A typical EDM sinker machine, shown diagrammatically in Fig. 1, resembles a vertical milling machine, with the electrode attached to the vertical slide. The slide is moved down and up by an electronic, servo-controlled drive unit that controls the spacing between the electrode and the workpiece on the table. The table can be adjusted in three directions, often under numerical control, to positions that bring a workpiece surface to within 0.0005 to 0.030 in. from the electrode surface, where a spark is generated.

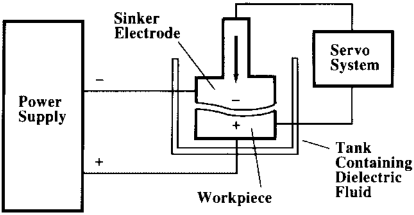


Fig. 1. Sinker or Plunge Type EDM Machines Are Used to Sink Cavities in Molds and Dies

Wire EDM, shown diagrammatically in Fig. 2, are numerically controlled and somewhat resemble a bandsaw with the saw blade replaced by a fine brass or copper wire, which forms the electrode. This wire is wound off one reel, passed through tensioning and guide rollers, then through the workpiece and through lower guide rollers before being wound onto another reel for storage and eventual recycling. One set of guide rollers, usually the lower, can be moved on two axes at 90 degrees apart under numerical control to adjust the angle of the wire when profiles of varying angles are to be produced. The table also is movable in two directions under numerical control to adjust the position of the workpiece relative to the wire. Provision must be made for the cut-out part to be supported when it is freed from the workpiece so that it does not pinch and break the wire.

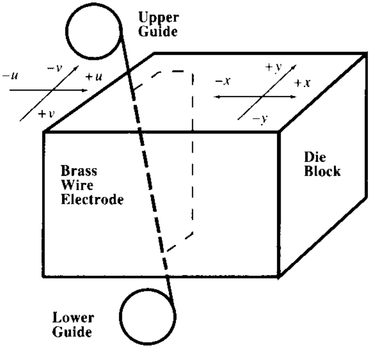


Fig. 2. Wire Type EDM Machines Are Used to Cut Stamping Die Profiles.

EDM applied to grinding machines is termed EDG. The process uses a graphite wheel as an electrode, and wheels can be up to 12 in. in diameter by 6 in. wide. The wheel periphery is dressed to the profile required on the workpiece and the wheel profile can then be transferred to the workpiece as it is traversed past the wheel, which rotates but does not touch the work. EDG machines are highly specialized and are mainly used for producing complex profiles on polycrystaline diamond cutting tools and for shaping carbide tooling such as form tools, thread chasers, dies, and crushing rolls.

EDM Terms*

Anode: The positive terminal of an electrolytic cell or battery. In EDM, incorrectly applied to the tool or electrode.

Barrel effect: In wire EDM, a condition where the center of the cut is wider than the entry and exit points of the wire, due to secondary discharges caused by particles being pushed to the center by flushing pressure from above and beneath the workpiece.

Capacitor: An electrical component that stores an electric charge. In some EDM power supplies, several capacitors are connected across the machining gap and the current for the spark comes directly from the capacitors when they are discharged.

Cathode: The negative terminal in an electrolytic cell or battery. In EDM incorrectly applied to the workpiece.

Colloidal suspension: Particles suspended in a liquid that are too fine to settle out. In EDM, the tiny particles produced in the sparking action form a colloidal suspension in the dielectric fluid.

Craters: Small cavities left on an EDM surface by the sparking action. Also known as pits.

Dielectric filter : A filter that removes particles from 5 μm (0.00020 in.) down to as fine as 1 μm (0.00004 in) in size, from dielectric fluid.

Dielectric fluid : The non-conductive fluid that circulates between the electrode and the workpiece to provide the dielectric strength across which an arc can occur, to act as a coolant to solidify particles melted by the arc, and to flush away the solidified particles.

Dielectric strength: In EDM, the electrical potential (voltage) needed to break down (ionize) the dielectric fluid in the gap between the electrode and the workpiece.

Discharge channel: The conductive pathway formed by ionized dielectric and vapor between the electrode and the workpiece.

Dither: A slight up and down movement of the machine ram and attached electrode, used to improve cutting stability.

Duty cycle: The percentage of a pulse cycle during which the current is turned on (on time), relative to the total duration of the cycle.

EDG: Electrical discharge grinding using a machine that resembles a surface grinder but has a wheel made from electrode material. Metal is removed by an EDM process rather than by grinding.

Electrode growth: A plating action that occurs at certain low-power settings, whereby workpiece material builds up on the electrode, causing an increase in size.

Electrode wear: Amount of material removed from the electrode during the EDM process. This removal can be end wear or corner wear, and is measured linearly or volumetrically but is most often expressed as end wear per cent, measured linearly.

Electro-forming: An electro-plating process used to make metal EDM electrodes.

Energy: Measured in joules, is the equivalent of volt-coulombs or volt-ampere- seconds.

Farad: Unit of electrical capacitance, or the energy-storing capacity of a capacitor.

---

* *Source:* Hansvedt Industries

Gap: The closest point between the electrode and the workpiece where an electrical discharge will occur. (See *Overcut*)

Gap current: The average amperage flowing across the machining gap.

Gap voltage: The voltage across the gap while current is flowing. The voltage across the electrode/workpiece before current flows is called the open gap voltage. Heat-affected zone. The layer below the recast layer, which has been subjected to elevated temperatures that have altered the properties of the workpiece metal.

Ion: An atom or group of atoms that has lost or gained one or more electrons and is therefore carrying a positive or negative electrical charge, and is described as being ionized.

Ionization: The change in the dielectric fluid that is subjected to a voltage potential whereby it becomes electrically conductive, allowing it to conduct the arc.

Low-wear: An EDM process in which the volume of electrode wear is between 2 and 15 per cent of the volume of workpiece wear. Normal negative polarity wear ratios are 15 to 40 per cent.

Negative electrode: When the electrode voltage potential is negative with respect to the workpiece.

No-wear: An EDM process in which electrode wear is virtually eliminated and the wear ratio is usually less than 2 per cent by volume.

Orbit: A programmable motion between the electrode and the workpiece, produced by a feature built in to the machine, or an accessory, that produces a cavity or hole larger than the electrode. The path can be planetary (circular), vectorial, or polygonal (trace). These motions can often be performed in sequence, and combined with x-axis movement of the electrode.

Overcut: The distance between one side of an electrode and the adjacent wall of the workpiece cavity.

Overcut taper: The difference between the overcut dimensions at the top (entrance) and at the bottom of the cavity.

Plasma: A superheated, highly ionized gas that forms in the discharge channel due to the applied voltage.

Positive electrode: The electrode voltage potential is positive with respect to the workpiece. is the opposite of this condition.

Power parameters: A set of power supply, servo, electrode material, workpiece material, and flushing settings that are selected to produce a desired metal removal rate and surface finish.

Quench: The rapid cooling of the EDM surface by the dielectric fluid, which is partially responsible for metallurgical changes in the recast layer and in the heat- affected zone.

Recast layer: A layer created by the solidification of molten metal on the workpiece surface after it has been melted by the EDM process.

Secondary discharge: A discharge that occurs as conductive particles are carried out along the side of the electrode by the dielectric fluid.

Spark in: A method of locating an electrode with respect to the workpiece, using high frequency, low amperage settings so that there is no cutting action. The electrode is advanced toward the workpiece until contact is indicated and this point is used as the basis for setting up the job.

Spark out: A technique used in orbiting, which moves the electrode in the same path until sparking ceases.

Square wave: An electrical wave shape generated by a solid state power supply.

Stroke: The distance the ram travels under servo control.

UV axis: A mechanism that provides for movement of the upper head of a wire EDM machine to allow inclined surfaces to be generated.

White layer: The surface layer of an EDM cut that is affected by the heat generated during the process. The characteristics of the layer depend on the material, and may be extremely hard martensite or an annealed layer.

Wire EDM: An EDM machine or process in which the electrode is a continuously unspooling, conducting wire that moves in preset patterns in relation to the workpiece.

Wire guide: A replaceable precision round diamond insert, sized to match the wire, that guides the wire at the entrance and exit points of a wire cut.

Wire speed: The rate at which the wire is fed axially through the workpiece (not the rate at which cutting takes place), adjusted so that clean wire is maintained in the cut but slow enough to minimize waste.

The EDM Process.—During the EDM process, energy from the sparks created between the electrode and the workpiece is dissipated by the melting and vaporizing of the workpiece material preferentially, only small amounts of material being lost from the electrode. When current starts to flow between the electrode and the work, the dielectric fluid in the small area in which the gap is smallest, and in which the spark will occur, is transformed into a plasma of hydrogen, carbon, and various oxides. This plasma forms a conducting passageway, consisting of ionized or electrically charged particles, through which the spark can form between the electrode and the workpiece. After current starts to flow, to heat and vaporize a tiny area, the striking voltage is reached, the voltage drops, and the field of ionized particles loses its energy, so that the spark can no longer be sustained. As the voltage then begins to rise again with the increase in resistance, the electrical supply is cut off by the control, causing the plasma to implode and creating a low-pressure pulse that draws in dielectric fluid to flush away metallic debris and cool the impinged area. Such a cycle typically lasts a few microseconds (millionths of a second, or μs), and is repeated continuously in various places on the workpiece as the electrode is moved into the work by the control system.

Flushing: An insulating dielectric fluid is made to flow in the space between the workpiece and the electrode to prevent premature spark discharge, cool the workpiece and the electrode, and flush away the debris. For sinker machines, this fluid is paraffin, kerosene, or a silicon-based dielectric fluid, and for wire machines, the dielectric fluid is usually deionized water. The dielectric fluid can be cooled in a heat exchanger to prevent it from rising above about 100°F, at which cooling efficiency may be reduced. The fluid must also be filtered to remove workpiece particles that would prevent efficient flushing of the spark gaps. Care must be taken to avoid the possibility of entrapment of gases generated by sparking. These gases may explode, causing danger to life, breaking a valuable electrode or workpiece, or causing a fire.

Flushing away of particles generated during the process is vital to successful EDM operations. A secondary consideration is the heat transferred to the side walls of a cavity, which may cause the workpiece material to expand and close in around the electrode, leading to formation of dc arcs where conductive particles are trapped. Flushing can be done by forcing the fluid to pass through the spark gap under pressure, by sucking it through the gap, or by directing a side nozzle to move the fluid in the tank surrounding the workpiece. In pressure flushing, fluid is usually pumped through strategically placed holes in the electrode or in the workpiece. Vacuum flushing is used when side walls must be accurately formed and straight, and is seldom needed on numerically controlled machines because the table can be programmed to move the workpiece sideways.

Flushing needs careful consideration because of the forces involved, especially where fluid is pumped or sucked through narrow passageways, and large hydraulic forces can easily be generated. Excessively high pressures can lead to displacement of the electrode, the workpiece, or both, causing inaccuracy in the finished product. Many low-pressure flushing holes are preferable to a few high-pressure holes. Pressure-relief valves in the system are recommended.

Electronic Controls: The electrical circuit that produces the sparks between the electrode and the workpiece is controlled electronically, the length of the extremely short on and off periods being matched by the operator or the programmer to the materials of the electrode and the workpiece, the dielectric, the rate of flushing, the speed of metal removal, and the quality of surface finish required. The average current flowing between the electrode and the workpiece is shown on an ammeter on the power source, and is the determining factor in machining time for a specific operation. The average spark gap voltage is shown on a voltmeter.

EDM machines can incorporate provision for orbiting the electrode so that flushing is easier, and cutting is faster and increased on one side. Numerical control can also be used to move the workpiece in relation to the electrode with the same results. Numerical control can also be used for checking dimensions and changing electrodes when necessary. The clearance on all sides between the electrode and the workpiece, after the machining operation, is called the overcut or overburn. The overcut becomes greater with increases in the on time, the spark energy, or the amperage applied, but its size is little affected by voltage changes. Allowances must be made for overcut in the dimensioning of electrodes. Sidewall encroachment and secondary discharge can take up parts of these allowances, and electrodes must always be made smaller to avoid making a cavity or hole too large.

Polarity: Polarity can affect processing speed, finish, wear, and stability of the EDM operation. On sinker machines, the electrode is generally, made positive to protect the electrode from excessive wear and preserve its dimensional accuracy. This arrangement removes metal at a slower rate than electrode negative, which is mostly used for high-speed metal removal with graphite electrodes. Negative polarity is also used for machining carbides, titanium, and refractory alloys using metallic electrodes. Metal removal with graphite electrodes can be as much as 50 per cent faster with electrode negative polarity than with electrode positive, but negative polarity results in much faster electrode wear, so it is generally restricted to electrode shapes that can be redressed easily.

Newer generators can provide less than 1 per cent wear with either copper or graphite electrodes during roughing operations. Roughing is typically done with a positive-polarity electrode using elevated on times. Some electrodes, particularly micrograin graphites, have a high resistance to wear. Fine-grain, high-density graphites provide better wear characteristics than coarser, less dense grades, and copper-tungsten resists wear better than pure copper electrodes.

Machine Settings: For vertical machines, a rule of thumb for power selection on graphite and copper electrodes is 50 to 65 amps per square inch of electrode engagement. For example, an electrode that is $\frac{1}{2}$ in. square might use $0.5 \times 0.5 \times 50 = 12.5$ amps. Although each square inch of electrode surface may be able to withstand higher currents, lower settings should be used with very large jobs or the workpiece may become overheated and it may be difficult to clean up the recast layer. Lower amperage settings are required for electrodes that are thin or have sharp details. The voltage applied across the arc gap between the electrode and the workpiece is ideally about 35 volts, but should be as small as possible to maintain stability of the process.

Spark Frequency: Spark frequency is the number of times per second that the current is switched on and off. Higher frequencies are used for finishing operations and for work on cemented carbide, titanium, and copper alloys. The frequency of sparking affects the surface finish produced, low frequencies being used with large spark gaps for rapid metal removal with a rough finish, and higher frequencies with small gaps for finer finishes. High frequency usually increases, and low frequency reduces electrode wear.

The Duty Cycle: Electronic units on modern EDM machines provide extremely close control of each stage in the sparking cycle, down to millionths of a second (µs). A typical EDM cycle might last 100 µs. Of this time, the current might be on for 40 µs and off for 60 µs. The relationship between the lengths of the on and off times is called the duty cycle and it indicates the degree of efficiency of the operation. The duty cycle states the on time as a percentage of the total cycle time and in the previous example it is 40 per cent. Although reducing the off time will increase the duty cycle, factors such as flushing efficiency, electrode and workpiece material, and dielectric condition control the minimum off time. Some EDM units incorporate sensors and fuzzy logic circuits that provide for adaptive control of cutting conditions for unattended operation. Efficiency is also reported as the amount of metal removed, expressed as in.^{3}/hr.

In the EDM process, work is done only during the on time, and the longer the on time, the more material is removed in each sparking cycle. Roughing operations use extended on time for high metal-removal rates, resulting in fewer cycles per second, or lower frequency. The resulting craters are broader and deeper so that the surface is rougher and the heat-affected zone (HAZ) on the workpiece is deeper. With positively charged electrodes, the spark moves from the electrode toward the workpiece and the maximum material is removed from the workpiece. However, every spark takes a minute particle from the electrode so that the electrode also is worn away. Finishing electrodes tend to wear much faster than roughing electrodes because more sparks are generated in unit time.

The part of the cycle needed for reionizing the dielectric (the off time) greatly affects the operating speed. Although increasing the off time slows the process, longer off times can increase stability by providing more time for the ejected material to be swept away by the flow of the dielectric fluid, and for deionization of the fluid, so that erratic cycling of the servo-mechanisms that advance and retract the electrode is avoided. In any vertical EDM operation, if the overcut, wear, and finish are satisfactory, machining speed can best be adjusted by slowly decreasing the off time setting in small increments of 1 to 5 µs until machining becomes erratic, then returning to the previous stable setting. As the off time is decreased, the machining gap or gap voltage will slowly fall and the working current will rise. The gap voltage should not be allowed to drop below 35 to 40 volts.

Metal Removal Rates (MRR): Amounts of metal removed in any EDM process depend largely on the length of the on time, the energy/spark, and the number of sparks/second. The following data were provided by Poco Graphite, Inc., in their *EDM Technical Manual*. For a typical roughing operation using electrode positive polarity on high-carbon steel, a 67 per cent duty cycle removed 0.28 in.^{3}/hr. For the same material, a 50 per cent duty cycle removed 0.15 in.^{3}/hr, and a 33 per cent duty cycle for finishing removed 0.075 in.^{3}/hr.

In another example, shown in the top data row in Table 1, a 40 per cent duty cycle with a frequency of 10 kHz and peak current of 50 amps was run for 5 minutes of cutting time. Metal was removed at the rate of 0.8 in.^{3}/hr with electrode wear of 2.5 per cent and a surface finish of 400 µin. R_a. When the on and off times in this cycle were halved, as shown in the second data row in Table 1, the duty cycle remained at 40 per cent, but the frequency doubled to 20 kHz. The result was that the peak current remained unaltered, but with only half the on time the MRR was reduced to 0.7 in.^{3}/hr, the electrode wear increased to 6.3 per cent, and the surface finish improved to 300 µin. R_a. The third and fourth rows in Table 1 show other variations in the basic cycle and the results.

Table 1. Effect of Electrical Control Adjustments on EDM Operations

On Time (μs)	Off Time (μs)	Frequency (kHz)	Peak Current (Amps)	Metal Removal Rate (in.^{3}/hr)	Electrode Wear (%)	Surface Finish (μ in. R_a)
40	60	10	50	0.08	2.5	400
20	30	20	50	0.7	6.3	300
40	10	20	50	1.2	1.4	430
40	60	10	25	0.28	2.5	350

The Recast Layer: One drawback of the EDM process when used for steel is the recast layer, which is created wherever sparking occurs. The oil used as a dielectric fluid causes the EDM operation to become a random heat-treatment process in which the metal surface is heated to a very high temperature, then quenched in oil. The heat breaks down the oil into hydrocarbons, tars, and resins, and the molten metal draws out the carbon atoms and traps them in the resolidified metal to form the very thin, hard, brittle surface called the recast layer that covers the heat-affected zone (HAZ). This recast layer has a white appearance and consists of particles of material that have been melted by the sparks, enriched with carbon, and drawn back to the surface or retained by surface tension. The recast layer is harder than the parent metal and can be as hard as glass, and must be reduced or removed by vapor blasting with glass beads, polishing, electrochemical or abrasive flow machining, after the shaping process is completed, to avoid cracking or flaking of surface layers that may cause failure of the part in service.

Beneath the thin recast layer, the HAZ, in steel, consists of martensite that usually has been hardened by the heating and cooling sequences coupled with the heat-sink cooling effect of a thick steel workpiece. This martensite is hard and its rates of expansion and contraction are different from those of the parent metal. If the workpiece is subjected to heating and cooling cycles in use, the two layers are constantly stressed and these stresses may cause formation of surface cracks. The HAZ is usually much deeper in a workpiece cut on a sinker than on a wire machine, especially after roughing, because of the increased heating effect caused by the higher amounts of energy applied.

The depth of the HAZ depends on the amperage and the length of the on time, increasing as these values increase, to about 0.012 to 0.015 in. deep. Residual stress in the HAZ can range up to 650 N/mm^2. The HAZ cannot be removed easily, so it is best avoided by programming the series of cuts taken on the machine so that most of the HAZ produced by one cut is removed by the following cut. If time is available, cut depth can be reduced gradually until the finishing cuts produce an HAZ having a thickness of less than 0.0001 in.

Workpiece Materials.—Most homogeneous materials used in metalworking can be shaped by the EDM process. Some data on typical workpiece materials are given in Table 2. Sintered materials present some difficulties caused by the use of a cobalt or other binder used to hold the carbide or other particles in the matrix. The binder usually melts at a lower temperature than the tungsten, molybdenum, titanium, or other carbides, so it is preferentially removed by the sparking sequence and the carbide particles are thus loosened and freed from the matrix. The structures of sintered materials based on tungsten, cobalt, and molybdenum require higher EDM frequencies with very short on times, so that there is less danger of excessive heat buildup, leading to melting. Copper-tungsten electrodes are recommended for EDM of tungsten carbides. When used with high frequencies for powdered metals, graphite electrodes often suffer from excessive wear.

Workpieces of aluminum, brass, and copper should be processed with metallic electrodes of low melting points such as copper or copper-tungsten. Workpieces of carbon and stainless steel that have high melting points should be processed with graphite electrodes.

Table 2. Characteristics of Common Workpiece Materials for EDM

Material	Specific Gravity	Melting Point °F	Melting Point °C	Vaporization Temperature °F	Vaporization Temperature °C	Conductivity (Silver = 100)
Aluminum	2.70	1220	660	4442	2450	63.00
Brass	8.40	1710	930	…		…
Cobalt	8.71	2696	1480	5520	2900	16.93
Copper	8.89	1980	1082	4710	2595	97.61
Graphite	2.07	N/A		6330	3500	70.00
Inconel	…	2350	1285	…		…
Magnesium	1.83	1202	650	2025	1110	39.40
Manganese	7.30	2300	1260	3870	2150	15.75
Molybdenum	10.20	4748	2620	10,040	5560	17.60
Nickel	8.80	2651	1455	4900	2730	12.89
Carbon Steel	7.80	2500	1371	…		12.00
Tool Steel	…	2730	1500	…		…
Stainless Steel	…	2750	1510	…		…
Titanium	4.50	3200	1700	5900	3260	13.73
Tungsten	18.85	6098	3370	10,670	5930	14.00
Zinc	6.40	790	420	1663	906	26.00

The melting points and specific gravities of the electrode material and of the workpiece should preferably be similar.

Electrode Materials.—Most EDM electrodes are made from graphite, which provides a much superior rate of metal removal than copper because of the ability of graphite to resist thermal damage. Graphite has a density of 1.55 to 1.85 g/cm^3, lower than most metals. Instead of melting when heated, graphite sublimates, that is, it changes directly from a solid to a gas without passing through the liquid stage. Sublimation of graphite occurs at a temperature of 3350°C (6062°F). EDM graphite is made by sintering a compressed mixture of fine graphite powder (1 to 100 micron particle size) and coal tar pitch in a furnace. The open structure of graphite means that it is eroded more rapidly than metal in the EDM process. The electrode surface is also reproduced on the surface of the workpiece. The sizes of individual surface recesses may be reduced during sparking when the work is moved under numerical control of workpiece table movements.

The fine grain sizes and high densities of graphite materials that are specially made for high-quality EDM finishing provide high wear resistance, better finish, and good reproduction of fine details, but these fine grades cost more than graphite of larger grain sizes and lower densities. Premium grades of graphite cost up to five times as much as the least expensive and about three times as much as copper, but the extra cost often can be justified by savings during machining or shaping of the electrode.

Graphite has a high resistance to heat and wear at lower frequencies, but will wear more rapidly when used with high frequencies or with negative polarity. Infiltrated graphites for EDM electrodes are also available as a mixture of copper particles in a graphite matrix, for applications where good machinability of the electrode is required. This material presents a trade-off between lower arcing and greater wear with a slower metal-removal rate, but costs more than plain graphite.

EDM electrodes are also made from copper, tungsten, silver-tungsten, brass, and zinc, which all have good electrical and thermal conductivity. However, all these metals have melting points below those encountered in the spark gap, so they wear rapidly. Copper with 5 per cent tellurium, added for better machining properties, is the most commonly used metal alloy. Tungsten resists wear better than brass or copper and is more rigid when used for thin electrodes but is expensive and difficult to machine. Metal electrodes, with their more even surfaces and slower wear rates, are often preferred for finishing operations on work that requires a smooth finish. In fine-finishing operations, the arc gap between the surfaces of the electrode and the workpiece is very small and there is a danger of dc arcs being struck, causing pitting of the surface. This pitting is caused when particles dislodged from a graphite electrode during fine-finishing cuts are not flushed from the gap. If struck by a spark, such a particle may provide a path for a continuous discharge of current that will mar the almost completed work surface.

Some combinations of electrode and workpiece material, electrode polarity, and likely amounts of corner wear are listed in Table 3. Corner wear rates indicate the ability of the electrode to maintain its shape and reproduce fine detail. The column headed Capacitance refers to the use of capacitors in the control circuits to increase the impact of the spark without increasing the amperage. Such circuits can accomplish more work in a given time, at the expense of surface-finish quality and increased electrode wear.

Table 3. Types of Electrodes Used for Various Workpiece Materials

Electrode	Electrode Polarity	Workpiece Material	Corner Wear (%)	Capacitance
Copper	+	Steel	2–10	No
Copper	+	Inconel	2–10	No
Copper	+	Aluminum	<3	No
Copper	–	Titanium	20–40	Yes
Copper	–	Carbide	35–60	Yes
Copper	–	Copper	34–45	Yes
Copper	–	Copper-tungsten	40–60	Yes
Copper-tungsten	+	Steel	1–10	No
Copper-tungsten	–	Copper	20–40	Yes
Copper-tungsten	–	Copper-tungsten	30–50	Yes
Copper-tungsten	–	Titanium	15–25	Yes
Copper-tungsten	–	Carbide	35–50	Yes
Graphite	+	Steel	<1	No
Graphite	–	Steel	30–40	No
Graphite	+	Inconel	<1	No
Graphite	–	Inconel	30–40	No
Graphite	+	Aluminum	<1	No
Graphite	–	Aluminum	10–20	No
Graphite	–	Titanium	40–70	No
Graphite	–	Copper	N/A	Yes

Electrode Wear: Wear of electrodes can be reduced by leaving the smallest amounts of finishing stock possible on the workpiece and using no-wear or low-wear settings to remove most of the remaining material so that only a thin layer remains for finishing with the redressed electrode. The material left for removal in the finishing step should be only slightly more than the maximum depth of the craters left by the previous cut. Finishing operations should be regarded as only changing the quality of the finish, not removing metal or sizing. Low power with very high frequencies and minimal amounts of offset for each finishing cut are recommended.

On manually adjusted machines, fine finishing is usually carried out by several passes of a full-size finishing electrode. Removal of a few thousandths of an inch from a cavity with such an arrangement requires the leading edge of the electrode to recut the cavity over the entire vertical depth. By the time the electrode has been sunk to full depth, it is so worn that precision is lost. This problem sometimes can be avoided on a manual machine by use of an orbiting attachment that will cause the electrode to traverse the cavity walls, providing improved speed, finish, and flushing, and reducing corner wear on the electrode.

Selection of Electrode Material: Factors that affect selection of electrode material include metal-removal rate, wear resistance (including volumetric, corner, end, and side, with corner wear being the greatest concern), desired surface finish, costs of electrode manufacture and material, and characteristics of the material to be machined. A major factor is the ability of the electrode material to resist thermal damage, but the electrode's density, the polarity, and the frequencies used are all important factors in wear rates. Copper melts at about 1085°C (1985°F) and spark-gap temperatures must generally exceed 3800°C (6872°F), so use of copper may be made unacceptable because of its rapid wear rates. Graphites have good resistance to heat and wear at low frequencies, but will wear more with high frequency, negative polarity, or a combination of these.

Making Electrodes.—Electrodes made from copper and its alloys can be machined conventionally by lathes, and milling and grinding machines, but copper acquires a burr on run-off edges during turning and milling operations. For grinding copper, the wheel must often be charged with beeswax or similar material to prevent loading of the surface. Flat grinding of copper is done with wheels having open grain structures (46-J, for instance) to contain the wax and to allow room for the soft, gummy, copper chips. For finish grinding, wheels of at least 60 and up to 80 grit should be used for electrodes requiring sharp corners and fine detail. These wheels will cut hot and load up much faster, but are necessary to avoid rapid breakdown of sharp corners.

Factors to be considered in selection of electrode materials are: the electrode material cost cost/in^3; the time to manufacture electrodes; difficulty of flushing; the number of electrodes needed to complete the job; speed of the EDM; amount of electrode wear during EDM; and workpiece surface-finish requirements.

Copper electrodes have the advantage over graphite in their ability to be discharge-dressed in the EDM, usually under computer numerical control (CNC). The worn electrode is engaged with a premachined dressing block made from copper-tungsten or carbide. The process renews the original electrode shape, and can provide sharp, burr-free edges. Because of its higher vaporization temperature and wear resistance, discharge dressing of graphite is slow, but graphite has the advantage that it can be machined conventionally with ease.

Machining Graphite: Graphites used for EDM are very abrasive, so carbide tools are required for machining them. The graphite does not shear away and flow across the face of the tool as metal does, but fractures or is crushed by the tool pressure and floats away as a fine powder or dust. Graphite particles have sharp edges and, if allowed to mix with the machine lubricant, will form an abrasive slurry that will cause rapid wear of machine guiding surfaces. The dust may also cause respiratory problems and allergic reactions, especially if the graphite is infiltrated with copper, so an efficient exhaust system is needed for machining.

Compressed air can be used to flush out the graphite dust from blind holes, for instance, but provision must be made for vacuum removal of the dust to avoid hazards to health and problems with wear caused by the hard, sharp-edged particles. Air velocities of at least 500 ft/min are recommended for flushing, and of 2000 ft/min in collector ducts to prevent settling out. Fluids can also be used, but small-pore filters are needed to keep the fluid clean. High-strength graphite can be clamped or chucked tightly but care must be taken to avoid crushing. Collets are preferred for turning because of the uniform pressure they apply to the workpiece. Sharp corners on electrodes made from less dense graphite are liable to chip or break away during machining.

For conventional machining of graphite, tools of high-quality tungsten carbide or polycrystaline diamond are preferred and must be kept sharp. Recommended cutting speeds for high-speed steel tools are 100 to 300, tungsten carbide 500 to 750, and polycrystaline diamond, 500 to 2000 surface ft/min. Tools for turning should have positive rake angles and nose radii of $\frac{1}{64}$ to $\frac{1}{32}$ in. Depths of cut of 0.015 to 0.020 in. produce a better finish than light cuts such as 0.005 in. because of the tendency of graphite to chip away rather than flow across the tool face. Low feed rates of 0.005 in./rev for rough- and 0.001 to 0.003 in./rev for finish-turning are preferred. Cutting off is best done with a tool having an angle of 20°.

For bandsawing graphite, standard carbon steel blades can be run at 2100 to 3100 surface ft/min. Low power feed rates should be used to avoid overloading the teeth and the feed rate should be adjusted until the saw has a very slight speed up at the point of breakthrough. Milling operations require rigid machines, short tool extensions, and firm clamping of parts. Milling cutters will chip the exit side of the cut, but chipping can be reduced by use of sharp tools, positive rake angles, and low feed rates to reduce tool pressure. Feed/tooth for two-flute end mills is 0.003 to 0.005 in. for roughing and 0.001 to 0.003 in. for finishing.

Standard high-speed steel drills can be used for drilling holes but will wear rapidly, causing holes that are tapered or undersized, or both. High-spiral, tungsten carbide drills should be used for large numbers of holes over $\frac{1}{16}$ in. diameter, but diamond-tipped drills will last longer. Pecking cycles should be used to clear dust from the holes. Compressed air can be passed through drills with through coolant holes to clear dust. Feed rates for drilling are 0.0015 to 0.002 in./rev for drills up to $\frac{1}{32}$, 0.001 to 0.003 in./rev for $\frac{1}{32}$- to $\frac{1}{8}$-in. drills, and 0.002 to 0.005 in./rev for larger drills. Standard taps without fluid are best used for through holes, and for blind holes, tapping should be completed as far as possible with a taper tap before the bottoming tap is used.

For surface grinding of graphite, a medium (60) grade, medium-open structure, vitreous-bond, green-grit, silicon-carbide wheel is most commonly used. The wheel speed should be 5300 to 6000 surface ft/min, with traversing feed rates at about 56 ft/min. Roughing cuts are taken at 0.005 to 0.010 in./pass, and finishing cuts at 0.001 to 0.003 in./pass. Surface finishes in the range of 18 to 32 μin. R_a are normal, and can be improved by longer spark-out times and finer grit wheels, or by lapping. Graphite can be centerless ground using a silicon-carbide, resinoid-bond work wheel and a regulating wheel speed of 195 ft/min.

Wire EDM, orbital abrading, and ultrasonic machining are also used to shape graphite electrodes. Orbital abrading uses a die containing hard particles to remove graphite, and can produce a fine surface finish. In ultrasonic machining, a water-based abrasive slurry is pumped between the die attached to the ultrasonic transducer and the graphite workpiece on the machine table. Ultrasonic machining is rapid and can reproduce small details down to 0.002 in. in size, with surface finishes down to 8 μin. R_a. If coolants are used, the graphite should be dried for 1 hour at over 400°F (but not in a microwave oven) to remove liquids before used.

Wire EDM.—In the wire EDM process, with deionized water as the dielectric fluid, carbon is extracted from the recast layer, rather than added to it. When copper-base wire is used, copper atoms migrate into the recast layer, softening the surface slightly so that wire-cut surfaces are sometimes softer than the parent metal. On wire EDM machines, very high amperages are used with very short on times, so that the heat-affected zone (HAZ) is quite shallow. With proper adjustment of the on and off times, the depth of the HAZ can be held below 1 micron (0.00004 in.).

The cutting wire is used only once, so that the portion in the cut is always cylindrical and has no spark-eroded sections that might affect the cut accuracy. The power source controls the electrical supply to the wire and to the drive motors on the table to maintain the preset arc gap within 0.l micron (0.000004 in.) of the programmed position. On wire EDM machines, the water used as a dielectric fluid is deionized by a deionizer included in the cooling system, to improve its properties as an insulator. Chemical balance of the water is also important for good dielectric properties.

Drilling Holes for Wire EDM: Before an aperture can be cut in a die plate, a hole must be provided in the workpiece. Such holes are often “drilled” by EDM, and the wire threaded through the workpiece before starting the cut. The “EDM drill” does not need to be rotated, but rotation will help in flushing and reduce electrode wear. The EDM process can drill a hole 0.04 in. in diameter through 4-in. thick steel in about 3 minutes, using an electrode made from brass or copper tubing. Holes of smaller diameter can be drilled, but the practical limit is 0.012 in. because of the overcut, the lack of rigidity of tubing in small sizes, and the excessive wear on such small electrodes. The practical upper size limit on holes is about 0.12 in. because of the comparatively large amounts of material that must be eroded away for larger sizes. However, EDM is commonly used for making large or deep holes in such hard materials as tungsten carbide. For instance, a 0.2-in. hole has been made in carbide 2.9 in. thick in 49 minutes by EDM. Blind holes are difficult to produce with accuracy, and must often be made with cut-and-try methods.

Deionized water is usually used for drilling and is directed through the axial hole in the tubular electrode to flush away the debris created by the sparking sequence. Because of the need to keep the extremely small cutting area clear of metal particles, the dielectric fluid is often not filtered but is replaced continuously by clean fluid that is pumped from a supply tank to a disposal tank on the machine.

Wire Electrodes: Wire for EDM generally is made from yellow brass containing copper 63 and zinc 37 per cent, with a tensile strength of 50,000 to 145,000 $\text{lb}_f/\text{in.}^2$, and may be from 0.002 to 0.012 in. diameter.

In addition to yellow brass, electrode wires are also made from brass alloyed with aluminum or titanium for tensile strengths of 140,000 to 160,000 $\text{lb}_f/\text{in.}^2$. Wires with homogeneous, uniform electrolytic coatings of alloys such as brass or zinc are also used. Zinc is favored as a coating on brass wires because it gives faster cutting and reduced wire breakage due to its low melting temperature of 419°C, and vaporization temperature of 906°C. The layer of zinc can boil off while the brass core, which melts at 930°C, continues to deliver current.

Some wires for EDM are made from steel for strength, with a coating of brass, copper, or other metal. Most wire machines use wire negative polarity (the wire is negative) because the wire is constantly renewed and is used only once, so wear is not important. Important qualities of wire for EDM include smooth surfaces, free from nicks, scratches and cracks, precise diameters to ±0.00004 in. for drawn and ±0.00006 in. for plated, high tensile strength, consistently good ductility, uniform spooling, and good protective packaging.

IRON AND STEEL CASTINGS

Cast irons and cast steels encompass a large family of ferrous alloys, which, as the name implies, are cast to shape rather than being formed by working in the solid state. In general, cast irons contain more than 2 per cent carbon and from 1 to 3 per cent silicon. Varying the balance between carbon and silicon, alloying with different elements, and changing melting, casting, and heat-treating practices can produce a broad range of properties. In most cases, the carbon exists in two forms: free carbon in the form of graphite and combined carbon in the form of iron carbide (cementite). Mechanical and physical properties depend strongly on the shape and distribution of the free graphite and the type of matrix surrounding the graphite particles.

The four basic types of cast iron are white iron, gray iron, malleable iron, and ductile iron. In addition to these basic types, there are other specific forms of cast iron to which special names have been applied, such as chilled iron, alloy iron, and compacted graphite cast iron.

Gray Cast Iron.—Gray cast iron may easily be cast into any desirable form and it may also be machined readily. It usually contains from 1.7 to 4.5 per cent carbon, and from 1 to 3 per cent silicon. The excess carbon is in the form of graphite flakes and these flakes impart to the material the dark-colored fracture which gives it its name. Gray iron castings are widely used for such applications as machine tools, automotive cylinder blocks, cast-iron pipe and fittings and agricultural implements.

The American National Standard Specifications for Gray Iron Castings—ANSI/ASTM A48-76 groups the castings into two categories. Gray iron castings in Classes 20A, 20B, 20C, 25A, 25B, 25C, 30A, 30B, 30C, 35A, 35B, and 35C are characterized by excellent machinability, high damping capacity, low modulus of elasticity, and comparative ease of manufacture. Castings in Classes 40B, 40C, 45B, 45C, 50B, 50C, 60B, and 60C are usually more difficult to machine, have lower damping capacity, a higher modulus of elasticity, and are more difficult to manufacture. The prefix number is indicative of the minimum tensile strength in pounds per square inch, i.e., 20 is 20,000 psi, 25 is 25,000 psi, 30 is 30,000 psi, etc.

High-strength iron castings produced by the Meehanite-controlled process may have various combinations of physical properties to meet different requirements. In addition to a number of general engineering types, there are heat-resisting, wear-resisting and corrosion-resisting Meehanite castings.

White Cast Iron.—When nearly all of the carbon in a casting is in the combined or cementite form, it is known as white cast iron. It is so named because it has a silvery-white fracture. White cast iron is very hard and also brittle; its ductility is practically zero. Castings of this material need particular attention with respect to design since sharp corners and thin sections result in material failures at the foundry. These castings are less resistant to impact loading than gray iron castings, but they have a compressive strength that is usually higher than 200,000 pounds per square inch as compared to 65,000 to 160,000 pounds per square inch for gray iron castings. Some white iron castings are used for applications that require maximum wear resistance but most of them are used in the production of malleable iron castings.

Chilled Cast Iron.—Many gray iron castings have wear-resisting surfaces of white cast iron. These surfaces are designated by the term “chilled cast iron” since they are produced in molds having metal chills for cooling the molten metal rapidly. This rapid cooling results in the formation of cementite and white cast iron.

Alloy Cast Iron.—This term designates castings containing alloying elements such as nickel, chromium, molybdenum, copper, and manganese in sufficient amounts to appreciably change the physical properties. These elements may be added either to increase the strength or to obtain special properties such as higher wear resistance, corrosion resistance, or heat resistance. Alloy cast irons are used extensively for such parts as automotive cylinders, pistons, piston rings, crankcases, brake drums; for certain machine tool castings, for certain types of dies, for parts of crushing and grinding machinery, and for application where the casting must resist scaling at high temperatures. Machinable alloy cast irons having tensile strengths up to 70,000 pounds per square inch or even higher may be produced.

Malleable-iron Castings.—Malleable iron is produced by the annealing or graphitization of white iron castings. The graphitization in this case produces temper carbon which is graphite in the form of compact rounded aggregates. Malleable castings are used for many industrial applications where strength, ductility, machinability, and resistance to shock are important factors. In manufacturing these castings, the usual procedure is to first produce a hard, brittle white iron from a charge of pig iron and scrap. These hard white-iron castings are then placed in stationary batch-type furnaces or car-bottom furnaces and the graphitization (malleablizing) of the castings is accomplished by means of a suitable annealing heat treatment. During this annealing period the temperature is slowly (50 hours) increased to as much as 1650 or 1700 degrees F, after which time it is slowly (60 hours) cooled. The American National Standard Specifications for Malleable Iron Castings—ANSI/ASTM A47-77 specifies the following grades and their properties: No. 32520, having a minimum tensile strength of 50,000 pounds per square inch, a minimum yield strength of 32,500 psi., and a minimum elongation in 2 inches of 10 per cent; and No. 35018, having a minimum tensile strength of 53,000 psi., a minimum yield strength of 35,000 psi., and a minimum elongation in 2 inches of 18 per cent.

Cupola Malleable Iron: Another method of producing malleable iron involves initially the use of a cupola or a cupola in conjunction with an air furnace. This type of malleable iron, called cupola malleable iron, exhibits good fluidity and will produce sound castings. It is used in the making of pipe fittings, valves, and similar parts and possesses the useful property of being well suited to galvanizing. The American National Standard Specifications for Cupola Malleable Iron — ANSI/ASTM 197-79 calls for a minimum tensile strength of 40,000 pounds per square inch; a minimum yield strength of 30.000 psi.; and a minimum elongation in 2 inches of 5 per cent.

Pearlitic Malleable Iron: This type of malleable iron contains some combined carbon in various forms. It may be produced either by stopping the heat treatment of regular malleable iron during production before the combined carbon contained therein has all been transformed to graphite or by reheating regular malleable iron above the transformation range. Pearlitic malleable irons exhibit a wide range of properties and are used in place of steel castings or forgings or to replace malleable iron when a greater strength or wear resistance is required. Some forms are made rigid to resist deformation while others will undergo considerable deformation before breaking. This material has been used in axle housings, differential housings, camshafts, and crankshafts for automobiles; machine parts; ordnance equipment; and tools. Tension test requirements of pearlitic malleable iron castings called for in ASTM Specification A 220–79 are given in the accompanying table.

Tension Test Requirements of Pearlitic Malleable Iron Castings *ASTM A 220-79*

Casting Grade Numbers		40010	45008	45006	50005	60004	70003	80002	90001
Min. Tensile Strength	1000s Lbs. per Sq. In.	60	65	65	70	80	85	95	105
Min. Yield Strength		40	45	45	50	60	70	80	90
Min. Elong. in 2 In., Per Cent		10	8	6	5	4	3	2	1

Ductile Cast Iron.—A distinguishing feature of this widely used type of cast iron, also known as spheroidal graphite iron or nodular iron, is that the graphite is present in ball-like form instead of in flakes as in ordinary gray cast iron. The addition of small amounts of magnesium- or cerium-bearing alloys together with special processing produces this spheroidal graphite structure and results in a casting of high strength and appreciable ductility. Its toughness is intermediate between that of cast iron and steel, and its shock resistance is comparable to ordinary grades of mild carbon steel. Melting point and fluidity are similar to those of the high-carbon cast irons. It exhibits good pressure tightness under high stress and can be welded and brazed. It can be softened by annealing or hardened by normalizing and air cooling or oil quenching and drawing.

Five grades of this iron are specified in ASTM A 536-80—Standard Specification for Ductile Iron Castings. The grades and their corresponding matrix microstructures and heat treatments are as follows: Grade 60-40-18, ferritic, may be annealed; Grade 65-45-12, mostly ferritic, as-cast or annealed; Grade 80-55-06, ferritic/pearlitic, as-cast; Grade 100-70-03, mostly pearlitic, may be normalized; Grade 120-90-02, martensitic, oil quenched and tempered. The grade nomenclature identifies the minimum tensile strength, on per cent yield strength, and per cent elongation in 2 inches. Thus, Grade 60–40–18 has a minimum tensile strength of 60,000 psi, a minimum 0.2 per cent yield strength of 40,000 psi, and minimum elongation in 2 inches of 18 per cent. Several other types are commercially available to meet specific needs. The common grades of ductile iron can also be specified by only Brinell hardness, although the appropriate microstructure for the indicated hardness is also a requirement. This method is used in SAE Specification J434C for automotive castings and similar applications. Other specifications not only specify tensile properties, but also have limitations in composition. Austenitic types with high nickel content, high corrosion resistance, and good strength at elevated temperatures, are specified in ASTM A439-80.

Ductile cast iron can be cast in molds containing metal chills if wear-resisting surfaces are desired. Hard carbide areas will form in a manner similar to the forming of areas of chilled cast iron in gray iron castings. Surface hardening by flame or induction methods is also feasible. Ductile cast iron can be machined with the same ease as gray cast iron. It finds use as crankshafts, pistons, and cylinder heads in the automotive industry; forging hammer anvils, cylinders, guides, and control levers in the heavy machinery field; and wrenches, clamp frames, face-plates, chuck bodies, and dies for forming metals in the tool and die field. The production of ductile iron castings involves complex metallurgy, the use of special melting stock, and close process control. The majority of applications of ductile iron have been made to utilize its excellent mechanical properties in combination with the castability, machinability, and corrosion resistance of gray iron.

Steel Castings.—Steel castings are especially adapted for machine parts that must withstand shocks or heavy loads. They are stronger than either wrought iron, cast iron, or malleable iron and are very tough. The steel used for making steel castings may be produced either by the open-hearth, electric arc, side-blow converter, or electric induction methods. The raw materials used are steel scrap, pig iron, and iron ore, the materials and their proportions varying according to the process and the type of furnace used. The open-hearth method is used when large tonnages are continually required while a small electric furnace might be used for steels of widely differing analyses, which are required in small lot production. The high frequency induction furnace is used for small quantity production of expensive steels of special composition such as high-alloy steels. Steel castings are used for such parts as hydroelectric turbine wheels, forging presses, gears, railroad car frames, valve bodies, pump casings, mining machinery, marine equipment, engine casings, etc.

Steel castings can generally be made from any of the many types of carbon and alloy steels produced in wrought form and respond similarly to heat treatment; they also do not exhibit directionality effects that are typical of wrought steel. Steel castings are classified into two general groups: carbon steel and alloy steel.

Table 1. Mechanical Properties of Steel Casings
For general information only. Not for use as design or specification limit values.

Tensile Strength, Lbs. per Sq. In.	Yield Point, Lbs. per Sq. In.	Elongation in 2 In., Per Cent	Brinell Hardness Number	Type of Heat Treatment	Application Indicating Properties
Structural Grades of Carbon Steel Castings					
60,000	30,000	32	120	Annealed	Low electric resistivity. Desirable magnetic properties. Carburizing and case hardening grades. Weldability.
65,000	35,000	30	130	Normalized	Good weldability. Medium strength with good machinability and high ductility.
70,000	38,000	28	140	Normalized	
80,000	45,000	26	160	Normalized and tempered	High strength carbon steels with good machinability, toughness and good fatigue resistance.
85,000	50,000	24	175	Normalized and tempered	
100,000	70,000	20	200	Quenched and tempered	Wear resistance. Hardness.
Engineering Grades of Low Alloy Steel Castings					
70,000	45,000	26	150	Normalized and tempered	Good weldability. Medium strength with high toughness and good machinability. For high temperature service.
80,000	50,000	24	170	Normalized and tempered	
90,000	60,000	22	190	Normalized and tempered[a]	Certain steels of these classes have good high temperature properties and deep hardening properties. Toughness.
100,000	68,000	20	209	Normalized and tempered[a]	
110,000	85,000	20	235	Quenched and tempered	Impact resistance. Good low temperature properties for certain steels. Deep hardening. Good combination of strength and toughness.
120,000	95,000	16	245	Quenched and tempered	
150,000	125,000	12	300	Quenched and tempered	Deep hardening. High strength. Wear and fatigue resistance.
175,000	148,000	8	340	Quenched and tempered	High strength and hardness. Wear resistance. High fatigue resistance.
200,000	170,000	5	400	Quenched and tempered	

[a] Quench and temper heat treatments may also be employed for these classes.

The values listed above have been compiled by the Steel Founders' Society of America as those normally expected in the production of steel castings. The castings are classified according to tensile strength values which are given in the first column. Specifications covering steel castings are prepared by the American Society for Testing and Materials, the Association of American Railroads, the Society of Automotive Engineers, the United States Government (Federal and Military Specifications), etc. These specifications appear in publications issued by these organizations.

Carbon Steel Castings.—Carbon steel castings may be designated as low-carbon medium-carbon, and high-carbon. Low-carbon steel castings have a carbon content of less than 0.20 per cent (most are produced in the 0.16 to 0.19 per cent range). Other elements present are: manganese, 0.50 to 0.85 per cent; silicon, 0.25 to 0.70 per cent; phosphorus, 0.05 per cent max.; and sulfur, 0.06 per cent max. Their tensile strengths (annealed condition) range from 40,000 to 70,000 pounds per square inch. Medium-carbon steel castings have a carbon content of from 0.20 to 0.50 per cent. Other elements present are: manganese, 0.50 to 1.00 per cent; silicon, 0.20 to 0.80 per cent; phosphorus, 0.05 per cent max.; and sulfur, 0.06 per cent max. Their tensile strengths range from 65,000 to 105,000 pounds per square inch depending, in part, upon heat treatment. High-carbon steel castings have a carbon content of more than 0.50 per cent and also contain: manganese, 0.50 to 1.00 per cent; silicon, 0.20 to 0.70 per cent; and phosphorus and sulfur, 0.05 per cent max. each. Fully annealed high-carbon steel castings exhibit tensile strengths of from 95,000 to 125,000 pounds per square inch. See Table 1 for grades and properties of carbon steel castings.

Table 2. Nominal Chemical Composition and Mechanical Properties of Heat-Resistant Steel Castings *ASTM A297-81*

Grade	Nominal Chemical Composition, Per Cent[a]	Tensile Strength, min		0.2 Per Cent Yield Strength, min		Per Cent Elongation in 2 in., or 50 mm, min.
		ksi	MPa	ksi	MPa	
HF	19 Chromium, 9 Nickel	70	485	35	240	25
HH	25 Chromium, 12 Nickel	75	515	35	240	10
HI	28 Chromium, 15 Nickel	70	485	35	240	10
HK	25 Chromium, 20 Nickel	65	450	35	240	10
HE	29 Chromium, 9 Nickel	85	585	40	275	9
HT	15 Chromium, 35 Nickel	65	450	…	…	4
HU	19 Chromium, 39 Nickel	65	450	…	…	4
HW	12 Chromium, 60 Nickel	60	415	…	…	…
HX	17 Chromium, 66 Nickel	60	415	…	…	…
HC	28 Chromium	55	380	…	…	…
HD	28 Chromium, 5 Nickel	75	515	35	240	8
HL	29 Chromium, 20 Nickel	65	450	35	240	10
HN	20 Chromium, 25 Nickel	63	435	…	…	8
HP	26 Chromium, 35 Nickel	62.5	430	34	235	4.5

[a] Remainder is iron.

ksi = kips per square inch = 1000s of pounds per square inch; MPa = megapascals.

Alloy Steel Castings.—Alloy cast steels are those in which special alloying elements such as manganese, chromium, nickel, molybdenum, vanadium have been added in sufficient quantities to obtain or increase certain desirable properties. Alloy cast steels are comprised of two groups—the low-alloy steels with their alloy content totaling less than 8 per cent and the high-alloy steels with their alloy content totaling 8 per cent or more. The addition of these various alloying elements in conjunction with suitable heat-treatments, makes it possible to secure steel castings having a wide range of properties. The three accompanying tables give information on these steels. The lower portion of Table 1 gives the engineering grades of low-alloy cast steels grouped according to tensile strengths and gives properties normally expected in the production of steel castings. Tables 2 and 3 give the standard designations and nominal chemical composition ranges of high-alloy castings which may be classified according to heat or corrosion resistance. The grades given in these tables are recognized in whole or in part by the Alloy Casting Institute (ACI), the American Society for Testing and Materials (ASTM), and the Society of Automotive Engineers (SAE).

Table 3. Nominal Chemical Composition and Mechanical Properties of Corrosion-Resistant Steel Castings *ASTM A743-81a*

Grade	Nominal Chemical Composition, Per Cent[a]	Tensile Strength, min		0.2% Yield Strength, min		Per Cent Elongation in 2 in., or 50 mm, min	Per Cent Reduction of Area, min
		ksi	MPa	ksi	MPa		
CF-8	9 Chromium, 9 Nickel	70[b]	485[b]	30[b]	205[b]	35	…
CG-12	22 Chromium, 12 Nickel	70	485	28	195	35	…
CF-20	19 Chromium, 9 Nickel	70	485	30	205	30	…
CF-8M	19 Chromium, 10 Nickel, with Molybdenum	70	485	30	205	30	…
CF-8C	19 Chromium, 10 Nickel with Niobium	70	485	30	205	30	…
CF-16 and CF-16Fa	19 Chromium, 9 Nickel, Free Machining	70	485	30	205	25	…
CH-20 and CH-10	25 Chromium, 12 Nickel	70	485	30	205	30	…
CK-20	25 Chromium, 20 Nickel	65	450	28	195	30	…
CE-30	29 Chromium, 9 Nickel	80	550	40	275	10	…
CA-15 and CA-15M	12 Chromium	90	620	65	450	18	30
CB-30	20 Chromium	65	450	30	205	…	…
CC-50	28 Chromium	55	380	…	…	…	…
CA-40	12 Chromium	100	690	70	485	15	25
CF-3	19 Chromium, 9 Nickel	70	485	30	205	35	…
CF-3M	19 Chromium, 10 Nickel, with Molybdenum	70	485	30	205	30	…
CG6MMN	Chromium-Nickel-Manganese -Molybdenum	75	515	35	240	30	…
CG-8M	19 Chromium, 11 Nickel, with Molybdenum	75	520	35	240	25	…
CN-7M	20 Chromium, 29 Nickel, with Copper and Molybdenum	62	425	25	170	35	…
CN-7MS	19 Chromium, 24 Nickel, with Copper and Molybdenum	70	485	30	205	35	…
CW-12M	Nickel, Molybdenum, Chromium	72	495	46	315	4.0	…
CY-40	Nickel, Chromium, Iron	70	485	28	195	30	…
CZ-100	Nickel Alloy	50	345	18	125	10	…
M-35-1	Nickel-Copper Alloy	65	450	25	170	25	…
M-35-2	Nickel-Copper Alloy	65	450	30	205	25	…
CA-6NM	12 Chromium, 4 Nickel	110	755	80	550	15	35
CD-4MCu	25 Chromium, 5 Nickel, 2 Molybdenum, 3 Copper	100	690	70	485	16	…
CA-6N	11 Chromium, 7 Nickel	140	965	135	930	15	50

[a] Remainder is iron.

[b] For low ferrite or non-magnetic castings of this grade, the following values shall apply: tensile strength, min, 65 ksi (450 MPa); yield point, min, 28 ksi (195 MPa).

The specifications committee of the Steel Founders Society issues a *Steel Castings Handbook* with supplements. Supplement 1 provides design rules and data based on the fluidity and solidification of steel, mechanical principles involved in production of molds and cores, cleaning of castings, machining, and functionality and weight aspects. Data and examples are included to show how these rules are applied. Supplement 2 summarizes the standard steel castings specification issued by the ASTM SAE, Assoc. of Am. Railroads (AAR), Am. Bur of Shipping (ABS), and Federal authorities, and provides guidance as to their applications. Information is included for carbon and alloy cast steels, high alloy cast steels, and centrifugally cast steel pipe. Details are also given of standard test methods for steel castings, including mechanical, non-destructive (visual, liquid penetrant, magnetic particle, radiographic, and ultrasonic), and testing of qualifications of welding procedures and personnel. Other supplements cover such subjects as tolerances, drafting practices, properties, repair and fabrication welding, of carbon, low alloy and high alloy castings, foundry terms, and hardenability and heat treatment.

Austenitic Manganese Cast Steel: Austenitic manganese cast steel is an important high-alloy cast steel which provides a high degree of shock and wear resistance. Its composition normally falls within the following ranges: carbon, 1.00 to 1.40 per cent; manganese, 10.00 to 14.00 per cent; silicon, 0.30 to 1.00 per cent; sulfur, 0.06 per cent max.; phosphorus, 0.10 per cent, max. In the as-cast condition, austenitic manganese steel is quite brittle. In order to strengthen and toughen the steel, it is heated to between 1830 and 1940 degrees F and quenched in cold water. Physical properties of quenched austenitic manganese steel that has been cast to size are as follows: tensile strength, 80,000 to 100,000 pounds per square inch; shear strength (single shear), 84,000 pounds per square inch; elongation in 2 inches, 15 to 35 per cent; reduction in area, 15 to 35 per cent; and Brinell hardness number, 180 to 220. When cold worked, the surface of such a casting increases to a Brinell hardness of from 450 to 550. In many cases the surfaces are cold worked to maximum hardness to assure immediate hardness in use. Heat-treated austenitic manganese steel is machined only with great difficulty since it hardens at and slightly ahead of the point of contact of the cutting tool. Grinding wheels mounted on specially adapted machines are used for boring, planing, keyway cutting, and similar operations on this steel. Where grinding cannot be employed and machining must be resorted to, high-speed tool steel or cemented carbide tools are used with heavy, rigid equipment and slow, steady operation. In any event, this procedure tends to be both tedious and expensive. Austenitic manganese cast steel can be arc-welded with manganese-nickel steel welding rods containing from 3 to 5 per cent nickel, 10 to 15 per cent manganese, and, usually, 0.60 to 0.80 per cent carbon.

Casting of Metals

Molten metals are shaped by pouring (casting) into a mold of the required form, which they enter under gravity, centrifugal force, or various degrees of pressure. Molds are made of refractory materials like sand, plaster, graphite, or metal. Sand molds are formed around a pattern or replica of the part to be made, usually of wood though plastics or metal may be used when large numbers of molds for similar parts are to be made.

Green-sand molding is used for most sand castings, sand mixed with a binder being packed around the pattern by hand, with power tools, or in a vibrating machine which may also exert a compressive force to pack the grains more closely. The term “green-sand” implies that the binder is not cured by heating or chemical reactions. The pattern is made in two “halves,” which usually are attached to opposite sides of a flat plate. Shaped bars and other projections are fastened to the plate to form connecting channels and funnels in the sand for entry of the molten metal into the casting cavities. The sand is supported at the plate edges by a box-shaped frame or flask, with locating tabs that align the two mold halves when they are later assembled for the pouring operation.

Hollows and undercut surfaces in the casting are produced by cores, also made from sand, that are placed in position before the mold is closed, and held in place by tenons in grooves (called prints) formed in the sand by pattern projections. An *undercut surface* is one from which the pattern cannot be withdrawn in a straight line, so must be formed by a core in the mold. When the poured metal has solidified, the frame is removed and the sand falls or is cleaned off, leaving the finished casting(s) ready to be cut from the runners.

Gray iron is easily cast in complex shapes in green-sand and other molds and can be machined readily. The iron usually contains carbon, 1.7–4.5, and silicon, 1–3 per cent by weight. Excess carbon in the form of graphite flakes produces the gray surface from which the name is derived, when a casting is fractured.

Shell molding: invented by a German engineer, Croning, uses a resin binder to lock the grains of sand in a $\frac{1}{4}$- to $\frac{3}{8}$-in.-thick layer of sand/resin mixture, which adheres to a heated pattern plate after the mass of the mixture has been dumped back into the container. The hot resin quickly hardens enough to make the shell thus formed sufficiently rigid to be removed from the pattern, producing a half mold. The other half mold is produced on another plate by the same method. Pattern projections form runner channels, basins, core prints, and locating tenons in each mold half. Cores are inserted to form internal passages and undercuts. The shell assembly is placed in a molding box and supported with some other material such as steel shot or a coarse sand, when the molten metal is to be poured in. Some shell molds are strong enough to be filled without backup, and the two mold halves are merely clamped together for metal to be poured in to make the casting(s).

V-Process is a method whereby dry, unbonded sand is held to the shape of a pattern by a vacuum. The pattern is provided with multiple vent passages that terminate in various positions all over its surface, and are connected to a common plenum chamber. A heat-softened, 0.002–0.005-in.-thick plastics film is draped over the pattern and a vacuum of 200–400 mm of mercury is applied to the chamber, sucking out the air beneath the film so that the plastics is drawn into close contact with the pattern. A sand box or flask with walls that also contain hollow chambers and a flat grid that spans the central area is placed on the pattern plate to confine the dry unbonded sand that is allowed to fall through the grid on to the pattern.

After vibration to compact the sand around the pattern, a former is used to shape a sprue cup into the upper surface of the sand, connecting with a riser on the pattern, and the top surface of the sand is covered with a plastics film that extends over the flask sides. The hollow chambers in the flask walls are then connected to the vacuum source. The vacuum is sufficient to hold the sand grains in their packed condition between the plastics films above and beneath, firmly in the shape defined by the pattern, so that the flask and the sand half-mold can be lifted from the pattern plate. Matching half molds made by these procedures are assembled into a complete mold, with cores inserted if needed. With both mold halves still held by vacuum, molten metal is poured through the sprue cup into the mold, the plastics film between the mold surfaces being melted and evaporated by the hot metal. After solidification, the vacuum is released and the sand, together with the casting(s), falls from the mold flasks. The castings emerge cleanly, and the sand needs only to be cooled before reuse.

Permanent mold, or gravity die, casting is mainly used for nonferrous metals and alloys. The mold (or die) is usually iron or steel, or graphite, and is cooled by water channels or by air jets on the outer surfaces. Cavity surfaces in metal dies are coated with a thin layer of heat-resistant material. The mold or die design is usually in two halves, although many multiple-part molds are in use, with loose sand or metal cores to form undercut surfaces. The cast metal is simply poured into a funnel formed in the top of the mold, although elaborate tilting mechanisms are often used to control the passage of metal into (and emergence of air from) the remote portions of die cavities.

Because the die temperature varies during the casting cycle, its dimensions vary correspondingly. The die is opened and ejectors push the casting(s) out as soon as its temperature is low enough for sufficient strength to build up. During the period after solidification and before ejection, cooling continues but shrinkage of the casting(s) is restricted by the die. The alloy being cast must be sufficiently ductile to accommodate these restrictions without fracturing. An alloy that tears or splits during cooling in the die is said to be *hot short* and cannot be cast in rigid molds. Dimensions of the casting(s) at shop temperatures will be related to the die temperature and the dimensions at ejection. Rules for casting shrinkage that apply to friable (sand) molds do not hold for rigid molds. Designers of metal molds and dies rely on temperature-based calculations and experience in evolving shrinkage allowances.

Low-pressure casting uses mold or die designs similar to those for gravity casting. The container (crucible) for the molten metal has provision for an airtight seal with the mold, and when gas or air pressure (6–10 lb/in.^{2}) is applied to the bath surface inside the crucible, the metal is forced up a hollow refractory tube (stalk) projecting from the die underside. This stalk extends below the bath level so that metal entering the die is free from oxides and impurities floating on the surface. The rate of filling is controlled so that air can be expelled from the die by the entering metal. With good design and control, high-quality, nonporous castings are made by both gravity and low-pressure methods, though the extra pressure in low-pressure die casting may increase the density and improve the reproduction of fine detail in the die.

Squeeze casting uses a metal die, of which one half is clamped to the bed of a large (usually) hydraulic press and the other to the vertically moving ram of the press. Molten metal is poured into the lower die and the upper die is brought down until the die is closed. The amount of metal in the die is controlled to produce a slight overflow as the die closes to ensure complete filling of the cavity. The heated dies are lubricated with graphite and pressures up to 25 tons per square inch may be applied by the press to squeeze the molten metal into the tiniest recesses in the die. When the press is opened, the solidified casting is pushed out by ejectors.

Finishing Operations for Castings

Removal of Gates and Risers from Castings.—After the molten iron or steel has solidified and cooled, the castings are removed from their molds, either manually or by placing them on vibratory machines and shaking the sand loose from the castings. The gates and risers that are not broken off in the shake-out are removed by impact, sawing, shearing, or burning-off methods. In the impact method, a hammer is used to knock off the gates and risers. Where the possibility exists that the fracture would extend into the casting itself, the gates or risers are first notched to assure fracture in the proper place. Some risers have a necked-down section at which the riser breaks off when struck. Sprue-cutter machines are also used to shear off gates. These machines facilitate the removal of a number of small castings from a central runner. Band saws, power saws. and abrasive cut-off wheel machines are also used to remove gates and risers. The use of band saws permits following the contour of the casting when removing unwanted appendages. Abrasive cut-off wheels are used when the castings are too hard or difficult to saw. Oxyacetylene cutting torches are used to cut off gates and risers and to gouge out or remove surface defects on castings. These torches are used on steel castings where the gates and risers are of a relatively large size. Surface defects are subsequently repaired by conventional welding methods.

Any unwanted material in the form of fins, gates, and riser pads that come above the casting surface, chaplets, parting-line flash, etc., is removed by chipping with pneumatic hammers, or by grinding with such equipment as floor or bench-stand grinders, portable grinders, and swing-frame grinders.

Blast Cleaning of Castings.—Blast cleaning of castings is performed to remove adhering sand, to remove cores, to improve the casting appearance, and to prepare the castings for their final finishing operation, which includes painting, machining, or assembling. Scale produced as a result of heat treating can also be removed. A variety of machines are used to handle all sizes of casting. The methods employed include blasting with sand, metal shot, or grit; and hydraulic cleaning or tumbling. In blasting, sharp sand, shot, or grit is carried by a stream of compressed air or water or by centrifugal force (gained as a result of whirling in a rapidly rotating machine) and directed against the casting surface by means of nozzles. The operation is usually performed in cabinets or enclosed booths. In some setups the castings are placed on a revolving table and the abrasive from the nozzles that are either mechanically or hand-held is directed against all the casting surfaces. Tumbling machines are also employed for cleaning, the castings being placed in large revolving drums together with slugs, balls, pins, metal punchings, or some abrasive, such as sandstone or granite chips, slag, silica, sand, or pumice. Quite frequently, the tumbling and blasting methods are used together, the parts then being tumbled and blasted simultaneously. Castings may also be cleaned by hydroblasting. This method uses a water-tight room in which a mixture of water and sand under high pressure is directed at the castings by means of nozzles. The action of the water and sand mixture cleans the castings very effectively.

Heat Treatment of Steel Castings.—Steel castings can be heat treated to bring about diffusion of carbon or alloying elements, softening, hardening, stress-relieving, toughening, improved machinability, increased wear resistance, and removal of hydrogen entrapped at the surface of the casting. Heat treatment of steel castings of a given composition follows closely that of wrought steel of similar composition. For discussion of types of heat treatment refer to the “Heat Treatment of Steel” section of this Handbook.

Estimating Casting Weight.—Where no pattern or die has yet been made, as when preparing a quotation for making a casting, the weight of a cast component can be estimated with fair accuracy by calculating the volume of each of the casting features, such as box- or rectangular-section features, cylindrical bosses, housings, ribs, and other parts, and adding them together. Several computer programs, also measuring mechanisms that can be applied to a drawing, are available to assist with these calculations. When the volume of metal has been determined it is necessary only to multiply by the unit weight of the alloy to be used, to arrive at the weight of the finished casting. The cost of the metal in the finished casting can then be estimated by multiplying the weight in lb by the cost/lb of the alloy. Allowances for melting losses, and for the extra metal used in risers and runners, and the cost of melting and machining may also be added to the cost/lb. Estimates of the costs of pattern- or die-making, molding, pouring and finishing of the casting(s), may also be added, to complete the quotation estimate.

Pattern Materials—Shrinkage, Draft, and Finish Allowances

Woods for Patterns.—Woods commonly used for patterns are white pine, mahogany, cherry, maple, birch, white wood, and fir. For most patterns, white pine is considered superior because it is easily worked, readily takes glue and varnish, and is fairly durable. For medium- and small-sized patterns, especially if they are to be used extensively, a harder wood is preferable. Mahogany is often used for patterns of this class, although many prefer cherry. As mahogany has a close grain, it is not as susceptible to atmospheric changes as a wood of coarser grain. Mahogany is superior in this respect to cherry, but is more expensive. In selecting cherry, never use young timber. Maple and birch are employed quite extensively, especially for turned parts, as they take a good finish. White wood is sometimes substituted for pine, but it is inferior to the latter in being more susceptible to atmospheric changes.

Selection of Wood.—It is very important to select well-seasoned wood for patterns; that is, it should either be kiln-dried or kept 1 or 2 years before using, the time depending upon the size of the lumber. During the seasoning or drying process, the moisture leaves the wood cells and the wood shrinks, the shrinkage being almost entirely across the grain rather than in a lengthwise direction. Naturally, after this change takes place, the wood is less liable to warp, although it will absorb moisture in damp weather. Patterns also tend to absorb moisture from the damp sand of molds, and to minimize troubles from this source they are covered with varnish. Green or water-soaked lumber should not be put in a drying room, because the ends will dry out faster than the rest of the log, thus causing cracks. In a log, there is what is called “sap wood” and “heart wood.” The outer layers form the sap wood, which is not as firm as the heart wood and is more likely to warp; hence, it should be avoided, if possible.

Pattern Varnish.—Patterns intended for repeated use are varnished to protect them against moisture, especially when in the damp molding sand. The varnish used should dry quickly to give a smooth surface that readily draws from the sand. Yellow shellac varnish is generally used. It is made by dissolving gum shellac in grain alcohol. Wood alcohol is sometimes substituted, but is inferior. The color of the varnish is commonly changed for covering core prints, in order that the prints may be readily distinguished from the body of the pattern. Black shellac varnish is generally used. At least three coats of varnish should be applied to patterns, the surfaces being rubbed down with sandpaper after applying the preliminary coats, in order to obtain a smooth surface.

Shrinkage Allowances.—The shrinkage allowances ordinarily specified for patterns to compensate for the contraction of castings in cooling are as follows: cast iron, $\frac{3}{32}$ to $\frac{1}{8}$ inch per foot; common brass, $\frac{3}{16}$ inch per foot; yellow brass, $\frac{7}{32}$ inch per foot; bronze, $\frac{5}{32}$ inch per foot; aluminum, $\frac{1}{8}$ to $\frac{5}{32}$ inch per foot; magnesium, $\frac{1}{8}$ to $\frac{11}{64}$ inch per foot; steel, $\frac{3}{16}$ inch per foot. These shrinkage allowances are approximate values only because the exact allowance depends upon the size and shape of the casting and the resistance of the mold to the normal contraction of the casting during cooling. It is, therefore, possible that more than one shrinkage allowance will be required for different parts of the same pattern. Another factor that affects shrinkage allowance is the molding method, which may vary to such an extent from one foundry to another, that different shrinkage allowances for each would have to be used for the same pattern. For these reasons it is recommended that patterns be made at the foundry where the castings are to be produced to eliminate difficulties due to lack of accurate knowledge of shrinkage requirements.

An example of how casting shape can affect shrinkage allowance is given in the Steel Castings Handbook. In this example a straight round steel bar required a shrinkage allowance of approximately $\frac{9}{32}$ inch per foot. The same bar but with a large knob on each end required a shrinkage allowance of only $\frac{3}{16}$ inch per foot. A third steel bar with large flanges at each end required a shrinkage allowance of only $\frac{7}{64}$ inch per foot. This example would seem to indicate that the best practice in designing castings and making patterns is to obtain shrinkage values from the foundry that is to make the casting because there can be no fixed allowances.

Metal Patterns.—Metal patterns are especially adapted to molding machine practice, owing to their durability and superiority in retaining the required shape. The original master pattern is generally made of wood, the casting obtained from the wood pattern being finished to make the metal pattern. The materials commonly used are brass, cast iron, aluminum, and steel. Brass patterns should have a rather large percentage of tin, to improve the casting surface. Cast iron is generally used for large patterns because it is cheaper than brass and more durable. Cast-iron patterns are largely used on molding machines. Aluminum patterns are light but they require large shrinkage allowances. White metal is sometimes used when it is necessary to avoid shrinkage. The gates for the mold may be cast or made of sheet brass. Some patterns are made of vulcanized rubber, especially for light match-board work.

Obtaining Weight of Casting from Pattern Weight.—To obtain the approximate weight of a casting, multiply the weight of the pattern by the factor given in the accompanying table. For example, if the weight of a white-pine pattern is 4 pounds what is the weight of a solid cast-iron casting obtained from that pattern? Casting weight = $4 \times 16 = 64$ pounds. If the casting is cored, fill the core-boxes with dry sand, and multiply the weight of the sand by one of the following factors: For cast iron, 4; for brass, 4.65; for aluminum, 1.4. Then subtract the product of the sand weight and the factor just given from the weight of the solid casting, to obtain the weight of the cored casting. The weight of wood varies considerably, so the results obtained by the use of the table are only approximate, the factors being based on the average weight of the woods listed. For metal patterns, the results may be more accurate.

Factors for Obtaining Weight of Casting from Pattern Weight

Pattern Material	Factors				
	Cast Iron	Aluminum	Copper	Zinc	Brass, 70% Copper, 30% Zinc
White pine	16.00	5.70	19.60	15.00	19.00
Mahogany, Honduras	12.00	4.50	14.70	11.50	14.00
Cherry	10.50	3.80	13.00	10.00	12.50
Cast Iron	1.00	0.35	1.22	0.95	1.17
Aluminum	2.85	1.00	3.44	2.70	3.30

Die Casting

Die casting is a method of producing finished castings by forcing molten metal into a hard metal die, which is arranged to open after the metal has solidified so that the casting can be removed. The die-casting process makes it possible to secure accuracy and uniformity in castings, and machining costs are either eliminated altogether or are greatly reduced. The greatest advantage of the die-casting process is that parts are accurately and often completely finished when taken from the die. When the dies are properly made, castings may be accurate within 0.001 inch or even less and a limit of 0.002 or 0.003 inch per inch of casting dimension can be maintained on many classes of work.

Die castings are used extensively in the manufacture of such products as cash registers, meters, time-controlling devices, small housings, washing machines, and parts for a great variety of mechanisms. Lugs and gear teeth are cast in place and both external and internal screw threads can be cast. Holes can be formed within about 0.001 inch of size and the most accurate bearings require only a finish-reaming operation. Figures and letters may be cast sunken or in relief on wheels for counting or printing devices, and with ingenious die designs, many shapes that formerly were believed too intricate for die casting are now produced successfully by this process.

Die casting uses hardened steel molds (dies) into which the molten metal is injected at high speed, reaching pressures up to 10 tons/in.^{2}, force being applied by a hydraulically actuated plunger moving in a cylindrical pressure chamber connected to the die cavity(s). If the plan area of the casting and its runner system cover 50 in.^{2}, the total power applied is 10 tons/in.^{2} of pressure on the metal $\times$ 50 in.^{2} of projected area, producing a force of 500 tons, and the die-casting machine must hold the die shut against this force. Massive toggle mechanisms stretch the heavy (6-in. diameter) steel tie bars through about 0.045 in. on a typical (500-ton) machine to generate this force. Although the die is hot, metal entering the die cavity is cooled quickly, producing layers of rapidly chilled, dense material about 0.015 in. thick in the metal having direct contact with the die cavity surfaces. Because the high injection forces allow castings to be made with thin walls, these dense layers form a large proportion of the total wall thickness, producing high casting strength. This phenomenon is known as the skin effect, and should be taken into account when considering the tensile strengths and other properties measured in (usually thicker) test bars.

As to the limitations of the die-casting process it may be mentioned that the cost of dies is high, and, therefore, die casting is economical only when large numbers of duplicate parts are required. The stronger and harder metals cannot be die cast, so that the process is not applicable for casting parts that must necessarily be made of iron or steel, although special alloys have been developed for die casting that have considerable tensile and compressive strength.

Many die castings are produced by the hot-chamber method in which the pressure chamber connected to the die cavity is immersed permanently in the molten metal and is automatically refilled through a hole that is uncovered as the (vertical) pressure plunger moves back after filling the die. This method can be used for alloys of low melting point and high fluidity such as zinc, lead, tin, and magnesium. Other alloys requiring higher pressure, such as brass, or that can attack and dissolve the ferrous pressure chamber material, such as aluminum, must use the slower cold-chamber method with a water-cooled (horizontal) pressure chamber outside the molten metal.

Porosity.—Molten metal injected into a die cavity displaces most of the air, but some of the air is trapped and is mixed with the metal. The high pressure applied to the metal squeezes the pores containing the air to very small size, but subsequent heating will soften the casting so that air in the surface pores can expand and cause blisters. Die castings are seldom solution heat treated or welded because of this blistering problem. The chilling effect of the comparatively cold die causes the outer layers of a die casting to be dense and relatively free of porosity. Vacuum die casting, in which the cavity atmosphere is evacuated before metal is injected, is sometimes used to reduce porosity. Another method is to displace the air by filling the cavity with oxygen just prior to injection. The oxygen is burned by the hot metal so that porosity does not occur.

When these special methods are not used, machining depths must be limited to 0.020–0.035 inch if pores are not to be exposed, but as-cast accuracy is usually good enough for only light finishing cuts to be needed. Special pore-sealing techniques must be used if pressure tightness is required.

Designing Die Castings.—Die castings are best designed with uniform wall thicknesses (to reduce cooling stresses) and cores of simple shapes (to facilitate extraction from the die). Heavy sections should be avoided or cored out to reduce metal concentrations that may attract trapped gases and cause porosity concentrations. Designs should aim at arranging for metal to travel through thick sections to reach thin ones if possible. Because of the high metal injection pressures, conventional sand cores cannot be used, so cored holes and apertures are made by metal cores that form part of the die. Small and slender cores are easily bent or broken, so should be avoided in favor of piercing or drilling operations on the finished castings. Ribbing adds strength to thin sections, and fillets should be used on all inside corners to avoid high stress concentrations in the castings. Sharp outside corners should be avoided. Draft allowances on a die casting are usually from 0.5 to 1.5 degrees per side to permit the castings to be pushed off cores or out of the cavity.

Alloys Used for Die Casting.—The alloys used in modern die-casting practice are based on aluminum, zinc, and copper, with small numbers of castings also being made from magnesium-, tin-, and lead-based alloys.

Aluminum-Base Alloys.—Aluminum-base die-casting alloys are used more extensively than any other base metal alloy because of their superior strength combined with ease of castability. Linear shrinkage of aluminum alloys on cooling is about 12.9 to 15.5×10^{-6} in./in.-°F. Casting temperatures are of the order of 1200 deg. F. Most aluminum die castings are produced in aluminum-silicon-copper alloys such as the Aluminum Association (AA) No. 380 (ASTM SC84A; UNS A038000), containing silicon 7.5 to 9.5 and copper 3 to 4 per cent. Silicon increases fluidity for complete die filling, but reduces machinability, and copper adds hardness but reduces ductility in aluminum alloys. A less-used alloy having slightly greater fluidity is AA No. 384 (ASTM SC114A; UNS A03840) containing silicon 10.5 to 12.0 and copper 3.0 to 4.5 per cent. For marine applications, AA 360 (ASTM 100A; UNS A03600) containing silicon 9 to 10 and copper 0.6 per cent is recommended, the copper content being kept low to reduce susceptibility to corrosion in salt atmospheres.

The tensile strengths of AA 380, 384, and 360 alloys are 47,000, 48,000, and 46,000 lb/in.^{2}, respectively. Although 380, 384, and 360 are the most widely used die-castable alloys, several other aluminum alloys are used for special applications. For instance, the AA 390 alloy, with its high silicon content (16 to 18 per cent), is used for internal combustion engine cylinder castings, to take advantage of the good wear resistance provided by the hard silicon grains. No. 390 alloy also contains 4 to 5 per cent copper, and has a hardness of 120 Brinell with low ductility, and a tensile strength of 41,000 lb/in.^{2}.

Zinc-Base Alloys.—In the molten state, zinc is extremely fluid and can therefore be cast into very intricate shapes. The metal also is plentiful and has good mechanical properties. Zinc die castings can be made to closer dimensional limits and with thinner walls than aluminum. Linear shrinkage of these alloys on cooling is about 9 to 13×10^{-6} in./in.-°F. The low casting temperatures (750–800 deg. F) and the hot-chamber process allow high production rates with simple automation. Zinc die castings can be produced with extremely smooth surfaces, lending themselves well to plating and other finishing methods. The established zinc alloys numbered 3, 5 and 7 [ASTM B86 (AG40A; UNS Z33520), AG41A (UNS Z35531), and AG40B (UNS Z33522)] each contains 3.5 to 4.3 per cent of aluminum, which adds strength and hardness, plus carefully controlled amounts of other elements. Recent research has brought forward three new alloys of zinc containing 8, 12, and 27 per cent of aluminum, which confer tensile strength of 50,000–62,000 lb/in.^{2} and hardness approaching that of cast iron (105–125 Brinell). These alloys can be used for gears and racks, for instance, and as housings for shafts that run directly in reamed or bored holes, with no need for bearing bushes.

Copper-Base Alloys.—Brass alloys are used for plumbing, electrical, and marine components where resistance to corrosion must be combined with strength and wear resistance. With the development of the cold-chamber casting process, it became possible to make die castings from several standard alloys of copper and zinc such as yellow brass (ASTM B176-Z30A; UNS C85800) containing copper 58, zinc 40, tin 1, and lead 1 per cent. Tin and lead are included to improve corrosion resistance and machinability, respectively, and this alloy has a tensile strength of 45,000 lb/in^2. Silicon brass (ASTM B176-ZS331A; UNS C87800) with copper 65 and zinc 34 per cent also contains 1 per cent silicon, giving it more fluidity for castability and with higher tensile strength (58,000 psi) and better resistance to corrosion. High silicon brass or tombasil (ASTM B176-ZS144A), containing copper 82, zinc 14, and silicon 4 per cent, has a tensile strength of 70,000 lb/in.2 and good wear resistance, but at the expense of machinability.

Magnesium-Base Alloys.—Light weight combined with good mechanical properties and excellent damping characteristics are principal reasons for using magnesium die castings. Magnesium has a low specific heat and does not dissolve iron so it may be die cast by the cold- or hot-chamber methods. For the same reasons, die life is usually much longer than for aluminum. The lower specific heat and more rapid solidification make production about 50 per cent faster than with aluminum. To prevent oxidation, an atmosphere of CO_2 and air, containing about 0.5 per cent of SF_6 gas, is used to exclude oxygen from the surface of the molten metal. The most widely used alloy is AZ91D (ASTM B94; UNS 11916), a high-purity alloy containing aluminum 9 and zinc 0.7 per cent, and having a yield strength of 23,000 lb/in.^{2} (Table 7a on page 559). AZ91D has a corrosion rate similar to that of 380 aluminum (see *Aluminum-Base Alloys*).

Tin-Base Alloys.—In this group tin is alloyed with copper, antimony, and lead. SAE Alloy No. 10 contains, as the principal ingredients, in percentages, tin, 90; copper, 4 to 5; antimony, 4 to 5; lead, maximum, 0.35. This high-quality babbitt mixture is used for mainshaft and connecting-rod bearings or bronze-backed bearings in the automotive and aircraft industries. SAE No. 110 contains tin, 87.75; antimony, 7.0 to 8.5; copper, maximum, 2.25 to 3.75 per cent and other constituents the same as No. 10. SAE No. 11, which contains a little more copper and antimony and about 4 per cent less tin than No. 10, is also used for bearings or other applications requiring a high-class tin-base alloy. These tin-base compositions are used chiefly for automotive bearings but they are also used for milking machines, soda fountains, syrup pumps, and similar apparatus requiring resistance against the action of acids, alkalies, and moisture.

Lead-Base Alloys.—These alloys are employed usually where a cheap noncorrosive metal is needed and strength is relatively unimportant. Such alloys are used for parts of lead-acid batteries, for automobile wheel balancing weights, for parts that must withstand the action of strong mineral acids and for parts of X-ray apparatus. SAE Composition No. 13 contains (in percentages) lead, 86; antimony, 9.25 to 10.75; tin, 4.5 to 5.5 per cent. SAE Specification No. 14 contains less lead and more antimony and copper. The lead content is 76; antimony, 14 to 16; and tin, 9.25 to 10.75 per cent. Alloys Nos. 13 and 14 are inexpensive owing to the high lead content and may be used for bearings that are large and subjected to light service.

Dies for Die-Casting Machines.—Dies for die-casting machines are generally made of steel although cast iron and nonmetallic materials of a refractory nature have been used, the latter being intended especially for bronze or brass castings, which, owing to their comparatively high melting temperatures, would damage ordinary steel dies. The steel most generally used is a low-carbon steel. Chromium-vanadium and tungsten steels are used for aluminum, magnesium, and brass alloys, when dies must withstand relatively high temperatures.

Making die-casting dies requires considerable skill and experience. Dies must be so designed that the metal will rapidly flow to all parts of the impression and at the same time allow the air to escape through shallow vent channels, 0.003 to 0.005 inch deep, cut into the parting of the die. To secure solid castings, the gates and vents must be located with reference to the particular shape to be cast. Shrinkage is another important feature, especially on accurate work. The amount usually varies from 0.002 to 0.007 inch per inch, but to determine the exact shrinkage allowance for an alloy containing three or four elements is difficult except by experiment.

Die-Casting Bearing Metals in Place.—Practically all the metals that are suitable for bearings can be die cast in place. Automobile connecting rods are an example of work to which this process has been applied sucessfully. After the bearings are cast in place, they are finished by boring or reaming. The best metals for the bearings, and those that also can be die cast most readily, are the babbitts containing about 85 per cent tin with the remainder copper and antimony. These metals should not contain over 9 per cent copper. The copper constitutes the hardening element in the bearing. A recommended composition for a high-class bearing metal is 85 per cent tin, 10 per cent antimony, and 5 per cent copper. The antimony may vary from 7 to 10 per cent and the copper from 5 to 8 per cent. To reduce costs, some bearing metals use lead instead of tin. One bearing alloy contains from 95 to 98 per cent lead. The die-cast metal becomes harder upon seasoning a few days. In die-casting bearings, the work is located from the bolt holes that are drilled previous to die casting. It is important that the bolt holes be drilled accurately with relation to the remainder of the machined surfaces.

Injection Molding of Metal.—The die casting and injection molding processes have been combined to make possible the injection molding of many metal alloys by mixing powdered metal, of 5 to 10 μm (0.0002 to 0.0004 in.) particle size with thermoplastic binders. These binders are chosen for maximum flow characteristics to ensure that the mixture can penetrate to the most remote parts of the die/mold cavities. Moderate pressures and temperatures are used for the injection molding of these mixtures, and the molded parts harden as they cool so that they can be removed as solids from the mold. Shrinkage allowances for the cavities are greater than are required for the die casting process, because the injection molded parts are subject to a larger shrinkage (10 to 35 per cent) after removal from the die, due to evaporation of the binder and consolidation of the powder.

Binder removal may take several days because of the need to avoid distortion, and when it is almost complete the molded parts are sintered in a controlled atmosphere furnace at high temperatures to remove the remaining binder and consolidate the powdered metal component that remains. Density can thus be increased to about 95 per cent of the density of similar material produced by other processes. Tolerances are similar to those in die casting, and some parts are sized by a coining process for greater accuracy. The main limitation of the process is size, parts being restricted to about a 1.5-in. cube.

Precision Investment Casting

Investment casting is a highly developed process that is capable of great casting accuracy and can form extremely intricate contours. The process may be utilized when metals are too hard to machine or otherwise fabricate; when it is the only practical method of producing a part; or when it is more economical than any other method of obtaining work of the quality required. Precision investment casting is especially applicable in producing either exterior or interior contours of intricate form with surfaces so located that they could not be machined readily if at all. The process provides efficient, accurate means of producing such parts as turbine blades, airplane, or other parts made from alloys that have high melting points and must withstand exceptionally high temperatures, and many other products. The accuracy and finish of precision investment castings may either eliminate machining entirely or reduce it to a minimum. The quantity that may be produced economically may range from a few to thousands of duplicate parts.

Investment casting uses an expendable pattern, usually of wax or injection-molded plastics. Several wax replicas or patterns are usually joined together or to bars of wax that are shaped to form runner channels in the mold. Wax shapes that will produce pouring funnels also are fastened to the runner bars. The mold is formed by dipping the wax assembly (tree) into a thick slurry containing refractory particles. This process is known as investing. After the coating has dried, the process is repeated until a sufficient thickness of material has been built up to form a one-piece mold shell. Because the mold is in one piece, undercuts, apertures, and hollows can be produced easily. As in shell molding, this invested shell is baked to increase its strength, and the wax or plastics pattern melts and runs out or evaporates (lost-wax casting). Some molds are backed up with solid refractory material that is also dried and baked to increase the strength. Molds for lighter castings are often treated similarly to shell molds described before. Filling of the molds may take place in the atmosphere, in a chamber filled with inert gas or under vacuum, to suit the metal being cast.

Materials That May Be Cast.—The precision investment process may be applied to a wide range of both ferrous and nonferrous alloys. In industrial applications, these include alloys of aluminum and bronze, Stellite, Hastelloys, stainless and other alloy steels, and iron castings, especially where thick and thin sections are encountered. In producing investment castings, it is possible to control the process in various ways so as to change the porosity or density of castings, obtain hardness variations in different sections, and vary the corrosion resistance and strength by special alloying.

General Procedure in Making Investment Castings.—Precision investment casting is similar in principle to the “lost-wax” process that has long been used in manufacturing jewelry, ornamental pieces, and individual dentures, inlays, and other items required in dentistry, which is not discussed here. When this process is employed, both the pattern and mold used in producing the casting are destroyed after each casting operation, but they may both be replaced readily. The “dispensable patterns” (or cluster of duplicate patterns) is first formed in a permanent mold or die and is then used to form the cavity in the mold or “investment” in which the casting (or castings) is made. The investment or casting mold consists of a refractory material contained within a reinforcing steel flask. The pattern is made of wax, plastics, or a mixture of the two. The material used is evacuated from the investment to form a cavity (without parting lines) for receiving the metal to be cast. Evacuation of the pattern (by the application of sufficient heat to melt and vaporize it) and the use of a master mold or die for reproducing it quickly and accurately in making duplicate castings are distinguishing features of this casting process. Modern applications of the process include many developments such as variations in the preparation of molds, patterns, investments, etc., as well as in the casting procedure. Application of the process requires specialized knowledge and experience.

Master Mold for Making Dispensable Patterns.—Duplicate patterns for each casting operation are made by injecting the wax, plastics, or other pattern material into a master mold or die that usually is made either of carbon steel or of a soft metal alloy. Rubber, alloy steels, and other materials may also be used. The mold cavity commonly is designed to form a cluster of patterns for multiple castings. The mold cavity is not, as a rule, an exact duplicate of the part to be cast because it is necessary to allow for shrinkage and perhaps to compensate for distortion that might affect the accuracy of the cast product. In producing master pattern molds there is considerable variation in practice. One general method is to form the cavity by machining; another is by pouring a molten alloy around a master pattern that usually is made of monel metal or of a high-alloy stainless steel. If the cavity is not machined, a master pattern is required. Sometimes, a sample of the product itself may be used as a master pattern, when, for example, a slight reduction in size due to shrinkage is not objectionable. The dispensable pattern material, which may consist of waxes, plastics, or a combination of these materials, is injected into the mold by pressure, by gravity, or by the centrifugal method. The mold is made in sections to permit removal of the dispensable pattern. The mold while in use may be kept at the correct temperature by electrical means, by steam heating, or by a water jacket.

Shrinkage Allowances for Patterns.—The shrinkage allowance varies considerably for different materials. In casting accurate parts, experimental preliminary casting operations may be necessary to determine the required shrinkage allowance and possible effects of distortion. Shrinkage allowances, in inches per inch, usually average about 0.022 for steel, 0.012 for gray iron, 0.016 for brass, 0.012 to 0.022 for bronze, 0.014 for aluminum and magnesium alloys. (See also *Shrinkage Allowances* on page 1340.)

Casting Dimensions and Tolerances.—Generally, dimensions on investment castings can be held to ±0.005 in. and on specified dimensions to as low as ±0.002 in. Many factors, such as the grade of refractory used for the initial coating on the pattern, the alloy composition, and the pouring temperature, affect the cast surface finish. Surface discontinuities on the as-cast products therefore can range from 30 to 300 microinches in height.

Investment Materials.—For investment casting of materials having low melting points, a mixture of plaster of Paris and powdered silica in water may be used to make the molds, the silica forming the refractory and the plaster acting as the binder. To cast materials having high melting points, the refractory may be changed to sillimanite, an alumina-silicate material having a low coefficient of expansion that is mixed with powdered silica as the binder. Powdered silica is then used as the binder. The interior surfaces of the mold are reproduced on the casting so, when fine finishes are needed, a first coating of fine sillimanite sand and a silicon ester such as ethyl silicate with a small amount of piperidine, is applied and built up to a thickness of about 0.06 in. This investment is covered with a coarser grade of refractory that acts to improve bonding with the main refractory coatings, before the back up coatings are applied.

With light castings, the invested material may be used as a shell, without further reinforcement. With heavy castings the shell is placed in a larger container which may be of thick waxed paper or card, and further slurry is poured around it to form a thicker mold of whatever proportions are needed to withstand the forces generated during pouring and solidification. After drying in air for several hours, the invested mold is passed through an oven where it is heated to a temperature high enough to cause the wax to run out. When pouring is to take place, the mold is pre-heated to between 700 and 1000°C, to get rid of any remaining wax, to harden the binder and prepare for pouring the molten alloy. Pouring metal into a hot mold helps to ensure complete filling of intricate details in the castings. Pouring may be done under gravity, under a vacuum under pressure, or with a centrifuge. When pressure is used, attention must be paid to mold permeability to ensure gases can escape as the metal enters the cavities.

Casting Operations.—The temperature of the flask for casting may range all the way from a chilled condition up to 2000 degrees F or higher, depending upon the metal to be cast, the size and shape of the casting or cluster, and the desired metallurgical conditions. During casting, metals are nearly always subjected to centrifugal force vacuum, or other pressure. The procedure is governed by the kind of alloy, the size of the investment cavity, and its contours or shape.

Investment Removal.—When the casting has solidified, the investment material is removed by destroying it. Some investments are soluble in water, but those used for ferrous castings are broken by using pneumatic tools, hammers, or by shot or abrasive blasting and tumbling to remove all particles. Gates, sprues, and runners may be removed from the castings by an abrasive cutting wheel or a band saw according to the shape of the cluster and machinability of the material.

Accuracy of Investment Castings.—The accuracy of precision investment castings may, in general, compare favorably with that of many machined parts. The overall tolerance varies with the size of the work, the kind of metal and the skill and experience of the operators. Under normal conditions, tolerances may vary from ±0.005 or ±0.006 inch per inch, down to ±0.0015 to ±0.002 inch per inch, and even smaller tolerances are possible on very small dimensions. Where tolerances applying to a lengthwise dimension must be smaller than would be normal for the casting process, the casting gate may be placed at one end to permit controlling the length by a grinding operation when the gate is removed.

Casting Weights and Sizes.—Investment castings may vary in weight from a fractional part of an ounce up to 75 pounds or more. Although the range of weights representing the practice of different firms specializing in investment casting may vary from about $\frac{1}{2}$ pound up to 10 or 20 pounds, a practical limit of 10 or 15 pounds is common. The length of investment castings ordinarily does not exceed 12 or 15 inches, but much longer parts may be cast. It is possible to cast sections having a thickness of only a few thousandths of an inch, but the preferred minimum thickness, as a general rule, is about 0.020 inch for alloys of high castability and 0.040 inch for alloys of low castability.

Design for Investment Casting.—As with most casting processes, best results from investment casting are achieved when uniform wall thicknesses between 0.040 and 0.375 in. are used for both cast components and channels forming runners in the mold. Gradual transition from thick to thin sections is also desirable. It is important that molten metal should not have to pass through a thin section to fill a thick part of the casting. Thin edges should be avoided because of the difficulty of producing them in the wax pattern. Fillets should be used in all internal corners to avoid stress concentrations that usually accompany sharp angles. Thermal contraction usually causes distortion of the casting, and should be allowed for if machining is to be minimized. Machining allowances vary from 0.010 in. on small, to 0.040 in. on large parts. With proper arrangement of castings in the mold, grain size and orientation can be controlled and directional solidification can often be used to advantage to ensure desired physical properties in the finished components.

Casting Milling Cutters by Investment Method.—Possible applications of precision investment casting in tool manufacture and in other industrial applications are indicated by its use in producing high-speed steel milling cutters of various forms and sizes. Removal of the risers, sand blasting to improve the appearance, and grinding the cutting edges are the only machining operations required. The bore is used as cast. Numerous tests have shown that the life of these cutters compares favorably with high-speed steel cutters made in the usual way.

Extrusion of Metals

The Basic Process.—Extrusion is a metalworking process used to produce long, straight semifinished products such as bars, tubes, solid and hollow sections, wire and strips by squeezing a solid slug of metal, either cast or wrought, from a closed container through a die. An analogy to the process is the dispensing of toothpaste from a collapsible tube.

During extrusion, compressive and shear, but no tensile, forces are developed in the stock, thus allowing the material to be heavily deformed without fracturing. The extrusion process can be performed at either room or high temperature, depending on the alloy and method. Cross sections of varying complexity can also be produced, depending on the materials and dies used.

In the specially constructed presses used for extrusion, the load is transmitted by a ram through an intermediate dummy block to the stock. The press container is usually fitted with a wear-resistant liner and is constructed to withstand high radial loads. The die stack consists of the die, die holder, and die backer, all of which are supported in the press end housing or platen, which resists the axial loads.

The following are characteristics of different extrusion methods and presses: 1) The movement of the extrusion relative to the ram. In "direct extrusion," the ram is advanced toward the die stack; in "indirect extrusion," the die moves down the container bore;

2) The position of the press axis, which is either horizontal or vertical; 3) The type of drive, which is either hydraulic or mechanical; and 4) The method of load application, which is either conventional or hydrostatic.

In forming a hollow extrusion, such as a tube, a mandrel integral with the ram is pushed through the previously pierced raw billet.

Cold Extrusion: Cold extrusion has often been considered a separate process from hot extrusion; however, the only real difference is that cold or only slightly warm billets are used as starting stock. Cold extrusion is not limited to certain materials; the only limiting factor is the stresses in the tooling. In addition to the soft metals such as lead and tin, aluminum alloys, copper, zirconium, titanium, molybdenum, beryllium, vanadium, niobium, and steel can be extruded cold or at low deformation temperatures. Cold extrusion has many advantages, such as no oxidation or gas/metal reactions; high mechanical properties due to cold working if the heat of deformation does not initiate recrystallization; narrow tolerances; good surface finish if optimum lubrication is used; fast extrusion speeds can be used with alloys subject to hot shortness.

Examples of cold extruded parts are collapsible tubes, aluminum cans, fire extinguisher cases, shock absorber cylinders, automotive pistons, and gear blanks.

Hot Extrusion: Most hot extrusion is performed in horizontal hydraulic presses rated in size from 250 to 12,000 tons. The extrusions are long pieces of uniform cross sections, but complex cross sections are also produced. Most types of alloys can be hot extruded.

Owing to the temperatures and pressures encountered in hot extrusion, the major problems are the construction and the preservation of the equipment. The following are approximate temperature ranges used to extrude various types of alloys: magnesium, 650–850 degrees F; aluminum, 650–900 degrees F; copper, 1200–2000 degrees F; steel, 2200–2400 degrees F; titanium, 1300–2100 degrees F; nickel 1900–2200 degrees F; refractory alloys, up to 4000 degrees F. In addition, pressures range from as low as 5000 to over 100,000 psi. Therefore, lubrication and protection of the chamber, ram, and die are generally required. The use of oil and graphite mixtures is often sufficient at the lower temperatures; while at higher temperatures, glass powder, which becomes a molten lubricant, is used.

Extrusion Applications: The stress conditions in extrusion make it possible to work materials that are brittle and tend to crack when deformed by other primary metalworking processes. The most outstanding feature of the extrusion process, however, is its ability to produce a wide variety of cross-sectional configurations; shapes can be extruded that have complex, nonuniform, and nonsymmetrical sections that would be difficult or impossible to roll or forge. Extrusions in many instances can take the place of bulkier, more costly assemblies made by welding, bolting, or riveting. Many machining operations may also be reduced through the use of extruded sections. However, as extrusion temperatures increase, processing costs also increase, and the range of shapes and section sizes that can be obtained becomes narrower.

While many asymmetrical shapes are produced, symmetry is the most important factor in determining extrudability. Adjacent sections should be as nearly equal as possible to permit uniform metal flow through the die. The length of their protruding legs should not exceed 10 times their thickness.

The size and weight of extruded shapes are limited by the section configuration and properties of the material extruded. The maximum size that can be extruded on a press of a given capacity is determined by the "circumscribing circle," which is defined as the smallest diameter circle that will enclose the shape. This diameter controls the die size, which in turn is limited by the press size. For instance, the larger presses are generally capable of extruding aluminum shapes with a 25-in.-diam circumscribing circle and steel and titanium shapes with about 22-in.-diam circle.

The minimum cross-sectional area and minimum thickness that can be extruded on a given size press are dependent on the properties of the material, the extrusion ratio (ratio of the cross-sectional area of the billet to the extruded section), and the complexity of shape. As a rule thicker sections are required with increased section size.

The following table gives the approximate minimum cross section and minimum thickness of some commonly extruded metals.

Material	Minimum Cross Section (sq in.)	Minimum Thickness (in.)
Carbon and alloy steels	0.40	0.120
Stainless steels	0.45-0.70	0.120-0.187
Titanium	0.50	0.150
Aluminum	<0.40	0.040
Magnesium	<0.40	0.040

Extruded shapes minimize and sometimes eliminate the need for machining; however, they do not have the dimensional accuracy of machined parts. Smooth surfaces with finishes better than 30 µin. rms are attainable in magnesium and aluminum; an extruded finish of 125 µin. rms is generally obtained with most steels and titanium alloys. Minimum corner and fillet radii of $\frac{1}{64}$ in. are preferred for aluminum and magnesium alloys; while for steel, minimum corner radii of 0.030 in. and fillet radii of 0.125 in. are typical.

Extrusion of Tubes: In tube extrusion, the metal passes through a die, which determines its outer diameter, and around a central mandrel, which determines its inner diameter. Either solid or hollow billets may be used, with the solid billet being used most often. When a solid billet is extruded, the mandrel must pierce the billet by pushing axially through it before the metal can pass through the annular gap between the die and the mandrel. Special presses are used in tube extrusion to increase the output and improve the quality compared to what is obtained using ordinary extrusion presses. These special hydraulic presses independently control ram and mandrel positioning and movement.

Powder Metallurgy

Powder metallurgy is a process whereby metal parts in large quantities can be made by the compressing and sintering of various powdered metals such as brass, bronze, aluminum, and iron. Compressing of the metal powder into the shape of the part to be made is done by accurately formed dies and punches in special types of hydraulic or mechanical presses. The "green" compressed pieces are then sintered in an atmosphere controlled furnace at high temperatures, causing the metal powder to be bonded together into a solid mass. A subsequent sizing or pressing operation and supplementary heat treatments may also be employed. The physical properties of the final product are usually comparable to those of cast or wrought products of the same composition. Using closely controlled conditions, steel of high hardness and tensile strength has also been made by this process.

Any desired porosity from 5 to 50 per cent can be obtained in the final product. Large quantities of porous bronze and iron bearings, which are impregnated with oil for self-lubrication, have been made by this process. Other porous powder metal products are used for filtering liquids and gases. Where continuous porosity is desired in the final product, the voids between particles are kept connected or open by mixing one per cent of zinc stearate or other finely powdered metallic soap throughout the metal powder before briquetting and then boiling this out in a low temperature baking before the piece is sintered.

The dense type of powdered metal products include refractory metal wire and sheet, cemented carbide tools, and electrical contact materials (products which could not be made as satisfactorily by other processes) and gears or other complex shapes which might also have been made by die casting or the precise machining of wrought or cast metal.

Advantages of Powder Metallurgy.—Parts requiring irregular curves, eccentrics, radial projections, or recesses often can be produced only by powder metallurgy. Parts that require irregular holes, keyways, flat sides, splines or square holes that are not easily machined, can usually be made by this process. Tapered holes and counter-bores are easily produced. Axial projections can be formed but the permissible size depends on the extent to which the powder will flow into the die recesses. Projections not more than one-quarter the length of the part are practicable. Slots, grooves, blind holes, and recesses of varied depths are also obtainable.

Limiting Factors in Powdered Metal Process.—The number and variety of shapes that may be obtained are limited by lack of plastic flow of powders, i.e., the difficulty with which they can be made to flow around corners. Tolerances in diameter usually cannot be held closer than 0.001 inch and tolerances in length are limited to 0.005 inch. This difference in diameter and length tolerances may be due to the elasticity of the powder and spring of the press.

Factors Affecting Design of Briquetting Tools.—High-speed steel is recommended for dies and punches and oil-hardening steel for strippers and knock-outs. One manufacturer specifies dimensional tolerances of 0.0002 inch and super-finished surfaces for these tools. Because of the high pressures employed and the abrasive character of certain refractory materials used in some powdered metal composition, there is frequently a tendency toward severe wear of dies and punches. In such instances, carbide inserts, chrome plating, or highly resistant die steels are employed. With regard to the shape of the die, corner radii, fillets, and bevels should be used to avoid sharp corners. Feather edges, threads, and reentrant angles are usually impracticable. The making of punches and dies is particularly exacting because allowances must be made for changes in dimensions due to growth after pressing and shrinkage or growth during sintering.

Flame Spraying Process

In this process, the forerunner of which was called the metal spraying process, metals, alloys, ceramics, and cermets are deposited on metallic or other surfaces. The object may be to build up worn or undersize parts, provide wear-resisting or corrosion-resisting surfaces, correct defective castings, etc.

Different types of equipment are available that provide the means of depositing the coatings on the surfaces. In one, wire is fed automatically through the nozzle of the spray gun; then a combustible gas, oxygen and compressed air serve to melt and blow the atomized metal against the surface to be coated. The gas usually used is acetylene but other gases may be used. Any desired thickness of metal may be deposited and the metals include steels, ranging from low to high carbon content, various brass and bronze compositions, babbitt metal, tin, zinc, lead, nickel, copper, and aluminum. The movement of the spray gun, in covering a given surface, is controlled either mechanically or by hand. In enlarging worn or undersize shafts, spindles, etc., it is common practice to clamp the gun in a lathe toolholder and use the feed mechanism to traverse the gun at a uniform rate while the metal is being deposited upon the rotating workpiece. The spraying operation may be followed by machining or grinding to obtain a more precise dimension.

Some typical production applications using the wire process are the coating of automotive exhaust valves, refinishing of transfer ink rollers for the printing industry and the rebuilding of worn truck clutch plates. Other production applications include the metallizing of glass meter box windows, the spraying of aluminum onto cloth gauze to produce electrolytic condenser plates, and the spraying of zinc or copper for coating ceramic insulators.

With another type of equipment, metal, refractory, and ceramic powder are used instead of wire. Ordinarily this equipment employs the use of two gases, oxygen and a fuel gas. The fuel gas is usually acetylene but in some instances hydrogen may be used. When handheld, a small reservoir supplies the powder to the equipment but a larger reservoir is used for lathe-mounted equipment or for large-scale production work. The four basic types of coating powders used with this equipment are ceramics, oxidation-resistant metals and alloys, self-bonding alloys, and alloys for fused coatings. These powders are used to produce wear-resistant, corrosion-resistant, heat-resistant, and electrically conductive coatings.

Still other equipment employs the use of plasma flame with which vapors of materials are raised to a higher energy level than the ordinary gaseous state. Its use raises the temperature ceiling and provides a controlled atmosphere by permitting employment of an inert or chemically inactive gas so that chemical action, such as oxidation, during the heating and application of the spray material can be controlled. The temperatures that can be obtained with commercially available plasma equipment often exceed 30,000 degrees F but for most plasma flame spray processes the temperature range of from 12,000 to 20,000 degrees F is optimum. Plasma flame spray materials include alumina, zirconia, tungsten, molybdenum, tantalum, copper, aluminum, carbides, and nickel-base alloys.

Regardless of the equipment used, what is important is the proper preparation of the surface that will receive the sprayed coating. Preparation activities include the degreasing or solvent cleaning of the surface, undercutting of the surface to provide room for the proper coating thickness, abrasive or grit blasting the substrate to provide a roughened surface, grooving (in the case of flat surfaces) or rough threading (in the case of cylindrical work) the surface to be coated, preheating the base metal. Methods of obtaining a bond between the sprayed material and the substrate are: heating the base, roughening the base, or spraying a “self-bonding” material onto a smooth surface; however, heating alone is seldom used in machine element work as the elevated temperatures required to obtain the proper bond causes problems of warpage and surface corrosion.

METAL JOINING, CUTTING, AND SURFACING

Metals may be joined without using fasteners by employing soldering, brazing, and welding. Soldering involves the use of a non-ferrous metal whose melting point is below that of the base metal and in all cases below 800 degrees F. Brazing entails the use of a non-ferrous filler metal with a melting point below that of the base metal but above 800 degrees F. In fusion welding, abutting metal surfaces are made molten, are joined in the molten state, and then allowed to cool. The use of a filler metal and the application of pressure are considered to be optional in the practice of fusion welding.

Soldering

Soldering employs lead- or tin-base alloys with melting points below 800 degrees F and is commonly referred to as soft soldering. Use of hard solders, silver solders and spelter solders which have silver, copper, or nickel bases and have melting points above 800 degrees F is known as brazing. Soldering is used to provide a convenient joint that does not require any great mechanical strength. It is used in a great many instances in combination with mechanical staking, crimping or folding, the solder being used only to seal against leakage or to assure electrical contact. The accompanying table gives some of the properties and uses of various solders that are generally available.

Forms Available.—Soft solders can be obtained in bar, cake, wire, pig, slab ingot, ribbon, segment, powder, and foil-form for various uses to which they are put. In bar form they are commonly used for hand soldering. The pigs, ingots, and slabs are used in operations that employ melting kettles. The ribbon, segment, powder and foil forms are used for special applications and the cake form is used for wiping. Wire forms are either solid or they contain acid or rosin cores for fluxing. These wire forms, both solid and core containing, are used in hand and automatic machine applications. Prealloyed powders, suspended in a fluxing medium, are frequently applied by brush and, upon heating, consistently wet the solderable surfaces to produce a satisfactory joint.

Fluxes for Soldering.—The surfaces of the metals being joined in the soldering operation must be clean in order to obtain an efficient joint. Fluxes clean the surfaces of the metal in the joint area by removing the oxide coating present, keep the area clean by preventing formation of oxide films, and lower the surface tension of the solder thereby increasing its wetting properties. Rosin, tallow, and stearin are mild fluxes which prevent oxidation but are not too effective in removing oxides present. Rosin is used for electrical applications since the residue is non-corrosive and non-conductive. Zinc chloride and ammonium chloride (sal ammoniac), used separately or in combination, are common fluxes that remove oxide films readily. The residue from these fluxes may in time cause trouble, due to their corrosive effects, if they are not removed or neutralized. Washing with water containing about 5 ounces of sodium citrate (for non-ferrous soldering) or 1 ounce of trisodium phosphate (for ferrous and non-ferrous soldering) per gallon followed by a clear water rinse or washing with commercial water-soluble detergents are methods of inactivating and removing this residue.

Methods of Application.—Solder is applied using a soldering iron, a torch, a solder bath, electric induction or resistance heating, a stream of hot neutral gas or by wiping. Clean surfaces which are hot enough to melt the solder being applied or accept molten solder are necessary to obtain a good clean bond. Pelts being soldered should be free of oxides, dirt, oil, and scale. Scraping and the use of abrasives as well as fluxes are resorted to for preparing surfaces for soldering. The procedures followed in soldering aluminum, magnesium and stainless steel differ somewhat from conventional soldering techniques and are indicated in the material which follows

Properties of Soft Solder Alloys *Appendix, ASTM:B 32-70*

Nominal Composition[a] Per Cent				Specific Gravity[b]	Melting Ranges,[c] Degrees Fahrenheit		Uses
Sn	Pb	Sb	Ag		Solidus	Liquidus	
70	30	…	…	8.32	361	378	For coating metals.
63	37	…	…	8.40	361	361	As lowest melting solder for dip and hand soldering methods.
60	40	…	…	8.65	361	374	"Fine Solder." For general purposes, but particularly where the temperature requirements are critical.
50	50	…	…	8.85	361	421	For general purposes. Most popular of all.
45	55	…	…	8.97	361	441	For automobile radiator cores and roofing seams.
40	60	…	…	9.30	361	460	Wiping solder for joining lead pipes and cable sheaths. For automobile radiator cores and heating units.
35	65	…	…	9.50	361	477	General purpose and wiping solder.
30	70	…	…	9.70	361	491	For machine and torch soldering.
25	75	…	…	10.00	361	511	For machine and torch soldering.
20	80	…	…	10.20	361	531	For coating and joining metals. For filling dents or seams in automobile bodies.
15	85	…	…	10.50	440[d]	550	For coating and joining metals.
10	90	…	…	10.80	514[d]	570	For coating and joining metals.
5	95	…	…	11.30	518	594	For coating and joining metals.
40	58	2	…	9.23	365	448	Same uses as (50-50) tin-lead but not recommended for use on galvanized iron.
35	63.2	1.8	…	9.44	365	470	For wiping and all uses except on galvanized iron.
30	68.4	1.6	…	9.65	364	482	For torch soldering or machine soldering, except on galvanized iron.
25	73.7	1.3	…	9.96	364	504	For torch and maching soldering, except on galvanized iron.
20	79	1	…	10.17	363	517	For machine soldering and coating of metals, tipping, and like uses, but not recommended for use on galvanized iron.
95	…	5	…	7.25	452	464	For joints on copper in electrical, plumbing and heating work.
…	97.5	…	2.5	11.35	579	579	For use on copper, brass, and similar metals with torch heating. Not recommended in humid environments due to its known susceptibility to corrosion.
1	97.5	…	1.5	11.28	588	588	For use on copper, brass, and similar metals with torch heating.

[a] Abbreviations of alloying elements are as follows: Sn, tin; Pb, lead; Sb, antimony; and Ag, silver.

[b] The specific gravity multiplied by 0.0361 equals the density in pounds per cubic inch.

[c] The alloys are completely solid below the lower point given, designated "solidus," and completely liquid above the higher point given, designated "liquidus." In the range of temperatures between these two points the alloys are partly solid and partly liquid.

[d] For some engineering design purposes, it is well to consider these alloys as having practically no mechanical strength above 360 degrees F.

Soldering Aluminum: Two properties of aluminum which tend to make it more difficult to solder are its high thermal conductivity and the tenacity of its ever-present oxide film. Aluminum soldering is performed in a temperature range of from 550 to 770 degrees F, compared to 375 to 400 degrees F temperature range for ordinary metals, because of the metal's high thermal conductivity. Two methods can be used, one using flux and one using abrasion. The method employing flux is most widely used and is known as flow soldering. In this method flux dissolves the aluminum oxide and keeps it from re-forming. The flux should be fluid at soldering temperatures so that the solder can displace it in the joint. In the friction method the oxide film is mechanically abraded with a soldering iron, wire brush, or multi-toothed tool while being covered with molten solder. The molten solder keeps the oxygen in the atmosphere from reacting with the newly-exposed aluminum surface; thus wetting of the surface can take place.

The alloys that are used in soldering aluminum generally contain from 50 to 75 per cent tin with the remainder zinc.

The following aluminum alloys are listed in order of ease of soldering: commercial and high-purity aluminum; wrought alloys containing not more than 1 per cent manganese or magnesium; and finally the heat-treatable alloys which are the most difficult.

Cast and forged aluminum parts are not generally soldered.

Soldering Magnesium: Magnesium is not ordinarily soldered to itself or other metals. Soldering is generally used for filling small surface defects, voids or dents in castings or sheets where the soldered area is not to be subjected to any load. Two solders can be used: one with a composition of 60 per cent cadmium, 30 per cent zinc, and 10 per cent tin has a melting point of 315 degrees F; the other has a melting point of 500 degrees F and has a nominal composition of 90 per cent cadmium and 10 per cent zinc.

The surfaces to be soldered are cleaned to a bright metallic luster by abrasive methods before soldering. The parts are preheated with a torch to the approximate melting temperature of the solder being used. The solder is applied and the surface under the molten solder is rubbed vigorously with a sharp pointed tool or wire brush. This action results in the wetting of the magnesium surface. To completely wet the surface, the solder is kept molten and the rubbing action continued. The use of flux is not recommended.

Soldering Stainless Steel: Stainless steel is somewhat more difficult to solder than other common metals. This is true because of a tightly adhering oxide film on the surface of the metal and because of its low thermal conductivity. The surface of the stainless steel must be thoroughly cleaned. This can be done by abrasion or by clean white pickling with acid. Muriatic (hydrochloric) acid saturated with zinc or combinations of this mixture and 25 per cent additional muriatic acid, or 10 per cent additional acetic acid, or 10 to 20 per cent additional water solution of orthophosphoric acid may all be used as fluxes for soldering stainless steel. Tin-lead solder can be used successfully. Because of the low thermal conductivity of stainless steel, a large soldering iron is needed to bring the surfaces to the proper temperature. The proper temperature is reached when the solder flows freely into the area of the joint. Removal of the corrosive flux is important in order to prevent joint failure. Soap and water or a suitable commercial detergent may be used to remove the flux residue.

Ultrasonic Fluxless Soldering.—This more recently introduced method of soldering makes use of ultrasonic vibrations which facilitates the penetration of surface films by the molten solder thus eliminating the need for flux. The equipment offered by one manufacturer consists of an ultrasonic generator, ultrasonic soldering head which includes a transducer coupling, soldering tip, tip heater, and heating platen. Metals that can be soldered by this method include aluminum, copper, brass, silver, magnesium, germanium, and silicon.

Brazing

Brazing is a metal joining process which uses a non-ferrous filler metal with a melting point below that of the base metals but above 800 degrees F. The filler metal wets the base metal when molten in a manner similar to that of a solder and its base metal. There is a slight diffusion of the filler metal into the hot, solid base metal or a surface alloying of the base and filler metal. The molten metal flows between the close-fitting metals because of capillary forces.

Filler Metals for Brazing Applications.—Brazing filler metals have melting points that are lower than those of the base metals being joined and have the ability when molten to flow readily into closely fitted surfaces by capillary action. The commonly used brazing metals may be considered as grouped into the seven standard classifications shown in Tables 1a and 1b. These are aluminum-silicon; copper-phosphorus; silver; nickel; copper and copper-zinc; magnesium; and precious metals.

The solidus and liquidus are given in the table instead of the melting and flow points in order to avoid confusion. The solidus is the highest temperature at which the metal is completely solid or, in other words, the temperature above which the melting starts. The liquidus is the lowest temperature at which the metal is completely liquid, that is, the temperature below which the solidification starts.

Fluxes for Brazing.—In order to obtain a sound joint the surfaces in and adjacent to the joint must be free from dirt, oil, and oxides or other foreign matter at the time of brazing. Cleaning may be achieved by chemical or mechanical means. Some of the mechanical means employed are filing, grinding, scratch brushing and machining. The chemical means include the use of trisodium phosphate, carbon tetrachloride, and trichloroethylene for removing oils and greases.

Fluxes are used mainly to prevent the formation of oxides and to remove any oxides on the base and filler metals. They also promote free flow of the filler metal during the course of the brazing operation.

They are made available in the following forms: powders; pastes or solutions; gases or vapors; and as coatings on the brazing rods.

In the powder form a flux can be sprinkled along the joint, provided that the joint has been preheated sufficiently to permit the sprinkled flux to adhere and not be blown away by the torch flame during brazing. A thin paste or solution is easily applied and when spread on evenly, with no bare spots, gives a very satisfactory flux coating. Gases or vapors are used in controlled atmosphere furnace brazing where large amounts of assemblies are mass-brazed. Coatings on the brazing rods protect the filler metal from becoming oxidized and eliminate the need for dipping rods into the flux, but it is recommended that flux be applied to the base metal since it may become oxidized in the heating operation. No matter which flux is used, however, it performs its task only if it is chemically active at the brazing temperature.

Chemical compounds incorporated into brazing fluxes include borates (sodium, potassium, lithium, etc.), fused borax, fluoborates (potassium, sodium, etc.), fluorides (sodium, potassium, lithium, etc.), chlorides (sodium, potassium, lithium), acids (boric, calcined boric acid), alkalies (potassium hydroxide, sodium hydroxide), wetting agents, and water (either as water of crystallization or as an addition for paste fluxes). The accompanying Table 2 provides a guide which will aid in the selection of brazing fluxes that are available commercially.

Table 1a. Brazing Filler Metals [Based on Specification and Appendix of AWS (American Welding Society) A5.8–81]

AWS Classification[a]	Nominal Composition,[b] Per Cent						Temperature, Degrees F			Standard Form[c]	Uses
	Ag	Cu	Zn	Al	Ni	Other	Solidus	Liquidus	Brazing Range		
BAlSi-2	…	…	…	92.5	…	Si, 7.5	1070	1135	1110–1150	7	For joining the following aluminum alloys: 1060, EC, 1100, 3003, 3004, 5005, 5050, 6053, 6061, 6062, 6063, 6951 and cast alloys A612 and C612. All of these filler metals are suitable for furnace and dip brazing. BAlSi-3, -4 and -5 are suitable for torch brazing. Used with lap and tee joints rather than butt joints. Joint clearances run from .006 to .025 inch.
BAlSi-3	…	4	…	86	…	Si, 10	970	1085	1160–1120	2, 3, 5	
BAlSi-4	…	…	…	88	…	Si, 12	1070	1080	1080–1120	2, 3, 4, 5	
BAlSi-5	…	…	…	90	…	Si, 10	1070	1095	1090–1120	7	
BAlSi-6	…	…	…	90	…	Si, 7.5 Mg. 2.5	1038	1125	1110–1150	7	BAlSi-6 through -11 are vacuum brazing filler metals. Magnesium is present as an O_2 getter. When used in vacuum, solidus & liquidus temperatures are different from those shown.
BAlSi-7	…	…	…	88.5	…	Si, 10 Mg, 1.5	1038	1105	1090–1120	7	
BAlSi-8	…	…	…	86.5	…	Si, 12 Mg, 1.5	1038	1075	1080–1120	2, 7	
BAlSi-9	…	…	…	87	…	Si, 12 Mg, 0.3	1044	1080	1080–1120	7	
BAlSi-10	…	…	…	86.5	…	Si, 11 Mg, 2.5	1038	1086	1080–1120	2	
BAlSi-11	…	…	…	88.4	…	Si, 10 Mg, 1.5 Bi, 0.1	1038	1105	1090–1120	7	
BCuP-1	…	95	…	…	…	P, 5	1310	1695	1450–1700	1	For joining copper and its alloys with some limited use on silver, tungsten and molybdenum. Not for use on ferrous or nickel-base alloys. Are used for cupro-nickels but caution should be exercised when nickel content is greater than 30 per cent. Suitable for all brazing processes. Lap joints recommended but butt joints may be used. Clearances used range from .001 to .005 inch.
BCuP-2	…	93	…	…	…	P, 7	1310	1460	1350–1550	2, 3, 4	
BCuP-3	5	89	…	…	…	P, 6	1190	1485	1300–1500	2, 3, 4	
BCuP-4	6	87	…	…	…	P, 7	1190	1335	1300–1450	2, 3, 4	
BCuP-5	15	80	…	…	…	P, 5	1190	1475	1300–1500	1, 2, 3, 4	
BCuP-6	2	91	…	…	…	P, 7	1190	1450	1350–1500	2, 3, 4	
BCuP-7	5	88	…	…	…	P, 6.8	1190	1420	1300–1500	2, 3, 4	
BAg-1	45	15	16	…	…	Cd, 24	1125	1145	1145–1400	1, 2, 4	For joining most ferrous and nonferrous metals except aluminum and magnesium. These filler metals have good brazing properties and are suitable for preplacement in the joint or for manual feeding into the joint. All methods of heating may be used. Lap joints are generally used; however, butt joints may be used. Joint clearances of .002 to .005 inch are recommended. Flux is generally required.
BAg-1a	50	15.5	16.5	…	…	Cd, 18	1160	1175	1175–1400	1, 2, 4	
BAg-2	35	26	21	…	…	Cd, 18	1125	1295	1295–1550	1, 2, 4, 7	

Table 1a. *(Continued)* Brazing Filler Metals [Based on Specification and Appendix of AWS (American Welding Society) A5.8–81]

AWS Classification[a]	Nominal Composition,[b] Per Cent						Temperature, Degrees F			Standard Form[c]	Uses
	Ag	Cu	Zn	Al	Ni	Other	Solidus	Liquidus	Brazing Range		
BAg-2a	30	27	23	…	…	Cd, 20	1125	1310	1310–1550	1, 2, 4	For joining most ferrous and nonferrous metals except aluminum and magnesium. These filler metals have good brazing properties and are suitable for preplacement in the joint or for manual feeding into the joint. All methods of heating may be used. Lap joints are generally used; however, butt joints may be used. Joint clearances of .002 to .005 inch are recommended. Flux is generally required.
BAg-3	50	15.5	15.5	…	3	Cd, 16	1170	1270	1270–1500	1, 2, 4, 7	
BAg-4	40	30	28	…	2	…	1240	1435	1435–1650	1, 2	
BAg-5	45	30	25	…	…	…	1250	1370	1370–1550	1, 2	
BAg-6	50	34	16	…	…	…	1270	1425	1425–1600	1, 2	
BAg-7	56	22	17	…	…	Sn, 5	1145	1205	1205–1400	1, 2	
BAg-8	72	28	…	…	…	…	1435	1435	1435–1650	1, 2, 4	
BAg-8a	72	27.8	…	…	…	Li, 2.	1410	1410	1410–1600	1, 2	
BAg-13	54	40	5	…	1	…	1325	1575	1575–1775	1, 2	
BAg-13a	56	42	…	…	2	…	1420	1640	1600–1800	1, 2	
BAg-18	60	30	…	…	…	Sn, 10	1115	1325	1325–1550	1, 2	
BAg-19	92.5	7.3	…	…	…	Li, 2	1435	1635	1610–1800	1, 2	
BAg-20	30	38	32	…	…	…	1250	1410	1410–1600	1, 2, 4	
BAg-21	63	28.5	…	…	2.5	Sn, 6	1275	1475	1475–1650	1, 2, 4	
BAg-22	49	16	23	…	4.5	Mn, 7.5	1260	1290	1290–1525	1, 2, 4, 7	
BAg-23	85	…	…	…	…	Mn, 15	1760	1780	1780–1900	1, 2, 4	
BAg-24	50	20	28	…	2	…	1220	1305	1305–1550	1, 2	
BAg-25	20	40	35	…	…	Mn, 5	1360	1455	1455–1555	2, 4	
BAg-26	25	38	33	…	2	Mn, 2	1305	1475	1475–1600	1, 2, 4, 7	
BAg-27	25	35	26.5	…	…	Cd, 13.5	1125	1375	1375–1575	1, 2, 4	
BAg-28	40	30	28	…	…	Sn, 2	1200	1310	1310–1550	1, 2, 4	

[a] These classifications contain chemical symbols preceded by "B" which stands for brazing filler metal.

[b] These are nominal compositions. Trace elements may be present in small amounts and are not shown. Abbreviations used are: Ag, silver; Cu, copper; Zn, zinc; Al, aluminum; Ni, nickel; Ot, other; Si, silicon; P, phosphorus; Cd, cadmium; Sn, tin; Li, lithium; Cr, chromium; B, boron; Fe, iron; O, oxygen; Mg, magnesium; W, tungsten; Pd, palladium; and Au, gold.

[c] Numbers specify standard forms as follows: 1, strip; 2, wire; 3, rod; 4, powder; 5, sheet; 6, paste; 7, clad sheet or strip; and 8, transfer tape.

Table 1b. Brazing Filler Metals [Based on Specification and Appendix of AWS (American Welding Society) A5.8–81]

AWS Classification[a]	Nominal Composition,[b] Per Cent						Temperature, Degrees F			Standard Form[c]	Uses
	Ni	Cu	Cr	B	Si	Other	Solidus	Liquidus	Brazing Range		
BNi-1	74	…	14	3.5	4	Fe, 4.5	1790	1900	1950–2200	1, 2, 3, 4, 8	For brazing AISI 300 and 400 series stainless steels, and nickel- and cobalt-base alloys. Particularly suited to vacuum systems and vacuum tube applications because of their very low vapor pressure. The limiting element is chromium in those alloys in which it is employed. Special brazing procedures required with filler metal containing manganese.
BNi-2	82.5	…	7	3	4.5	Fe, 3	1780	1830	1850–2150	1, 2, 3, 4, 8	
BNi-3	91	…	…	3	4.5	Fe, 1.5	1800	1900	1850–2150	1, 2, 3, 4, 8	
BNi-4	93.5	…	…	1.5	3.5	Fe, 1.5	1800	1950	1850–2150	1, 2, 3, 4, 8	
BNi-5	71	…	19	…	10	…	1975	2075	2100–2200	1, 2, 3, 4, 8	
BNi-6	89	…	…	…	…	P, 11	1610	1610	1700–1875	1, 2, 3, 4, 8	
BNi-7	77	…	13	…	…	P, 10	1630	1630	1700–1900	1, 2, 3, 4, 8	
BNi-8	65.5	4.5	…	…	7	Mn, 23	1800	1850	1850–2000	1, 2, 3, 4, 8	
BCu-1	…	100	…	…	…	…	1980	1980	2000–2100	1, 2	For joining various ferrous and nonferrous metals. They can also be used with various brazing processes. Avoid overheating the Cu-Zn alloys. Lap and butt joints are commonly used.
BCu-1a	…	99	…	…	…	Ot, 1	1980	1980	2000–2100	4	
BCu-2	…	86.5	…	…	…	O, 13.5	1980	1980	2000–2100	6	
RBCuZn-A	…	59	…	…	…	Zn, 41	1630	1650	1670–1750	1, 2, 3	
RBCuZn-C	…	58	…	…	0.1	Zn, 40; Fe, 0.7; Mn, 0.3; Sn, 1	1590	1630	1670–1750	2	
RBCuZn-D	10	48	…	…	0.2	Zn, 42	1690	1715	1720–1800	1, 2, 3	
BCuZn-E	…	50	…	…	…	Zn, 50	1595	1610	1610–1725	1, 2, 3, 4, 5	
BCuZn-F	…	50	…	…	…	Zn, 46.5 Sn, 3.5	1570	1580	1580–1700	1, 2, 3, 4, 5	
BCuZn-G	…	70	…	…	…	Zn, 30	1680	1750	1750–1850	1, 2, 3, 4, 5	
BCuZn-H	…	80	…	…	…	Zn, 20	1770	1830	1830–1950	1, 2, 3, 4, 5	
BMg-1	…	…	…	…	…	[a]	830	1100	1120–1160	2, 3	BMg-1 is used for joining AZ10A, K1A, and M1A magnesium-base metals.
BAu-1	…	63	…	…	…	Au, 37	1815	1860	1860–2000	1, 2, 4	For brazing of iron, nickel, and cobalt-base metals where resistance to oxidation or corrosion is required. Low rate of interaction with base metal facilitates use on thin base metals. Used with induction, furnace, or resistance heating in a reducing atmosphere or in a vacuum and with no flux. For other applications, a borax-boric acid flux is used.
BAu-2	…	20.5	…	…	…	Au, 79.5	1635	1635	1635–1850	1, 2, 4	
BAu-3	3	62.5	…	…	…	Au, 34.5	1785	1885	1885–1995	1, 2, 4	
BAu-4	18.5	…	…	…	…	Au, 81.5	1740	1740	1740–1840	1, 2, 4	
BAu-5	36	…	…	…	…	Au, 30 Pd, 34	2075	2130	2130–2250	1, 2, 4	
BAu-6	22	…	…	…	…	Au, 70 Pd, 8	1845	1915	1915–2050	1, 2, 4	
BCo-1	17	…	…	…	8	Cr, 19; W, 4; B, 0.8; C, 0.4; Co, 59	2050	2100	2100–2250	1, 3, 4, 8	Generally used for high temperature properties and compatability with cobalt-base metals.

[a] Al, 9; Zn, 2; Mg, 89.

Table 2. Guide to Selection of Brazing Filler Metals and Fluxes

Base Metals Being Brazed	Filler Metals Recommended[a]	Flux				
		American Welding Society Brazing Flux Type No.	Effective Temperature Range, Degrees F	Ingredients Contained Therein	Form Supplied In	Method of Use[b]
All brazeable aluminum alloys	BA1Si	1	700 to 1190	Chlorides Fluorides	Powder	1, 2 3, 4
All brazeable magnesium alloys	BMg	2	900 to 1200	Chlorides Fluorides	Powder	3, 4
Alloys such as aluminum-bronze; aluminum-brass containing additions of aluminum of 0.5 per cent or more	BCuZn BCuP	4[c]	1050 to 1800	Chlorides Fluorides Borates Wetting agent	Paste or Powder	1, 2, 3
Titanium and zirconium in base alloys	BAg	6	700 to 1600	Chlorides Fluorides Wetting agent	Paste or Powder	1, 2, 3
Any other brazeable alloys not listed above	All brazing filler metals except BA1Si and BMg	3	700 to 2000	Boric acid Borates Fluorides Fluoborates (must contain fluorine compound) Wetting agent	Paste, Powder, or Liquid	1, 2, 3
	All brazing filler metals except BA1Si, BMg, and BAg 1 through BAg 7	5	1000 to 2200	Borax Boric acid Borates Wetting agent *No fluorine in any form*	Paste, Powder, or Liquid	1, 2, 3

[a] Abbreviations used in this column are as follows: B, brazing filler metal; Al, aluminum; Si, silicon; Mg, magnesium; Cu, copper; Zn, zinc; P, phosphorus; and Ag, silver.

[b] Explanation of numbering system used is as follows: 1—dry powder is sprinkled in joint region; 2—heated metal filler rod is dipped into powder or paste; 3—flux is mixed with alcohol, water, monochlorobenzene, etc., to form a paste or slurry; 4—flux is used molten in a bath.

[c] Types 1 and 3 fluxes, alone or in combination, may be used with some of these base metals also.

Methods of Steadying Work for Brazing.—Pieces to be joined by brazing after being properly jointed may be held in a stable position by means of clamping devices, spot welds, or mechanical means such as crimping, staking, or spinning. When using clamping devices care must be taken to avoid the use of devices containing springs for applying pressure because springs tend to lose their properties under the influence of heat. Care must also be taken to be sure that the clamping devices are no larger than is necessary for strength considerations, because a large metal mass in contact with the base metal near the brazing area would tend to conduct heat away from the area too quickly and result in an inefficient braze. Thin sections that are to be brazed are frequently held together by spot welds. It must be remembered that these spot welds may interfere with the flow of the molten brazing alloy and appropriate steps must be taken to be sure that the alloy is placed where it can flow into all portions of the joint.

Methods of Supplying Heat for Brazing.—The methods of supplying heat for brazing form the basis of the classification of the different brazing methods and are given as follows.

Torch or Blowpipe Brazing: Air-gas, oxy-acetylene, air-acetylene, and oxy-other fuel gas blowpipes are used to bring the areas of the joint and the filler material to the proper heat for brazing. The flames should generally be neutral or slightly reducing but in some instances some types of bronze welding require a slightly oxidizing flame.

Dip Brazing: Baths of molten alloy, covered with flux, or baths of molten salts are used for dip brazing. The parts to be brazed are first assembled, usually with the aid of jigs, and are dipped into the molten metal, then raised and allowed to drain. The molten alloy enters the joint by capillary action. When the salt bath is used, the filler metal is first inserted between the parts being joined, or, in the form of wire, is wrapped around the area of the joint. The brazing metal melts and flows into the joint, again by capillary action.

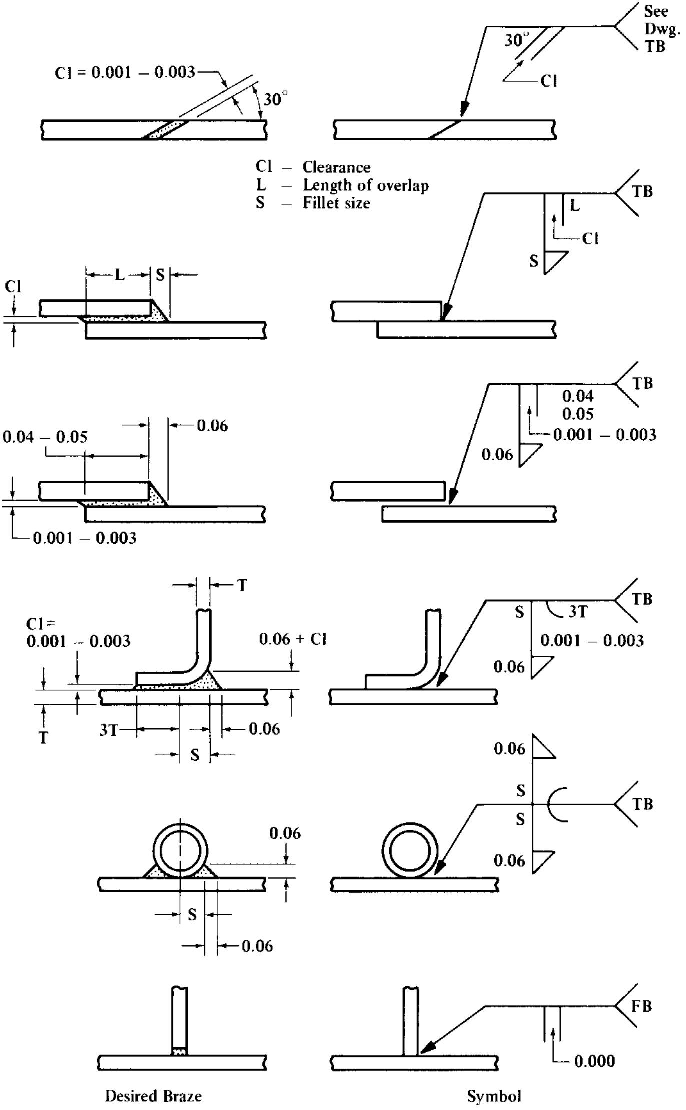
Furnace Brazing: Furnaces that are heated electrically or by gas or oil with auxiliary equipment that maintains a reducing or protective atmosphere and controlled temperatures therein are used for brazing large numbers of units, usually without flux.

Resistance Brazing: Heat is supplied by means of hot or incandescent electrodes. The heat is produced by the resistance of the electrodes to the flow of electricity and the filler metal is frequently used as an insert between the parts being joined.

Induction Brazing: Parts to be joined are heated by being placed near a coil carrying an electric current. Eddy current losses of the induced electric current are dissipated in the form of heat raising the temperature of the work to a point higher than the melting point of the brazing alloy. This method is both quick and clean.

Vacuum Furnace Brazing: Cold-wall vacuum furnaces, with electrical-resistance radiant heaters, and pumping systems capable of evacuating a conditioned chamber to moderate vacuum (about 0.01 micron) in 5 minutes are recommended for vacuum brazing. Metals commonly brazed in vacuum are the stainless steels, heat-resistant alloys, titanium, refractory metals, and aluminum. Fluxes and filler metals containing alloying elements with low boiling points or high vapor pressure are no t used.

Brazing Symbol Application.—ANSI/AWS A2.4.-79 symbols for brazing are also used for welding with the exception of the symbol for a scarf joint (see the diagram at the top of the following page, and the symbol for a scarf joint in the table *Basic Weld Symbols* on page 1394, for applications of brazing symbols). The second, third and fourth figures from the top of the next page show how joint clearances are indicated. If no special joint preparation is required, only the arrow is used with the brazing process indicated In the tail.



Typical Applications of Standard Brazing Symbols

WELDING

Welding of metals requires that they be heated to a molten state so that they fuse together. A filler wire or rod is held in the heated zone to add material that will replace metal consumed by the process and to produce a slightly raised area that can be dressed down to make a level surface if needed. Most welding operations today use an electric arc, though the autogenous method using a torch that burns a mixture of (usually) acetylene and oxygen gases to heat the components is still used for certain work. Lasers are also used as the heating medium for some welding operations. In arc welding, a low-voltage, high-current arc is struck between the end of an electrode in a holder and the work, generating intense heat that immediately melts tile surface.

Welding Electrodes, Fluxes, and Processes

Electrodes for welding may be made of a tungsten or other alloy that does not melt at welding temperatures (nonconsumable) or of an alloy similar to that of the work so that it melts and acts as the filler wire (consumable). In welding with a nonconsumable electrode, filler metal is added to the pool as welding proceeds. Filler metals that will produce welds having strength properties similar to those of the work are used where high-strength welds are specified.

Briefly, the effects of the main alloying elements in welding filler wires and electrodes are: carbon adds strength but may cause brittle weld metal if cooling is rapid, so low-carbon wire is preferred; silicon adds strength and reduces oxidation, changes fluidity, and gives a flatter weld bead; manganese strengthens and assists deoxidation, plus it reduces effects of sulfur, lowering the risk of hot cracking; sulfur may help form iron sulfide, which increases the risk of hot cracking; and phosphorus, may contribute to hot cracking.

Fluxes in (usually) granular form are added to the weld zone, as coatings on the filler wire or as a core in the tube that forms the (consumable) electrode. The flux melts and flows in the weld zone, shielding the arc from the oxygen in the atmosphere, and often contains materials that clean impurities from the molten metal and prevent grain growth during recrystallization.

Processes.—There are approximately 100 welding and allied welding processes but the four manual arc welding processes: gas metal arc welding (GMAW) (which is also commonly known as MIG for metal inert gas), flux-cored arc (FCAW), shielded metal arc (SMAW), gas tungsten arc welding (GTAW), account for over 90 per cent of the arc welding used in production, fabrication, structural, and repair applications. FCAW and SMAW use fluxes to shield the arc and FCAW uses fluxes and gases to protect the weld from oxygen and nitrogen. GMAW and GTAW use mixtures of gases to protect the weld.

There are two groups of weld types, groove and fillet, which are self-explanatory. Each type of weld may be made with the work at any angle from horizontal (flat) to inverted (overhead). In a vertical orientation, the electrode tip may move down the groove or fillet (vertical down), or up (vertical up). In any weld other than flat, skill is needed to prevent the molten metal falling from the weld area.

Because of the many variables, such as material to be welded and its thickness, equipment, fluxes, gases, electrodes, degree of skill, and strength requirements for the finished welds, it is not practicable to set up a complete list of welding recommendations that would have general validity. Instead, examples embracing a wide range of typical applications, and assuming common practices, are presented here for the most-used welding processes. The recommendations given are intended as a guide to finding the best approach to any welding job, and are to be varied by the user to fit the conditions encountered in the specific welding situation.

Gas Metal Arc Welding (GMAW)

The two most cost-effective manual arc welding processes are GMAW and FCAW. These two welding processes are used with more than 50 per cent of the arc welding consumable electrodes purchased. Gas metal arc welding modes extend from short-circuit welding, where the consumable electrode wire is melted into the molten pool in a rapid succession of short circuits during which the arc is extinguished, to pulsed and regular spray transfer, where a stream of fine drops and vaporized weld metal is propelled across the continuous arc gap by electromagnetic forces in the arc.

GMAW is the most-used welding process and the two most common GMAW low-carbon steel electrodes used for production welding in North America are the E70S-3 and E70S-6 from the ANSI/AWS Standard A5 series of specifications for arc welding. The E70S-3 contains manganese and silicon as deoxidants and is mainly used for welding low-carbon steels, using argon mixtures as shielding gases. The wire used in the E70S-6 electrodes has more silicon than wire used for the E70S-3 electrodes, and is preferred where straight CO_2 or argon mixes are used as the shielding gas or if the metal to be welded is contaminated. The deoxidizing properties of the E70S-6 electrode also may be beneficial for high-current, deep-penetration welds, and welds in which higher than normal impact-strength properties are required.

E80S-D2 wire contains more manganese and silicon, plus 0.5 per cent molybdenum for welding such steels as AISI 4130, and steels for high-temperature service. The argon + CO_2 mixture is preferred to exert the influence of argon's inertness over the oxidizing action of CO_2. E70S-2 electrodes contain aluminum, titanium, and zirconium to provide greater deoxidation action and are valuable for welding contaminated steel plate.

When the GMAW welding process is used for galvanized steels, minute welding cracks may be caused by the reaction of the zinc coating on the work with silicon in the electrode. Galvanized steel should be welded with an electrode having the lowest possible silicon content such as the E70S-3. For welding low-carbon and low-alloy steels with conventional argon mixture shielding gases, there is little difference between the E70S-3 and E70S-6.

Electrode Diameters.—One of the most important welding decisions is selecting the optimum GMAW electrode diameter. Selection of electrode diameters should be based on the material thickness, as shown for carbon and stainless steels in Table 1, the compatibility of the electrode current requirements with the material thickness, the mode of weld metal transfer, and the deposition rate potential shown in Table 2. The two most popular GMAW electrode sizes are 0.035 in. (1.0 mm) and 0.045 in. (1.2 mm). Diameters of electrodes used for GMAW exert a strong influence on cost of welding. Table 2 also shows how the weld deposition rate varies in short-circuit and spray transfer modes in welding carbon and stainless steels.

Table 1. GMAW Electrode Sizes for Welding Carbon and Stainless Steels

	Electrode Diameter			
Material Thickness	0.030 in. (0.8 mm)	0.035 in. (1.0 mm)	0.045 in. (1.2 mm)	0.062 in. (1.6 mm)
25 to 21 gage (0.020 to 0.032 in.)	yes	…	…	…
20 gage to 1⁄4 in. (0.036 to 0.25 in.)	…	yes	…	…
3⁄16 to 7⁄16 in. flat and horizontal	…	…	yes	…
1⁄2 in. and up	…	…	…	yes

The table is based on suitability of the electrode size to mode of weld transfer, material thickness, and cost effectiveness. If a smaller electrode size is selected, the lower deposition rates could increase welding costs by 20 to 60 per cent.

Table 2. Typical Maximum GMAW Deposition Rates for Carbon and Stainless Steels. Constant-Voltage 450-amp Power Source and Standard Wire Feeder

Weld transfer mode	Electrode Diameter			
	0.030 in. (0.8 mm)	0.035 in. (1.0 mm)	0.045 in. (1.2 mm)	0.062 in. (1.6 mm)
Short circuit	5 lb/h (2.3 kg/h)	7 lb/h (3.2 kg/h)	9 lb/h (4 kg/h)	…
Spray transfer	9 lb/h (4 kg/h)	11 lb/h (5 kg/h)	19 lb/h (8.6 kg/h)	21 lb/h (9.5 kg/h)

For the lowest-cost welds with GMAW electrodes larger than 0.030 in. in diameter, the power source should provide a minimum of 350 amps. The compatibility of the optimum current range of the 0.035-in. (1.0-mm) electrode and its deposition potential make it the first choice for welding of 20 gage to ¼ in. (0.88 to 6.4 mm) thicknesses. For welding thinner sheet metals of 25 to 21 gage, the optimum electrode diameter is 0.030 in. (0.8 mm). The 0.045-in. (1.2-mm) electrode is the most practical choice for spray transfer applications on materials over ¼ in. (6.4 mm) thick and thicker.

As an example, when welding ¼-in. (6.4-mm) thick steel, with 100 per cent arc-on time and a labor cost of $15/h, the deposition rate with a 0.035-in. (0.9-mm) electrode is approximately 11 lb/h (5 kg/h). The labor cost per lb at $15/h ÷ 11 lb/h = $1.36/lb ($3.00/kg). If an electrode of 0.045-in. (1.2-mm) diameter is used for the same application, the deposition rate is 16 lb/h (7.2 kg/h) and at a $15/h labor rate, the cost of weld metal deposited = $15/h ÷ 16 lb/h = $0.93/lb ($2.00/kg). The 0.045-in. diameter electrode would also cost less per pound than a smaller wire, and the weld time with the 0.045-in. electrode would be reduced, so less shielding gas also would be consumed.

GMAW Welding of Sheet Steel.—In GMAW, the short-circuit transfer mode is used to weld carbon steel, low-alloy steel, and stainless steel sheet of 24 gage (0.023 in., or 0.6 mm) to 11 gage (0.12 in., or 3 mm). The most common gage sizes welded with short-circuit transfer are 20 gage to 11 gage (0.88 to 3 mm) and the best GMAW electrode for these thin, sheet metal gages is the 0.035-in. (1-mm) diameter electrode. The short-circuit current requirements for these operations are typically 50 to 200 amps with voltages in the range of 14 to 22 volts. The optimum short-circuit voltage for the majority of applications is 16 to 18 volts.

Shielding Gases for Welding Carbon and Low-Alloy Steels.—With more than 40 GMAW gas mixtures available for welding carbon steels, low-alloy steels, and stainless steels, selection is often confusing. Reactive oxygen and carbon dioxide (CO_2) are added to argon to stabilize the arc and add energy to the weld. CO_2 can provide more energy to the weld than oxygen. As the CO_2 content in a shielding gas mixture is increased to certain levels, the voltage requirements are increased. Argon + oxygen mixtures will require lower voltages than mixtures containing argon with 10 to 25 per cent CO_2. Helium may also be added to argon if increased weld energy is required.

Shielding Gases for Short-Circuit Welding of Carbon Steels.—GMAW short-circuit transfer (SCT) is used mainly for welding thin metals of less than 10 gage, and gaps. With the SCT mode of weld metal transfer, the arc short circuits many times each second. The numerous short circuits switch the arc energy on and off. The short circuits and low current cause the transferred weld to freeze rapidly. Short-circuit transfer on carbon steel gage metals thicker than ¹⁄₁₆ in. (1.6 mm) requires a shielding gas that will provide substantial weld energy. For these applications, argon with 15–25 per cent CO_2 is recommended.

If short-circuit transfer is used on metals thinner than 18 gage (0.047 in., 1.2 mm), melt-through and distortion often occur. Melt-through and distortion can be reduced on very thin-gage carbon and low-alloy steels by using a shielding gas that provides less weld energy than argon + 15 to 25 per cent CO_2 mixes. Argon + oxygen mixtures can utilize lower voltages to sustain the arc. Argon mixed with 2 to 5 per cent oxygen is a practical mixture for thin carbon steel of less than 16 gage, where there is sensitivity to heat.

Shielding Gases for Spray Transfer Welding of Carbon Steels.—With GMAW spray transfer, all traditional argon gas mixtures will provide spatter-free spray weld transfer, depending on the electrode diameter and welding parameters used. The electrode diameter and the electrode current density influence the formation of the weld metal to be transferred. For example, with a 0.035-in. diameter electrode using a mixture containing argon 75 + CO_2 25 per cent, a small globular weld droplet is formed on the end of the electrode tip in the conventional spray transfer parameter range. With the same gas mixture, a 0.045-in. (1.2-mm) diameter electrode, and current above 330 amps, the globular formation disappears and the metal transfers in the spray mode.

Spatter potential stemming from shielding gas, with 0.035-in. (1.0-mm) and smaller diameter electrodes can be controlled by reducing the CO_2 content in the argon mixture to less than 21 per cent. Each different shielding gas will primarily influence the open arc spray transfer mode by variations in the weld energy provided through the welding voltage requirements.

Gas selection in spray transfer must be given careful consideration. In welding of clean cold-rolled carbon steel or low-alloy steel less than $\frac{3}{8}$ in. (9.5 mm) thick, the energy potential of the arc is less important than it is for welding of steels thicker than $\frac{1}{4}$ in. (13 mm) or steels with mill scale. The energy level of the arc is also a key factor in welding steels for which higher than normal impact properties are specified.

A simple, practical multipurpose gas mixture for carbon and low-alloy steels is argon + 15 to 20 per cent CO_2, and a mixture of argon + 17 per cent CO_2 would be ideal. This two-part argon/CO_2 mixture provides higher weld energy than two-component argon + CO_2 mixtures having less than 10 per cent CO_2, argon + oxygen mixtures, or argon + CO_2 + oxygen tri-component mixtures. The argon + 17 per cent CO_2 mixture will provide an arc slightly less sensitive to mill scale than the other mixtures mentioned.

The argon + 17 per cent CO_2 mixture also has practical benefits in that it provides sufficient weld energy for all GMAW short-circuit and spray transfer applications with cylinder or bulk gases. The argon + 17 per cent CO_2 mixture may also be used for all-position FCAW electrodes in welding carbon steels, low-alloy steels, and stainless steels.

Shielding Gases for GMAW Welding of Stainless Steels.—The major problems encountered when using GMAW on stainless steels of thinner than 14 gage include controlling potential melt-through, controlling distortion, and black oxidation on the weld surface. These three welding problems have a common denominator, which is heat. The key to welding thin stainless steel is to minimize the potential heat when welding, by appropriate choice of gas mixture.

A popular gas mixture that is often recommended for GMAW welding of thin-gage stainless steel is the three-part helium gas mixture containing helium 90 + argon 7.5 + CO_2 2.5 per cent. In contrast to gas mixtures without helium, the helium tri-mixture requires the use of higher voltages to sustain the arc, which adds unnecessary heat to the heat-sensitive thin-gage welds.

A practical and lower-cost alternative for GMAW short-circuit transfer on stainless steels is an argon mixture with 2 to 4 per cent CO_2. The argon + CO_2 mixture allows use of lower voltages than is practical with argon/helium mixtures, and the lower voltages resulting from the argon + CO_2 mixture will help to reduce distortion and oxidation, and decrease the melt-through potential. The mixture that works with short-circuit transfer is also a logical practical choice for spray transfer welding of stainless steel because it is less oxidizing than argon/oxygen mixtures. Table 3 provides practical gas mixture recommendations for specific applications.

Table 3. Shielding Gases for Welding Carbon Steels and Stainless Steels

Application	Gas mixtures					
	Argon + Oxygen	Argon + CO_2 + Oxygen	Argon + 2–4% CO_2	Argon + 6–10% CO_2	Argon + 13–20% CO_2	Argon + 25% CO_2
Short-circuit melt-through problems; less than 20 gage	1	1	1	1	2	3
Short-circuit 18 to 11 gage	…	…	…	…	1	1
Spray if mill scale or surface problems; carbon steels	…	…	…	…	1	2
Spray if low energy required; carbon steel	1	1	1	1	…	…
Spray, best impact strengths, lowest porosity; carbon steels	…	…	…	…	1	…
Best single gas mixture for carbon steels	…	…	…	…	1	…
Short-circuit; stainless steels	…	…	1	…	…	…
Spray; stainless steels	2	…	1	…	…	…
Best single gas mixture for stainless and duplex steels	…	…	1	…	…	…

Preferred choice of shielding gas is 1, followed by 2 and 3.

For GMAW spray transfer welding of stainless steels thicker than 11 gage, the traditional GMAW shielding gas has been argon 98 + oxygen 2 per cent. The argon + oxygen mixture provides excellent, stable, spray transfer, but the oxygen promotes oxidation, leaving the weld with a black surface. To reduce the oxidation, the 2 per cent oxygen can be replaced with the less oxidizing 2–4 per cent CO_2.

Shielding Gases for GMAW Welding of Aluminum.—For GMAW welding of aluminum, helium is added to argon to provide additional weld energy, increasing penetration width, and reducing porosity potential. A gas mixture that has worked well in practice and can be used on the majority of aluminum applications is argon + 25 to 35 per cent helium. Mixtures with higher helium content, of 50 to 90 per cent, require voltages and flow rates that may be excessive for many established aluminum applications.

Welding Controls.—The two primary controls for welding with GMAW are the electrode wire feed control on the wire feeder and the voltage control on the power source. As shown in Fig. 1, these controls typically consist of switches and knobs but do not have the scales, seen enlarged at the upper left, that indicate combinations of wire feed rate, wire gage, volts, and amps. These scales have been added here to allow clearer explanation of the functioning of the wire feed control.

The typical wire feed unit provides maximum feed rates of 600 to 800 in./min. The scale surrounding the setting knob on a wire feed control unit usually has only 10 unnumbered graduations, somewhat like the hour markers on a clock face. On most machines, each of these graduations represents an adjustment of the feed rate of approximately 70 in./min. For each increase in the wire feed rate of 70 in./min, depending on the voltage, the welding current increases by approximately 20 to 40 amps, depending on the wire diameter and wire feed positions.

In Fig. 1, a black sector has been drawn in on the wire feed rate adjustment knob to indicate the range of wire feed rates usable with the gas mixture and the electrode diameter (gage) specified. The wire feed and voltage settings shown are for welding thin-gage carbon, low-alloy, or stainless steels with a 0.030- or 0.035-in. (0.8- or 1-mm) diameter electrode. The left edge of the sector on the wire feed knob is set to the eight o'clock position, corresponding to 70 in./min. The optimum voltage for this wire feed rate is 15. If a setting is too low, the knob is turned to the second (nine o'clock) or third (ten o'clock) position to increase the current. The voltage typically increases or decreases by 1 volt for each graduation of the wire feed quadrant.

The short-circuit transfer current range of 50 to 200 amps corresponds to a wire feed rate of 70 to 420 in./min, and is typically found between the eight and one o'clock positions on the scale, as indicated by the black sector on the knob in Fig. 1.

Diagrammatic quadrants have been added at the left in Fig. 1, to show the material thickness, voltage, and current that correspond to the setting of the wire feed rate adjustment knob. Optimum settings are easily made for short-circuit welding of sheet metals. When using a 0.030-in. (0.8-mm) or 0.035-in. (1-mm) diameter GMAW electrode, for instance, to weld 16-gage carbon or stainless steel with a conventional 200-to 450-amp constant-voltage power source and wire feeder, the wire feed control is set to the ten o'clock position for a feed rate of 210 in./min. With digital wire feed units, the short-circuit current range is typically between 100 and 400 in./min, so a good starting point is to set the wire feeder at 210 in./min. The welding voltage is set to 17.

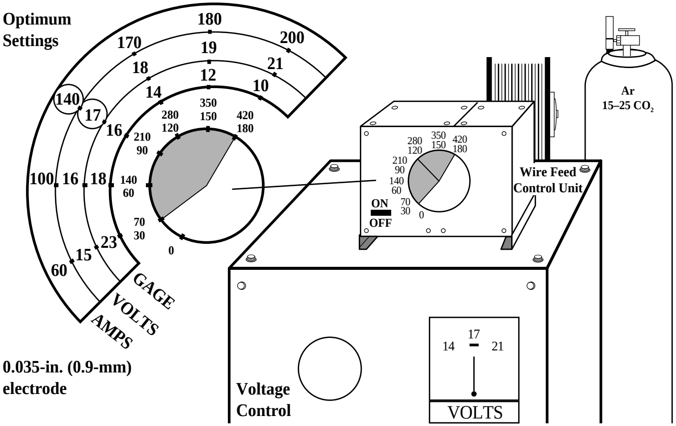


Fig. 1. Wire Feed Settings for Short-Circuit Welding of Carbon, Low-Alloy, and Stainless Steel Sheet.

Many welders set their parameters by an established mark on the equipment or by the sound of the arc as the weld is being made. The sound of the arc, influenced by the optimum current and voltage set, should be a consistent, smooth, crackling noise. If the SCT sound is harsh, the voltage should be increased slightly. If the sound is soft, the voltage should be decreased in volt increments until the sound becomes a smooth crackle. For welding metals thicker than 16 gage but less than 10 gage, the wire feed control should be moved to the eleven o'clock position (280 in./min), and the voltage reset to 18.

Welding of thicknesses less than 16 gage should be started with the wire feed control at the nine o'clock position (140 in./min) and the voltage control set to 16. The parameters discussed above apply when using argon mixtures containing 15 to 25 per cent CO_2.

GMAW Spray Transfer.— In the spray transfer mode, spatter is often caused by the voltage being set so low that the electrode runs into the weld, resulting in expulsion of molten metal from the weld pool. GMAW spray transfer is normally used for welding carbon, low-alloy, and stainless steels of a minimum thickness of ⅛ in. (3.2 mm).

In Table 4, typical deposition rates with a 0.045-in. (1.2-mm) carbon steel electrode are compared with rates for larger carbon steel GMAW and flux-cored electrodes. These welds are typically carried out in the flat and horizontal positions. The practical GMAW electrode diameters commonly used for spray transfer are 0.035-in. (1-mm), 0.045-in. (1.2-mm), and 0.062-in. (1.6-mm) diameter. The most cost-effective GMAW electrode that also has the greatest range of applications on metals over 3⁄16 in. thick is the 0.045-in. (1.2-mm) diameter size.

Table 4. Typical Deposition Rates for Carbon Steel Welding Electrodes

Electrode Diameter				Deposit Rates	
in.	(mm)	Electrode Type	Amperage[a]	lb/h	(kg/h)
0.035	(1.0)	GMAW	350	11	(5)
0.045	(1.2)	GMAW	380	13	(6)
0.062	(1.6)	GMAW	400	14	(6.4)
1⁄16	(1.6)	FCAW	350	15	(7)
3⁄32	(2.4)	FCAW	450	16	(7.3)

[a] The optimum ampere value for the electrode type is shown. The 0.045 GMAW electrode is the most versatile and cost-effective electrode for welding material of 14 gage to 1 in. thick.

GMAW Spray Transfer Welding of Metal Thicknesses Less than ¼ in. (6.4 mm).—

The most versatile GMAW electrode for a welding shop that welds carbon, low-alloy, and stainless steels from 20 gage to ¼ in. (6.4 mm) thick is the 0.035-in. (1.0-mm) diameter electrode. The traditional practical spray transfer current range of between 200 and 350 amps for the 0.035-in. electrode is well suited for welding thicknesses from 10 gage to ¼ in. (6.4 mm).

The correct parameters for a 0.035-in. (1-mm) electrode and spray transfer welding are found on the wire feed unit between the one and five o'clock positions, or, on a digital wire feeder, between 420 and 700 in./min. In the drawing at the left in Fig. 2, the spray transfer wire feed range is shaded. When the wire feed rate has been set, the voltage should be fine-tuned so that the electrode wire tip is just touching the weld and a smooth crackling sound without spatter is produced.

An optimum single spray transfer mode current setting for a 0.035-in. (1-mm) diameter electrode for most welding applications is approximately 280 amps with the wire feed set at the three o'clock position for 560 in./min. Manual or high-speed mechanized welds on material of 10 gage to ¼ in. thick can be made at the three o'clock wire feed position with only an adjustment for voltage, which should be set initially at 31 volts, when using an argon + CO_2 mixture.

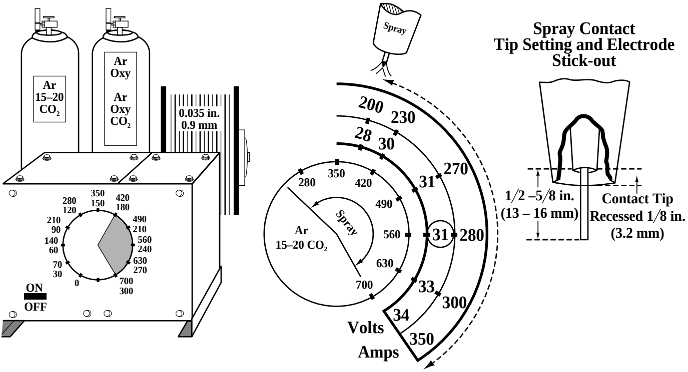


Fig. 2. GMAW Spray Transfer Parameters with 0.035-in. (0.9-mm) Diameter Electrodes

GMAW Spray Transfer for Metal Thicknesses ¼ in. (6.4 mm) and Up.—The 0.45-in. (1.2-mm) diameter is the most cost-effective GMAW electrode for spray transfer welding of carbon, low-alloy, and stainless steels ¼ in. and thicker. A 7⁄16-in. (11.2-mm) single-pass, no-weave, fillet weld can be produced with this electrode. If larger single-pass welds are required, use of flux-cored electrodes should be considered.

A 400-amp power source is a practical cost-effective unit to use with the 0.045-in. diameter electrode. Globular spray transfer, obtained at the ten o'clock position on the wire feed adjustment knob, starts at current levels of approximately 230 amps and requires a wire feed rate of approximately 210 in./min (90 mm/s). Most spray applications are carried out in the higher-energy, deeper-penetrating 270- to 380-amp range, or between twelve and two o'clock wire feed positions giving 350 to 490 in./rain (150 to 210 mm/s). In this range, in which there is minimum weld spatter, the weld deposits are in the form of minute droplets and vaporized weld metal.

The quadrants at the top in Fig. 3 show some typical settings for feed rate, voltage, and current, with different shielding gases. An ideal starting point with a 0.045-in. (1.2-mm) diameter electrode is to set the wire feed rate knob at the one o'clock position, or 420 in./min, at which rate the current drawn, depending on the power source used, should be about 320 to 350 amps. The best starting voltage for the 0.045-in. (1.2-mm) electrode is 30 volts. The arc length should then be set as indicated in Fig. 4. With current over 400 amps at 560 in./min, the 0.045-in. diameter electrode may produce a turbulent weld puddle and a digging arc, which can lead to lack of fusion, porosity, and cracks.

GMAW Spray Transfer with 0.062-in. (1.6-mm) Diameter Electrodes.—Electrode wire of 0.062-in. (1.6-mm) diameter is the largest size in normal use and is often chosen for its high deposition rates. Due to the high-current requirements for the spray transfer mode, use of these thicker electrodes is generally restricted to metal thicknesses of ½ in. (13 mm) and thicker. The high-current requirement reduces ease of welding. This electrode size is suitable for mechanized welding in which fillet welds greater than ⅜ in. (9.6 mm) are required.

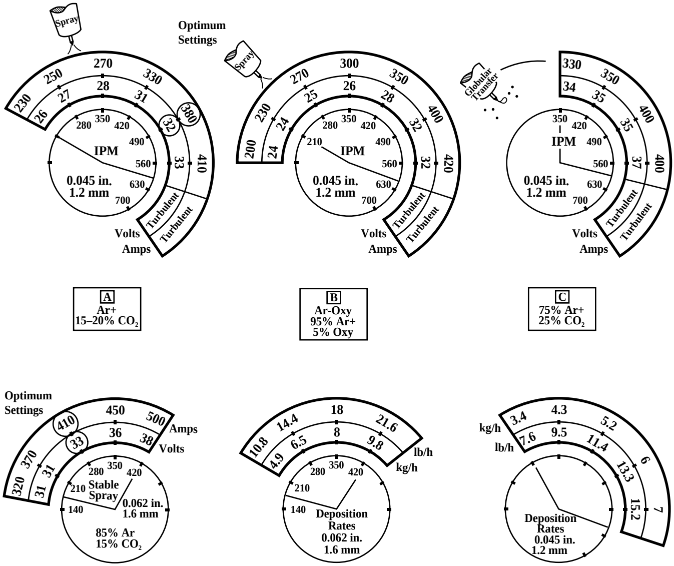


Fig. 3. GMAW Spray Transfer Parameters for Various Electrodes and Gases.

As indicated at the lower left in Fig. 3, the current range for 0.062-in. (1.6-mm) electrodes is narrow and most welds are made in the range of 360 to 420 amps, or between the ten and eleven o'clock positions on the wire feed control unit for 210 to 280 in./min (90 to 120 mm/s). The quadrants at the lower center and lower right in Fig. 3 show deposition rates in lb/h and kg/h for 0.045-in. (1.2-mm) and 0.062-in. (1.6-mm) diameter electrodes.

Some optimum settings for GMAW welding with a mixture of argon + 15 to 20 per cent CO_2 gases are given in Table 5.

Table 5. Optimum Settings for GMAW with Argon + 15–20 per cent CO_2

Diameters		Wire Feed Rates			
in.	mm	in./min	m/min	Amps	Volts
0.035	1.0				
short circuit		210	5.3	140	17
spray transfer		560	14.2	280	29–30
0.045	1.2				
short circuit		210	5.3	190	18
spray transfer		420	10.7	380	30–31
0.052	1.4				
spray transfer		280	7.1	370	31–32
0.062	1.6				
spray transfer		280	7.1	410	31–32

Note: If argon + oxygen gas mixtures are used, voltage should be lowered by 1 to 4 volts for the spray transfer mode. The faster the weld travel speed, the lower the voltage required.

Spray Transfer Voltage.—The usual setting for spray transfer welding with commonly used electrode diameters is between 25 and 35 volts (see Fig. 4A). To set the optimum voltage for GMAW spray transfer, set the voltage initially so that it is too high, usually between 30 and 35 volts. With excess voltage, there should be a visible gap between the tip of the electrode and the weld, and the arc sound should be free from crackle. With the sequence shown in Fig. 4, the voltage should now be reduced until a consistent smooth crackle sound is produced. If the voltage is lowered too much, the electrode will run into the weld, making a harsh crackling sound, and the resulting weld expulsion will cause spatter.

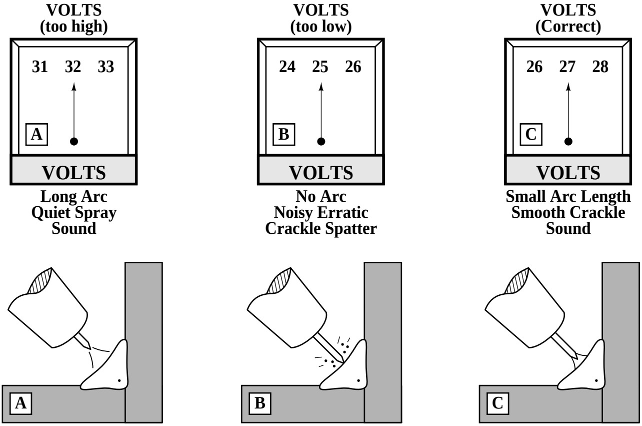


Fig. 4. Setting Optimum Voltage for GMAW Spray Transfer Welding.

Flux-Cored Arc Welding

FCAW welding offers unique benefits for specific applications, but flux-cored consumable electrodes cost more than the solid electrodes used in gas metal arc welding, so users need to be aware of FCAW benefits and disadvantages compared with those of GMAW welding. Generally, flux-cored electrodes designed for use without a shielding gas are intended for welding outdoors. Most indoor FCAW welding is done with gas-shielded FCAW welding electrode wire. Some Standards for gas-shielded FCAW electrodes for various countries are listed in Table 1.

Table 1. Standards for Gas-Shielded, Flux-Cored Welding Electrodes

Steel Type	Country	Standard
Low-Carbon Steels	USA	AWS A5.20
	Canada	CSA W48.5
	Japan	JIS Z3313
	Germany	DIN 8559
Low-Alloy Steels	USA	AWS A5.29
	Canada	CSA W48.3-M
	United Kingdom	BS 639-2492
Stainless Steels	USA	AWS A5.22

All-Position, Gas-Shielded Electrodes.—The term "all-position" does not necessarily mean that these electrodes are the best choice for all positions. Also, flux-cored electrodes may meet all standard specifications, but there will inevitably be subtle differences in weld transfer characteristics and recommended current, voltage, and other settings between electrodes made by different manufacturers. The chemistry and slag of the electrodes developed for welding in the flat and horizontal positions (E70T-X) typically provide superior results when they are used for flat and horizontal applications where the surface conditions of the plate are suspect or large, deep-penetrating welds are required. All-position electrodes are intended for, and best used in, vertical and overhead welds. For extensive welding in flat or horizontal positions, the welder is better served with the electrodes designed for these specific positions.

All-position, gas-shielded FCAW electrodes provide unique benefits and potential for cost savings. In contrast with short-circuit GMAW, or pulsed GMAW, the all-position FCAW electrodes used for vertical up welding of carbon, low-alloy, or stainless steels are simpler to operate, are capable of greater weld quality, and will provide two to three times the rate of weld deposition. The electrode most commonly used in the USA for vertical up welding on carbon steels is the type E71T-1. The equivalent to the E71T-1 standardized electrode specification now in use in other countries include: Canada, E4801T9; Germany, SGR1; and Japan, YFW 24.

If the end user selects the correct all-position electrode diameter, the routine weaving of the electrode during vertical up and overhead applications may be minimized. Keeping the weld weave to a minimum reduces the skill level needed by the welder and increases the potential for consistent side-wall fusion and minimum porosity. If weaving is necessary, a straight-line oscillation technique is often preferred. Typical settings for welding with various sizes of gas-shielded FCAW electrodes are shown in Table 2.

Table 2. Typical Settings for Welding with Gas-Shielded FCAW Electrodes

Electrode Diameter in.	(mm)	Vertical Up Welds		Flat and Horizontal Welds	
0.035	(1)	Feed rate Current Voltage	450 ipm 165 amps 28 volts	Feed rate Current Voltage	630 ipm 250 amps 30 volts
0.045	(1.2)	Feed rate Current Voltage	350 ipm 200 amps 25 volts	Feed rate Current Voltage	560 ipm 280 amps 26 Volts
0.052	(1.4)	Feed rate Current Voltage	240 ipm 200 amps 25 volts	Feed rate Current Voltage	520 ipm 300 amps 30 volts
0.062	(1.6)	Feed rate Current Voltage	210 ipm 240 amps 25 volts	Feed rate Current Voltage	350 ipm 340 amps 29 volts
$\frac{3}{32}$	(2.4)	…		Feed rate Current Voltage	210 ipm 460 amps 32 volts

Material Condition and Weld Requirements.—Practical considerations for selecting a gas-shielded, flux-cored electrode depend on the material condition and weld requirements. FCAW electrodes are beneficial if the surface of the material to be welded is contaminated with mill scale, rust, oil, or paint; the fillet weld size is to be over $\frac{3}{8}$ in. (9.6 mm) wide (a GMAW single-pass fillet weld with an electrode size of 0.045 in. is typically $\frac{3}{8}$ in. wide); the weld is vertical up, or overhead; the required impact strengths and other mechanical properties are above normal levels; crack resistance needs to be high; and increased penetration is required.

Selecting an FCAW Electrode.—Selection of FCAW electrodes is simplified by matching the characteristics of flux-cored types with the material and weld requirements listed above. Once the correct electrode type is selected, the next step is to choose the optimum size. In selecting an all-position, flux-cored electrode for vertical up or overhead welding, the steel thickness is the prime consideration. Selecting the optimum electrode diameter allows the high current capability of the electrode to be fully used to attain maximum deposition rates and allows use of the highest penetrating current without concern for excessive heat-related problems during welding. When used in the optimum current range, the deposited filler metal matches the required amount of filler metal for the specific size of the weld, determined by the plate thickness.

The following suggestions and recommendations are made for FCAW welding of carbon, low-alloy, and stainless steels having flat surfaces. For vertical up welds on steels of thicknesses from $\frac{1}{8}$ to $\frac{3}{16}$ in. (3.2 to 4.8 mm) and for vertical up welds on pipe in the thickness range of $\frac{1}{4}$ to $\frac{1}{2}$ in. (6.4 to 13 mm), consider the 0.035-in. (1.0-mm) diameter E71T-1 electrode. For vertical up welds on steels in the range of $\frac{1}{4}$ to $\frac{3}{8}$ in. (6.4 to 9.6 mm) thickness, consider the 0.045-in. (1.2-mm) diameter E71T-1 electrode or, in nonheat-sensitive applications, the 0.062-in. (1.6-mm) diameter E71T-1 electrode. For vertical up welds on steels of over $\frac{3}{8}$ in. (9.6 mm) thickness, consider the 0.062-in. (1.6-mm) diameter E71T-1 electrodes for optimum deposition rates. For flat and horizontal welds on steels of $\frac{3}{8}$ to $\frac{3}{4}$ in. (9.6 to 19 mm) thickness, consider the $\frac{1}{16}$-in. (1.6-mm) diameter E70T-X electrodes. For flat and horizontal welds on steels over $\frac{3}{4}$ in. (19 mm) in thickness, consider the $\frac{3}{32}$-in. (2.4-mm) E70T-X electrodes.

FCAW Welding of Low-Carbon Steels.—Low-carbon steel is usually called carbon steel or mild steel. The most-used FCAW electrode for welding carbon steels in the flat or horizontal welding positions is the type E70T-1. which is suited to welding of reasonably clean steel using single-pass or multi-pass welds. Type E70T-2 has added deoxidizers and is suited to surfaces with mill scale or other contamination. This type is used when no more than two layers of weld are to be applied. Type E70T-5 is used for single-pass or multi-pass welds where superior impact properties or improved crack resistance are required. The E70T-X electrodes typically range in size from 0.045 to $\frac{3}{32}$ in. (1.2 to 2.4 mm) in diameter. Type E71T-1 all-position electrodes are available in diameters of 0.035 in. (1 mm) to 0.062 in. (1.6 mm). With the FCAW process, multi-pass welds are defined as a condition where three or more weld passes are placed on top of each other.

Settings for Gas-Shielded, All-Position, FCAW Electrodes.—The optimum setting range (volts and amps) for vertical up welding with all-position FCAW electrodes is rather narrow. The welder usually obtains the greatest degree of weld puddle control at the recommended low to medium current settings. The electrode manufacturers' recommended current range for an E71T-1 electrode of 0.045-in. (1.2-mm) diameter for vertical up welding may be approximately 130 to 250 amps. Using the 0.045-in. (1.2-mm) diameter electrode at 250 amps for a vertical up weld in $\frac{1}{4}$-in. (6.4-mm) thick steel, the welder may find that after 3 to 4 inches (75–100 mm) of weld, the weld heat built up in the steel being welded is sufficient to make the weld puddle fluidity increasingly difficult to control. Reducing the current to 160–220 amps will make it possible to maintain control over the weld puddle.

A typical optimum setting for a vertical up weld with an E71T-1, 0.035-in. (1.2-mm) diameter, all-position electrode is as follows. First, set the wire feed rate. If the wire feeder maximum rate is 650 to 750 in./min, the setting mark on the adjustment knob should be set between the one and two o'clock positions on the dial to obtain a feed rate of 450 in./min. If the wire feeder has a digital readout, the rate setting should be the same. At the 450-in./min setting, the welding current with the 0.035-in. all-position electrode should be optimized at between 160 and 170 amps. The welding voltage should be set at 27 to 28 volts with the electrode tip just touching the weld. If there is a gap causing the weld puddle to become too fluid, the voltage should be lowered. If the electrode runs into the weld, causing spatter, the voltage needs to be increased.

With the above conditions, welding steel of ⅛ to ¼ in. thickness will deposit 5 to 7 lb/h (2.2 to 3 kg/h). The 0.035-in. electrode is also ideal for welding steel pipe with wall thicknesses of less than ½ in. (13 mm). The thickness of the pipe after bevelling controls the size of electrode to be used. The 0.035-in. (6.4-mm) electrode can produce a ¼-in. (6.4-mm) vertical up fillet weld on such a pipe without weaving.

Contact Tip Recess.—The dimension labeled contact tip recess in Fig. 2, and indicated as ⅛ in., should be about ½ in. (13 mm) for a minimum electrode extension of ¾ in. (19 mm), for FCAW welding. This dimension is critical for obtaining high-quality welds with all-position electrodes because they have a fast-freezing slag and operate with low to medium current and voltage. If the recess dimension is less than the optimum, the voltage may be lower than the minimum recommended, and if the settings are less than the minimum, the fast-freezing slag may solidify too rapidly, causing excess porosity or "worm tracks" on the weld surface.

The recommended length of electrode extension for all-position FCAW, E71T-1 electrodes is ¾ to 1 in. (19 to 25 mm). The size of this extension not only affects the minimum required parameters, but a long electrode extension also ensures preheating of the electrode and allows lower current to be used. Preheating the electrode is further beneficial as it reduces moisture on the electrode surface, and in the electrode flux. When a change is made from the GMAW to the FCAW process, welders must be aware of the influence on weld quality of the electrode extension in the FCAW process.

Porosity and Worm Tracks.—As mentioned above, porosity and worm tracks typically result from a combination of incorrect electrode extension, incorrect welding settings, humidity, electrode moisture, refill scale, rust, paint, oils, or poor welding technique. Where humidity levels are high, potential for porosity and worm tracks increases. The FCAW process is less sensitive to mill scale than the GMAW spray transfer mode but mill scale will often cause excess weld porosity. The best way to avoid the effects of mill scale, rust, oil, and surface contaminants is to grind the area to be welded.

Another way to reduce porosity is to keep weaving to a minimum. If the correct size flux-cored electrode is used, weaving can be kept to a minimum for most flux-cored applications. The forehand technique produces the best weld bead surface on fillet weld beads up to ¾ in. (19 mm) steel thickness in the flat and horizontal weld positions. On larger single-pass fillet welds, the backhand technique is beneficial because the voltage directed at the weld provides additional weld puddle control to the fluid welds. The backhand technique used for flat and horizontal welds produces a more convex weld bead, reduces potential for porosity, and increases penetration.

If porosity or worm tracks occur, the prime solution is in weld practices that increase heat at the weld, but the following remedies can also be tried. Grind clean the surface to be welded; use recommended electrode extensions; increase current (wire feed rate) decrease voltage; use the backhand welding technique; slow down travel speed, consider use of a different electrode formulation containing increased deoxidizers, avoid weaving; change from argon + CO_2 mixture to straight CO_2; and provide a protective cover to keep the electrode spool clean and dry.

Welding with 0.045-in. (1.2-mm) Diameter All-Position Electrodes.—Fig. 5 shows wire feed settings for welding of steel with 0.045-in. (1.2-mm) diameter, E71T-1 all-position electrodes using a mixture of argon + 15 to 25 per cent CO_2 as the shielding gas, and an electrode extension of ¾ in. (18 mm). Parameters for vertical up welding, shown at the left in Fig. 5, include setting the wire feed rate at the twelve o'clock position, or about 350 in./min, using 200 to 190 amps, and setting the voltage between 24 and 25 volts. Optimum parameters for flat welding, shown at the right in Fig. 5 include setting the wire feed rate at three o'clock position, or 560 in./min (240 mm/s), and 270 amps at 25 to 27 volts.

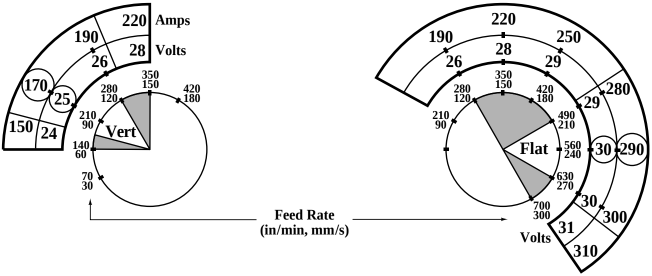


Fig. 5. Wire Feed and Voltage Settings for FCAW Welding with 0.045-in. (1.2-mm) Diameter E71T-1 Electrodes. Optimum settings are circled.

Welding with 0.052-in. (1.3-mm) Diameter All-Position Electrodes.—Settings for vertical up and flat welding with all-position E71T-1 electrodes of 0.052-in. (1.3-mm) diameter are seen at the left in Fig. 6. These electrodes are suited to welding steel having thicknesses of $\frac{1}{4}$ in. (6 mm) and thicker. For vertical up welding, the wire feed rate is set between the ten and eleven o'clock positions, or 250 in./min (106 mm/s), with about 200 amps at 25 volts. Flat welding with these electrodes is best done with the wire feed rate set between the two and three o'clock positions, or 490 to 560 in./min (207 to 237 mm/s), giving approximately 300 amps at 28 volts.

Settings for all-position E71T-1 electrodes of 0.062-in. (1.6-mm) diameter, shown at the right in Fig. 6, for vertical up welding are just before the ten o'clock position, or 190 in./min, giving 230 to 240 amps with voltage adjusted to 24–25 volts. For flat welding, the wire feed is set to the twelve o'clock position, giving 340–350 amps with a voltage of 29–30 volts.

High-Deposition, All-Position Electrodes.—Vertical up weld deposition rates of 10 to 14 lb/h can be achieved with the E71T-1, 0.062-in. (1.6-mm) and 0.045-in. (1.2-mm) flux-cored electrodes. Settings are shown in Fig. 6 for E71T-1, FCAW electrodes of 0.052- and 0.062-in. (1.4- and 1.6-mm) diameter. These electrodes are suited to applications in which the steel thickness is $\frac{1}{4}$ in. and thicker, and are the most cost-effective diameter for all-position welds on carbon and stainless steels of $\frac{1}{4}$ in. (6.35 mm) thickness and thicker. In contrast, vertical up welds, using GMAW or SMAW, may deposit an average of 2 to 4 lb/h (1 to 2 kg/h). Deposition rates are based on welding 60 minutes of each hour. Pulsed GMAW provides deposition rates of 3 to 6 lb/h (1.3-2.7 kg/h). Average rates for vertical up welding with all-position, flux-cored electrodes are shown in Table 3.

The average deposition rates in Table 4 are to be expected with FCAW electrodes available today. Special electrodes are also available that are specifically designed to provide higher deposition rates. A typical manual welder, welding on steel of $\frac{1}{4}$ to $\frac{3}{8}$ in. thickness for 30 minutes of each hour with an all-position flux-cored 0.062-in. (1.6-mm) or 0.045-in. (1.2-mm) diameter electrode would deposit about 4–5 lb/h.

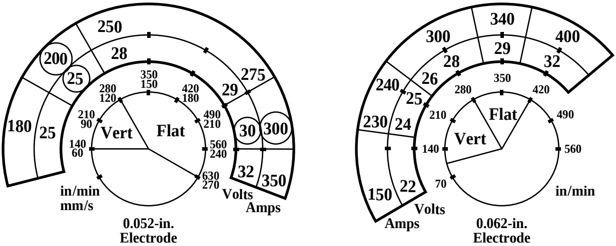


Fig. 6. Wire Feed and Voltage Settings for Vertical Up Welding with 0.052- and 0.062-in. Diameter Electrodes

Table 3. Deposition Rates for Vertical Up Welding with All-Position, Flux-Cored Electrodes (ET71T-1)

Electrode Diameter		Typical Deposition Rate Range		Average Deposition Rate	
in.	(mm)	lb/h	(kg/h)	lb/h	(kg/h)
0.035	(1)	2.7–6.5	(1.2–3)	5	(2.3)
0.045	(1.2)	5–11	(2.3–5)	8	(3.6)
0.052	(1.4)	4–8	(1.8–3.6)	6.5	(3)
0.062	(1.6)	4–11	(1.8–5)	8.5	(4)

Table 4. Average Deposition Rates for Flat and Horizontal Welds

Process	Electrode Size		Cost-Effective Current Range	Optimum Current	Deposition Rate	
	in.	(mm)	(amps)	(amps)	lb/h	(kg/h)
GMAW spray transfer	0.035	(1)	250–350	285	9	(4)
	0.045	(1.2)	300–400	385	13	(5.9)
	0.052	(1.4)	350–470	410	11	(5)
	0.062	(1.6)	375–500	450	17	(7.7)
FCAW	0.045	(1.2)	225–310	300	14	(6.4)
	0.052	(1.4)	260–350	310	15	(6.8)
	0.062	(1.6)	300–400	340	15	(6.8)
	3/32	(2.4)	380–560	460	17	(7.7)

The average deposition rates of pulsed GMAW and FCAW for vertical up welds are similar for applications where the steel thickness is 1/8 in. (3.2 mm) or less. On steels thicker than 1/8 in., where the current may be increased, and larger-diameter all-position FCAW electrodes may be used, deposition rates will be much greater than with pulsed GMAW. Compared with GMAW electrodes for pulsed welding, FCAW all-position electrodes require less costly equipment, less welding skill, and have potential for increased weld fusion with less porosity than with GMAW pulsed techniques.

Electrode Diameters and Deposition Rates.—A cost-effective welding shop can achieve deposition rates on flat and horizontal welds of 12 to 15 lb/h (5 to 7 kg/h) with both the GMAW 0.045-in. wire and the 0.062-in. flux-cored wire electrodes, without welder discomfort, and with welds of consistent quality.

The first consideration in selecting the optimum size of gas-shielded FCAW E70T-X electrode for manual flat and horizontal welds on steels thicker than 1/4 in. (6.4 mm) is the current requirements needed to achieve deposition rates of 12 to 15 lb/h (5 to 7 kg/h).

Large-size electrodes of $\frac{3}{32}$-in. (2.4-mm) diameter require 500 amps or more to attain optimum deposition rates. These $\frac{3}{32}$-in. diameter electrodes are often used with power sources in the 300–400 amp range, but even when the power source provides 500 to 600 amps, welding is often performed at the low end of the electrode's current requirements. With the large, $\frac{3}{32}$-in. diameter electrodes, welder appeal is low, smoke is often excessive, and deposition rates are often only comparable with smaller, easier-to-operate FCAW electrodes.

Typical deposition rates for flat and horizontal welds with various electrode sizes and weld settings are shown in Table 4. In connection with this table, it may be noted that high deposition rates in welding steel plate thicker than $\frac{1}{4}$ in. require use of currents above the minimum shown for the various sizes of electrodes. The optimum current requirements for the most popular electrode sizes indicate that a 450-amp power source is the most suitable for welding steel of more than $\frac{1}{4}$ in. thickness. The two most cost-effective and versatile consumables for thin and thick steel sections are the 0.045 in. for GMAW and the 0.062 in. for FCAW electrodes.

The approach to a welding application is critical to achievement of optimum weld quality at minimum cost. In many applications, minimal consideration is given to weld costs. Half of every man-hour of welding in many shops could be saved with selection of the correct electrode diameter used with optimum parameter settings. A practical point that is often overlooked in selection of FCAW electrodes is that the larger the electrode diameter, the more restricted is the application thickness range. Large FCAW electrodes such as the $\frac{3}{32}$ in. (2.4 mm) are neither suitable nor cost-effective for the common steel thickness range of $\frac{1}{4}$ to $\frac{1}{2}$ in. (6.4 to 13 mm). Smaller FCAW electrodes such as the $\frac{1}{16}$-in. (1.6-mm) diameter, are suitable for both thin and thick applications. A $\frac{1}{6}$-in. diameter FCAW electrode used in the 300- to 350-amp range provides excellent deposition rates with superior welder appeal and negligible smoke.

Large-diameter $\frac{3}{32}$-in. (2.4-mm) electrodes are popular for manual applications. However, from a practical point of view, this electrode size is often better suited to mechanized high-current welding in which the high currents required for optimum deposition rates may be safely used without health risks. Use of an electrode at 60 to 80 per cent of its welding current capability indicates that the correct diameter electrode has been selected for the application. When an electrode is used at its maximum-current capability, it shows that the next size larger electrode should be preferred, and when the low end of the current capability is in use, the electrode selected is typically too large.

The 0.062-in. (1.6-mm) Diameter, E70T-X Electrode.—The 0.062-in. (1.6-mm) diameter FCAW electrode is the most practical size of its type and will provide excellent deposition rate potential with a practical current range and the broadest application range. Settings for the common $\frac{1}{16}$-in. diameter E70T-1 electrode are shown in Fig. 7. With the GMAW process, a $\frac{3}{8}$- to $\frac{7}{16}$-in. (9.6- to 11-mm) minimum-weave fillet weld is typically the maximum size that can be made in a single pass. The 0.062-in. ($\frac{1}{16}$-in, 1.6-mm) FCAW electrode can easily produce a $\frac{3}{4}$-in. (19-mm), nonweave, single-pass fillet weld. This size of electrode is also a practical choice for welding steel of $\frac{1}{4}$ in. (6.4 mm) or greater thickness. From a cost perspective, FCAW consumable electrodes should be used whenever the GMAW process is not suitable.

The average deposition efficiency of a flux-cored electrode is 85 per cent, which means that for every 100 lb or kg of electrode material used, 85 lb or kg ends up as weld material. In contrast, the average deposition efficiency of a GMAW electrode used with argon mixtures and correct equipment settings should be a minimum of 99 per cent.

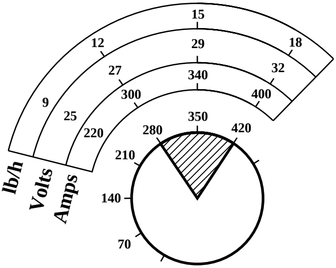


Fig. 7. Settings for $\frac{1}{16}$-in. (1.6-mm) FCAW, E70T-X Electrodes.

Shielding Gases and FCAW Electrodes.—The E70T-X flux-cored electrodes that are recommended for flat and horizontal welds use CO_2 gas shielding. Because of new OSHA welding smoke restrictions, manufacturers of FCAW electrodes now provide E70T-X consumable electrodes that can be used with less reactive argon + CO_2 mixtures to reduce smoke levels. The fast-freezing slag, all-position, E71T-1 flux-cored electrodes can use either CO_2 or argon + 15 to 25 per cent CO_2 mixtures for welding carbon, low-alloy, or stainless steels. The argon + CO_2 mixture is often selected because it provides the highest energy from a reactive gas mixture with a compatible voltage range.

Instead of CO_2, welders often prefer the arc characteristics, lower smoke levels, and lower voltage requirements of the argon + CO_2 mixtures for all-position welding. However, if lower reactive argon mixtures such as argon + oxygen, or argon with less than 13 per cent CO_2, are used, the weld voltage requirements and the arc plasma energy are reduced, adding to the possibility of changing the mechanical properties significantly, increasing the porosity, and raising the potential for forming worm tracks.

Shielded Metal Arc Welding

With the shielded metal arc welding (SMAW) process, commonly known as stick welding, it is most important to select an electrode that is suited to the application. For welding austenitic stainless or high-alloy steels, the electrode is first selected to match the mechanical and chemical requirements of the metal to be welded. Secondary requirements such as the welding position, penetration potential, deposition capabilities, and ease of slag removal are then considered. Many electrodes for SMAW welding of low- to medium-carbon steels have unique characteristics making them the most suitable and cost-effective for a specific welding application.

In interpreting the ANSI/AWS Standard specification code for SMAW electrodes shown in Table 1, for example, E60XX, the E stands for a low-carbon steel, metal arc welding electrode. The next two digits, such as 60 or 70, indicate the approximate tensile strength of the weld deposit in thousands of psi.

Of the last two digits, the first indicates the usability as follows: 1 = usable in all welding positions; 2 = usable for flat or horizontal positions; and 3 = usable in flat position only.

The final digit, combined with the above, indicates the type of flux coating, as shown in Table 1.

British Standard BS 639:1986 defines requirements for covered carbon- and carbon-manganese-steel electrodes for manual metal arc welding, depositing weld metal having a tensile strength of not more than 650 N/mm^2. Appendix A of this standard lists minimum mandatory and optional characteristics of these electrodes. The extensive classifications provide for electrodes to be rated for strength, toughness, and covering (STC), with codes such as E 51 5 4 BB [160 3 0 H]. In this series, E indicates that the electrode is covered and is for manual metal arc welding. The next two digits (51) indicate the strength (tensile, yield, and elongation) properties. The next digits (5 and 4) give the temperatures at which minimum average impact strengths of 28J (at −40°C) and 47J (at −30°C), using Charpy V-notch test specimens, are required. The next group is for the covering and the BB stands for basic, high efficiency. Other letters are B for basic; C for cellulosic; R for rutile, RR for rutile, heavy coated; and S for other.

Table 1. Significance of Digits in ANSI/AWS A5.18-1979 Standard

Third and Fourth Digits	Flux Type and Characteristics, SMAW Electrodes
10	High-cellulose coating bonded with sodium silicate. Deep penetration, energetic spray-type arc. All-positional, DCEP[a] only
11	Similar to 10 but bonded with potassium silicate to permit use with AC or DCEP
12	High-rutile coating, bonded with sodium silicate. Quiet arc, medium penetration, all-positional, AC or DCEN
13	Similar to 12 but bonded with sodium silicate and with easily ionized materials added. Gives steady arc on low voltage. All-positional, AC or DCEN
14	Similar to 12 with addition of medium amount of iron powder. All-positional, AC or DC
15	Lime-fluoride coating (basic low-hydrogen) bonded with sodium silicate. All-positional. For welding high-tensile steels. DCEP only
16	Similar to 15 but bonded with potassium silicate. AC or DCEP
18	Similar to 15 but with addition of iron powder. All-positional, AC or DC
20	High iron-oxide coating bonded with sodium silicate. Flat or HV positions. Good X-ray quality. AC or DC
24	Heavy coating containing high percentage of iron powder for fast deposition rates. Flat and horizontal positions only. AC or DC
27	Very heavy coating with ingredients similar to 20 and high percentage of iron powder. Flat or horizontal positions. High X-ray quality. AC or DC
28	Similar to 18 but heavier coating and suited for use in flat and HV positions only. AC or DC
30	High-iron-oxide-type coating but produces less fluid slag than 20. For use in flat position only (primarily narrow-groove butt welds). Good X-ray quality. AC or DC

[a] DC = direct current, AC = alternating current, EP = electrode positive, EN = electrode negative.

The letters in brackets are optional, and the first group indicates the efficiency, which is the ratio of the mass of weld metal to the mass of nominal diameter core wire consumed with the largest diameter electrode, rounded up to the nearest multiple of 10. The next digit (3) is the maker's advice for the position(s) to be used. Codes for this category include 1, all positions; 2, all positions except vertical down; 3, flat, and for fillet welds, horizontal/vertical; 4, flat; 5, flat, vertical/down; and for fillet welds, horizontal/vertical; and 9, other. The digit at (0), which may have numbers from 0 to 9, shows the polarity, and the minimum open-circuit voltage to be used for that electrode. A 0 here indicates that the electrode is not suited for use with AC. The (H) is included only for hydrogen-controlled electrodes that will deposit not more than 15 ml of diffusible hydrogen for each 100 g of deposited weld metal. The corresponding ISO Standard for BS 639 is ISO 2560. Low-alloy steel electrodes and chromium and chromium nickel steel electrodes are covered in BS 2493 and BS 2926.

The most common electrodes used for the SMAW process are the AWS types E60XX and E70XX. SMAW welding electrode Standards are issued by the American Welding Society (AWS), the British Standards Institute (BS), Canada (CSA), Germany (DIN), and Japan (JIS) and are shown in Table 2.

AWS E60XX Electrodes.—Characteristics of the E60XX electrodes influence the weld position capability, ease of slag removal, penetration potential, weld travel speed capability, and weld deposition rates. These electrodes are designed for welding low-carbon steels and they provide welds with typical tensile strength in the range of 58,000 to 65,000 lb_f/in^2, depending on the specific electrode utilized, the base metal condition and chemistry, and the amount of weld dilution. In selecting an electrode for SMAW welding, knowing that the mechanical and chemical requirements have been matched, it is necessary to choose electrodes with characteristics that influence the features required, as shown in Table 2.

Recommended current ranges, shown in Table 4 for the various sizes of AWS E60XX electrodes most commonly used for welding carbon steel, will give optimum results with SMAW electrodes. An ideal starting point for the current setting for any SMAW electrode diameter is in the middle of the range. The current ranges shown are average values taken from literature of electrode manufacturers in three different countries.

Table 2. Characteristics of SMAW Welding Electrodes Made to Standards of Various Countries

Standard	Description
AWS E6010 CSA E41010 BS E4343C10 DIN E4343C4 JIS	Designed for welding pipe and general structures. Excellent for all-position and vertical down welding. Slag is light and easy to remove. Deep, penetrating arc. Low deposition rates. Polarity DC + (electrode positive).
AWS E6011 CSA E41011 BS E4343C13 DIN E4343C4 JIS D4311	Similar to E6010 but modified to allow use of AC. Excellent for welding sheet metal corner joints vertical down. Polarity AC or DC + (electrode positive).
AWS 6012 CSA E41012 BS E4332R12 DIN E4332R(C) JIS D4313	Designed for welding sheet metal and light structural steels. Medium penetration suitable for gaps or where minimum weld dilution is needed. Ideal for flat, horizontal, or vertical down welding. Will weld faster than the E6010-11 electrode. Polarity AC or DC—(electrode negative).
AWS E6013 CSA E41013 BS E4332R21 DIN E4332R3 JIS D4313	Excellent AC or DC—performance. All-position. Shallow penetration. Good choice for low open-circuit welding machines. AC or DC both excellent on thin structural applications. Polarity AC or DC (DC both polarities).
AWS 6027 CSA 41027 BSE4343A13035 DIN 4343AR11 JIS D4327	Iron powder is added to the flux to provide higher deposition rates. Ideal for multipass groove and fillet welding in flat and horizontal positions. Polarity AC or DC (both polarities).

Table 3. Diameters of AWS E6010/E6011 SMAW Electrodes for Welding Low-Carbon Steel Sheet Metal

SWG of Sheet Metal to be Welded	Electrode Diameter		Current Starting Level
	in.	(mm)	(amps)
18	3⁄32	(2.5)	45–60
16–14	1⁄8	(3.2)	80–110
12	5⁄32	(4)	125–135
10	3⁄16	(5)	135–150

Table 4. Current Ranges for AWS E60XX SMAW Electrodes

Electrode Diameter in.	(mm)	E6010/E6011 (amps)	E6012 (amps)	E6013 (amps)	E6027 (amps)
$\frac{1}{16}$	(1.6)	…	25–50	20–40	…
$\frac{3}{32}$	(2.5)	40–75	40–100	50–100	…
$\frac{1}{8}$	(3.2)	75–130	85–140	75–135	120–180
$\frac{5}{32}$	(4)	90–170	115–185	110–185	155–245
$\frac{3}{16}$	(5)	135–220	145–240	150–235	200–300
$\frac{1}{4}$	(6.4)	205–325	250–390	240–340	300–410
$\frac{5}{16}$	(8)	260–420	290–480	310–425	370–480

Table 3 shows approximate current requirements for AWS E60XX electrodes for welding sheet metal carbon steels. The current ranges specified vary slightly with different electrode manufacturers. For welding sheet metal start at the low end of the given current requirements with electrodes of $\frac{3}{16}$-in (5-mm) diameter or smaller. For metals thicker than 10 gage (0.134 in.), start in the center of the current range, then adjust to suit. A high DC current may result in arc blow, and improved results may then be obtained with AC.

For welding thicker materials, a good starting setting is in the middle of the current range shown in Table 3. In welding material less than $\frac{1}{4}$-in. (6.4-mm) thick, vertically, with an E6010 electrode, try a $\frac{1}{8}$-in. (3.2-mm) electrode at 90 to 100 amps. For welding thicknesses between $\frac{3}{16}$ and $\frac{5}{16}$ in. (5 and 8 mm) with the E6010 electrode, vertically, try the $\frac{5}{16}$-in. (8-mm) diameter electrode at 100 to 125 amps. For thicknesses of $\frac{3}{8}$ to 1 in. (9.5 to 25 mm), try a $\frac{3}{16}$-in. (5-mm) diameter electrode at 155 to 165 amps.

AWS E70XX Electrodes.—Information on the most commonly used AWS E70XX electrodes is given in Table 6. For critical welding applications, low-hydrogen electrodes are typically used. It is most important that manufacturers' instructions regarding storage requirements for keeping low-hydrogen electrodes free from moisture are followed. Current ranges for welding low-carbon steel sheet metal with E70XX electrodes of diameters from $\frac{3}{32}$ to $\frac{3}{16}$ in. (2.5 to 5 mm) are shown in Table 5. The optimum starting point is in the middle of the current range indicated.

Table 5. Current Ranges for SMAW E70XX Welding Electrodes

Electrode Diameter in.	(mm)	E7014 (amps)	E7018 (amps)	E7024 (amps)
$\frac{3}{32}$	(2.5)	75–120	70–105	85–135
$\frac{1}{8}$	(3.2)	110–155	110–160	130–180
$\frac{5}{32}$	(4)	145–210	150–215	175–240
$\frac{3}{16}$	(5)	190–280	180–275	230–315
$\frac{7}{32}$	(5.5)	255–335	255–350	280–370
$\frac{1}{4}$	(6.4)	330–415	295–360	325–450
$\frac{5}{16}$	(8)	380–490	370–480	390–530

In using AWS E7018 electrodes for vertical up welding of plate thicknesses of $\frac{3}{16}$ to $\frac{5}{16}$ in. (5 to 8 mm), try a $\frac{1}{8}$-in. (3.2-mm) diameter electrode. For vertical up welding of thicknesses greater than 5⁄16 in. (8 mm), try a 5⁄32-in. (4-mm) electrode. With AWS E7018 electrodes, to make horizontal fillet welds in plate thicknesses of 10 swg (0.135 in., 3.4 mm), try a 3⁄16-in. (5-mm) electrode, for 1⁄4-in. (6.4-mm) plate, try the 7⁄32-in. (5.5-mm) electrode, and for steel plate thicker than 1⁄4 in., try the 1⁄4-in. (6.4-mm) diameter electrode.

Table 6. Characteristics of AWS Electrodes for SMAW Welding

Standard	Description
AWS E7014 CSA E48014 BS E5121RR11011 DIN E5121RR8 JIS D4313	An iron-powder, all-position electrode for shallow penetration. Excellent for vertical down and applications with poor fit. Similar to AWS E6012-E6013 with added iron powder. For welding mild and low-alloy steels. Polarity AC or DC, + or –.
AWS E7018 CSA E48018 BS E5154B11026(H) DIN E5154B(R)10 JIS D5016	An iron-powder, low-hydrogen, all-position electrode. Excellent for rigid, highly stressed structures of low- to medium-carbon steel. Can also be used for welding mild and high-strength steels, high-carbon steels, and alloy steels. Polarity AC or DC + reverse polarity.
AWS 7024 CSA E48024 BS E5122RR13034 DIN E5122RR11 JIS D4324	An iron-powder electrode with low hydrogen, usable in all positions. Excellent for high-amperage, large, fillet welds in flat and horizontal positions. Polarity AC or DC, + or –.
AWS E7028 CSA E48028 BS E514B12036(H) DIN E5143B(R)12 JIS D5026	An iron-powder, low-hydrogen electrode suitable for horizontal fillets and grooved flat position welding. Higher deposition rates. More cost-effective than the AWS E7018 electrode. Polarity AC or DC + reverse polarity.

The E7024 electrode is suggested for horizontal fillet welds. For 10-gage (0.135-in, 3.4-mm) material, try the 1⁄8-in. (3.2-mm) diameter electrode; for above 10-gage to 3⁄16-in. (5-mm) material, try the 5⁄32-in. (4-mm) diameter electrode. For plate of 3⁄16- to 1⁄4-in. thickness, try the 3⁄16-in. size, and for plate thicker than 1⁄4 in., try the 1⁄4-in. (6.4-mm) electrode.

Gas Tungsten Arc Welding

Often called TIG (for tungsten inert gas) welding, gas tungsten arc welding (GTAW) uses a nonconsumable tungsten electrode with a gas shield, and was, until the development of plasma arc welding (PAW), the most versatile of all common manual welding processes. Plasma arc welding is a modified GTAW process. In contrast to GTAW, plasma arc welding has less sensitivity to arc length variations, superior low-current arc stability, greater potential tungsten life, and the capability for single-pass, full-penetration welds on thick sections.

In examining a potential welding application, the three primary considerations are: achieving a quality weld, ease of welding, and cost. Selecting the optimum weld process becomes more complex as sophisticated electronic technology is applied to conventional welding equipment and consumable electrodes. Rapid advances in gas metal arc and PAW welding power source technology, and the development of many new flux-cored electrodes, have made selection of the optimum welding process or weld consumable more difficult. When several manual welding processes are available, the logical approach in considering GTAW for production welding is to first examine whether the job can be welded by gas metal arc or flux-cored methods.

GTAW Welding Current.—A major benefit offered by GTAW, compared with GMAW, FCAW, or SMAW, is the highly concentrated, spatter-free, inert heat from the tungsten arc, which is beneficial for many applications. The GTAW process can use any of three types of welding current, including: direct-current straight polarity, electrode negative (DC–), direct-current reverse polarity, electrode positive (DC+), alternating current with high frequency for arc stabilization (ACHF). Each of the different current types provides benefits that can be used for a specific application.

GTAW Direct-Current Straight Polarity (DC–): The most common GTAW current is straight polarity, where the electrode is connected to the negative terminal on the power source and the ground is connected to the positive terminal. Gas tungsten arc welding is used with inert gases such as argon, and argon + helium to weld most metals. During a DC– straight-polarity weld, electrons flow from the negative tungsten electrode tip and pass through the electric field in the arc plasma to the positive workpiece, as shown in Fig. 1.

Plasma is a high-temperature, ionized, gaseous column that is formed when electrons in the arc collide with the shielding gas molecules. The gas atoms lose one or more electrons, leaving them positively charged. The electrons and the resulting plasma are concentrated at the electrode tip, where they cause the plasma pressure to be at its greatest. The electron density thins out as the electrons travel from the straight-polarity, negatively charged, tungsten electrode across the open arc. As the electrons traverse the arc to the work, the resulting arc column width increases slightly, controlled in part by the electromagnetic forces generated by the current. With the increase in the arc column width, the density and pressure of the plasma decrease. The electrons collide with the work, liberating much heat. The downward pressure of the plasma is exerted against the surface of the weld pool. The gas ions in the plasma are positively charged and greater in mass than the electrons.

In DC–, straight-polarity welding, the positive gas ions are drawn to the negative electrode. The electron flow to the weld ensures that most of the arc heat is generated at the positive work side of the arc. This current setup provides maximum penetration potential, as indicated in Fig. 1. With DC–, straight polarity, the tungsten electrode can carry a higher current and operate at lower temperatures than with the other current arrangements.

Direct-Current Reverse Polarity (DC+): With direct-current positive polarity (DC+), the tungsten electrode is connected to the power-source positive terminal so that the electrons flow from the negative work to the positive electrode. As illustrated in Fig. 2, the electrons impinging on the electrode tip reverse the direction of the heat concentration that occurs with straight polarity, as described above. Approximately two-thirds of the heat generated with DC+ reverse polarity is at the electrode tip, and the electrode becomes very hot, even with low current levels. DC+ reverse polarity requires large-diameter electrodes.

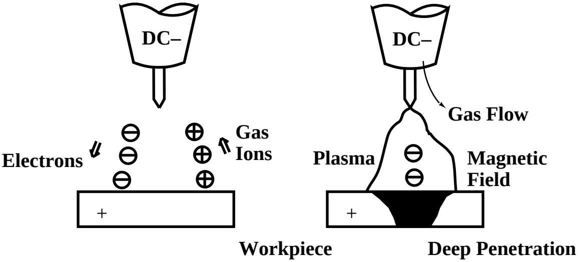


Fig. 1. Straight Polarity (DC–) Provides Highest Electrode Current Capacity and Deepest Penetration Potential.

In the current range of 100 to 150 amps, DC+ reverse polarity requires a $\frac{1}{4}$-in. (6.4-mm) diameter electrode. This larger electrode produces a weld puddle almost twice as wide as that produced by a 120-amp, $\frac{1}{16}$-in. (1.6-mm) diameter, DC– straight polarity electrode. Most of the heat is generated at the electrode tip with DC+ reverse polarity, so penetration is much less than with DC– straight polarity. With DC+ reverse polarity, the positive gas ions in the arc plasma are drawn to the negative workpiece where they bombard and break up the surface oxides that form on metals such as aluminum and magnesium. However, the best welding method for aluminum and magnesium is to use alternating current (AC), which combines the benefits of DC– straight and DC+ reverse polarity.

Alternating Current (AC): The surface oxides formed on metals such as aluminum and magnesium disturb the arc and reduce the weld quality. Welding of these metals requires DC+ reverse or AC polarity to break up the surface oxides. An alternating current (AC) cycle consists of one-half cycle of straight polarity and one-half cycle of reverse polarity. With alternating current, the cleaning action benefits of the reverse-polarity arc can be combined with the electrode current-carrying capacity of the straight-polarity arc. In welding aluminum and magnesium, the half cycles of AC polarity may become unbalanced. During the AC cycle, the reverse electrode-positive portion of the cycle is restricted by the oxides on the surfaces of these materials. The surface oxides are poor conductors and make it difficult for the electrons generated by the reverse-polarity part of the cycle to flow from the work to the electrode tip, but they do not upset the straight polarity in which the electrons flow from the electrode to the work.

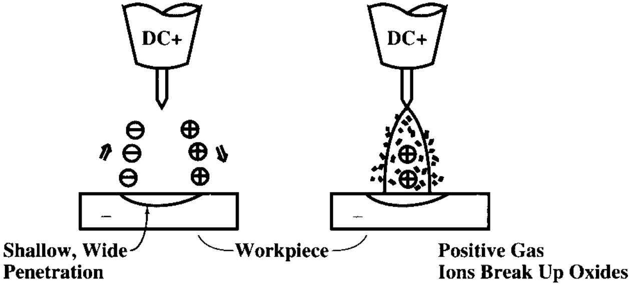


Fig. 2. Direct-Current (DC+) Reverse Polarity Provides a Shallow, Wide, Weld Pool.

DC Component: The part of the reverse-polarity cycle of alternating current (AC) that is upset by the poor conductivity of the oxides is changed into direct-current, straight polarity (DC–) and is directed back to the power source where it may cause overheating. The feedback is referred to as the DC component and its characteristics are important in deciding which process to use because, if an AC power source designed for shielded metal arc welding is to be used to weld aluminum by the GTAW process, the power source must be derated to protect the equipment. The power-source manufacturer will provide information on the level of derating required.

Power sources are available for GTAW that provide a balanced AC wave, and manufacturers will provide information about the benefits of balanced wave versus unbalanced wave, GTAW power sources, and equipment to protect against the DC component.

High Frequency and AC: To maintain the stability of the alternating-current (AC) arc when the positive cycle of the arc is upset by the aluminum oxide, and to avoid contamination of the tungsten electrode, high-frequency current is used to assist in arc ignition during each AC cycle. In direct-current, straight-polarity (DC–) welding of carbon and stainless steels, the high-frequency current is typically selected by the HF arc start-only switch. During AC welding of steels without oxide problems, the HF switch may be left on the arc start-only setting. When AC is used on aluminum, magnesium, or other metals with poor electron-conductive oxides, the HF switch should be moved to the continuous setting.

High-frequency current is also beneficial in that it promotes gas ionization. The more positively charged molecules produced, the more cleaning action takes place in the direct-current, reverse-polarity (DCRP) cycle.

Selecting the Tungsten Electrode Type.—Use of the correct tungsten electrode composition is vital to producing good-quality GTAW welds. Tungsten has the highest melting temperature of all metals. Pure tungsten provides a low-current capacity and requires addition of such alloying elements as thorium or zirconium to increase the current-carrying capability. The electrode diameter and the electrode tip configuration also require consideration as both have a great influence on the performance and application potential of GTAW welding.

Table 8 shows typical compositions of commonly used GTAW tungsten electrode materials from the American Welding Society AWS A5.12 Standard. New electrode compositions have been designed that utilize other alloys and rare-earth metals. These electrodes are designed for longer lives in both GTAW and plasma welding.

Pure Tungsten: Pure tungsten electrode material provides good arc stability with alternating current (AC). Tungsten has low current capacity and low resistance to electrode contamination. Pure tungsten is good for low-amperage welding of aluminum and magnesium alloys. On medium- to high-current ferrous applications, there is a potential for tungsten inclusions in the weld.

With DC, the current capacity of pure tungsten is lower than with the alloyed tungsten electrodes. During AC welding, a molten ball shape forms at the pure tungsten electrode tip, and this formation is desirable for welding aluminum.

Table 7. Selection of Gas Tungsten Arc Welding (GTAW) Electrodes

Base Metal	Electrode	Current	Recommendations
Carbon, low-alloy, stainless, and nickel steels	Thoriated	DCEN	Use EWZr electrodes with AC on thin materials
Aluminum	Zirconium or pure tungsten	AC	Use EWZr on critical applications
Aluminum	Thoriated zirconium	DCEP	Use EWZr or EWP electrodes with DCEP on thin sections
Copper and copper alloys	Thoriated	DCEN	Use EWZr or EWP with AC on thin sections
Magnesium	Zirconium	AC	Use DCEP with same electrode on thin sections
Titanium	Thoriated	DCEN	…

Table 8. Common Tungsten Electrode Compositions

Classification	Color	Tungsten (%)	Thorium Oxide (%)	Zirconium Oxide (%)
EWP	Green	99.50	…	…
EWTh-1	Yellow	98.50	0.8–1.2	…
EWTh-2	Red	97.50	1.7–2.2	…
EWTh-3	Blue	98.95	0.35–0.55	…
EWZr	Brown	99.20	…	0.15–0.4

In the classification column, E = electrode; W = tungsten; P = pure; Th = thoriated (thorium oxide); Zr = zirconiated (zirconium oxide). The colors are codes used by manufacturers to identify the material. Tungsten percentages are minimum requirements. The EWTh-3 is also called striped tungsten because it is made with a strip of thoriated material along the length. This electrode needs to be preheated by striking an arc to melt the tip, providing for the thorium and the tungsten to combine before welding is started.

The electrode recommendations in Table 7 are a guide to attaining good-quality GTAW welds from the venous types of polarities available.

Electrode and Current Selection.—Tables 9 and 10 show approximate current recommendations for common electrode types and diameters. The GTAW electrode size should be selected so that its midrange current provides the energy required for the intended application. If the electrode is too thin, excess current may be required, causing the electrode to wear too quickly or melt and contaminate the weld. If the electrodes used are found to be constantly at the top end of the current range, a change should be made to the next larger size. Tables 11 and 12 show recommended sizes of electrodes and filler metal rods or wires for welding various thicknesses of carbon, low-alloy, and stainless steels and aluminum.

Table 9. Recommended Current Ranges for Thoriated GTAW Electrodes

Electrode		Current Range (amps)
1⁄16 in.	(1.6 mm)	60–150
3⁄32 in.	(2.4 mm)	150–250
1⁄8 in.	(3.2 mm)	250–400
5⁄32 in.	(4 mm)	400–500

The electrode selected must suit the application and the current capacity of the power source.

Table 10. Current Ranges for EWP and EWZr GTAW Electrodes

Electrode		Ampere Range AC Balanced		Ampere Range AC Unbalanced	
in.	(mm)	EWP	EWZr	EWP	EWZr
1⁄16	(1.6)	30–80	60–120	50–100	70–150
3⁄32	(2.4)	60–130	100–180	100–160	140–235
1⁄8	(3.2)	100–180	160–250	150–210	225–325
5⁄32	(4)	160–240	200–320	200–275	300–400

Table 11. Electrode and Current Recommendations for Carbon, Low-Alloy, and Stainless Steels

Material Thickness		Electrode Diameter		Filler Rod Diameter		Current Range (amps)
in.	(mm)	in.	(mm)	in.	(mm)	DCEN EWTh
1⁄16	(1.6)	1⁄16	(1.6)	1⁄16	(1.6)	60–100
1⁄8	(3.2)	3⁄32	(2.4)	3⁄32	(2.4)	150–170
3⁄16	(4.8)	3⁄32	(2.4)	1⁄8	(3.2)	180–220
1⁄4	(6.4)	1⁄8	(3.2)	5⁄32	(7.2)	260–300

Note: The shielding gas is argon at 15 to 20 cu ft/h (CFH). For stainless steel, reduce the current by approximately 10 per cent.

Table 12. Recommendations for GTAW Welding of Aluminum with EWP Electrodes Using AC and High-Frequency Current

Material Thickness		Electrode Diameter		Filler Rod Diameter		AC Current Range
in.	(mm)	in.	(mm)	in.	(mm)	(amps)
1⁄16	(1.6)	1⁄16	(1.6)	1⁄16	(1.6)	40–70
1⁄8	(3.2)	3⁄32	(2.4)	3⁄32	(2.4)	70–125
3⁄16	(4.8)	1⁄8	(3.2)	1⁄8	(3.2)	110–170
1⁄4	(6.4)	5⁄32	(4)	3⁄16	(4.8)	170–220

Thoriated Electrodes: In contrast with the pure EWP electrodes, thoriated electrodes have a higher melting temperature and up to about 50 per cent more current-carrying capacity, with superior arc starting and arc stability. These electrodes are typically the first choice for critical DC welding applications, but do not have the potential to maintain a rounded ball shape at the tip. The best welding mode for these electrodes is with the tip ground to a tapered or fine point.

Zirconiated Electrodes: Tungsten electrodes with zirconium are practical for critical applications and have less sensitivity to contamination and superior current capacity than pure tungsten electrodes.

Protecting and Prolonging Electrode Life: To improve tungsten electrode life, the tip should be tapered in accordance with the manufacturer's recommendations. There must also be preflow, postflow shielding gas coverage to protect the electrode before and after the weld. When possible, high frequency should be used to avoid scratch starts, which contaminate the electrode. The shortest possible electrode extension should be employed, to avoid the possibility of the electrode touching the filler or weld metal. The grinding wheel used to sharpen the tungsten must not be contaminated from grinding other metals or with dirt.

Filler Metals.—Specifications covering composition and mechanical properties for GTAW filler metal are published by the American Welding Society under the following classifications: A5.7, copper and copper alloys; A5.9, chromium and chromium nickel;

A5.10, aluminum; A5.14, nickel; A5.16, titanium; A5.18, carbon steels; A5.19, magnesium; and A5.28, low-alloy steels.

Filler metals must be kept dry and clean if they are to be used satisfactorily.

Shielding Gases.—Inert gases such as argon, and argon + helium mixtures are most commonly used for GTAW. Helium provides greater thermal conductivity and additional arc voltage potential than argon, and is normally added to argon when more weld energy is required for improved penetration and increased mechanized welding travel speeds. Argon gas mixtures containing 30 to 75 per cent helium provide benefits for manual welding of aluminum over $\frac{3}{8}$ in. (9.6 mm) thick; mechanized welding of aluminum where high speeds are required; mechanized welding of carbon and stainless steels where good penetration is needed; mechanized welding of stainless steel where good penetration and faster speeds are required; and for copper of $\frac{1}{4}$ in. (6.4 mm) thickness and thicker.

Shielding gas purity for GTAW welding is important. Welding-grade argon is supplied at a purity of at least 99.996 per cent and helium is produced to a minimum purity of 99.995 per cent. However, shielding gases may be contaminated due to poor cylinder filling practices. If impure gas is suspected, the following test is suggested. With the HF and power on, create an arc without welding and hold the arc for about 30 seconds. Examine the electrode tip for signs of unusual coloration, oxidation, or contamination, which result from impurities in the shielding gas.

Plasma Arc Welding (PAW)

When an electric current passes between two electrodes through certain gases, the energy of the gas molecules is increased so that they accelerate and collide with each other more often. With increases in energy, the binding forces between the nuclei and the electrons are exceeded, and electrons are released from the nuclei. The gas now consists of neutral molecules, positively charged atoms, and negatively charged electrons. The plasma gas is said to be ionized, so that it is capable of conducting electric current. Plasma forms in all welding arcs but in plasma arc welding it is generated by a series of events that begins with inert gas passing through the welding torch nozzle. High-frequency current is then generated between the tungsten electrode (cathode) and the torch nozzle (anode), forming a low-current pilot arc. The ionized path of this nontransferred arc is then transferred from the tungsten electrode to the work, and a preset plasma current is generated.

The above sequence of events provides the ionized path for the plasma current between the electrode and the work so that arcing between the electrode and the nozzle ceases. (Nontransferred arcs may be used for metal spraying or nonmetallic welds.) Forcing the ionized gas through the small orifice in the nozzle increases both the level of ionization and the arc velocity, and arc temperatures between 30,000 and 50,000°F (16,650 and 27,770°C) are generated.

Gases for Plasma Arc Welding

Welding Gases.—Argon is the preferred gas for plasma arc welding (PAW) as it is easily ionized and the plasma column formed by argon can be sustained by a low voltage. The low thermal conductivity of argon produces a plasma column with a narrow, concentrated hot core surrounded by a cooler outer zone. Argon plasmas are suited to welding steel up to $\frac{1}{8}$ in. (3.2 mm). For thicker materials, requiring a hotter arc and using higher current melt-in technique, a mixture of argon 25 + helium 75 per cent may be used. Additions of helium and hydrogen to the gas mixture improve heat transfer, reduce porosity, and increase weld travel speed. For welding materials thinner than $\frac{1}{8}$ in. thick by the plasma gas keyhole method (full penetration welds), gases may contain up to 15 per cent hydrogen with the remainder argon. Good results are obtained with argon + 5 per cent hydrogen in welding stainless and nickel steels over $\frac{1}{8}$ in. thick.

Shielding Gases.—A shielding gas is needed to protect the narrow plasma arc column and the weld pool, and generally is provided by mixtures of argon, argon + hydrogen, argon + helium, or argon + O_2 + CO_2, depending on compatibility with the material being welded. Shielding gas flow rates vary from 5 to 35 cu ft/h (2.4 to 17 l/min). However, if argon is used for both plasma and shielding, the plasma gas will become less concentrated. The normally tight plasma arc column will expand in contact with the colder shielding gas, reducing ionization and thus concentration and intensity of the plasma column. With no shielding gas, the tight column is unaffected by the surrounding oxygen and nitrogen of the atmosphere, which are not easily ionized.

Hydrogen is added to the shielding gas when welding low-alloy steels of less than $\frac{1}{16}$ in. (1.6 mm) thickness, or stainless and nickel steels, with many benefits. The hydrogen molecules dissociate in contact with the arc at temperatures of about 7,000°F (3,870°C) and the energy thus created is released when the hydrogen molecules recombine on contact with the work surface. The diatomic molecular action creates a barrier around the plasma, maintaining column stiffness. Hydrogen in the shielding gas combines with oxygen in the weld zone, releasing it into the atmosphere and keeping the weld clean. Hydrogen reduces the surface tension of the weld pool, increasing fluidity, and the added energy increases penetration.

Helium mixed with the argon shielding gas is beneficial for all metals as it increases the ionization potential, allowing use of higher voltages that give increased welding temperatures. Flow rates are in the range of 15 to 50 cu ft/h (7 to 24 l/min). Arc-starting efficiency is reduced with pure helium, but adding 25 per cent of argon helps both arc starting and stability. Helium additions of 25 to 75 per cent are made to obtain increased thermal benefits.

Argon + CO_2 shielding gas mixtures are beneficial in fusion welding of carbon steels. A mixture of argon with 20 to 30 per cent CO_2 improves weld fluidity. Shielding gas mixtures of argon + CO_2 with an argon + 5 per cent hydrogen plasma should be considered for welding carbon steel of $\frac{1}{16}$ to $\frac{1}{4}$ in. thickness. Steels with higher amounts of carbon have higher heat conductivity and need application of more heat than is needed with stainless steels. Manufacturers usually make recommendations on types of gas mixtures to use with their equipment.

PAW Welding Equipment.—The PAW process uses electrode negative (DCEN) polarity in a current range from 25 to 400 amps, and equipment is offered by many manufacturers. Solid-state inverter units are available with nonmechanical contactors. Most PAW units contain a high-frequency generator, a small DC power supply, controls for welding and shielding gas mixtures, and a torch coolant control. A weld sequencer is recommended, especially for keyhole mode welding, but it is also useful in automated fusion welding. The sequencer provides control of up-slope and down-slope conditions for gas mixtures and current, so that it is possible to make welds without run-on and run-off tabs, as is necessary with circumferential welds.

Generally, plasma arc torches are liquid-cooled using deionized water in the coolant lines to the torch to avoid effects of electrolysis. Electrodes are usually tungsten with 2 per cent thorium. If the welding shop already has a constant-current power supply and a coolant recirculator, plasma arc welding may be used by addition of a pilot arc welding console and a torch.

Applications.—Fusion welding is the main use for plasma arc welding. The process is used for high-volume, repetitive, high-duty cycle, manual and automated operations on lap, flange, butt, and corner fusion welds, in all positions. Joint design for materials less than 0.01 in. (0.254 mm) thick may require a flange type joint for rigidity and to allow use of extra, weld metal reinforcement. Filler metal may be added during fusion welding, and automated hot or cold wire feeders can be used. Fusion welding uses a soft, less-restricted arc with low gas flows, and the current level may vary from approximately 25 to 200 amps. The soft arc is obtained by setting the end of the tungsten electrode level with the face of the torch nozzle, in which position lower currents and gas flows are required. With these conditions, the weld bead is slightly wider than a bead produced with a recessed electrode.

Low-Current Plasma Fusion Welding: With the reduced consumption of gas and electric current, the low-current plasma fusion welding method is ideal for welding metals down to 0.001 in. (0.025 mm) in thickness, as the low-current plasma pilot arc allows arcs to be started consistently with currents of less than 1 amp. With currents below 1 amp, the pilot arc is usually left in the continuous mode to maintain the arc. In the conditions described, arc stability is improved and the process is much less sensitive to variations in the distance of the torch from the workpiece. Given this height tolerance, setting up is simplified, and with the smaller torches required, it is often easier to see the weld pool than with the GTAW process. Some plasma welding units incorporate gas flow meters that are designed for low flow rates, and currents in the range of 0.1 to 15 amps can be selected.

Low-current plasma arc welding is more economical than other gas tungsten arc welding methods, especially with solid-state inverter systems and smaller torches. The process is useful for sealing type welds where joint access is good, and for welding components of office furniture, household items, electronic and aerospace parts, metallic screening, and thin-wall tubing.

Keyhole mode welding describes a method whereby abutting edges of two plates are melted simultaneously, forming a vapor capillary (or keyhole) and the resulting molten-walled hole moves along the joint line. This method requires the end of the tungsten electrode to be positioned well back inside the torch nozzle to produce a high-velocity, restricted arc column with sufficient energy to pierce the workpiece. This mode is also used for the plasma cutting process, but the major difference is that welding uses very low plasma flow rates of the order of 1 to 3 cu ft/h (0.5 to 1.4 l/min) for work thicknesses of $\frac{1}{16}$ to $\frac{5}{32}$ in. (1.6 to 4 mm). These low rates avoid unwanted displacement of the weld metal. After the arc pierces the workpiece, the torch moves along the weld line and the thin layer of molten metal is supported by surface tension as it flows to the rear of the line of movement, where it solidifies and forms the weld.

As it passes through the keyhole, the high-velocity plasma gas column flushes the molten weld pool and carries away trapped gases and contaminants that otherwise would be trapped in the weld. Plasma arc keyhole welding is affected less by surface and internal defects in the work material than is the GTAW process. Most metals that can be welded by the gas tungsten arc method can be plasma arc welded with the conventional DC electrode, negative keyhole method, except aluminum, which requires a variable polarity keyhole method.

Plasma keyhole welding is usually automated because it requires consistent travel speed and torch height above the work. A typical operation is welding steel with square abutting edges (no bevels) in thicknesses of 0.09 to 0.375 in. (2.3 to 9 mm), where 100 per cent penetration in a single pass is required. Producing square-groove butt welds in materials thicker than $\frac{1}{2}$ in. by the plasma arc keyhole process requires some edge preparation and several filler passes. The finished weld is uniformly narrow and the even distribution of heat means that distortion is minimized.

Welding Aluminum.—The variable polarity plasma arc (VPPA) process was developed for welding metals that form an oxide skin, such as aluminum. Electrode negative (straight) polarity is necessary for the plasma arc to provide sufficient heat to the workpiece and minimize heat buildup in the tungsten electrode. With electrode negative polarity, electrons move rapidly from the negative cathode tungsten electrode to the positive anode workpiece, generating most of the heat in the workpiece. Because of the oxide skin on aluminum, however, straight polarity produces an erratic arc, poor weld fluidity, and an irregularly shaped weld bead. The oxide skin must be broken up if the metal flow is to be controlled, and this breakup is effected by a power supply that constantly switches from negative to positive polarity.

A typical cycle uses a 20-ms pulse of electrode negative polarity and a 3-ms pulse of electrode positive polarity. The pulses are generated as square waves and the positive (cleaning) pulse is set at 30 to 80 amps higher than the negative pulse for greater oxide-breaking action. The tenacious oxide skin is thus broken constantly and the rapid cycle changes result in optimum cathode cleaning with minimum deterioration of the tungsten electrode and consistent arc stability. Varying polarity has advantages in both gas metal arc and plasma arc welding, but with the keyhole process it allows single-pass, square-groove, full-penetration welds in materials up to $\frac{1}{2}$ in. (12.7 mm) thick.

The VPPA process ensures extremely low levels of porosity in weld areas in aluminum. VPPA welding is often used in the vertical up position for aluminum because it provides superior control of root reinforcement, which tends to be excessive when welding is done in the flat position. Pulsing in the VPPA process when welding aluminum of $\frac{1}{8}$ to $\frac{1}{4}$ in. thickness in the flat position gives satisfactory root profiles. Pulsing gives improved arc control in keyhole welds in both ferrous and nonferrous metals and is beneficial with melt-in fusion welding of thin materials as it provides better control of heat input to the workpiece.

Plasma Arc Surface Coating

Plasma Arc Surfacing uses an arc struck between the electrode and the workpiece, or transferred arc, to apply coatings of other metals or alloys to the workpiece surface. This high-temperature process produces homogeneous welds in which the ionized plasma gas stream melts both the work surface and a stream of powdered alloy or filler wire fed into the arc. Dilution of the base metal can be held below 5 per cent if required. With arc temperatures between 25,000 and 50,000°F (14,000 and 28,000°C), deposition occurs rapidly, and a rate of 15 lb/h (6.8 kg/h) of powdered alloy is not unusual. Deposition from wire can be performed at rates up to 28 lb/h (12.7 kg/h), much higher than with oxygen/fuel or gas metal/arc methods.

In the nontransferred arc process used for coating of surfaces, the arc is struck between the electrode and the torch nozzle, so that it does not attach to the work surface. This process is sometimes called metal spraying, and is used for building up surfaces for hard facing, and for application of anticorrosion and barrier layers. Argon is frequently used as the plasma gas. As the coating material in the form of powder or wire enters the plasma, it is melted thoroughly by the plasma column and is propelled toward the work at high velocity to form a mechanical bond with the work surface. Some 500 different powder combinations are available for this process, so that a variety of requirements can be fulfilled, and deposition rates up to 100 lb/h (45 kg/h) can be achieved.

The plasma arc process allows parts to be modified or recovered if worn, and surfaces with unique properties can be provided on new or existing components. Low levels of porosity in the deposited metal can be achieved. Metal spraying can be performed manually or automatically, and its use depends primarily on whether a mechanical bond is acceptable. Other factors include the volume of parts to be treated, the time needed for the process and for subsequent finishing, the quality requirements for the finished parts, rejection rates, and costs of consumable materials and energy.

Some systems are available that can use either metal powder or wire as the spray material, and can be operated at higher voltage settings that result in longer plasma arc lengths at temperatures over 10,000°F (5,537°C). With these systems, the plasma velocity is increased to about 12,000 ft/s (3,658 m/s), giving an extremely dense coating with less than 1 per cent porosity. Current ranges of 30 to 500 amps are available, and nitrogen is frequently used as the plasma gas, coupled with CO_2, nitrogen, or compressed air as the shielding gas. Gas flow rates are between 50 and 350 cu ft/h (24 and 165 l/min). Large or small surface areas can be coated at low cost, with minimum heat input, if other aspects of the process are compatible with the product being made.

Plasma Arc Cutting.—Higher current and gas flow rates than for plasma arc welding are used for the plasma arc cutting (PAC) process, which operates on DC straight polarity, and uses a transferred arc to melt through the material to be cut. The nozzle is positioned close to the work surface and the velocity of the plasma jet is greatly increased by a restricting nozzle orifice so that it blows away the metal as it is melted to make the cut. The higher energy level makes the process much faster than cutting with an oxygen/fuel torch on cutting steel of less than $\frac{1}{2}$ in. thick, but the process produces kerfs with some variation in the width and in the bevel angle, affecting the precision of the part. Some of the molten metal may recast itself on the edges of the cut and may be difficult to remove.

Factors that affect plasma cutting include the type and pressure of the gas, its flow pattern, the current, the size and shape of the nozzle orifice, and its closeness to the work surface. To reduce noise and fumes, mechanized plasma arc cutting is often performed with the workpiece submerged in water. Oxidation of cut surfaces is almost nonexistent with the underwater method.

Precision Plasma Arc Cutting.—A later development of the above process uses a magnetic field in the cutter head to stabilize the plasma arc by means of Lorentz forces that cause it to spin faster and tighter on the electrode tip. The magnetic field also confines the spinning plasma so that a narrower kerf is produced without adverse effect on cutting speed. Results from this process are somewhat comparable with those from laser cutting and, with numerical control of machine movements, it is used for production of small batches of blanks for stamping and similar applications. With galvanized and aluminized steel, edges are clean and free from burrs, but some slag may cling to edges of mild-steel parts.

Electron-Beam (EB) Welding

Heat for melting of metals in electron-beam welding is obtained by generating electrons, concentrating them into a beam, and accelerating them to between 30 and 70 per cent of the speed of light, using voltages between 25 and 200 kV. The apparatus used is called an electron-beam gun, and it is provided with electrical coils to focus and deflect the beam as needed for the welding operation. Energy input depends on the number of electrons impinging on the work in unit time, their velocity, the degree of concentration of the beam, and the traveling speed of the workpiece being welded. Some 6.3×10^{15} electrons/s are generated in a 1-mA current stream. With beam diameters of 0.01 to 0.03 in. (0.25 to 0.76 mm), beam power can reach 100 kW and power density can be as high as 10^7 W/in^2 (1.55×10^4 W/mm^2), higher than most arc welding levels.

At these power densities, an electron beam can penetrate steel up to 4 in thick and form a vapor capillary or keyhole, as described earlier. Although patterns can be traced by deflecting the beam, the method used in welding is to move the electron gun or the workpiece. A numerical control, or computer numerical control, program is used because of the accuracy required to position the narrow beam in relation to the weld line.

Equipment is available for electron-beam welding under atmospheric pressure or at various degrees of vacuum. The process is most efficient (produces the narrowest width and deepest penetration welds) at high levels of vacuum, of the order of 10^{-6} to 10^{-3} torr or lower (standard atmospheric pressure is about 760 torr, or 760 mm of mercury), so that a vacuum chamber large enough to enclose the work is needed. Operation in a vacuum minimizes contamination of the molten weld material by oxygen and nitrogen. Gases produced during welding are also extracted rapidly by the vacuum pump so that welding of reactive metals is eased. However, the pumping time and the size of many workpieces restrict the use of high-vacuum enclosures.

At atmospheric pressures, scattering of the beam electrons by gas molecules is increased in relation to the number of stray molecules and the distance traveled, so that penetration depth is less and the beam spread is greater. In the atmosphere, the gun-to-work distance must be less than about 1.5 in. (38 mm). Electron-beam welding at atmospheric pressure requires beam-accelerating voltages above 150 kV, but lower values can be used with a protective gas. Helium is preferred because it is lighter than air and permits greater penetration. Argon, which is heavier than air and allows less penetration, can also be used to prevent contamination.

Required safety precautions, such as radiation shields to guard workers against the effects of X-rays when the electron beam strikes the work, are essential when electron-beam welding is done at atmospheric pressure. Such barriers are usually built into enclosures that are designed specifically for electron-beam welding in a partial vacuum. Adequate ventilation is also required to remove ozone and other gases generated when the process is used in the atmosphere.

Carbon, low-alloy, and stainless steels; high-temperature and refractory alloys; copper and aluminum alloys can be electron-beam welded, and single-pass, reasonably square, butt welds can be made in materials up to 1 in. (25.4 mm) thick at good speeds with nonvacuum equipment rated at 60 kW. Edges of thick material to be electron-beam welded require precision machining to provide good joint alignment and minimize the joint gap. Dissimilar metals usually may be welded without problems.

Because of the heat-sink effect, electron-beam welds solidify and cool very rapidly, causing cracking in certain materials such as low-ferrite stainless steel. Although capital costs for electron-beam welding are generally higher than for other methods, welding of large numbers of parts and the high welding travel rates make the process competitive.

Weld and Welding Symbols

American National Standard Weld and Welding Symbols.—Graphical symbols for welding provide a means of conveying complete welding information from the designer to the welder by means of drawings. The symbols and their method of use (examples of which are given in the table following this section) are part of the American National Standard ANSI/AWS A2.4-79 sponsored by the American Welding Society.

In the Standard a distinction is made between the terms *weld symbol* and *welding symbol*. Weld symbols, shown in the table *Basic Weld Symbols,* are ideographs used to indicate the type of weld desired, whereas welding symbol denotes a symbol made up of as many as eight elements conveying explicit welding instructions.

The eight elements which may appear in a welding symbol are: reference line; arrow;

basic weld symbols; dimensions and other data; supplementary symbols; finish symbols; tail and specification; and process or other reference.

The standard location of elements of a welding symbol are shown in Fig. 1.

Reference Line: This is the basis of the welding symbol. All other elements are oriented with respect to this line. The arrow is affixed to one end and a tail, when necessary, is affixed to the other.

Arrow: This connects the reference line to one side of the joint in the case of groove, fillet, flange, and flash or upset welding symbols. This side of the joint is known as the *arrow side* of the joint. The opposite side is known as the *other side* of the joint. In the case of plug, slot, projection, and seam welding symbols, the arrow connects the reference line to the outer surface of one of the members of the joint at the center line of the weld. In this case the member to which the arrow points is the *arrow side* member: the other member is the *other side* member. In the case of bevel and J-groove weld symbols, a two-directional arrow pointing toward a member indicates that the member is to be chamfered.

Basic Weld Symbols: These designate the type of welding to be performed. The basic symbols which are shown in the table *Basic Weld Symbols* are placed approximately in the center of the reference line, either above or below it or on both sides of it as shown in Fig. 1. Welds on the arrow side of the joint are shown by placing the weld symbols on the side of the reference line towards the reader (lower side). Welds on the other side of the joint are shown by placing the weld symbols on the side of the reference line away from the reader (upper side).

Supplementary Symbols: These convey additional information relative to the extent of the welding, where the welding is to be performed, and the contour of the weld bead. The “weld-all-around” and “field” symbols are placed at the end of the reference line at the base of the arrow as shown in Fig. 2 and the table *Supplementary Weld Symbols*.

Dimensions: These include the size, length, spacing, etc., of the weld or welds. The size of the weld is given to the left of the basic weld symbol and the length to the right. If the length is followed by a dash and another number, this number indicates the center-to-center spacing of intermittent welds. Other pertinent information such as groove angles, included angle of countersink for plug welds and the designation of the number of spot or projection welds are also located above or below the weld symbol. The number designating the number of spot or projection welds is always enclosed in parentheses.

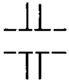
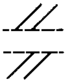
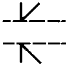
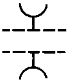
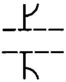
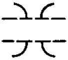
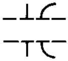
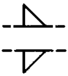
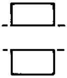
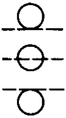
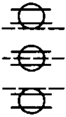
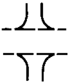
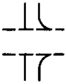
Contour and Finish Symbols: The contour symbol is placed above or below the weld symbol. The finish symbol always appears above or below the contour symbol (see Fig. 1).

The following finish symbols indicate the method, not the degrees of finish: C—chipping; G—grinding; M—machining; R—rolling; and H—hammering.

For indication of surface finish refer to the Surface Texture section.

Tail: The tail which appears on the end of the reference line opposite to the arrow end is used when a specification, process, or other reference is made in the welding symbol. When no specification, process, or other reference is used with a welding symbol, the tail may be omitted.

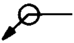
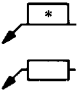
Table 1. Basic Weld Symbols

Groove Weld Symbols							
Square	Scarf[a]	V	Bevel	U	J	Flare V	Flare bevel
							
Other Weld Symbols							
Fillet	Plug or slot	Spot or projection	Seam	Back or backing	Surfacing	Flange	
						Edge	Corner
							

[a] This scarf symbol used for brazing only (see page 1361).

For examples of basic weld symbol applications see starting on page 1397.

Table 2. Supplementary Weld Symbols

Weld all around	Field weld	Melt-thru	Backing or spacer material	Countour		
				Flush	Convex	Concave
	 					

Melt-Thru Symbol: The melt-thru symbol is used only where 100 per cent joint or member penetration plus reinforcement are required.

Specification, Process, or Other Designation: These are placed in the tail of the welding symbol and are in accordance with the American National Standard. They do not have to be used if a note is placed on the drawing indicating that the welding is to be done to some specification or that instructions are given elsewhere as to the welding procedure to be used.

Letter Designations: American National Standard letter designations for welding and allied processes are shown in the table on page 1396.

Further Information: For complete information concerning welding specification by the use of standard symbols, reference should be made to American National Standard ANSI/AWS A2.4-79, which may be obtained from either the American National Standards Institute or the American Welding Society listed below.

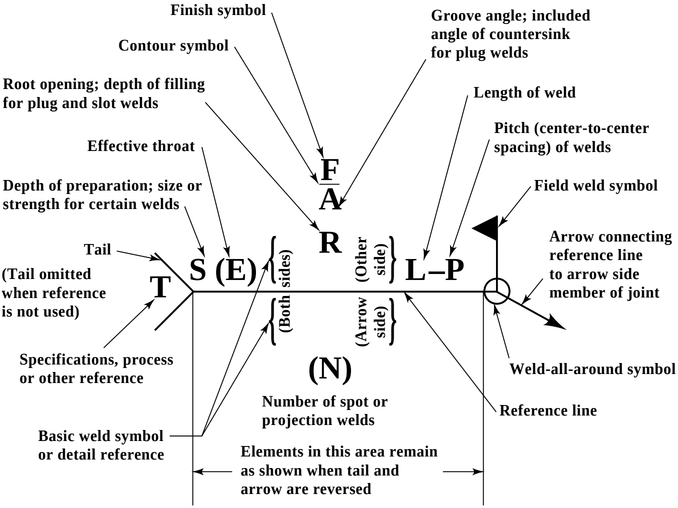


Fig. 1. Standard Location of Elements of a Welding Symbol

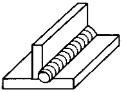
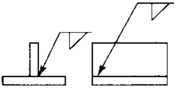
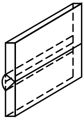
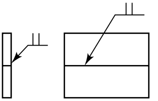
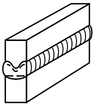
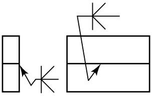
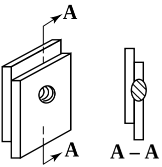
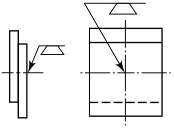
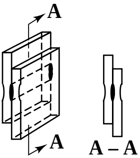
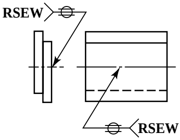
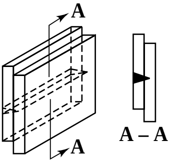
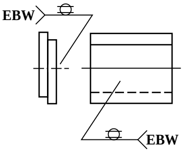
Welding Codes, Rules, Regulations, and Specifications.—Codes recommending procedures for obtaining specified results in the welding of various structures have been established by societies, institutes, bureaus, and associations, as well as state and federal departments.

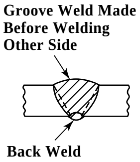
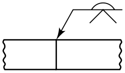
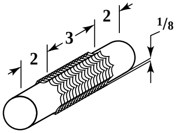
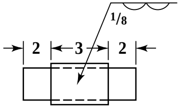
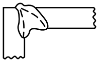
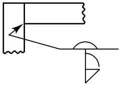
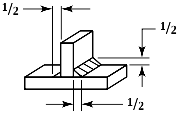
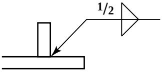
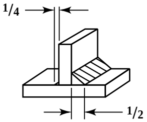
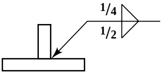
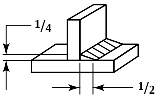
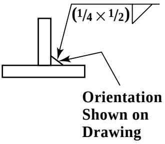
The latest codes, rules, etc., may be obtained from these agencies, whose names and addresses are listed as follows: PV = Pressure Vessels; P = Piping; T = Tanks; SB = Structural and Bridges; S = Ships; AC = Aircraft Construction; and EWM = Electrical Welding Machinery.

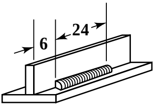
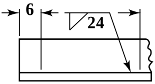
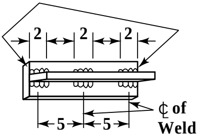
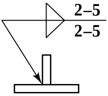
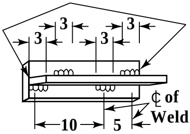
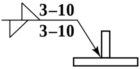
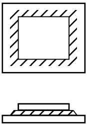
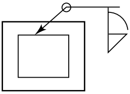
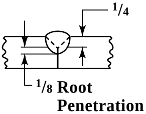
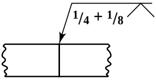
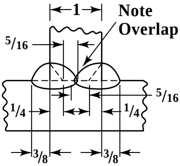
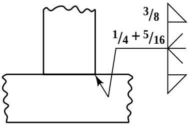
Air Force/LGM, Department of the Air Force, Washington, DC 20330. (AC)
American Bureau of Shipping, 2 World Trade Center, NY, NY 10048. (S)
American Institute of Steel Cons., 1 E. Wacker Drive, Chicago, IL 60601. (SB)
American National Stds Inst., 11 West 42nd St. NY, NY 10036. (PV, P, EWM)
American Petroleum Institute, 1220 L St., NW, Washington, DC 20005. (PV)
American Soc. of Mechanical Engineers, 345 E. 47th St., NY, NY 10017. (PV)
American Welding Society, 550 LeJeune Road, Miami, FL 33135. (T, S, SB, AC)
Fed. Aviation Admin., Dept. of Transportation, Washington, DC 20590. (AC)
Insurance Services Office, 7 World Trade Center, NY, NY 10048. (PV)
Lloyd's Register of Shipping, 17 Battery Place, NY, NY 10004. (S)
Mechanical Contractors Assn., 1385 Piccard Drive, Rockville, MD. (P)
National Electrical Mfrs. Assn., 2101 L St. NW, Washington, DC 20037. (EWM)
Naval Facilities Eng'g Command, 200 Stovall St., Alexandria, VA 22332. (SB)
Naval Ship Engineering Center, Dept. of the Navy, Hyattsville, MD 20782. (PV, S)
U.S. Government Printing Office, Washington, DC 20402. (PV)

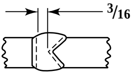
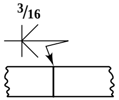
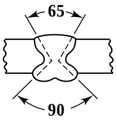
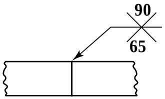
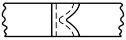
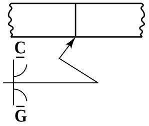
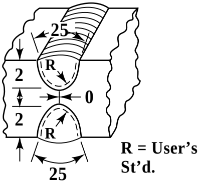
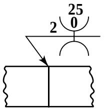
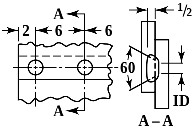
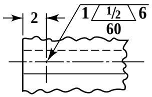
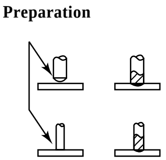
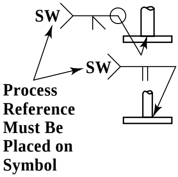
American National Standard Letter Designations for Welding and Allied Processes
ANSI/AWS A2.4-91

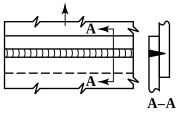
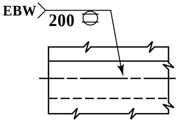
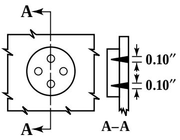
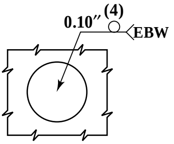
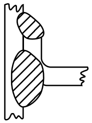
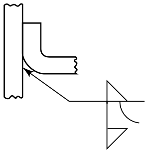
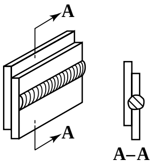
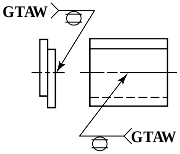
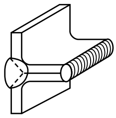
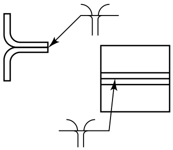
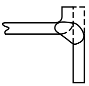
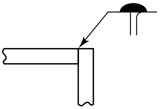
Letter Designation	Welding and Allied Processes
AAC	air carbon arc cutting
AAW	air acetylene welding
AB	arc brazing
ABD	adhesive bonding
AC	arc cutting
AHW	atomic hydrogen welding
AOC	oxygen arc cutting
ASP	arc spraying
AW	carbon arc welding
B	brazing
BB	block brazing
BMAW	bare metal arc welding
CAB	carbon arc brazing
CAC	carbon arc cutting
CAW	carbon arc welding
CAW-G	gas carbon arc welding
CAW-S	shielded carbon arc welding
CAW-T	twin carbon arc welding
CEW	coextrusion welding
CW	cold welding
DB	dip brazing
DFB	diffusion brazing
DFW	diffusion welding
DS	dip soldering
EBC	electron beam cutting
EBW	electron beam welding
EBW-HV	electron beam welding—high vacuum
EBW-MV	electron beam welding—medium vacuum
EBW-NV	electron beam welding—nonvacuum
EGW	electrogas welding
ESW	electroslag welding
EXW	explosion welding
FB	furnace brazing
FCAW	flux-cored arc welding
FLB	flow brazing
FLOW	flow welding
FLSP	flame spraying
FOC	chemical flux cutting
FOW	forge welding
FRW	friction welding
FS	furnace soldering
FW	flash welding
GMAC	gas metal arc cutting
GMAW	gas metal arc welding
GMAW-P	gas metal arc welding—pulsed arc
GMAW-S	gas metal arc welding—short-circuiting arc
GTAC	gas tungsten arc cutting
GTAW	gas tungsten arc welding
GTAW-P	gas tungsten arc welding—pulsed arc
HPW	hot pressure welding
IB	induction brazing
INS	iron soldering
IRB	infrared brazing
IRS	infrared soldering
IS	induction soldering
IW	induction welding
LBC	laser beam cutting
LBC-A	laser beam cutting—air
LBC-EV	laser beam cutting—evaporative
LBC-IG	laser beam cutting—inert gas
LBC-O	laser beam cutting—oxygen
LBW	laser beam welding
LOC	oxygen lance cutting
MAC	metal arc cutting
OAW	oxyacetylene welding
OC	oxygen cutting
OFC	oxyfuel gas cutting
OFC-A	oxyacetylene cutting
OFC-H	oxyhydrogen cutting
OFC-N	oxynatural gas cutting
OFC-P	oxypropane cutting
OFW	oxyfuel gas cutting
OHW	oxyhydrogen welding
PAC	plasma arc cutting
PAW	plasma arc welding
PEW	percussion welding
PGW	pressure gas welding
POC	metal powder cutting
PSP	plasma spraying
PW	projection welding
RB	resistance brazing
RS	resistance soldering
RSEW	resistance seam welding
RSEW-HF	resistance seam welding—high frequency
RSEW-I	resistance seam welding—induction
RSW	resistance spot welding
ROW	roll welding
RW	resistance welding
S	soldering
SAW	submerged arc welding
SAW-S	series submerged arc welding
SMAC	shielded metal arccutting
SMAW	shielded metal arc welding
SSW	solid state welding
SW	stud arc welding

Desired Weld	Symbol	Symbol Meaning
		Symbol indicates fillet weld on *arrow side* of the joint.
		Symbol indicates square-groove weld on *other side* of the joint.
		Symbol indicates bevel-groove weld on both sides of joint. Breaks in arrow indicate bevels on upper member of joint. Breaks in arrows are used on symbols designating bevel and J-groove welds.
		Symbol indicates plug weld on *arrow side* of joint.
		Symbol indicates resistance-seam weld. Weld symbol appears on both sides of reference line pointing up the fact that *arrow* and *other side* of joint references have no significance.
		Symbol indicates electron beam seam weld on *other side* of joint.

Desired Weld	Symbol	Symbol Meaning
		Symbol indicates single-pass back weld.
		Symbol indicates a built-up surface ⅛ inch thick.
		Symbol indicates a bead-type back weld on the *other side* of joint, and a J-groove grooved horizontal member (shown by break in arrow) and fillet weld on *arrow side* of the joint.
		Symbol indicates two fillet welds, both with ½-inch leg dimensions.
		Symbol indicates a ½-inch fillet weld on *arrow side* of the joint and a ¼-inch fillet weld on *far side* of the joint.
		Symbol indicates a fillet weld on *arrow side* of joint with ¼- and ½-inch legs. Orientation of legs must be shown on drawing.

Desired Weld	Symbol	Symbol Meaning
		Symbol indicates a 24-inch long fillet weld on the *arrow side* of the joint.
Locate Welds at Ends of Joint 		Symbol indicates a series of intermittent fillet welds each 2 inches long and spaced 5 inches apart on centers directly opposite each other on both sides of the joint.
Locate Welds at Ends of Joint 		Symbol indicates a series of intermittent fillet welds each 3 inches long and spaced 10 inches apart on centers. The centers of the welds on one side of the joint are displaced from those on the other.
		Symbol indicates a fillet weld around the perimeter of the member.
		Symbol indicates a ¼-inch V-groove weld with a ⅛-inch root penetration.
		Symbol indicates a ¼-inch bevel weld with a 5⁄16-inch root penetration plus a subsequent ⅜-inch fillet weld.

Desired Weld	Symbol	Symbol Meaning
		Symbol indicates a bevel weld with a root opening of 3⁄36 inch.
		Symbol indicates a V-groove weld with a groove angle of 65 degrees on the *arrow side* and 90 degrees on the *other side*.
		Symbol indicates a flush surface with the reinforcement removed by chipping on the *other side* of the joint and a smooth grind on the *arrow side*. The symbols *C* and *G* should be the user's standard finish symbols.
		Symbol indicates a 2-inch U-groove weld with a 25-degree groove angle and no root opening for both sides of the joint.
		Symbol indicates plug welds of 1-inch diameter, a depth of filling of ½ inch and a 60-degree angle of countersink spaced 6 inches apart on centers.
		Symbol indicates all-around bevel and square-groove weld of these studs.

Desired Weld	Symbol	Symbol Meaning
Min. Acceptable Shear Strength 200 lb/lin. in.  	 	Symbol indicates an electron beam seam weld with a minimum acceptable joint strength of 200 pounds per lineal inch.
 	 	Symbol indicates four 0.10-inch diameter electron beam spot welds located at random.
		Symbol indicates a fillet weld on the *other side* of joint and a flare-bevel-groove weld and a fillet weld on the *arrow side* of the joint.
 	 	Symbol indicates gas tungsten-arc seam weld on *arrow side* of joint.
		Symbol indicates edge-flange weld on *arrow side* of joint and flare-V-groove weld on *other side* of joint.
		Symbol indicates melt-thru weld. By convention, this symbol is placed on the opposite side of the reference line from the corner-flange symbol.

Pipe Welding

Pipe Welding.—Welding of (usually steel) pipe is commonly performed manually, with the pipe joint stationary, or held in a fixture whereby rotation can be used to keep the weld location in a fixed, downhand, position. Alternatively, pipe may need to be welded on site, without rotation, and the welder then has to exert considerable skill to produce a satisfactory, pressure-tight joint. Before welding stationary pipe, a welder must be proficient in welding in the four basic positions: 1G flat, 2G horizontal, 3G vertical and 4G overhead, depicted at the top in Figs. 1a, 1b, and 1c.

Positioning of Joint Components in Pipe Welding

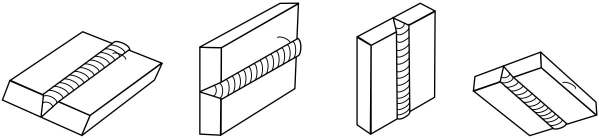


Fig. 1a. Flat Position 1G

Fig. 1b. Horizontal Position 2G

Fig. 1c. Vertical Position 3G

Fig. 1d. Overhead Position 4G

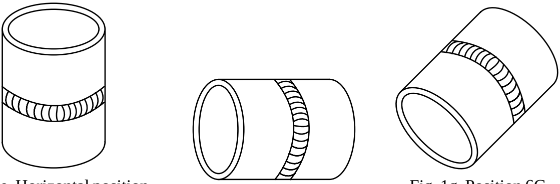


Fig. 1e. Horizontal position 2G Pipe Axis Vertical

Fig. 1f. Position 5G Pipe Fixed, Axis Horizontal

Fig. 1g. Position 6G Pipe Fixed, Axis Inclined

At the bottom are shown pipe joints in three positions, the first of which, Fig. 1d, corresponds to the 2G horizontal (non-rotational) position in the upper row. The remaining two are respectively 5G, Fig. 1e, that represents pipe with the weld in a fixed vertical (non-rotational) position; and 6G, Fig. 1f, that typifies pipe to be welded at an angle and not rotated during welding.

For satisfactory pipe welding, consideration must be given to the chemical composition and thickness of the metal to be welded; selection of a suitable electrode material composition and size; determination of the current, voltage and wire feed rate to be used; preparation of the joint or edges of the pipes; and ways of holding the pipes in the positions needed while welding is carried out. High-quality tack welds, each about 1.5 inches (38 mm) long, and projecting about $\frac{1}{16}$ inch (1.6 mm) beyond the inner wall of the pipe, are usually made to hold the parts of the assembly in position during welding.

SMAW (stick) welding was used almost exclusively for pipe welding until the advent of MIG welding with its potential for much greater rates of deposition. It cannot be emphasized too strongly that practices suitable for SMAW cannot be transferred to MIG welding, for which greater expertise is required if satisfactory welds are to be produced. MIG short-circuit, globular, and spray transfer, and pulsed MIG, with flux or metal-cored consumables (electrodes) can now all be used for pipe welding. Use of all-position, flux-cored, MIG consumables in particular, can reduce skill requirements, improve weld quality, and hold down costs in pipe welding.

Among the important items involved in the change to the MIG process is the automatic wire feeder. With today's wire feeding equipment, an increase of one increment on the dial, say from the 9 to the 10 o'clock position, can increase the wire feed rate by 70 in/min.

As an example, such an increase could raise the weld current from 110 to 145 amps and the weld voltage from 16 to 17, resulting in an increase of 40 per cent in the energy supplied to the weld. Another vital parameter is the amount that the wire sticks out from the contact tip. In low-parameter, short-circuit welding, a small change in the wire stick-out can alter the energy supplied to the weld by 20 to 30 per cent.

Root passes: Whatever welding process is selected, the most important step in pipe welding, as in other types of welding, is the root pass, which helps to determine the degree of penetration of the weld metal, and affects the amount of lack of fusion in the finished weld. During the root pass, the action of the arc in the weld area should reshape the gap between the adjacent sides of the joint into a pear-shaped opening, often called a "keyhole." As the work proceeds, this keyhole opening is continuously being filled, on the trailing side of the weld, by the metal being deposited from the electrode. The keyhole travels along with the weld so that the root pass produces a weld that penetrates slightly through the inner wall of the pipe.

MIG short-circuit root welding of carbon steel pipe requires a gap of $\frac{5}{32} \pm \frac{1}{32}$ (4 ± 0.8 mm), between the ends of the pipe, and the width of the root faces (at the base of the bevels) should be $\frac{1}{16}$ to $\frac{3}{32}$ inch (1.6 to 2.4 mm). The recommended bevel angle for MIG pipe welding is 40E (80E included angle) and the maximum root gap is $\frac{3}{16}$ inch (4.8 mm). The root pass in 1G welds should be made in the vertical-down direction with the electrode held between the 2 and 3 o'clock positions. When an 0.035-inch (0.9-mm) diameter E70S-3 MIG wire is used with the above root dimensions, weaving is not needed for the root pass except when welding over tack welds.

Fill passes: In welding carbon steel pipe in the 1G position with an 0.035-inch diameter electrode wire, MIG short circuit fill passes should use a minimum of 135 amps and be done in the vertical-up position. Fill passes should deposit a maximum thickness of no more than $\frac{1}{8}$ inch (3.2 mm). Inclusion of CO_2 gas in the mixture will improve weld fusion. With flux-cored electrodes, the minimum amount of wire stick out is $\frac{3}{4}$ inch (19 mm). Weld fusion can be improved in welding pipe of 0.4 inch (10 mm) wall thickness and thicker by preheating the work to a temperature between 400 and 500°F.

Horizontal Pipe Welding: In 1G welds (see Fig. 1a), the pipe should be rotated in the direction that moves the solidifying area away from the wire tip, to minimize penetration and resulting breakthrough. Welding of pipe in the 2G, horizontal position is made more difficult by the tendency for the molten metal to drip from the weld pool. Such dripping may cause an excessively large keyhole to form during the root-welding pass, and in subsequent passes electrode metal may be lost. Metal may also be lost from the edge of the upper pipe, causing an undercut at that side of the weld.

Vertical-down welding: With the pipe axis horizontal (as in the 5G position in Fig. 1f), vertical-down welding is usually started at the top or 12 o'clock location, and proceeds until the 6 o'clock location is reached. Welding then starts again at the 12 o'clock location and continues in the opposite direction until the 6 o'clock location is reached. Vertical-down welding is mainly used for thin-walled, low-carbon steel pipe of $\frac{1}{8}$ to $\frac{5}{16}$ inch (3.2 to 7.9 mm) wall thickness, which has low heat-retaining capacity so that the weld metal cools slowly, producing a soft and ductile structure. The slow rate of cooling also permits faster weld deposition, and, when several beads are deposited, causes an annealing effect that may refine the entire weld structure.

Vertical-up welding: In the 5G position, vertical-up welding normally begins at the 6 o'clock location and continues up to the 12 o'clock location, the weld then being completed by starting at the 6 o'clock location on the other side of the pipe and traversing up to the 12 o'clock location again. Vertical-up welding is more suited to pipe with thick walls and to alloy steels. However, the greater heat sink effect of the heavy-walled pipe may result in a faster cooling rate and embrittlement of the material, especially in alloy steels.

The cooling rate can be reduced by slowing the rate of traverse and depositing a heavier bead of metal, both facilitated by welding in the vertical-up direction.

Using a thicker electrode and higher current for thicker-walled pipe to reduce the number of beads required may result in dripping from the molten puddle of metal. Defects such as pin holes, lack of fusion, and cold lap, may then appear in the weld. Vertical-up welding of pipe in the 5G, fixed, horizontal position, Fig. 1f, used for thick-walled pipe, is probably the most difficult for a welder, but once mastered will form the basis for other methods of pipe welding. Starting at the 6 o'clock location, the arc for the root pass is struck overhead, with the electrode at an angle of 5 to 10° from the vertical, on the joint, not on the tack weld. A long arc should be maintained for a short-period while weaving the electrode to pre-heat the area ahead of the weld. Only small amounts of filler metal will be transferred while this long arc is maintained in the overhead position. The electrode tip is then advanced to establish the correct arc length and held in position long enough for the keyhole to form before starting to lay down the root bead, moving up toward the 12 o'clock location.

Thin-wall pipe: The optimum globular/spray parameters for welding rotated, (1G position) thin-wall pipe of less than 12 inch diameter are 0.035-inch electrode wire fed at 380 to 420 in/min with a protective gas mixture of argon 80 to 85, CO_2 15 to 20 per cent, and current of 190 to 210 amps. These conditions will provide deposition rates of about 6 lb/hr (3 kg/hr).

Use of Flux-cored Electrodes.—Small diameter, flux cored electrodes developed in the eighties are still a rarity in many pipe welding shops, but flux cored welding can produce consistent, high-quality, low-cost welds on carbon steel or stainless pipe. Flux cored E71T-1, 035-inch (1 mm) diameter wire provides a continuous, medium energy, open arc, with a practical current range of 135 to 165 amps for welding pipe. This current range is similar to the optimum MIG short-circuit current range, and is 25 to 30 percent less current than the minimum open arc spray transfer current for an 0.035-inch diameter MIG wire.

In contrast to MIG short circuit welding, FCAW works with an open arc and no short circuits. The FCAW arc energy is continuous, and, in contrast to short-circuit transfer, provides increased weld fusion potential. The weld metal from the flux-cored tubular wire is transferred from the periphery and the center of the wire, resulting in broad coverage of the weld. The plasma in the flux cored arc is wider than MIG plasma, and the flux-cored arc is less focused and easier to control than the MIG spray arc.

Open arc, gas shielded, flux-cored welding can produce spray type transfer at lower currents than open arc MIG spray transfer. With FCAW, the current density is high because the electrode wire cross-sectional area is less than that of the same size MIG solid wire due to the central core of flux. This higher density provides for improved weld penetration potential. The FCAW process produces slag, which serves as a mold to hold the fluid molten metal in place, an ideal arrangement for vertical-up and overhead welds.

All position, flux-cored wires require less operator skill for vertical-up and overhead welds than MIG, SMAW, and TIG processes. Fill passes can also be completed in 30 to 50 percent less time with all-position, flux-cored wires than with MIG short circuit and SMAW wires.

For good quality FCAW, welders need to know the best root and bevel dimensions, and the importance of maintaining those dimensions for continuous weld fusion; the preferred direction of pipe rotation; the diameter of flux cored electrode best suited for welding thin wall pipe; the optimum parameter range for that electrode on 1G and 5G welds; the preferred amount of wire stick out (typically 0.7 inch or 18 mm); and how to fine tune the voltage. When flux-cored welding is to be used for the fill passes, MIG short circuit welding is recommended for the root welds to reduce the possibility of slag from the flux being trapped in the weld. Higher weld deposit rates are provided with flux-cored, vertical-up welding, and there is the temptation to weld faster with a process that's easy to use. Conservative wire feed setting are recommended unless the high deposition rates are shown to provide consistent weld fusion. Wire feed settings should allow the welder time to control and direct the weave into the critical groove locations.

Complete Weld Fusion.—It is essential that new weld metal deposits be completely fused with the pipe components, and with metal laid down in successive passes. Factors that can prevent complete fusing are too numerous to list here. Some basic rules that, if followed, will improve weld fusion and quality in MIG welding in the 1G and 5G positions are:

1) The maximum gap at the root should be $\frac{3}{16}$ inch (5 mm)
2) The root land should be $\frac{1}{16}$ to $\frac{3}{32}$ inch (1.6 to 2.4 mm) wide
3) A bevel angle of 80° inclusive should be used for MIG and flux-cored welding of pipe to provide width for weaving and improve fusion.
4) An 0.035-in MIG electrode should have a minimum short circuit current of 135 amps for fill passes
5) Tack and root welds should be made in the vertical-down position.
6) Tack welds should be about 1.5 in (38 mm) long by $\frac{1}{16}$ to $\frac{3}{32}$ inch (1.6 to 2.4 mm) thick.
7) Short circuit fill passes should be made in the vertical-up position.
8) With flux-cored electrodes, a minimum of 0.7 inch (18 mm) wire stick out from the contact tip must be maintained.
9) Current and voltage must be related to the pipe wall thickness
10) Argon+25 per cent CO$_2$ is recommended for short circuit welding of pipe roots.
11) Use of undiluted CO$_2$ gas will improve MIG weld fusion in fill passes because of the "digging" action of the arc, and the increased weld energy
12) With pipe wall thicknesses of 0.4 in (10 mm) or greater, preheating to between 400 and 500° F (205 and 260°C), will help make fusion complete

Other Methods.—Pulsed MIG is a viable alternative to flux-cored for all-position welds on 5G pipe, but requires more costly equipment. The pulsed MIG process however, has few advantages over conventional MIG and flux-cored when the latter are used correctly. Pulsed MIG may have some advantage on mechanized 5G welds, and on welding of stainless steel, pipe in the 5G position.

Metal-cored electrode wire also has few advantages for pipe welds because they work best with low-energy gas welds, which cancels out the increased current density claimed for them.

On most manual pipe welds, the welder needs time to control and direct the weave to ensure even heating and avoid lack of fusion. Satisfactory welds are often performed at travel speeds of 4 to 12 in/min giving deposit rates of 3 to 5 lb/hr.

Pipe Welding Procedure

Because of the variety of parameter combinations that can be used in pipe welding, it is suggested that charts be prepared and displayed in welding booths to remind welders of the basic settings to be used. Examples of such charts for tack, root, fill and cover passes, are included in what follows:

FCAW 5G (Non-rotated) MIG Welding of Thick-walled, Carbon-steel Pipes, Procedure for Root Welding.—This procedure can be applied to most pipe sizes, and should be given special consideration for 5G (non-rotated) welds on carbon steel pipe with $\frac{3}{8}$ inch (10 mm) wall thickness and thicker.

Pipe and Weld Data

Pipe bevel included angle = 80° *Root face land* = 3/32 ± $\frac{1}{32}$ inch (2.4 ± 0.8 mm)
Root gap between faces = $\frac{5}{32}$ ± $\frac{1}{32}$ inch (4 ± 0.8 mm)
Electrode for root weld = 0.035-inch (0.9 mm) diameter, E70S-3 flux-cored.
Gas = argon with 15–25% CO$_2$

Gas flow rates = 30 to 40 cubic ft/hr

Set wire feeder to 210–280 in/min(10 to 11 o'clock position on many feeders) for current of 140–170 amps, 17–18 volts.

Wire extension: For MIG root weld, set contact tip to stick outside the nozzle, $\frac{1}{16}$ to $\frac{1}{8}$ inch (1.6 to 3 mm). Maintain $\frac{3}{8}$ to $\frac{5}{8}$ inch (10 to 16 mm) maximum wire stick out from contact tip.

Tack Welding Procedures for FCAW 5G Pipe Welds: Make tack welds 1.5 to 2 inches (38 to 50 mm) long. After welding, grind full length of tack to thickness of approximately $\frac{1}{16}$ inch (1.6 mm). Feather tack ends back $\frac{3}{8}$ to $\frac{1}{2}$ inches (9.5 to 13 mm).

On pipes of less than 6 inches (15 cm) outside diameter, use three tack welds, equally spaced, starting at 12 o'clock.

On pipes over 6 inches outside diameter use 4 tack welds. Locate tack welds at 12, 3, 6, and 9 o'clock.

Root Welding Procedures for FCAW 5G Pipe Welds: Root weld MIG vertical-down. Weld sequence: 12 to 3, 9 to 6, 3 to 6, and 12 to 9 o'clock positions.

Start and finish MIG root welds at tack centers. Use slight weave oscillation over tacks. No weave necessary if $\frac{1}{8}$- to $\frac{5}{32}$-inch root gap is maintained. Weaving may be required if root gap is less than $\frac{1}{8}$ inch (3 mm). Weaving is also beneficial for root welds between 7 and 6 o'clock, and between 5 and 6 o'clock. After each root pass, blend the starts and stops back to the original tack thickness.

To complete the root, ensure that the weld stops and starts on the last tack, and that the root weld center is ground flat or slightly concave. Remove any slag islands.

FCAW 5G (Non-rotated) MIG Welding of Thick-walled, Carbon-steel Pipes, Procedure for Fill and Cover Welds.—This procedure can be applied to most common pipe sizes, and should be given special consideration for 5G (non-rotated) welds on carbon steel pipe with $\frac{3}{8}$ inch (10 mm) wall thickness and thicker.

Pipe and Weld Data

Electrode for fill and cover passes = 0.035 inch (0.9 mm) diameter, 71T-1 flux-cored

Gas = argon with 15–25% CO_2

Gas flow rates = 30 to 40 cubic ft/hr

Set an initial wire feed rate of 350 to 450 in/min (12 to 1 o'clock position on typical wire feed unit), 135–165 amps, 25–28 volts. Alternatively, use a wire feed setting of 350 in/min (12 o'clock on wire feed unit), which should result in about 135–145 amps, 25–26 volts. If the weld pool and weld heat build up permit, increase the wire feed rate to 380 in/min (between the 12 and 1 o'clock positions), 150 amps, 27 volts. Try also a wire feed setting of 420 in/min (1 o'clock on the wire feeder), 165 amps, 28 volts. Determine the low and maximum wire feed rates to be used by examination of the weld fusion obtained in sectioned test samples.

Wire extension: Adjust contact tip so it is recessed $\frac{1}{2}$ inch within the nozzle to provide a total wire stick out from the contact tip of 0.7 to 1 inch (18 to 25 mm).

Fill and Cover Pass Procedures for FCAW 5G Pipe Welds: Weld vertical-up. If the pipe diameter allows the fill pass to be made in two passes, start at the 7 o'clock position and weld to the 1 o'clock position. This approach is preferable to starting and finishing on the root tacks. Starting at the 7 o'clock position will ensure that optimum weld energy is achieved as the first pass welds over the initial 6 o'clock root tack location. Use the grinder to feather the first 1 inch (25 mm) of the weld start and stop of the first pass, before applying the second vertical-up weld pass. Use a slight weave action for the fill pass.

Remove all flux-cored slag between weld passes. Make sure no fill pass is greater in depth than $\frac{1}{8}$ inch (3 mm). Use a straight weave across the root face. At the bevel edge use a slight upward motion with the gun. The motion should be no greater than the wire diameter. Then use a slight back step for added bevel fusion and to avoid undercuts.

Leave 1⁄32 to 1⁄16 inch (0.8 to 1.6 mm) of the groove depth to provide for the optimum cover pass profile. The bevel edge will act as a guide for the cover pass weld. If more weld fusion is required for pipe thicker than 3⁄8 inch (10 mm), after the root weld is complete, preheat the pipe to between 400 and 600°F (200–300°C) before welding. Preheating is typically not necessary for a cover pass.

For pipe diameters on which the welder needs more than two passes for the vertical-up welds, the recommended sequence for vertical-up welding is:

1) First pass, weld from the 7 to the 4 o'clock position. Start with a slight forehand nozzle angle. At the 4 o'clock position, the gun should be at the same angle as the pipe.
2) Second pass, weld from the 10 to the 1 o'clock position, then grind all stops and start again at the 1-inch (25 mm) position.
3) Third pass, weld from the 4 to the 1 o'clock position.
4) Fourth pass, weld from the 7 to the 10 o'clock position.

FCAW 5G (Non-rotated) Welding of Thin-Walled Carbon Steel Pipes, Procedure for Root, Fill and Cover Pass Welding.—This procedure can be applied to most common pipe sizes, and should be given special consideration for 5G (non-rotated) welding of carbon steel pipe with wall thicknesses up to 3⁄8 inch (10 mm).

Pipe and Weld Data

Electrode for root weld = 0.035 inch diameter, E70S-6 flux cored.
Gas = argon with 15–25% CO_2
Gas flow rates = 30 to 40 cubic ft/hr

Root Welding Procedure for 5G Welds: Use root welding data from *Root Welding Procedures for FCAW 5G Pipe Welds*, above.

Fill and Cover Pass Procedures for 5G Welds: Use MIG short-circuit, vertical-up for fill and cover passes. Electrode wire and gas, same as for root weld.

Weld vertical-up. If the vertical-up fill pass can be made in two passes, weld from the 7 to the 1 o'clock position, to avoid starting and finishing on the root tacks. Starting just past 6 o'clock ensures that optimum weld energy is achieved as the first pass welds over the initial 6 o'clock root tack location. Feather 1 inch (25 mm) of the weld start and stop on the first pass with the grinder before applying the second vertical-up weld pass. Use a slight weave action.

Use MIG short-circuit wire feed, 200–230 in/min 125–135 amps, 19–22 volts. Start at optimum 210 in/min (10 o'clock on the wire feeder) for 130 amps, 21–22 volts. Fine tune voltage by listening to arc sound to obtain a consistent rapid crackle sound.

Electrode sticks out 1⁄2 to 5⁄8 inch, contact tip flush with nozzle end.

Remove MIG surface slag islands between weld passes. No fill pass should be thicker than 1⁄8 inch (3 mm). Use straight weave across the root face. At the bevel, use a slight upward motion with the gun. The motion should be no greater than the wire diameter. Then use a slight back step for added bevel fusion and to avoid possibility of undercut.

For the cover pass, leave 1⁄32 to 1⁄16 inch of the groove depth for the optimum cover pass profile. The bevel edge will act as a guide for the cover pass weld.

If more weld fusion is required after the root is complete and between fill passes, pre-heat pipe to 200 to 400°F.

For pipe diameters on which more than two passes are required for the circumference the weld sequence is:

1) First pass, weld from the 7 to the 4 o'clock position. Start with a slight forehand nozzle angle. At the 4 o'clock position the gun should point straight at the joint.

2) Second pass, weld from the 10 to the 1 o'clock position, then grind all stops and starts for at least 1 inch (25 mm).
3) Third pass, weld from the 4 to the 1 o'clock position.
4) Fourth pass, weld from the 7 to the 10 o'clock position.

Nondestructive Testing

Nondestructive Testing.—Nondestructive testing (NDT) is aimed at examination of a component or assembly, usually for surface or internal cracks or other nonhomogeneities, to determine the structure, or to measure thickness, by some means that will not impair its use for the intended purpose. Traditional methods include use of radiography, ultrasonic vibration, dye penetrants, magnetic particles, acoustic emission, leakage, and eddy currents. These methods are simple to use but some thought needs to be given to their application and to interpretation of the results. Space limitations preclude a full discussion of NDT here, but the nature of the welding process makes these methods particularly useful, so some information on use of NDT for testing welds is given below.

Nondestructive Testing Symbol Application.—The application of nondestructive testing symbols is also covered in American National Standard ANSI/AWS 2.4–79.

Basic Testing Symbols: These are shown in the following table.

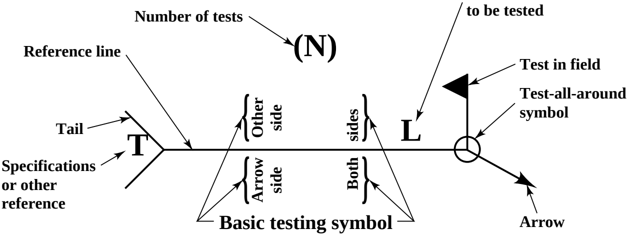
American National Standard Basic Symbols for Nondestructive Testing
ANSI/AWS 2.4–79

Symbol	Type of Test	Symbol	Type of Test
AET	Acoustic Emission	PT	Penetrant
ET	Eddy Current	PRT	Proof
LT	Leak	RT	Radiographic
MT	Magnetic Particle	UT	Ultrasonic
NRT	Neutron Radiographic	VT	Visual

Testing Symbol Elements: The testing symbol consists of the following elements:

Reference Line
  Arrow
  Basic Testing Symbol
  Test-all-around Symbol
  (N) Number of Tests
  Test in Field
Tail
  Specification or other reference

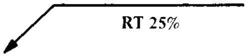
The standard location of the testing symbol elements are shown in the following figure.

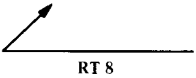


Locations of Testing Symbol Elements

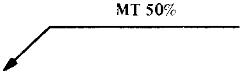
The arrow connects the reference line to the part to be tested. The side of the part to which the arrow points is considered to be the *arrow side*. The side opposite the arrow side is considered to be the *other side*.

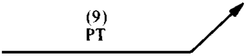
Location of Testing Symbol: Tests to be made on the arrow side of the part are indicated by the basic testing symbol on the side of the reference line toward the reader.





Tests to be made on the other side of the part are indicated by the basic testing symbol on the side of the reference line away from the reader.



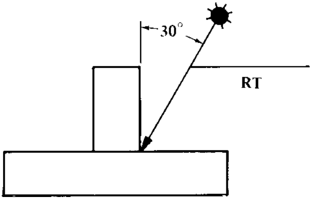


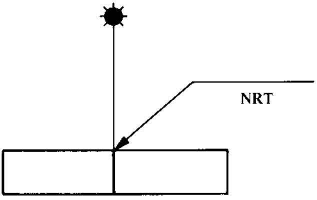
To specify where only a certain length of a section is to be considered, the actual length or percentage of length to be tested is shown to the right of the basic test symbol. To specify the number of tests to be taken on a joint or part, the number of tests is shown in parentheses.

Tests to be made on both sides of the part are indicated by test symbols on both sides of the reference line. Where nondestructive symbols have no arrow or other significance, the testing symbols are centered in the reference line.

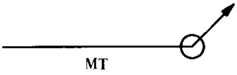
Combination of Symbols: Nondestructive basic testing symbols may be combined and nondestructive and welding symbols may be combined.

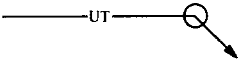
Direction of Radiation: When specified, the direction of radiation may be shown in conjunction with the radiographic or neutron radiographic basic testing symbols by means of a radiation symbol located on the drawing at the desired angle.





Tests Made All Around the Joint: To specify tests to be made all around a joint a circular test-all-around symbol is used.





Areas of Revolution: For nondestructive testing of areas of revolution, the area is indicated by the test-all-around symbol and appropriate dimensions.

Plane Areas: The area to be examined is enclosed by straight broken lines having a small circle around the angle apex at each change in direction.

LASERS

Lasers are used for cutting, welding, drilling, surface treatment, and marking. The word laser stands for Light Amplification by Stimulated Emission of Radiation, and a laser is a unit that produces optical-frequency radiation in intense, controllable quantities of energy. When directed against the surface of a material, this quantity of energy is high enough to cause a localized effect. Heating by a laser is controlled to produce only the desired result in a specific area, ensuring low part distortion.

The four basic components of a laser, shown in Fig. 1, are an amplifying medium, a means to excite this medium, mirrors arranged to form an optical resonator, and an output transmission device to cause beam energy to exit from the laser. The laser output wavelength is controlled by the type of amplifying medium used. The most efficient industrial lasers use optical excitation or electrical discharge to stimulate the medium and start the lasing action.

Solid-state lasers, in which the medium is a solid crystal of an optically pure material such as glass or yttrium aluminum garnet (YAG) doped with neodymium (Nd), are excited by a burst of light from a flashlamp(s) arranged in a reflective cavity that acts to concentrate the excitation energy into the crystal. Neodymium lasers emit radiation at 1.06 μm (1 μm = 0.00004 in.), in the near infrared portion of the spectrum.

The carbon dioxide (CO_2) laser uses a gaseous mixture of helium, nitrogen, and carbon dioxide. The gas molecules are energized by an electric discharge between strategically placed cathodes and anodes. The light produced by CO_2 lasers has a wavelength of approximately 10.6 μm.

Laser Light.—The characteristics of light emitted from a laser are determined by the medium and the design of the optical resonator. Photons traveling parallel to the optical axis are amplified and the design provides for a certain portion of this light energy to be transmitted from the resonator. This amplifier/resonator action determines the wavelength and spatial distribution of the laser light.

The transmitted laser light beam is monochromatic (one color) and coherent (parallel rays), with low divergence and high brightness, characteristics that distinguish coherent laser light from ordinary incoherent light and set the laser apart as a beam source with high energy density. A typical industrial laser operating in a very narrow wavelength band determined by the laser medium is called monochromatic because it emits light in a specific segment of the optical spectrum. The wavelength is important for beam focusing and material absorption effects.

Coherent laser light can be 100,000 times higher in energy density than equivalent-power incoherent light. The most important aspect of coherent light for industrial laser applications is directionality. which reduces dispersion of energy as the beam is directed over comparatively long distances to the workpiece.

Laser Beams.—The slight tendency of a laser beam to expand in diameter as it moves away from its source is called beam divergence, and is important in determining the size of the spot where it is focused on the work surface. The beam-divergence angle for high-power lasers used in processing industrial materials is larger than the diffraction-limited value because the divergence angle tends to increasewith increasing laser output power. The amount of divergence thus is a major factor in concentration of energy in the work.

The power emitted per unit area per unit solid angle is called brightness. Because the laser can produce very high levels of power in very narrowly collimated beams, it is a source of high brightness energy. This brightness factor is a major characteristic of solid-state lasers. Other important beam characteristics in industrial lasers include spatial mode and depth of focus. Ideally, the output beam of the laser selected should have a mode structure, divergence, and wavelength sufficient to process the application in optimum time and with a minimum of heat input. A beam-quality factor, M^2, is commonly used to define the productive performance of a laser. This factor is a measure of the ratio between the spot diameter of a given laser to that of a theoretically perfect beam. Beam quality is expressed as "times diffraction" and is always greater than 1. For CO_2 lasers at the 1-kW level, $M^2 = 1.5$, and for YAG lasers at 500 W, $M^2 = 12.0$ is typical.

The mode of a laser beam is described by the power distribution profile over its cross-section. Called transverse modes, these profiles are represented by the term TEM_{mn}, where TEM stands for transverse electromagnetic, and m and n are small integers indicating that power distribution is bell-shaped (Gaussian) TEM_{00}, or donut-shaped TEM_{01}*.

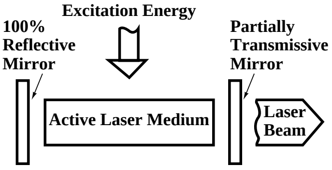


Fig. 1. Basic Components of a Laser

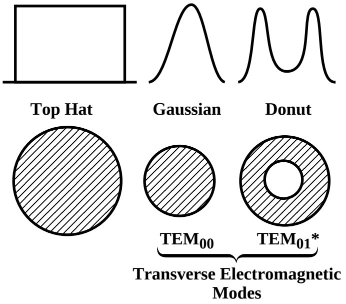


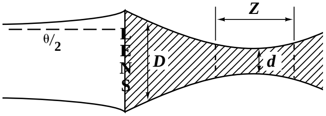
Fig. 2. Spatial Intensity Distribution in Laser Beams

Fig. 2 shows various transverse electromagnetic modes commonly used in materials processing applications. For such applications, it is helpful to determine the peak and total power generated by the laser. Diffraction in Gaussian beams is inherently limited and other modes of operation may have larger beam-divergence angles, causing less power to be delivered to the workpiece. The selection process for industrial applications should consider only those lasers that produce the lowest-order mode beam, in a Gaussian-shaped energy profile (see Fig. 2), with a narrow beam divergence. Solid-state lasers do not meet all these criteria, and with high-power CO_2 lasers, it is sometimes necessary to compromise because of reduced output power, large physical size, and complexity of the laser design.

Although a laser with a TEM_{00} output beam is preferred for optimum performance, the application may not always require such a beam. For example, many CO_2 laser cutting operations are performed with a TEM_{01}* beam and welding is often done with a mixture of each of these modes. Lasers can be operated in three temporal modes, continuous wave (CW), pulsed, and superpulsed (called Q-switched for YAG lasers), depending on the materials being processed.

The smallest focused spot diameter that will provide the highest energy intensity can be produced by a TEM_{00} laser. The fundamental mode output of CO_2 lasers is limited to 2500 watts. Complex spatial patterns are often caused by inhomogeneities in solid-state laser crystals and are controlled by insertion of apertures that greatly reduce output power. However, standard lasers suit the needs of most industrial users as beam divergence is only one factor in laser design.

Beam Focusing.—The diameter of a focused laser beam spot can be estimated by multiplying the published beam divergence value by the focal length of the lensor by the relationship of the wavelength to the unfocused beam diameter. Thus, the beam from a CO_2 laser operating at a 10.6-μm wavelength, using the same focal length lens, will produce a focused spot ten times larger than the beam from a Nd:YAG laser operating at a 1.06-μm wavelength.



Spot Diameter, $d = f\theta = 4\lambda F/\pi D$

Power Density, $H = 4P/\ d^2$

Depth of Focus, $Z = \pm d^2/4\pi$

Fig. 3. Focus Characteristics of a Laser Beam.

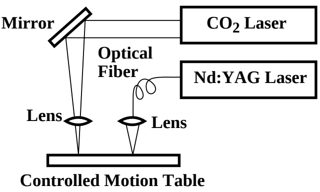


Fig. 4. Typical Laser Systems.

Effects of various beam spot sizes and depths of focus are shown in Fig. 3. High-power density is required for most focused beam applications such as cutting, welding, drilling, and scribing, so these applications generally require a tightly focused beam. The peak power density of a Gaussian beam is found by dividing the power at the workpiece by the area of the focused spot. Power density varies with the square of the area, so that a change in the focused spot size can influence power density by a factor of 4 and careful attention must be given to maintaining beam focus.

Another factor of concern in laser processing is depth of focus, defined as the range of depth over which the focused spot varies by ±5 per cent. This relationship is extremely important in cutting sheet metal, where it is affected by variations in surface flatness. Cutting heads that adapt automatically to maintain constant surface-to-nozzle spacing are used to reduce this effect.

Types of Industrial Lasers.—Specific types of lasers are suited to specific applications, and Fig. 1 lists the most common lasers used in processing typical industrial materials. Solid-state lasers are typically used for drilling, cutting, spot and seam welding, and marking on thin sheet metal. CO_2 lasers are used to weld, cut, surface treat, and mark both metals and nonmetals. For example, CO_2 lasers are suited to ceramic scribing and Nd:YAG lasers for drilling turbine blades. Factors that affect suitability include wavelength, power density, and spot size. Some applications can use more than one laser type. Cutting sheet metal, an established kilowatt-level CO_2 laser application, can also be done with kilowatt-level Nd:YAG lasers. For some on-line applications that require multiaxis beam motion, the Nd:YAG laser may have advantages in close coupling the laser beam to the workpiece through fiber optics.

Table 1. Common Industrial Laser Applications

Type	Wavelength (μm)	Operating Mode	Power Range (watts)	Applications
Nd:YAG	1.06	Pulsed	10–2,000	A, B, D, E, F
Nd: YAG	1.06	Continuous	500–3,000	A, B, C
Nd: YAG	1.06	Q-switched	5–150	D, E, F
CO_2	10.6	Pulsed	5–3,000	A, B, D, E
CO_2	10.6	Superpulsed	1,000–5,000	A
CO_2	10.6	Continuous	100–25,000	A, B, C

Applications: A = cutting, B = welding, C = surface treatment, D =drilling, E = marking, F = micromachining.

Industrial Laser Systems.—The laser should be located as close as possible to the workpiece to minimize beam-handling problems. Ability to locate the beam source away from its power supply and ancillary equipment, and to arrange the beam source at an angle to the workpiece allows the laser to be used in many automatic and numerically controlled set ups. Fig. 4 shows typical laser system arrangements.

Lasers require power supplies and controllers for lasers are usually housed in industrial grade enclosures suited to factory floor conditions. Because the laser is a relatively inefficient converter of electrical energy to electromagnetic energy (light), the waste heat from the beam source must be removed by heat exchangers located away from the processing area. Flowing gas CO_2 lasers require a source of laser gas, used to make up any volume lost in the normal recycling process. Gas can be supplied from closely linked tanks or piped from remote bulk storage.

Delivery of a high-quality beam from the laser to the workpiece often requires subsystems that change the beam path by optical means or cause the beam to be directed along two or more axes. Five-axis beam motion systems, for example, using multiple optical elements to move the beam in X, Y, Z, and rotation/tilt, are available.

Solid-state laser beams can be transmitted through flexible optical fibers. If there is no beam motion, the workpiece must be moved. The motion systems used can be as simple as an XY or rotary table, or as complex as a multistation, dual-feed table. Hybrid systems offer a combination of beam and workpiece motion and are frequently used in multiaxis cutting applications. All motions are controlled by an auxiliary unit such as a CNC, NC, paper tape, or programmable controller. Newer types of controllers interface with the beam source to control the entire process. Gas jet nozzles, wire feed, or seam tracking equipment are often used, and processing may be monitored and controlled by signals from height sensors, ionized by-product (plasma) detectors, and other systems.

Safety.—Safety for lasers is covered in ANSI Z136.1-1993: Safe Use Of Lasers. Most industrial lasers require substantial electrical input at high-voltage and -amperage conditions. Design of the beam source and the associated power supply should be to accepted industry electrical standards. Protective shielding is advised where an operator could interact, physically, with the laser beam, and would be similar to safety shields provided on other industrial equipment.

Radiation from a laser is intense light concentrated in tight bundles of energy. The high energy density and selective absorption characteristics of the laser beam have the potential to cause serious damage to the eye. For this reason, direct viewing of the beam from the laser should be restricted. Safety eyewear is commercially available to provide protection for each type of laser used. Certain lasers, such as the 1.06-μm solid-state units, should be arranged in a system such that workers are shielded from direct and indirect radiation. Other types of lasers, such as the 10.6-μm CO_2 laser, when operated without shielding, should meet industry standards for maximum permissible exposure levels. Much information is published on laser radiation safety, so that the subject is highly documented. Laser suppliers are very familiar with local regulations and are a good source for prepurchase information. Certain materials, notably many plastics compositions, when vaporized, will produce potentially harmful fumes.Precautionary measures such as workstation exhaust systems typically handle this problem.

Laser Beam/Material Interaction.—Industrial lasers fall into categories of effectiveness because the absorption of laser light by industrial materials depends on the specific wavelength. However, at room temperature, CO_2 laser light at 10.6 μm wavelength is fully absorbed by most organic and inorganic nonmetals.

Both CO_2 and YAG can be used in metalworking applications, although YAG laser light at 1.06 μm is absorbed to a higher degree in metals. Compensation for the lower absorption of CO: light by metals is afforded by high-energy-density beams, which create small amounts of surface temperature change that tend to increase the beam-coupling coefficient.

At CO_2 power densities in excess of 10^6 W/cm^2, effective absorptivity in metals approaches that of nonmetals. Above certain temperatures, metals will absorb more infrared energy. In steel at 400°C, for instance, the absorption rate is increased by 50 per cent. In broad-area beam processing, where the energy density (10^4 W/cm^2) is low, some form of surface coating may be required to couple the beam energy into a metal surface.

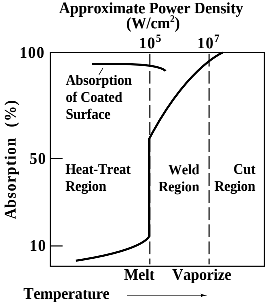


Fig. 5. Laser Energy Absorption Intensity vs. Temperature

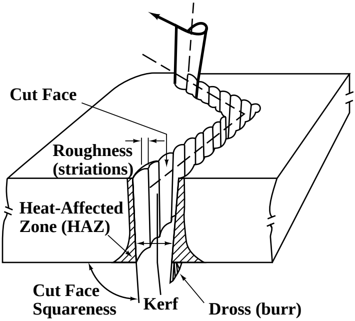


Fig. 6. Factors in Laser Cutting.

Thermal Properties of Workpieces.—When a laser beam is coupled to a workpiece, initial conversion of energy to work, in the form of heat, is confined to a very thin layer (100-200 Ångstroms) of surface material. The absorbed energy converted to heat will change the physical state of the workpiece, and depending on the energy intensity of the beam, a material will heat, melt, or vaporize. Fig. 5 shows percentage of energy absorption versus temperature for various phase changes in materials.

Heating, melting, and vaporization of a material by laser radiation depends on the thermal conductivity and specific heat of the material. The heating rate is inversely proportional to the specific heat per unit volume, so that the important factor for heat flow is the thermal diffusivity of the work material. This value determines how rapidly a material will accept and conduct thermal energy, and a high thermal diffusivity will allow a greater depth of fusion penetration with less risk of thermal cracking.

Heat produced by a laser in surface layers is rapidly quenched into the material and the complementary cooling rate is also rapid. In some metals, the rate is 10^6 C°/s. This rapid cooling results in minimum residual heat effects, due to the slower thermal diffusivity of heat spreading from the processed area. However, rapid cooling may produce undesired effects in some metals. Cooling that is too rapid prevents chemical mixing and may result in brittle welds.

Thermosetting plastics are specifically sensitive to reheating, which may produce a gummy appearance or a charred, ashlike residue. Generally, the sensitivity of a material to heat from a laser is as apparent as with any other localized heating process. Any literature describing the behavior of materials when exposed to heat will apply to laser processing.

Cutting Metal with Lasers

The energy in a laser beam is absorbed by the surface of the impinged material, and the energy is converted into work in the form of heat, which raises the temperature to the melting or vaporization point. A jet of gas is arranged to expel excess molten metal and vapor from the molten area. Moving the resulting molten-walled hole along a path with continuous or rapidly pulsed beam power produces a cut. The width of this cut (kerf), the quality of the cut edges, and the appearance of the underside of the cut (where the dross collects) are determined by choice of laser, beam quality, delivered power, and type of motion employed (beam, workpiece, or combination). Fig. 6 identifies the factors involved in producing a high-quality cut.

Power versus penetration and cutting rate are essentially straight-line functions for most ferrous metals cut with lasers. A simple relationship states that process depth is proportional to power and inversely proportional to speed. Thus, for example, doubling power will double penetration depth. The maximum possible thickness that can be cut is, therefore, a function of power, cutting rate, and compromise on cut quality. Currently, 25 mm (1 in.) is considered the maximum thickness of steel alloys that can be cut. The most economically efficient range of thicknesses is up to 12.5 mm (0.49 in.).

Metals reflect laser light at increasing percentages with increasing wavelength. The high-energy densities generated by high-power CO_2 lasers overcome these reflectivity effects. Shorter-wavelength lasers such as Nd:YAG do not suffer these problems because more of their beam energy is absorbed.

Beam Assistance Techniques.—In cutting ferrous alloys, a jet of oxygen concentric with the laser beam is directed against the heated surface of the metal. The heat of the molten puddle of steel produced by the laser power causes the oxygen to combine with the metal, so that the jet burns through the entire thickness of the steel. This melt ablation process also uses the gas pressure to eject the molten metal from the cut kerf. Control of the gas pressure, shape of the gas stream, and positioning of the gas nozzle orifice above the metal surface are critical factors. A typical gas jet nozzle is shown in Fig. 7. Cutting highly alloyed steels, such as stainless steel, is done with pulsed CO_2 laser beams. High-pressure gas jets with the nozzle on the surface of the metal and nonoxidizing gas assistance can be used to minimize or eliminate clinging dross.

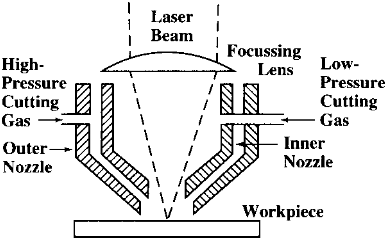


Fig. 7. Laser Gas Cutting Nozzle for Steel.

The narrow kerf produced by the laser allows cut patterns to be nested as close as one beam diameter apart, and sharply contoured and profiled cuts can be made, even in narrow angle locations. For this type of work and for other reasons, confining the kerf width to a dimension equal to, or slightly greater than, the diameter of the laser beam is important. Kerf width is a function of beam quality, focus, focus position, gas pressure, gas nozzle to surface spacing, and processing rate. Table 2 shows typical kerf widths.

Table 2. Typical Kerf Widths in CO_2 Laser Cutting

Material	Thickness		Kerf	
	mm	in.	mm	in.
Carbon Steel	1.5	0.06	0.05	0.002
	2.25	0.09	0.12	0.005
	3.12	0.12	0.2	0.008
	6.25	0.25	0.3	0.012
Aluminum	2.25	0.09	0.25	0.01
Plastics	<4.0	<0.16	2 × beam diameter	

Cut Edge Roughness.—Cutting with a continuous-wave (CW) output CO_2 laser can produce surface roughness values of 8–15 μm (315–590 μin) in 1.6-mm (0.063-in) cold-rolled steel and 30-35 μm (1180–1380 μin) in mild steel. Surface roughness of 30–50 μm (1180–1970 μin) in thin-gage stainless steel sheets is routine when using oxygen to assist cutting. Table 3 lists some surface roughness values.

Table 3. Surface Roughness Values for Laser Cutting with Oxygen

Material	Thickness		Surface Finish	
	mm	in.	μm	μin
Stainless Steel	1	0.04	30	1200
	2	0.08	35	1400
	3	0.12	50	2000
Cold-Rolled Steel	1	0.04	8	320
	2	0.08	10	400
	3	0.12	15	600
Mild Steel	1	0.04	30	1200
	2	0.08	30	1200
	3	0.12	35	1400

Heat-Affected Zones.—Control of beam focus, focus position, assist gas conditions, and processing rates produces differences in hardness that are barely discernible in steels up to 2 mm (0.078 in.) thick. Small increases in hardness to a depth of 0.1–0.2 mm (0.004–0.008 in.) are common. Cutting with a pulsed CO_2 laser reduces these values to less than 0.1 mm (0.004 in.), making this mode of operation beneficial for some end-use applications. Table 4 shows typical values for the heat-affected zone in mild steels.

Table 4. Heat-Affected Zone in Mild Steels

Material Thickness		CW HAZ		Pulsed HAZ	
mm	in.	mm	in.	mm	in.
4	0.157	0.50	0.020	0.15	0.006
3	0.118	0.37	0.015	0.15	0.006
2	0.078	0.10	0.004	0.12	0.005
1	0.039	0.75	0.030	0.07	0.003

Rates for laser cutting of metals are typically reported as data developed under ideal conditions, that is, in a controlled development laboratory environment using technician-operated equipment. Rates achieved on the shop floor using semiskilled system operators to produce complicated shapes may vary dramatically from published data. Speed versus thickness for cutting steel is shown in Fig. 8 for 1000- and 1500-W power levels, and cutting performance for several other metals of various thicknesses is shown in Table 5. Cutting rate data for pulsed and CW Nd:YAG lasers for steel also are shown in Fig. 8, and for Nd:YAG cutting of other metals in Table 5.

Table 5. CO_2 and Nd: YAG Cutting Speeds for Nonferrous Metals

	CO_2 (1500 watts)				Nd: YAG				
	Thickness		Speed		Thickness		Speed		Power
Material	mm	in.	m/min	ft/min	mm	in.	m/min	ft/min	watts
Copper	1	0.04	2.25	7.4	…		…		…
	2	0.08	0.75	2.5	…		…		…
	3	0.12	0.35	1.15	…		…		…
Aluminum	1	0.04	8	26.2	1.5	0.06	2.5	8.2	1000
	2	0.08	4	13.1	2.5	0.1	1.0	3.3	1000
	3	0.12	1.5	4.9	3.5	0.14	0.5	1.6	1000
Titanium	1	0.04	6	19.7	0.4	0.016	1.0	3.3	150
	2	0.08	3	9.8	…		…		…
Tungsten	…		…		0.08	0.003	0.03	0.1	250
Brass	1	0.04	3	9.8	…		…		…
	2	0.08	1.5	4.9	…		…		…
Hastalloy	2.5	0.1	2.8	9.2	…		…		…
Hastalloy X	…		…		0.08	0.003	0.5	1.6	150
Inconel 718	4	0.16	1.1	3.6	…		…		…

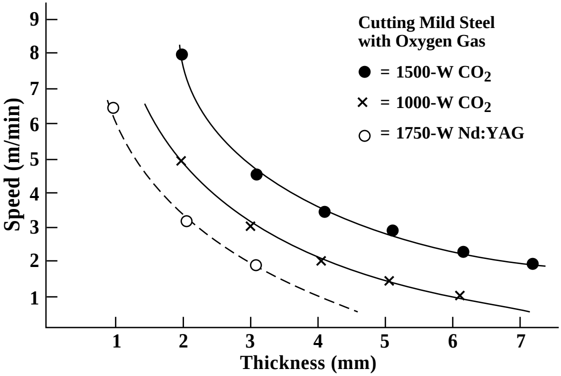


Fig. 8. Typical Cutting Rates for CO_2 and YAG Lasers.

Cutting of Nonmetals.—Laser cutting of nonmetals has three requirements: a focused beam of energy at a wavelength that will be absorbed easily by the material so that melting or vaporization can occur; a concentric jet of gas, usually compressed air, to remove the by-products from the cut area; and a means to generate cuts in straight or curved outlines. Residual thermal effects resulting from the process present a greater problem than in cutting of metals and limit applications of lasers in nonmetal processing.

When subjected to a laser beam, paper, wood, and other cellular materials undergo vaporization caused by combustion. The cutting speed depends on laser power, material thickness, and water and air content of the material. Thermoplastic polymer materials are cut by melting and gas jet expulsion of the melted material from the cut area. The cutting speed is governed by laser power, material thickness, and pressure of gas used to eject the displaced material.

Polymers that may be cut by combustion or chemical degradation include the thermosetting plastics, for example, epoxies and phenolics. Cutting speed is determined by the laser power and is higher for thermosets than for other polymers due to the phase change to vapor.

Composite materials are generally easy to cut, but the resulting cut may not be of the highest quality, depending on the heat sensitivity of the composite materials. High-pressure cutting processes such as fluid jets have proven to be more effective than lasers for cutting many composite materials.

Nonmetal cutting processes require moderate amounts of power, so the only limitation on cut thickness is the quality of the cut. In practice, the majority of cutting applications are to materials less than 12 mm thick. Cutting rates for some commonly used nonmetals are shown in Table 6. Nonmetal cutting applications require a gas jet to remove molten, vaporized, or chemically degraded matter from the cut area.

Compressed air is used for many plastics cutting applications because it is widely available and cheap to produce, so it is a small cost factor in nonmetal cutting. A narrow kerf is a feature of nonmetal cutting, and it is especially important in the cutting of compactly nested parts such as those produced in cutting of fabrics. Nonmetals react in a variety of ways to laser-generated heat, so that it is difficult to generalize on edge roughness, but thermally sensitive materials will usually show edge effects.

Table 6. CO_2 Laser Cutting Rates for Nonmetals

	Thickness		Speed		Power
Material	mm	in	m/min	ft/min	watts
Polythene	1	0.04	11	36	500
Polypropylene	1	0.04	17	56	500
Polystyrene	1	0.04	19	62	500
Nylon	1	0.04	20	66	500
ABS	1	0.04	21	69	500
Polycarbonate	1	0.04	21	69	500
PVC	1	0.04	28	92	500
Fiberglass	1.6	0.063	5.2	17	450
Glass	1	0.04	1.5	4.9	500
Alumina	1	0.04	1.4	4.6	500
Hardwood	10	0.39	2.6	8.5	500
Plywood	12	0.47	4.8	15.7	1000
Cardboard	4.6	0.18	9.0	29.5	350

Welding with Lasers

Laser Welding Theory.—Conversion of absorbed laser energy into heat causes metals to undergo a phase change from solid to liquid and, as energy is removed, back to solid. This fusion welding process is used to produce selective area spot welds or linear continuous seam welds. The two types of laser welding processes, conduction and deep penetration, or keyhole, are shown in Fig. 9.

Conduction welding: relies on the thermal diffusivity characteristics of the metal to conduct heat into the joint area. By concentrating heat into the focused beam diameter and programming this heat input for short time periods, more heat is conducted into the joint than is radiated outward from the joint. Conduction welds are generally used for spot welding and partial penetration seam welding.

Deep penetration keyhole welding: is produced by beam energy converted to heat that causes a hole to be produced through the thickness of the metal. Vapor pressure of evaporated metal holds a layer of molten metal in place against the hole wall.

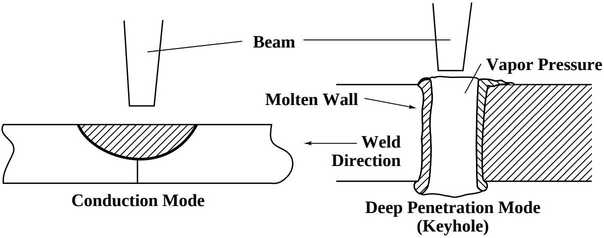


Fig. 9. Types of Laser Welds.

Movement of the hole, by beam or workpiece motion, causes the molten metal to flow around the hole and solidify behind the beam interaction point. The resolidified metal has a different structure than the base metal. Maximum practical penetration limits are approximately 25 mm (2 in.) with today's available laser power technology.

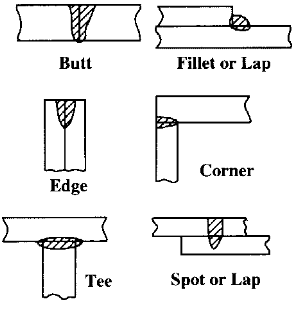


Fig. 10. Examples of Laser Weld Joint Designs.

If the physical change from solid to liquid to solid does not produce a ductile fusion zone, and if the brittleness of the resolidified metal cannot be reduced easily by postweld annealing, then the laser welding process, as with other fusion welding processes, may not be viable. If the metal-to-metal combination does not produce an effective weld, other considerations such as filler metal additions to modify fusion zone chemistry should be considered.

Welded Joint Design.—For optimum results, the edges of parts to be laser beam welded should be in close contact. When a part is being designed and there is a choice of welding process, designers should design joints and joint tolerances to the optimum for laser welding. Fig. 10 shows suitable joint designs for the laser fusion welding process. Joint tolerances are one of the more important parameters influencing part weldability, and for corner, tee, and lap joints, gaps should be not more than 25 per cent of the thickness of the thinnest section. For butt and edge joints, the percentage is reduced to 10. Addition of filler metal to compensate for large joint gaps is becoming popular.

Welding Rates.—The information presented in Fig. 11 for welding with CO_2 and Nd:YAG lasers should be considered as typical for the specific lasers shown and is for use in optimum conditions. These data are provided only as guidelines.

Processing Gas.—The proper choice of processing gas is important for both conduction and keyhole welding. Gases that ionize easily should not be used to shield the beam/material interaction point. Energy intensities of 10^6 W/cm^2 or higher can occur in the zone where incident and reflected laser light overlap and gases can vaporize, producing a plasma that attenuates further beam transmission.

One of the most important advantages of laser welding is the low total heat input characteristic of the focused high-energy density beam. Heat concentration resulting from the beam energy conversion at the workpiece surface causes most conduction to be perpendicular to the direction of motion. With the beam (or workpiece) moving faster than the speed of thermal conduction, there is significant heat flow only in the perpendicular direction. Thus, material solid to solid, or solid to liquid, changes tend to occur only in the narrow path of heat conduction, and the amount of heat necessary to penetrate a given material thickness is reduced to only that needed to fuse the joint. With limited excess heat through the low total heat mechanism, parts can be produced by laser welding with minimum thermal distortion.

Helium is the ideal gas for laser welding, but other gases such as CO_2 and argon have been used. Neither CO_2 nor argon produces a clean, perfectly smooth weld, but weld integrity seems sufficient to suggest them as alternatives. The cost of welding assistance gas can be greater than for laser gases in CO_2 laser welding and may be a significant factor in manufacturing cost per welded part.

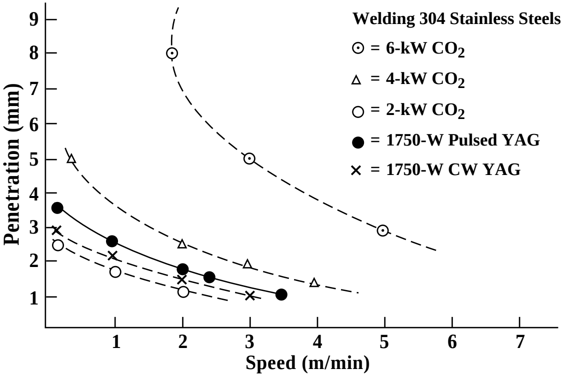


Fig. 11. Rates for CO_2 and Nd:YAG Laser Welding.

Drilling with Lasers

Laser Drilling Theory.—Laser drilling is performed by direct, percussive, and trepanning methods that produce holes of increasing quality respectively, using increasingly more sophisticated equipment. The drilling process occurs when the localized heating of the material by a focused laser beam raises the surface temperature above the melting temperature for metal or, for nonmetals, above the vaporization temperature.

Direct Drilling.—The single-pulse, single-hole process is called direct drilling. The process hole size is determined by the thermal characteristics of the material, the beam spot size, the power density, the beam quality, and the focus location. Of these parameters, beam quality, in terms of beam divergence, is an important criterion because of its effect on the hole size. Single-pulse drilled holes are usually limited to a depth of 1.5 mm (0.06 in.) in metals and up to 8 mm (0.315 in.) in nonmetals. Maximum hole diameter for pulsed solid-state laser metal drilling is in the 0.5-to 0.75-mm (0.02- to 0.03-in) range, and CO_2 direct drilling can produce holes up to 1.0 mm (0.04 in.) in diameter. The aspect ratio (depth to midhole diameter) is typically under 10:1 in metals and for many nonmetals it can be 15:1. Hole taper is usually present in direct drilling of metals. The amount of taper (entrance hole to exit hole diameter change) can be as much as 25 per cent in many metals. Direct drilling produces a recast layer with a depth of about 0.1 mm (0.004 in.). Diameter tolerances are ±10 per cent for the entrance hole, depending on beam quality and assist gas pressure.

Percussive Drilling.—Firing a rapid sequence of pulses produces a hole of higher quality than direct drilling in metal thicknesses up to 25 mm (1 in.). This process is known as percussive drilling. Multiple pulses may be necessary, depending on the metal thickness. Typical results using percussion drilled holes are: maximum depth achievable, 25 mm (1 in.); maximum hole diameter, 1.5 mm (0.06 in.); aspect ratio, 50:1; recast layer, 0.5 mm (0.02 in.); taper under 10 per cent; and hole diameter tolerance ±5 per cent.

Trepanning.—To improve hole quality, some companies use the trepanning method to cut a hole. In this process, a focused beam is moved around the circumference of the hole to be drilled by a rotating mirror assembly. The closeness of spacing of the beam pulses that need to be overlapped to produce the hole depends on the quality requirements. Typical results are: maximum hole depth, 10 mm (0.39 in.); maximum hole diameter, 2.5 mm (0.1 in.); and recast layer thickness, 25 μm (985 μin).

Drilling Rates.—Laser drilling is a fast process but is very dependent on the above-mentioned process factors. It is difficult to generalize on laser drilling rates because of the large number of combinations of material, hole diameter, depth, number of holes per part, and part throughput. With Nd:YAG lasers, direct drilling rates of 1 ms are typical.

Heat Treatment with Lasers

The defocused beam from a CO_2 laser impinging on a metal surface at room temperature will have 90 per cent or more of its power reflected. In steels, the value is about 93 per cent. Compared with focused beam processing, which uses power densities greater than 10^5 W/cm^2, the power density of laser beams designed for heat treatment, at less than 10^4 W/cm^2, is insufficient to overcome reflectivity effects. Therefore, the metal surface needs to be prepared by one of several processes that will enhance absorption characteristics. Surface roughening can be used to produce tiny craters that can trap portions of the beam long enough to raise the surface temperature to a point where more beam energy is absorbed. Coating the metal surface is a common expedient. Black enamel paint is easy to apply and the laser beam causes the enamel to vaporize, leaving a clean surface.

The absorbed laser beam energy, converted to heat, raises the temperature of the metal in the beam pattern for as long as the beam remains in one place. The length of the dwell time is used to control the depth of the heat treatment and is an extremely effective means for control of case depth in hardening.

Materials Applicability.—Hardenable ferrous metals, such as medium- and high-carbon steels, tool steels, low-alloy steels and cast irons, and steels with fine-carbide dispersion, are good candidates for laser heat treating. Marginally hardenable metals include annealed carbon steels, spheroidized carbon steels, mild-carbon steels (0.2 per cent C), and ferritic nodular cast irons. Low-carbon steels (<0.1 per cent C), austenitic stainless steels, and nonferrous alloys and metals are not hardenable.

The effect of the metal microstructure on depth of hardening is an important factor. Cast iron, with a graphite and tempered martensite structure, presents a low carbon-diffusion distance that favors deep-hardened cases. The same is true for steel with a tempered martensite or bainite structure. On the other hand, cast iron with a graphite/ferrite structure and spheroidized iron (Fe_3C plus ferrite) structures have large carbon-diffusion patterns and therefore produce very shallow or no case depths.

Hardening Rates.—Laser hardening is typically slower than conventional techniques such as induction heating. However, by limiting the area to be hardened, the laser can prove to be cost-effective through the elimination of residual heat effects that cause part distortion. A typical hardening rate is 130 cm^2/min. (20 in^2/min.) for a 1-mm (0.039-in) case depth in 4140 steel.

Cladding with Lasers

In laser cladding, for applying a coating of a hard metal to a softer alloy, for instance, a shaped or defocused laser beam is used to heat either preplaced or gravity-fed powdered alloys. The cladding alloy melts and flows across the surface of the substrate, rapidly solidifying when laser power is removed. Control of laser power, beam or part travel speed, clad thickness, substrate thickness, powder feed rate, and shielding gas are process variables that are determined for each part.

Many of the alloys currently used in plasma arc or metal inert gas cladding techniques can be used with the laser cladding process. Among these materials, Stellites, Colmonoys, and other alloys containing carbides are included, plus Inconel, Triballoy, Fe-Cr-C-X alloys, and tungsten and titanium carbides.

Controlled minimal dilution may be the key technical advantage of the laser cladding process. Dilution is defined as the total volume of the surface layer contributed by melting of the substrate, and it increases with increasing power, but decreases with either increasing travel speed or increasing beam width transverse to the direction of travel. Tests comparing laser dilution to other cladding techniques show the laser at <2 per cent compared to 5–15 per cent for plasma arc and 20–25 per cent for stick electrode processes.

The laser cladding process results in a dense, homogenous, nonporous clad layer that is metallurgically bonded to the substrate. These qualities are in contrast to the mechanically bonded, more porous layer produced by other methods.

Marking with Lasers

Laser marking technology can be divided into two groups; those that produce a repetitive mark are listed as mask marking, and those that involve rapid changes of mark characteristics are classified as scanned beam marking. The amount of data that can be marked in a unit of time (writing speed) depends on laser energy density, galvanometer speed, computer control, and the dimensions of the mark. Heat-type marks have been made at rates up to 2500 mm/s (100 in/s) and engraved marks at rates of 500–800 mm/s (20–30 in/s). Writing fields are of various sizes, but a typical field measures 100 × 100 mm (4 × 4 in.).

Mask Marking.—In mask marking, the beam from a CO_2 laser is projected through a reflective mask that passes beam energy only through uncoated areas. The beam energy is reimaged by a wide field lens onto the material's surface where the absorbed heat changes the molecular structure of the material to produce a visible mark. Examples are clouding PVC or acrylics, effecting a change in a colored surface (usually by adjusting proportions of pigment dyes), or by ablating a surface layer to expose a sublayer of a different color.

CO_2 lasers can be pulsed at high rates and have produced legible marks at line speeds of 20,000 marks/h. These lasers produce energy densities in the 1–20 J/cm^2 range, which corresponds to millions of $watts/cm^2$ of power density and allows marking to be performed in areas covering 0.06 to 6 cm^2. The minimum width of an individual line is 0.1 mm (0.004 in.). Mask marking is done by allowing the beam from a laser to be projected through a mask containing the mark to be made. Reimaging the beam by optics onto the workpiece causes a visible change in the material, resulting in a permanent mark. Mask marking is used for materials that are compatible with the wavelength of the laser used.

Scanned-Beam Marking.—Focusing a pulsed laser beam to a small diameter concentrates the power and produces high-energy density that will cause a material to change its visual character. Identified by several names (spot, stroke, pattern generation, or engraving), this application is best known as scanned beam.

In the scanned-beam method, the beam from a pulsed YAG or CO_2 laser is directed onto the surface of a part by a controlled mirror oscillation that changes the beam path in a preprogrammed manner. The programming provides virtually unlimited choice of patterns to be traced on the part. The pulsed laser output can be sequenced with beam manipulation to produce a continuous line or a series of discrete spots that visually suggest a pattern (dot matrix).

The energy density in the focused beam is sufficient to produce a physical or chemical change in most materials. For certain highly reflective metals, such as aluminum, better results are obtained by pretreating the surface (anodizing). Not all scanned beam applications result in removal of base metal. Some remove only a coating or produce a discoloration, caused by heating, that serves as a mark.

Hard Facing

Hard facing is a method of adding a coating, edge, or point, of a metal or alloy capable of resisting abrasion, corrosion, heat, or impact, to a metal component. The process can be applied equally well to new parts or old worn parts. The most common welding methods used to apply hard-facing materials include the oxyacetylene gas, shielded-metal arc, submerged arc, plasma arc, and inert-gas-shielded arc (consuming and nonconsuming electrode). Such coatings can also be applied by a spraying process, using equipment designed to handle the coating material in the form of a wire or a powder.

Hard-Facing Materials.—The first thing to be considered in the selection of a hard-facing material is the type of service the part in question is to undergo. Other considerations include machinability, cost of hard-facing material, porosity of the deposit, appearance in use, and ease of application. Only generalized information can be given here to guide the selection of a material as the choice is dependent upon experience with a particular type of service. Generally, the greater the hardness of the facing material, the greater is its resistance to abrasion and shock or impact wear. Many hardenable materials may be used for hard facing such as carbon steels, low-alloy steels, medium-alloy steels, and medium-high alloys but none of these is outstanding. Some of the materials that might be considered to be preferable are high-speed steel, austenitic manganese steel, austenitic high-chromium iron, cobalt-chromium alloy, copper-base alloy, and nickel-chromium-boron alloy.

High-Speed Steels.—These steels are available in the form of welding rods (RFe5) and electrodes (EFe5) for hard facing where hardness is required at service temperatures up to 1100 degrees F and where wear resistance and toughness are also required. Typical surfacing operations are done on cutting tools, shear blades, reamers, forming dies, shearing dies, guides, ingot tongs, and broaches using these metals.

Hardness: These steels have a hardness of 55 to 60 on the Rockwell C scale in the as-welded condition and a hardness of 30 Rockwell C in the annealed condition. At a temperature of 1100 degrees F, the as-deposited hardness of 60 Rockwell C falls off very slowly to 47 Rockwell C. At about 1200 degrees F, the maximum Rockwell C hardness is 30.

Resistance Properties: As deposited, the alloys can withstand only medium impact, but when tempered, the impact resistance is increased appreciably. Deposits of these alloys will oxidize readily because of their high molybdenum content but can withstand atmospheric corrosion. They do not withstand liquid corrosives.

Other Properties or Characteristics: The metals are well suited for metal-to-metal wear especially at elevated temperatures. They retain their hardness at elevated temperatures and can take a high polish. For machining, these alloys must first be annealed. Full hardness may be regained by a subsequent heat treatment of the metal.

Austenitic Manganese Steels.—These metals are available in the form of electrodes (EFeMn) for hard facing when dealing with metal-to-metal wear and impact. Uses include facing rock-crushing equipment and railway frogs and crossings.

Hardness: Hardness of the as-deposited metals are 170 to 230 Bhn, but they can be work-hardened to 450 to 550 Bhn very readily. For all practical purposes, these metals have no hot hardness as they become brittle when reheated above 500 to 600 degrees F.

Resistance Properties: These metals have high impact resistance. Their corrosion and oxidation resistance are similar to those of ordinary carbon steels. Their resistance to abrasion is only mediocre compared with hard abrasives like quartz.

Other Properties or Characteristics: The yield strength of the deposited metal in compression is low, but any compressive deformation rapidly raises it until plastic flow ceases. This property is an asset in impact wear situations. Machining is difficult with ordinary tools and equipment; finished surfaces are usually ground.

Austenitic High-Chromium Irons.—These metals are available in rod (RFeCr-A) and electrode (EFeCr-A) form and are used for facing agricultural machinery parts, coke chutes, steel mill guides, sand-blasting equipment, and brick-making machinery.

Hardness: The as-welded deposit ranges in hardness from 51 to 62 Rockwell C. Under impact, the deposit work hardens somewhat, but the resulting deformation also leads to cracking and impact service is therefore avoided. Hot hardness decreases slowly at temperatures up to 800 and 900 degrees F. At 900 degrees F, the instantaneous hardness is 43 Rockwell C. In 3 minutes under load, the hardness drops to 37 Rockwell C. At 1200 degrees F, the instantaneous hardness is 5 Rockwell C. The decrease in hardness during hot testing is practically recovered on cooling to ambient temperatures.

Resistance Properties: Deposits will withstand only light impact without cracking. Dynamic compression stresses above 60,000 pounds per square inch should be avoided. These metals exhibit good oxidation resistance up to 1800 degrees F and can be considered for hot wear applications where hot plasticity is not objectionable. They are not very resistant to corrosion from liquids and will rust in moist air, but are more stable than ordinary iron and steel. Resistance to low-stress scratching is outstanding and is related to the amount of hard carbides present. However, under high-stress grinding abrasion, performance is only mediocre and they are not deemed suitable for such service.

Other Properties or Characteristics: The deposited metals have a yield strength (0.1 per cent offset) of between 80,000 and 140,000 pounds per square inch in compression and an ultimate strength of from 150,000 to 280,000 pounds per square inch. Their tensile strength is low and therefore tension uses are avoided in design. These deposits are considered to be commercially unmachinable and are also very difficult to grind. When ground, a grinding wheel of aluminum oxide abrasive with a 24-grit size and a hard (Q) and medium-spaced resinoid bond is recommended for off-hand high-speed work and a slightly softer (P) vitrified bond for off-hand low-speed work.

Cobalt-Base Alloys.—These metals are available in both rod (RCoCr) and electrode (ECoCr) form and are frequently used to surface the contact surfaces of exhaust valves in aircraft, truck, and bus engines. Other uses include parts such as valve trim in steam engines, and on pump shafts, where conditions of corrosion and erosion are encountered. Several metals with a greater carbon content are available (CoCr-B, CoCr-C) and are used in applications requiring greater hardness and abrasion resistance but where impact resistance is not mandatory or expected to be a factor.

Hardness: Hardness ranges on the Rockwell C scale for gas-welded deposits are as follows: CoCr-A, 38 to 47; CoCr-B, 45 to 49; and CoCr-C, 48 to 58. For arc-welded deposits, hardness ranges (Rockwell C) as follows: CoCr-A, 23 to 47; CoCr-B, 34 to 47; and CoCr-C, 43 to 58. The values for arc-weld deposits depend for the most part on the base metal dilution. The greater the dilution, the lower the hardness. Many surfacing alloys are softened permanently by heating to elevated temperatures, however, these metals are exceptional. They do exhibit lower hardness values when hot but return to their approximate original hardness values upon cooling. Elevated-temperature strength and hardness are outstanding properties of this group. Their use at 1200 degrees F and above is considered advantageous but between 1000 and 1200 degrees F, their advantages are not definitely established, and at temperatures below 1000 degrees F, other surfacing metals may prove better.

Resistance Properties: In the temperature range from 1000 to 1200 degrees F, weld deposits of these metals have a great resistance to creep. Tough martensitic steel deposits are considered superior to cobalt-base deposits in both flow resistance and toughness. The chromium in the deposited metal promotes the formation of a thin, tightly adherent scale that provides a scaling resistance to combustion products of internal combustion engines, including deposits from leaded fuels. These metals are corrosion-resistant in such media as air, food, and certain acids. It is advisable to conduct field tests to determine specific corrosion resistance for the application being considered.

Other Properties or Characteristics: Deposits are able to take a high polish and have a low coefficient of friction and therefore are well suited for metal-to-metal wear resistance. Machining of these deposits is difficult; the difficulty increases in proportion to the increase in carbon content. CoCr-A alloys are preferably machined with sintered carbide tools. CoCr-C deposits are finished by grinding.

Copper-Base Alloys.—These metals are available in rod (RCuA1-A2, RCuA1-B, RCuA1-C, RCuA1-D, RCuA1-E, RCuSi-A, RCuSn, RCuSn-D, RCuSn-E, and RCuZn-E) and electrode (ECuA1-A2, ECuA1-B, ECuA1-C, ECuA1-D, ECuA1-E, ECuSi, ECuSn-A, ECuSn-C, ECuSn-E, and ECuZn-E) forms and are used in depositing overlays and inlays for bearing, corrosion-resistant, and wear-resistant surfaces. The CuA1-A2 rods and electrodes are used for surfacing bearing surfaces between the hardness ranges of 130 to 190 Bhn as well as for corrosion-resistant surfaces. The CuA1-B and CuA1-C rods and electrodes are used for surfacing bearing surfaces of hardness ranges 140 to 290 Bhn. The CuA1-D and CuA1-E rods and electrodes are used on bearing and wear-resistant surfaces requiring the higher hardnesses of 230 to 390 Bhn such as are found on gears, cams, wear plates, and dies. The copper-tin (CuSn) metals are used where a lower hardness is required for surfacing, for corrosion-resistant surfaces, and sometimes for wear-resistant applications.

Hardness: Hardness of a deposit depends upon the welding process employed and the manner of depositing the metal. Deposits made by the inert-gas metal-arc process (both consumable and nonconsumable electrode) will be higher in hardness than deposits made with the gas, metal-arc, and carbon-arc processes because lower losses of aluminum, tin, silicon, and zinc are achieved due to the better shielding from oxidation. Copper-base alloys are not recommended for use at elevated temperatures because their hardness and mechanical properties decrease consistently as the temperature goes above 400 degrees F.

Resistance Properties: The highest impact resistance of the copper-base alloy metals is exhibited by CuA1-A2 deposits. As the aluminum content increases, the impact resistance decreases markedly. CuSi weld deposits have good impact properties. CuSn metals as deposited have low impact resistance and CuZn-E deposits have a very low impact resistance. Deposits of the CuA1 filler metals form a protective oxide coating upon exposure to the atmosphere. Oxidation resistance of CuSi deposits is fair and that of CuSn deposits are comparable to pure copper. With the exception of the CuSn-E and CuZn-E alloys, these metals are widely used to resist many acids, mild alkalies, and salt water. Copper-base alloy deposits are not recommended for use where severe abrasion is encountered in service. CuA1 filler metals are used to overlay surfaces subjected to excessive wear from metal-to-metal contact such as gears, cams, sheaves, wear plates, and dies.

Other Properties or Characteristics: All copper-base alloy metals are used for overlays and inlays for bearing surfaces with the exception of the CuSi metals. Metals selected for bearing surfaces should have a Brinell hardness of 50 to 75 units below that of the mating metal surface. Slight porosity is generally acceptable in bearing service as a porous deposit is able to retain oil for lubricating purposes. CuA1 deposits in compression have elastic limits ranging from 25,000 TO 65,000 lb/in.^{2} and ultimate strengths of 120,000 to 171,000 lb/in.^{2} The elastic limit and ultimate strength of CuSi deposits in compression are 22,000 lb/in.^{2} and 60,000 lb/in.^{2}, respectively. CuZn-E deposits in compression have an elastic limit of only about 5000 lb/in.^{2} and an ultimate strength of 20,000 lb/in.^{2} All copper-base alloy deposits can be machined.

Nickel-Chromium-Boron Alloys.—These metals are available in both rod (RNiCr) and electrode (ENiCr) form and their deposits have good metal-to-metal wear resistance, good low-stress, scratch-abrasion resistance, corrosion resistance, and retention of hardness at elevated temperatures. These properties make the alloys suitable for use on seal rings, cement pump screws, valves, screw conveyors, and cams. Three different formulations of these metals are recognized (NiCr-A, NiCr-B, and NiCr-C).

Hardness: Hardness of the deposited NiCr-A from rods range from 35 to 40 Rockwell C; of NiCr-B rods, 45 to 50 Rockwell C; of NiCr-C rods, 56 to 62 Rockwell C. Hardness of the deposited NiCr-A from electrodes ranges from 24 to 35 Rockwell C; of NiCr-B from electrodes, 30 to 45 Rockwell C; and of NiCr-C electrodes, 35 to 56. The lower hardness values and greater ranges of hardness values of the electrode deposits are attributed to the dilution of deposit and base metals. Hot Rockwell C hardness values of NiCr-A electrode deposits range from 30 to 19 in the temperature range from 600 to 1000 degrees F from instantaneous loading to a 3-minute loading interval. NiCr-A rod deposits range from 34 to 24 in the same temperature range and under the same load conditions. Hot Rockwell C hardness values of NiCr-B electrode deposits range from 41 to 26 in the temperature range from 600 to 1000 degrees F from instantaneous loading to a 3-minute loading interval. NiCr-B rod deposits range from 46 to 37 in the same temperature range and under the same load conditions. Hot Rockwell C hardness values of NiCr-C electrode deposits range from 49 to 31 in the temperature range from 600 to 1000 degrees F from instantaneous loading to a 3-minute loading interval. NiCr-C rod deposits range from 55 to 40 in the same temperature range and under the same load conditions.

Resistance Properties: Deposits of these metal alloys will withstand light impact fairly well. When plastic deformation occurs, cracks are more likely to appear in the NiCr-C deposit than in the NiCr-A and NiCr-B deposits. NiCr deposits are oxidation-resistant up to 1800 degrees F. Their use above 1750 degrees F is not recommended because fusion may begin near this temperature. NiCr deposits are completely resistant to atmospheric, steam, salt water, and salt spray corrosion and to the milder acids and many common corrosive chemicals. It is advisable to conduct field tests when a corrosion application is contemplated. These metals are not recommended for high-stress grinding abrasion. NiCr deposits have good metal-to-metal wear resistance, take a high polish under wearing conditions, and are particularly resistant to galling. These properties are especially evident in the NiCr-C alloy.

Other Properties or Characteristics: In compression, these alloys have an elastic limit of 42,000 lb/in.^{2} Their yield strength in compression is 92,000 lb/in.^{2} (0.01 per cent offset), 150,000 lb/in.^{2} (0.10 per cent offset), and 210,000 lb/in.^{2} (0.20 per cent offset). Deposits of NiCr filler metals may be machined with tungsten carbide tools using slow speeds, light feeds, and heavy tool shanks. They are also finished by grinding using a soft-to-medium vitrified silicon carbide wheel.

Chromium Plating.—Chromium plating is an electrolytic process of depositing chromium on metals either as a protection against corrosion or to increase the surface-wearing qualities. The value of chromium-plating plug and ring gages has probably been more thoroughly demonstrated than any other single application of this treatment. Chromium-plated gages not only wear longer, but when worn, the chromium may be removed and the gage replated and reground to size.

In general, chromium-plated tools have operated well, giving greatly improved performance on nearly all classes of materials such as brass, bronze, copper, nickel, aluminum, cast iron, steel, plastics, asbestos compositions, and similar materials. Increased cutting life has been obtained with chromium-plated drills, taps, reamers, files, broaches, tool tips, saws, thread chasers, and the like. Dies for stamping, drawing, hot forging, die casting, and for molding plastics materials have shown greatly increased life after being plated with hard chromium.

Special care is essential in grinding and lapping tools preparatory to plating the cutting edges, because the chromium deposit is influenced materially by the grain structure and hardness of the base metal. The thickness of the plating may vary from 0.0001 to 0.001 or 0.002 inch, the thicker platings being used to build up undersize tools such as taps and reamers. A common procedure in the hard chromium plating of tools, as well as for parts to be salvaged by depositing chromium to increase diameters, is as follows:

1) Degrease with solvent;
2) Mount the tools on racks;
3) Clean in an anodic alkali bath held at a temperature of 82 degrees C for from 3 to 5 minutes;
4) Rinse in boiling water;
5) Immerse in a 20 per cent hydrochloric acid solution for 2 to 3 seconds;
6) Rinse in cold water;
7) Rinse in hot water;
8) Etch in a reverse-current chromic acid bath for 2 to 5 minutes;
9) Place work immediately in the chromium plating bath; and
10) Remove hydrogen embrittlement, if necessary, by immersing the plated tools for 2 hours in an oil bath maintained at 177 degrees C.

Chromium has a very low coefficient of friction. The static coefficient of friction for steel on chromium-plated steel is 0.17, and the sliding coefficient of friction is 0.16. This value may be compared with the static coefficient of friction for steel on steel of 0.30 and a sliding coefficient of friction of 0.20. The static coefficient of friction for steel on babbitt is 0.25, and the sliding coefficient of friction 0.20, whereas for chromium-plated steel on babbitt, the static coefficient of friction is 0.15, and the sliding coefficient of friction is 0.13. These figures apply to highly polished bearing surfaces. Articles that are to be chromium plated in order to resist frictional wear should be highly polished before plating so that full advantage can be taken of the low coefficient of friction that is characteristic of chromium. Chromium resists attack by almost all organic and inorganic compounds, except muriatic and sulfuric acids. The melting point of chromium is 2930 degrees F, and it remains bright up to 1200 degrees F. Above 1200 degrees F, a light adherent oxide forms and does not readily become detached. For this reason, chromium has been used successfully for protecting articles that must resist high temperatures, even above 2000 degrees F.

Cutting Metals with an Oxidizing Flame

The oxyhydrogen and oxyacetylene flames are especially adapted to cutting metals. When iron or steel is heated to a high temperature, it has a great affinity for oxygen and readily combines with it to form various oxides, and causing the metal to be disintegrated and burned with great rapidity. The metal-cutting or burning torch operates on this principle. A torch tip is designed to preheat the metal, which is then burned or oxidized by a jet of pure oxygen. The kerf or path left by the flame is suggestive of a saw cut when the cutting torch has been properly adjusted and used. The traversing motion of the torch along the work may be controlled either by hand or mechanically.

The Cutting Torch.—The ordinary cutting torch consists of a heating jet using oxygen and acetylene, oxygen and hydrogen, or, in fact, any other gas that, when combined with oxygen, will produce sufficient heat. By the use of this heating jet, the metal is first brought to a sufficiently high temperature, and an auxiliary jet of pure oxygen is then turned onto the red-hot metal, and the action just referred to takes place. Some cutting torches have a number of preheating flame ports surrounding the central oxygen port, so that a preheating flame will precede the oxygen regardless of the direction in which the torch is moved. This arrangement has been used to advantage in mechanically guided torches. The rate of cutting varies with the thickness of the steel, the size of the tip, and the oxygen pressure.

Adjustment and Use of Cutting Torch.—When using the cutting torch for the cutting of steel plate, the preheating flame first comes into contact with the edge of the plate and quickly raises it to a white-hot temperature. The oxygen valve is then opened, and as the pure oxygen comes into contact with the heated metal, the latter is burned or oxidized.

Metals That Can Be Cut.—Metals such as wrought iron and steels of comparatively low-carbon content can be cut readily with the cutting torch. High-carbon steels may be cut successfully if preheated to a temperature that depends somewhat on the carbon content. The higher the carbon content, the greater the degree of preheating required. A black heat is sufficient for ordinary tool steel, but a low red heat may be required for some alloy tool steels. Brass and bronze plates have been cut by interposing them between steel plates.

Cutting Stainless Steel.—Stainless steel can be cut readily by the flux-injection method. The elements that give stainless steels their desirable properties produce oxides that reduce the flame cutting operation to a slow melting-away process when the conventional oxy-acetylene cutting equipment is used. By injecting a suitable flux directly into the stream of cutting oxygen before it enters the torch, the obstructing oxides can be removed. Portable flux feeding units are designed to inject a predetermined amount of the flux powder. The rate of flux flow is accurately regulated by a vibrator type of dispenser with rheostat control. The flux-injection method is applicable either to machine cutting or to a hand-controlled torch. The operating procedure and speed of cutting are practically the same as in cutting mild steel.

Cutting Cast Iron.—The cutting of cast iron with the oxyacetylene torch is practicable, although it cannot be cut as readily as steel. The ease of cutting seems to depend largely on the physical character of the cast iron, very soft cast iron being more difficult to cut than harder varieties. The cost is much higher than that for cutting the same thickness of steel, because of the larger preheating flame necessary and the larger oxygen consumption. In spite of this extra cost, however, this method is often economical. The slag from a cast-iron cut contains considerable melted cast iron, whereas in steel, the slag is practically free from particles of the metal, indicating that cast-iron cutting is partly a melting operation. Increased speed and decreased cost often can be obtained by feeding a steel rod, about $\frac{1}{4}$ inch in diameter, into the top of the cut, beneath the torch tip. This rod furnishes a large amount of slag that flows over the cut and increases the temperature of the cast iron. Special tips are used because of the larger amounts of heat and oxygen required.

Mechanically Guided Torches.—Cutting torches used for cutting openings in plates or blocks or for cutting parts to some definite outline are often guided mechanically or by numerical control. Torches guided by pantograph mechanisms are especially adapted for tracing the outline to be cut from a pattern or drawing. Other designs are preferable for straight-line cutting and one type is designed for circular cutting.

Cutting Steel Castings.—When cutting steel castings, care should be taken to prevent burning pockets in the metal when the flame strikes a blowhole. If a blowhole is penetrated, the molten oxide will splash into the cavity and the flame will be diverted. The presence of the blowhole is generally indicated by excessive sparks. The operator should immediately move the torch back along the cut and direct it at an angle so as to strike the metal beneath the blowhole and burn it away if possible beyond the cavity. Cutting in the normal position then may be resumed.

Thickness of Metal That Can Be Cut.—The maximum thickness of metal that can be cut by these high-temperature flames depends largely upon the gases used and the pressure of the oxygen, which may be as high as 150 lb/in.^{2} The thicker the metal, the higher the pressure required. When using an oxyacetylene flame, it might be practicable to cut iron or steel up to 12 or 14 inches in thickness, whereas an oxyhydrogen flame has been used to cut steel plates 24 inches thick. The oxyhydrogen flame will cut thicker material principally because it is longer than the oxyacetylene flame and can penetrate to the full depth of the cut, thus keeping all the oxide in a molten condition so that it can be easily blown out by the oxygen cutting jet. A mechanically guided torch will cut thick material more satisfactorily than a hand-guided torch, because the flame is directed straight into the cut and does not wobble, as it tends to do when the torch is held by hand. With any flame, the cut is less accurate and the kerf wider, as the thickness of the metal increases. When cutting light material, the kerf might be $\frac{1}{16}$ inch wide, whereas for heavy stock, it might be $\frac{1}{4}$ or $\frac{3}{8}$ inch wide.

Arc Cutting of Metals

Arc Cutting.—According to the *Procedure Handbook of Arc-Welding Design & Practice*, published by The Lincoln Electric Co., a steel may be cut easily, and with great accuracy by means of the oxyacetylene torch. All metals, however, do not cut as easily as steel. Cast iron, stainless steels, manganese steels, and nonferrous materials are not as readily cut and shaped with the oxyacetylene cutting process because of their reluctance to oxidize. For these materials, arc cutting is often used to good advantage.

The cutting of steel is a chemical action. The oxygen combines readily with the iron to form iron oxide. In cast iron, this action is hindered by the presence of carbon in graphite form. Thus, cast iron cannot be cut as readily as steel; higher temperatures are necessary and cutting is slower. In steel, the action starts at bright red heat, whereas in cast iron, the temperature must be nearer to the melting point to obtain a sufficient reaction.

Plasma Cutting of Metals.—Because of its convenience and ability for close control, much precision cutting of outlines in sheet steel today is carried out with the plasma cutting torch, as discussed on page 1391 in the section on welding.

FILES AND BURS

Definitions of File Terms.—The following file terms apply to hand files but not to rotary files and burs.

Axis: Imaginary line extending the entire length of a file equidistant from faces and edges.

Back: The convex side of a file having the same or similar cross-section as a half-round file.

Bastard Cut: A grade of file coarseness between coarse and second cut of American pattern files and rasps.

Blank: A file in any process of manufacture before being cut.

Blunt: A file whose cross-sectional dimensions from point to tang remain unchanged.

Coarse Cut: The coarsest of all American pattern file and rasp cuts.

Coarseness: Term describing the relative number of teeth per unit length, the coarsest having the least number of file teeth per unit length; the smoothest, the most. American pattern files and rasps have four degrees of coarseness: coarse, bastard, second and smooth. Swiss pattern files usually have seven degrees of coarseness: 00, 0, 1, 2, 3, 4, 6 (from coarsest to smoothest). Curved tooth files have three degrees of coarseness: standard, fine and smooth.

Curved Cut: File teeth which are made in curved contour across the file blank.

Cut: Term used to describe file teeth with respect to their coarseness or their character (single, double, rasp, curved, special).

Double Cut: A file tooth arrangement formed by two series of cuts, namely the overcut followed, at an angle, by the upcut.

Edge: Surface joining faces of a file. May have teeth or be smooth.

Face: Widest cutting surface or surfaces that are used for filing.

Heel or Shoulder: That portion of a file that abuts the tang.

Hopped: A term used among file makers to represent a very wide skip or spacing between file teeth.

Length: The distance from the heel to the point.

Overcut: The first series of teeth put on a double-cut file.

Point: The front end of a file; the end opposite the tang.

Rasp Cut: A file tooth arrangement of round-topped teeth, usually not connected, that are formed individually by means of a narrow, punch-like tool.

Re-cut: A worn-out file which has been re-cut and re-hardened after annealing and grinding off the old teeth.

Safe Edge: An edge of a file that is made smooth or uncut, so that it will not injure that portion or surface of the workplace with which it may come in contact during filing.

Second Cut: A grade of file coarseness between bastard and smooth of American pattern files and rasps.

Set: To blunt the sharp edges or corners of file blanks before and after the overcut is made, in order to prevent weakness and breakage of the teeth along such edges or corners when the file is put to use.

Shoulder or Heel: See *Heel or Shoulder*.

Single Cut: A file tooth arrangement where the file teeth are composed of single unbroken rows of parallel teeth formed by a single series of cuts.

Smooth Cut: An American pattern file and rasp cut that is smoother than second cut.

Tang: The narrowed portion of a file which engages the handle.

Upcut: The series of teeth superimposed on the overcut, and at an angle to it, on a double-cut file.

File Characteristics.—Files are classified according to their shape or cross-section and according to the pitch or spacing of their teeth and the nature of the cut.

Cross-section and Outline: The cross-section may be quadrangular, circular, triangular, or some special shape. The outline or contour may be tapered or blunt. In the former, the point is more or less reduced in width and thickness by a gradually narrowing section that extends for one-half to two-thirds of the length. In the latter the cross-section remains uniform from tang to point.

Cut: The character of the teeth is designated as single, double, rasp or curved. The *single cut file* (or *float* as the coarser cuts are sometimes called) has a single series of parallel teeth extending across the face of the file at an angle of from 45 to 85 degrees with the axis of the file. This angle depends upon the form of the file and the nature of the work for which it is intended. The single cut file is customarily used with a light pressure to produce a smooth finish. The *double cut file* has a multiplicity of small pointed teeth inclining toward the point of the file arranged in two series of diagonal rows that cross each other. For general work, the angle of the first series of rows is from 40 to 45 degrees and of the second from 70 to 80 degrees. For *double cut finishing files* the first series has an angle of about 30 degrees and the second, from 80 to 87 degrees. The second, or upcut, is almost always deeper than the first or overcut. Double cut files are usually employed, under heavier pressure, for fast metal removal and where a rougher finish is permissible. The *rasp* is formed by raising a series of individual rounded teeth from the surface of the file blank with a sharp narrow, punch-like cutting tool and is used with a relatively heavy pressure on soft substances for fast removal of material. The curved tooth file has teeth that are in the form of parallel arcs extending across the face of the file, the middle portion of each arc being closest to the point of the file. The teeth are usually single cut and are relatively coarse. They may be formed by steel displacement but are more commonly formed by milling.

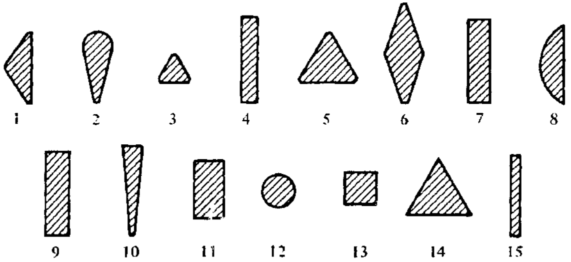
With reference to coarseness of cut the terms *coarse, bastard, second* and *smooth cuts* are used, the coarse or bastard files being used on the heavier classes of work and the second or smooth cut files for the finishing or more exacting work. These degrees of coarseness are only comparable when files of the same length are compared, as the number or teeth per inch of length decreases as the length of the file increases. The number of teeth per inch varies considerably for different sizes and shapes and for files of different makes. The coarseness range for the curved tooth files is given as standard, fine and smooth. In the case of Swiss pattern files, a series of numbers is used to designate coarseness instead of names; Nos. 00, 0, 1, 2, 3, 4 and 6 being the most common with No. 00 the coarsest and No. 6 the finest.

Classes of Files.—There are five main classes of files: mill or saw files; machinists' files; curved tooth files; Swiss pattern files; and rasps. The first two classes are commonly referred to as American pattern files.

Mill or Saw Files: These are used for sharpening mill or circular saws, large crosscut saws; for lathe work; for draw filing; for filing brass and bronze; and for smooth filing generally.

Cantsaw files 1) have an obtuse isosceles triangular section, a blunt outline, are single cut and are used for sharpening saws having “M”-shaped teeth and teeth of less than 60-degree angle. *Crosscut files*; 2) have a narrow triangular section with short side rounded, a blunt outline, are single cut and are used to sharpen crosscut saws. The rounded portion is used to deepen the gullets of saw teeth and the sides are used to sharpen the teeth themselves. *Double ender files*; 3) have a triangular section, are tapered from the middle to both ends, are tangless are single cut and are used reversibly for sharpening saws. The *mill file*; 4) itself, is usually single cut, tapered in width, and often has two square cutting edges in addition to the cutting sides. Either or both edges may be rounded, however, forfiling the gullets saw teeth. The *blunt mill file* has a uniform rectangular cross-section from tip to tang. The *triangular saw files* or *taper saw files*; 5) have an equilateral triangular section, are tapered, are single cut and are used for filing saws with 60-degree angle teeth. They come in taper, slim taper, extra slim taper and double extra slim taper thicknesses *Blunt triangular* and *blunt hand saw files* are without taper *Web saw files*; 6) have a diamond-shaped section, a blunt outline, are single cut and are used for sharpening pulpwood or web saws. *Machinists' Files:* These files are used throughout industry where metal must be removed rapidly and finish is of secondary importance. Except for certain exceptions in the round and half-round shapes, all are double cut. *Flat files*; 7) have a rectangular section, are tapered in width and thickness, are cut on both sides and edges and are used for general utility work. *Half round files*; 8) have a circular segmental section, are tapered in width and thickness, have their flat side double cut, their rounded side mostly double but sometimes single cut, and are used to file rounded holes, concave corners, etc. in general filing work. *Hand files*;

9) are similar to flat files but taper in thickness only. One edge is uncut or “safe.” *Knife files*; 10) have a “knife-blade” section, are tapered in width only, are double cut, and are used by tool and die makers on work having acute angles. *Machinist's General Purpose files* have a rectangular section, are tapered and have single cut teeth divided by angular serrations which produce short cutting edges. These edges help stock removal but still leave a smooth finish and are suitable for use on various materials including aluminum, bronze, cast iron, malleable iron, mild steels and annealed tool steels. *Pillar files*; 11) are similar to hand files but are thicker and not as wide. *Round files*; 12) have a circular section, are tapered, single cut, and are generally used to file circular openings or curved surfaces. *Square files*; 13) have a square section, are tapered, and are used for filing slots, keyways and for general surface filing where a heavier section is preferred. *Three square files*; 14) have an equilateral triangular section and are tapered on all sides. They are double cut and have sharp corners as contrasted with taper triangular files which are single cut and have somewhat rounded corners. They are used for filing accurate internal angles, for clearing out square corners, and for filing taps and cutters. *Warding files*; and 15) have a rectangular section, and taper in width to a narrow point. They are used for general narrow space filing. *Wood files* are made in the same sections as flat and half round files but with coarser teeth especially suited for working on wood..



Curved Tooth Files: Regular curved tooth files are made in both rigid and flexible forms. The rigid type has either a tang for a conventional handle or is made plain with a hole at each end for mounting in a special holder. The flexible type is furnished for use in special holders only. The curved tooth files come in standard fine and smooth cuts and in parallel flat, square, pillar, pillar narrow, half round and shell types. A special curved tooth file is available with teeth divided by long angular serrations. The teeth are cut in an “off center” arc. When moved across the work toward one edge of the file a fast cutting action is provided; when moved toward the other edge, a smoothing action; thus the file is made to serve a dual purpose.

Swiss Pattern Files: These are used by tool and die makers, model makers and delicate instrument parts finishers. They are made to closer tolerances than the conventional American pattern files although with similar cross-sections. The points of the Swiss pattern files are smaller, the tapers are longer and they are available in much finer cuts. They are primarily finishing tools for removing burrs left from previous finishing operations truing up narrow grooves, notches and keyways, cleaning out corners and smoothing small parts. For very fine work, *round* and *square handled needle files,* available in numerous cross-sectional shapes in overall lengths from 4 to 7 $\frac{3}{4}$ inches, are used. Die sinkers use *die sinkers files* and *die sinkers rifflers.* The files, also made in many different cross-sectional shapes, are 3$\frac{1}{2}$ inches in length and are available in the cut Nos. 0, 1, 2, and 4. The rifflers are from 5$\frac{1}{2}$ to 6$\frac{3}{4}$ inches long, have cutting surfaces on either end, and come in numerous cross-sectional shapes in cut Nos. 0, 2, 3, 4 and 6. These rifflers are used by die makers for getting into corners, crevices, holes and contours of intricate dies and molds. Used in the same fashion as die sinkers rifflers, *silversmiths rifflers,* that have a much heavier cross-section, are available in lengths from 6 $\frac{7}{8}$ to 8 inches and in cuts Nos. 0, 1, 2, and 3. *Blunt machine files* in Cut Nos. 00, 0, and 2 for use in ordinary and bench filing machines are available in many different cross-sectional shapes, in lengths from 3 to 8 inches.

Rasps: Rasps are employed for work on relatively soft substances such as wood, leather, and lead where fast removal or material is required. They come in rectangular and half round cross-sections, the latter with and without a sharp edge.

Special Purpose Files: Falling under one of the preceding five classes of files, but modified to meet the requirements of some particular function, are a number of special purpose files. The *long angle lathe file* is used for filing work that is rotating in a lathe. The long tooth angle provides a clean shear, eliminates drag or tear and is self-clearing. This file has safe or uncut edges to protect shoulders of the work which are not to be filed. The *foundry file* has especially sturdy teeth with heavy set edges for the snagging of castings—the removing of fins, sprues, and other projections. The *die casting file* has extra strong teeth on corners and edges as well as sides for working on die castings of magnesium, zinc, or aluminum alloys. A special file for stainless steel is designed to stand up under the abrasive action of stainless steel alloys. *Aluminum rasps* and *files* are designed to eliminate clogging. A special tooth construction is used in one type of aluminum tile which breaks up the filings, allows the file to clear itself and overcomes chatter. A *brass file* is designed so that with a little pressure the sharp, high-cut teeth bite deep while with less pressure, their short uncut angle produces a smoothing effect. The *lead float* has coarse, single cut teeth at almost right angles to the file axis. These shear away the metal under ordinary pressure and produce a smoothing effect under light pressure. The *shear tooth file* has a coarse single cut with a long angle for soft metals or alloys, plastics, hard rubber and wood. *Chain saw files* are designed to sharpen all types of chain saw teeth. These files come in round, rectangular, square and diamond-shaped sections. The round and square sectioned files have either double or single cut teeth, the rectangular files have single cut teeth and the diamond-shaped files have double cut teeth.

Effectiveness of Rotary Files and Burs.—There it very little difference in the efficiency of rotary files or burs when used in electric tools and when used in air tools, provided the speeds have been reasonably well selected. Flexible-shaft and other machines used as a source of power for these tools have a limited number of speeds which govern the revolutions per minute at which the tools can be operated.

The carbide bur may be used on hard or soft materials with equally good results. The principle difference in construction of the carbide bur is that its teeth or flutes are provided with a negative rather than a radial rake. Carbide burs are relatively brittle, and must be treated more carefully than ordinary burs. They should be kept cutting freely, in order to prevent too much pressure, which might result in crumbling of the cutting epics.

At the same speeds, both high-speed steel and carbide burs remove approximately the same amount of metal. However, when carbide burs are used at their most efficient speeds, the rate of stock removal may be as much as four times that of ordinary burs. In certain cases, speeds much higher than those shown in the table can be used. It has been demonstrated that a carbide bur will last up to 100 times as long as a high-speed steel bur of corresponding size and shape.

Approximate Speeds of Rotary Files and Burs

Tool Diam., Inches	Medium Cut, High-Speed Steel Bur or File		
	Mild Steel	Cast Iron	Bronze
	Speed, Revolutions per Minute		
⅛	4600	7000	15,000
¼	3450	5250	11,250
⅜	2750	4200	9000
½	2300	3500	7500
⅝	2000	3100	6650
¾	1900	2900	6200
⅞	1700	2600	5600
1	1600	2400	5150
1⅛	1500	2300	4850
1¼	1400	2100	4500

Tool Diam., Inches	Medium Cut, High-Speed Steel Bur or File		Carbide Bur	
	Speed, Revolutions Per Minute		Medium Cut	Fine Cut
	Aluminum	Magnesium	Any Material	
⅛	20,000	30,000	45,000	30,000
¼	15,000	22,500	30,000	20,000
⅜	12,000	18,000	24,000	16,000
½	10,000	15,000	20,000	13,350
⅝	8900	13,350	18,000	12,000
¾	8300	12,400	16,000	10,650
⅞	7500	11,250	14,500	9650
1	6850	10,300	13,000	8650
1⅛	6500	9750	…	…
1¼	6000	9000	…	…

As recommended by the Nicholson File Company.

Power Brush Finishing

Power brush finishing is a production method of metal finishing that employs wire, elastomer bonded wire, or non-metallic (cord, natural fiber or synthetic) brushing wheels in automatic machines, semi-automatic machines and portable air tools to smooth or roughen surfaces, remove surface oxidation and weld scale or remove burrs.

Description of Brushes.—Brushes work in the following ways: the wire points of a brush can be considered to act as individual culling tools so that the brush, in effect, is a multiple-tipped cutting tool. The fill material, as it is rotated, contacts the surface of the work and imparts an impact action which produces a coldworking effect. The type of finish produced depends upon the wheel material, wheel speed, and how the wheel is applied.

Brushes differ in the following ways 1) fill material (wire—carbon steel, stainless steel; synthetic; Tampico; and cord); 2) length of fill material (or trim); and 3) the density of the fill material.

To aid in wheel selection and use, the accompanying table made up from information supplied by *The Osborn Manufacturing Company* lists the characteristics and mayor uses of brushing wheels.

Use of Brushes.—The brushes should be located so as to bring the full face of the brush in contact with the work. Full face contact is necessary to avoid grooving the brush. Operations that are set up with the brush face not in full contact with the work require some provision for dressing the brush face. When the tips of a brush, used with full face contact, become dull during use with subsequent loss of working clearance, reconditioning and resharpening is necessary. This is accomplished simply and efficiently by alternately reversing the direction of rotation during use.

Deburring and Producing a Radius on the Tooth Profile of Gears.—The brush employed for deburring and producing a radius on the tooth profile of gears is a short trim, dense, wire-fill radial brush. The brush should be set up so as to brush across the edge as shown in Fig. 1A. Line contact brushing, as shown in Fig. 1B should be avoided because the Crisis face will wear non-uniformly; and the wire points, being flexible, tend to flare to the side, thus minimizing the effectiveness of the brushing operation. When brushing gears, the brushes are spaced and contact the tooth profile on the center line of the gear as shown in Fig. 2. This facilitates using brush reversal to maintain the wire brushing points at their maximum cutting efficiency.

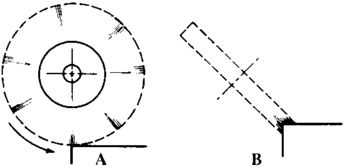


Fig. 1. Methods of Brushing an Edge;
(A) Correct, (B) Incorrect

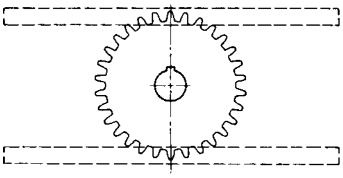


Fig. 2. Setup for Deburring Gears

The setup for brushing spline bores differs from brushing gears in that the brushes are located off-center, as illustrated in Fig. 3. When helical gears are brushed, it is sometimes necessary to favor the acute side of the gear tooth to develop a generous radius prior to shaving. This can be accomplished by locating the brushes as shown In Fig. 4. Elastomer bonded wire-filled brushes are used for deburring fine pitch gears. These brushes remove the burrs without leaving any secondary roll. The use of bonded brushes is necessary when the gears are not shaved after hobbing or gear shaping.

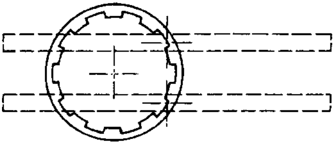


Fig. 3. Setup for Brushing Broached Splines

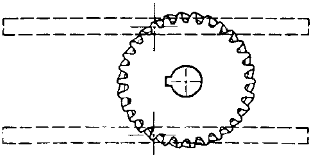


Fig. 4. Setup for Finishing Helical Gears

Adjustments for Eliminating Undesirable Conditions in Power Brush Finishing

Undesirable Condition	Possible Adjustments for Eliminating Condition
Brush works too slowly	(1) Decrease trim length and increase fill density. (2) Increase filament diameter. (3) Increase surface speed by increasing R.P.M. or outside diameter.
Brush works too fast	(1) Reduce filament diameter. (2) Reduce surface speed by reducing R.P.M. or outside diameter. (3) Reduce fill density. (4) Increase trim length.
Action of brush peens burr to adjacent surface	(1) Decrease trim length and increase fill density. (2) If wire brush tests indicate metal too ductile (burr is peened rather than removed), change to nonmetallic brush such as a treated Tampico brush used with a burring compound.
Finer or smoother finish required	(1) Decrease trim length and increase fill density. (2) Decrease filament diameter. (3) Try treated Tampico or cord brushes with suitable compounds at recommended speeds. (4) Use auxiliary buffing compound with brush.
Finish too smooth and lustrous	(1) Increase trim length. (2) Reduce brush fill density. (3) Reduce surface speed. (4) Increase filament diameter.
Brushing action not sufficiently uniform	(1) Devise hand-held or mechanical fixture or machine which will avoid irregular off-hand manipulation. (2) Increase trim length and decrease fill density.

Characteristics and Applications of Brushes Used in Power Finishing

Brush Type	Description	Operating Speed Range, sfpm	Uses	Remarks
Radial, short trim dense wire fill	Develops very little impact action but maximum cutting action.	6500	Removal of burrs from gear teeth and sprockets. Produces blends and radii at juncture of intersecting surfaces.	Brush should be set up so as to brush across any edge. Reversal of rotation needed to maintain maximum cutting efficiency of brush points.
Radial, medium to long trim twisted knot wire fill	Normally used singly and on portable tools. Brush is versatile and provides high impact action.	7500–9500 for high speeds. 1200 for slow speeds.	For cleaning welds in the automotive and pipeline industries. Also for cleaning surfaces prior to painting, stripping rubber flash from molded products and cleaning mesh-wire conveyor belts.	Surface speed plays an important role since at low speeds the brush is very flexible and at high speeds it is extremely hard and fast cutting.
Radial, medium to long trim crimped wire fill	With the 4- to 8-inch diameter brush, part is hand held. With the 10- to 15-inch diameter brush, part is held by machine.	4500–6000	Serves as utility tool on bench grinder for removing feather grinding burrs, machining burrs, and for cleaning and producing a satin or matte finish.	Good for hand held parts as brush is soft enough to conform to irregular surfaces and hard-to-reach areas. Smaller diameter brushes are not recommended for high-production operations.
Radial, sectional, nonmetallic fill (treated and untreated Tampico or cord)	Provides means for improving finish or improving surface for plating. Works best with grease base deburring or buffing compound.	5500–6500 7500 for polishing	For producing radii and improving surface finish. Removes the sharp peaks that fixed abrasives leave on a surface so that surface will accept a uniform plating. Polishing marks and draw marks can be successfully blended.	Brush is selective to an edge which means that it removes metal from an edge but not from adjoining surfaces. It will produce a very uniform radius without peening or rolling any secondary metal.
Radial, wide-face, nonmetallic fill (natural fibers or synthetics)	Can be used with flow-through mounting which facilitates feeding of cold water and hot alkaline solutions through brush face to prevent buildup.	750–1200 for cleaning steel. 600 when used with slurries	For cleaning steel. Used in electrolytic tinplate lines, continuous galvanizing and annealing lines, and cold reduction lines. Used to produce dull or matte-type finishes on stainless steel and synthetics.	Speeds above 3600 sfpm will not appreciably improve operation as brush wear will be excessive. Avoid excessive pressures. Ammeters should be installed in drive-motor circuit to indicate brushing pressure.

Characteristics and Applications of Brushes Used in Power Finishing *(Continued)*

Brush Type	Description	Operating Speed Range, sfpm	Uses	Remarks
Radial, wide face, metallic fill	This brush is made to customer's specifications. It is dynamically balanced at the speed at which it will operate.	2000–4000	Removes buildup of aluminum oxide from work rolls in aluminum mill. Removes lime or magnesium coatings from certain types of steel. Burnishes hot-dipped galvanized steel to produce a minimum spangled surface.	Each brush should have its own drive. An ammeter should be present in drive-motor circuit to measure brushing pressure. If strip is being brushed, a steel backup roll should be opposite the brush roll.
Radial, wide face, strip (interrupted brush face)	Performs cleaning operations that would cause a solid face brush to become loaded and unusable.	When cleaning conveyor belts, brush speed is 2 to 3 times that of conveyer belt.	Need for cleaning rubber and fabric conveyor belts of carry-back material which would normally foul snubber pulley and return idlers.	Designed for medium- to light-duty work. Brush face does not load.
Radial, Cup, Flared End, and Straight End, wire fill elastomer bonded	Extremely fast cutting with maximum operator safety. No loss of wire through fatigue. Always has uniform face.	3600–9000	For removing oxide weld scale, burrs, and insulation from wire.	Periodic reversing of brush direction will result in a brush life ten times greater than non-bonded wheels. Fast cutting action necessitates precise holding of part with respect to brush.
Cup, twisted knot wire fill	Fast cutting wheel used on portable tools to clean welds, scale, rust, and other oxides.	8000–10,000 4500–6500 for deburring and producing a radius around periphery of holes.	Used in shipyards and in structural steel industry. For cleaning outside diameter of pipe and removing burrs and producing radii on heat exchanger tube sheets and laminations for stator cores.	Fast acting brush cleans large areas economically. Setup time is short.
Radial, wire or treated Tampico or cord	For use with standard centerless grinders. Brush will not remove metal from a cylindrical surface. Parts must be ground to size before brushing.	…	For removing feather grinding burrs and improving surface finish. Parts of 24 microinches can be finished down to 15 to 10 microinches. Parts of 10 to 12 microinches can be finished down to 7 to 4 microinches.	Follows centerless grinding principles, except that accuracy in pressure and adjustment is not critical. A machine no longer acceptable for grinding can be used for brushing.

Polishing and Buffing

The terms "polishing" and "buffing" are sometimes applied to similar classes of work in different plants, but according to approved usage of the terms, there is the following distinction: Polishing is any operation performed with wheels having abrasive glued to the working surfaces, whereas buffing is done with wheels having the abrasive applied loosely instead of imbedding it into glue; moreover, buffing is not so harsh an operation as ordinary polishing, and it is commonly utilized to obtain very fine surfaces having a "grainless finish."

Polishing Wheels.—The principal materials from which polishing wheels are made are wood, leather, canvas, cotton cloth, plastics, felt, paper, sheepskin, impregnated rubber, canvas composition, and wool. Leather and canvas are the materials most commonly used in polishing wheel construction. Wooden wheels covered with material to which emery or some other abrasive is glued are employed extensively for polishing flat surfaces, especially when good edges must be maintained. Cloth wheels are made in various ways; wheels having disks that are cemented together are very hard and used for rough, coarse work, whereas those having sewn disks are made of varying densities by sewing together a larger or smaller number of disks into sections and gluing then.

Wheels in which the disks are held together by thread or metal stitches and which are not stiffened by the use of glue usually require metal side plates to support the canvas disks. Muslin wheels are made from sewed or stapled buffs glued together, but the outer edges of a wheel frequently are left open or free from glue to provide an open face of any desired depth. Wool felt wheels are flexible and resilient, and the density may be varied by sewing two or more disks together and then cementing to form a wheel. Solid felt wheels are quite popular for fine finishing but have little value as general utility wheels. Paper wheels are made from strawboard paper disks and are cemented together under pressure to form a very hard wheel for rough work. Softer wheels are similarly made from felt paper. The "compress" canvas wheel has a cushion of polishing material formed by pieces of leather, canvas, or felt, that are held in a crosswise radial position by two side plates attached to the wheel hub. This cushion of polishing material may be varied in density to suit the requirements; it may be readily shaped to conform to the curvature of the work and this shape can be maintained. Sheepskin polishing wheels and paper wheels are little used.

Polishing Operations and Abrasives.—Polishing operations on such parts as chisels, hammers, screwdrivers, wrenches, and similar parts that are given a fine finish but are not plated, usually require four operations, which are "roughing," "dry fining," "greasing," and "coloring." The roughing is frequently regarded as a solid grinding wheel job. Sometimes there are two steps to the greasing operation—rough and fine greasing. For some hardware, such as the cheaper screwdrivers, wrenches, etc., the operations of roughing and dry fining are considered sufficient. For knife blades and cutlery, the roughing operation is performed with solid grinding wheels and the polishing is known as fine or blue glazing, but these terms are never used when referring to the polishing of hardware parts, plumbers' supplies, etc. A term used in finishing German silver, white metal, and similar materials is "sand-buffing," which, in distinction from the ordinary buffing operation that is used only to produce a very high finish, actually removes considerable metal, as in rough polishing or flexible grinding. For sand-buffing, pumice and other abrasive powders are loosely applied.

Aluminum oxide abrasives are widely used for polishing high-tensile-strength metals such as carbon and alloy steels, tough iron, and nonferrous alloys. Silicon carbide abrasives are recommended for hard, brittle substances such as grey iron, cemented carbide tools, and materials of low tensile strength such as brass, aluminum, and copper.

Buffing Wheels.—Buffing wheels are manufactured from disks (either whole or pieced) of bleached or unbleached cotton or woolen cloth, and they are used as the agent for carrying abrasive powders, such as tripoli, crocus, rouge, lime, etc., which are mixed with waxes or greases as a bond. There are two main classes of buffs, one of which is known as the "pieced-sewed" buffs, and is made from various weaves and weights of cloth. The other is the "full-disk" buffs, which are made from specially woven material. Bleached cloth is harder and stiffer than unbleached cloth, and is used for the faster cutting buffs. Coarsely woven unbleached cloth is recommended for highly colored work on soft metals, and the finer woven unbleached cloths are better adapted for harder metals. When working at the usual speed, a stiff buff is not suitable for "cutting down" soft metal or for light plated ware, but is used on harder metals and for heavy nickel-plated articles.

Speed of Polishing Wheels.—The proper speed for polishing is governed to some extent by the nature of the work, but for ordinary operations, the polishing wheel should have a peripheral speed of about 7500 ft/min. If run at a lower speed, the work tends to tear the polishing material from the wheel too readily, and the work is not as good in quality. Muslin, felt, or leather polishing wheels having wood or iron centers should be run at peripheral speeds varying from 300 to 7000 ft/min. It is rarely necessary to exceed 6000 ft/min, and for most purposes, 4000 ft/min is sufficient. If the wheels are kept in good condition, in perfect balance, and are suitably mounted on substantial buffing lathes, they can be used safely at speeds within the limits given. However, manufacturers' recommendations concerning wheel speeds should be followed, where they apply.

Grain Numbers of Emery.—The numbers commonly used in designating the different grains of emery, corundum, and other abrasives are 10, 12, 14, 16, 18, 20, 24, 30, 36, 40, 46, 54, 60, 70, 80, 90, 100, 120, 150, 180, and 200, ranging from coarse to fine, respectively. These numbers represent the number of meshes per linear inch in the grading sieve. An abrasive finer than No. 200 is known as "flour" and the degree of fineness is designated by the letters CF, F, FF, FFF, FFFF, and PCF or SF, ranging from coarse to fine. The methods of grading flour-emery adopted by different manufacturers do not exactly agree, the letters differing somewhat for the finer grades. Again, manufacturers' recommendations should be followed.

Grades of Emery Cloth.—The coarseness of emery cloth is indicated by letters and numbers corresponding to the grain number of the loose emery used in the manufacture of the cloth. The letters and numbers for grits ranging from fine to coarse are as follows: FF, F, 120, 100, 90, 80, 70, 60, 54, 46, and 40. For large work roughly filed, use coarse cloth such as numbers 46 or 54, and then finer grades to obtain the required polish. If the work has been carefully filed, a good polish can be obtained with numbers 60 and 90 cloth, and a brilliant polish can be achieved by finishing with number 120 and flour-emery.

Mixture for Cementing Emery Cloth to a Lapping Wheel.—Many proprietary adhesives are available for application of emery cloth to the periphery of a buffing or lapping wheel, and generally are supplied with application instructions. In the absence of such instructions, clean the wheel thoroughly before applying the adhesive, and then rub the emery cloth down so as to exclude all air from between the surface of the wheel and the cloth.

Etching and Etching Fluids

Etching Fluids for Different Metals.—A common method of etching names or simple designs upon steel is to apply a thin, even coating of beeswax or some similar substance which will resist acid; then mark the required lines or letters in the wax with a sharp-pointed scriber, thus exposing the steel (where the wax has been removed by the scriber point) to the action of an acid, which is finally applied. To apply a very thin coating of beeswax, place the latter in a silk cloth, warm the piece to be etched, and tub the pad over it. Regular coach varnish is also used instead of wax, as a "resist."

An etching fluid ordinarily used for carbon steel consists of nitric acid, 1 part; water, 4 parts. It may be necessary to vary the amount of water, as the exact proportion depends upon the carbon content and whether the steel is hard or soft. For hard steel, use nitric acid, 2 parts; acetic acid, 1 part. For high-speed steel, nickel or brass, use nitro-hydrochloric acid (nitric, 1 part; hydrochloric, 4 parts). For high-speed steel it is sometimes better to add a little more nitric acid. For etching bronze, use nitric acid, 100 parts; muriatic acid, 5 parts. For brass, nitric acid, 16 parts; water, 160 parts, dissolve 6 parts potassium chlorate in 100 parts of water; then mix the two solutions and apply.

A fluid which may be used either for producing a frosted effect or for deep etching (depending upon the time it is allowed to act) is composed of 1 ounce sulphate of copper (blue vitriol); ¼ ounce alum; ½ teaspoonful of salt; 1 gill of vinegar, and 20 drops of nitric acid. For aluminum, use a solution composed of alcohol, 4 ounces; acetic acid, 6 ounces; antimony chloride, 4 ounces; water, 40 ounces.

Various acid-resisting materials are used for covering the surfaces of steel rules etc., prior to marking off the lines on a graduating machine. When the graduation lines are fine and very closely spaced, as on machinists' scales which are divided into hundredths or sixty-fourths, it is very important to use a thin resist that will cling to the metal and prevent any under-cutting of the acid: the resist should also enable fine lines to be drawn without tearing or crumbling as the tool passes through it. One resist that has been extensively used is composed of about 50 per cent of asphaltum, 25 per cent of beeswax, and, in addition, a small percentage of Burgundy pitch, black pitch, and turpentine. A thin covering of this resisting material is applied to the clean polished surface to be graduated and, after it is dry, the work is ready for the graduating machine. For some classes of work, paraffin is used for protecting the surface surrounding the graduation lines which are to be etched. The method of application consists in melting the paraffin and raising its temperature high enough so that it will flow freely; then the work is held at a slight angle and the paraffin is poured on its upper surface. The melted paraffin forms a thin protective coating.

Conversion Coatings and the Coloring of Metals

Conversion Coatings.—Conversion coatings are thin, adherent chemical compounds that are produced on metallic surfaces by chemical or electrochemical treatment. These coatings are insoluble, passive, and protective, and are divided into two basic systems: oxides or mixtures of oxides with other compounds, usually chromates or phosphates. Conversion coatings are used for corrosion protection, as an adherent paint base; and for decorative purposes because of their inherent color and because they can absorb dyes and colored sealants.

Conversion coatings are produced in three or four steps. First there is a pretreatment, which often involves mechanical surface preparation followed by decreasing and/or chemical or electrochemical cleaning or etching. Then thermal, chemical, or electrochemical surface conversion processes take place in acid or alkaline solutions applied by immersion spraying, or brushing. A post treatment follows, which includes rinsing and drying, and may also include sealing or dyeing. If coloring is the main purpose of the coating, then oiling, waxing, or lacquering may be required.

Passivation of Copper.—The blue-green patina that forms on copper alloys during atmospheric exposure is a passivated film; i.e., it prevents corrosion. This patina may be produced artificially or its growth may be accelerated by a solution of ammonium sulfate, 6 pounds; copper sulfate, 3 ounces; ammonia (technical grade, 0.90 specific gravity), 1.34 fluid ounces; and water, 6.5 gallons. This solution is applied as a fine spray to a chemically cleaned surface and is allowed to dry between each of five or six applications. In about 6 hours a patina somewhat bluer than natural begins to develop and continues after exposure to weathering.

Small copper parts can be coated with a passivated film by immersion in or brushing with a solution consisting of the following weight proportions: copper, 30; nitric acid, concentrated, 60; acetic acid (6%), 600; ammonium chloride, 11; and ammonium hydroxide (technical grade, 0.90 specific gravity), 20. To prepare the solution, the copper is dissolved in the nitric acid before the remaining chemicals are added, and the solution is allowed to stand for several days before use. A coating of linseed oil is applied to the treated parts.

Coloring of Copper Alloys.—Metals are colored to enhance their appearance, to produce an undercoat for an organic finish, or to reduce light reflection. Copper alloys can be treated to produce a variety of colors, with the final color depending on the base metal composition, the coloring solution's composition, the immersion time, and the operator's skill. Cleaning is an important part of the pretreatment; nitric and sulfuric acid solutions are used to remove oxides and to activate the surface.

The following solutions are used to color alloys that contain 85 per cent or more of copper. A dark red color is produced by immersing the parts in molten potassium nitrate, at 1200–1300°F, for up to 20 seconds, followed by a hot water quench. The parts must then be lacquered. A steel black color can be obtained by immersing the parts in a 180°F solution of arsenious oxide (white arsenic), 4 ounces; hydrochloric acid (1.16 specific gravity), 8 fluid ounces; and water, 1 gallon. The parts are immersed until a uniform color is obtained; they are scratch brushed while wet, and then dried and lacquered. A light brown color is obtained using a room-temperature solution of barium sufate, 0.5 ounce; ammonium carbonate, 0.25 ounce; and water, 1 gallon.

The following solutions are used to color alloys that contain less than 85 per cent copper. To color brass black, parts are placed in an oblique tumbling barrel made of stainless steel and covered with 3 to 5 gallons of water. Three ounces of copper sulfate and 6 ounces of sodium thiosulfate are dissolved in warm water and added to the barrel's contents. After tumbling for 15 to 30 minutes to obtain the finish, the solution is drained from the barrel, and the parts are washed thoroughly in clean water, dried in sawdust or air-blasted and, if necessary, lacquered. To produce a blue-black color, the parts are immersed in a 130–175°F solution of copper carbonate 1 pound; ammonium hydroxide (0.89 specific gravity), 1 quart; and water, 3 quarts. Excess copper carbonate should be present. The proper color is obtained in 1 minute. To color brass a hardware green, immerse the parts in a 160°F solution of ferric nitrate, 1 ounce; sodium thiosulfate, 6 ounces; and water, 1 gallon. To color brass a light brown, immerse the parts in a 195–212°F solution of potassium chlorate, 5.5 ounces; nickel sulfate, 2.75 ounces; copper sulfate, 24 ounces; and water, 1 gallon.

Post treatment: The treated parts should be scratch brushed to remove any excess or loose deposits. A contrast of colors may be obtained by brushing with a slurry of fine pumice, hand nabbing with an abrasive paste, mass finishing, or buffing to remove the color from the highlights. In order to prolong the life of parts used for outdoor decorative purposes, a clear lacquer should be applied. Parts intended for indoor purposes are often used without additional protection.

Coloring of Iron and Steel.—Thin black oxide coatings are applied to steel by immersing the parts to be coated in a boiling solution of sodium hydroxide and mixtures of nitrates nitrites. These coatings serve as paint bases and, in some cases, as final finishes. When the coatings are impregnated with oil or wax, they furnish fairly good corrosion resistance. These finishes are relatively inexpensive compared to other coatings.

Phosphate Coatings: Phosphate coatings are applied to iron and steel parts by reacting them with a dilute solution of phosphoric acid and other chemicals. The surface of the metal is converted into an integral, mildly protective layer of insoluble crystalline phosphate. Small items are coated in tumbling barrels; large items are spray coated on conveyors.

The three types of phosphate coatings in general use are zinc, iron, and manganese. Zinc phosphate coatings vary from light to dark gray. The color depends on the carbon content and pretreatment of the steel's surface, as well as the composition of the solution. Zinc phosphate coatings are generally used as a base for paint or oil, as an aid in cold working, for increased wear resistance, or for rustproofing. Iron phosphate coatings were the first type to be used; they produce dark gray coatings and their chief application is as a paint base. Manganese phosphate coatings are usually dark gray; however, since they are used almost exclusively as an oil base, for break in and to prevent galling, they become black in appearance.

In general, stainless steels and certain alloy steels cannot be phosphated. Most cast irons and alloy steels accept coating with various degrees of difficulty depending on alloy content.

Anodizing Aluminum Alloys.—In the anodizing process, the aluminum object to be treated is immersed as the anode in an acid electrolyte, and a direct current is applied. Oxidation of the surface occurs, producing a greatly thickened, hard, porous film of aluminum oxide. The object is then immersed in boiling water to seal the porosity and render the film impermeable. Before sealing, the film can be colored by impregnation with dyes or pigments. Special electrolytes may also be used to produce colored anodic films directly in the anodizing bath. The anodic coatings are used primarily for corrosion protection and abrasion resistance, and as a paint base.

The three principal types of anodizing processes are: chromic, in which the active agent is chromic acid; sulfuric, in which the active agent is sulfuric acid, and hard anodizing, in which sulfuric acid is used by itself or with additives in a low-temperature electrolyte bath. Most of the anodic coatings range in thickness from 0.2 to 0.7 mil. The hard anodizing process can produce coatings up to 2 mils. The chromic acid coating is less brittle than the sulfuric, and, since the chromic electrolyte does not attack aluminum, it does not present a corrosion problem when it is trapped in crevices. The chromic coating is less resistant to abrasion than the sulfuric, but it cannot be used with alloys containing more than 5 per cent copper due to corrosion of the base metal.

Chemical Conversion Coatings for Aluminum: Chemical conversion coatings for aluminum alloys are adherent surface layers of low volubility oxide, phosphate, or chromate compounds produced by the reaction of the metal surface with suitable reagents. The conversion coatings are much thinner and softer than anodic coatings but they are less expensive and serve as an excellent paint base.

Magnesium Alloys.—Chemical treatment of magnesium alloys is used to provide a paint base and to improve corrosion resistance. The popular conversion “dip” coatings are chrome pickle and dichromate treatments, and they are very thin. Anodic coatings are thicker and harder, and, after sealing, give the same protection against corrosion, although painting is still desirable.

Titanium Alloys.—Chemical conversion coatings are used on titanium alloys to improve lubricity by acting as a base for the retention of lubricants. The coatings are applied by immersion, spraying, or brushing. A popular coating bath is an aqueous solution of phosphates, fluorides, and hydrofluoric acid. The coating is composed primarily of titanium and potassium fluorides and phosphates.

Plating

Surface Coatings.—The following is a list of military plating and coating specifications.

Anodize (Chromic and Sulfuric), MIL-A-8625F: Conventional Types I, IB, and II anodic coatings are intended to improve surface corrosion protection under severe conditions or as a base for paint systems. Coatings can be colored with a large variety of dyes and pigments. Class 1 is non-dyed; Class 2 dyed. Color is to be specified on the contract. Prior to dying or sealing, coatings shall meet the weight requirements.

Type I and IB coatings should be used on fatigue critical components (due to thinness of coating). Type I unless otherwise specified shall not be applied to aluminum alloys with over 5% copper or 7% silicon or total alloying constituents over 7.5%. Type IC is a mineral or mixed mineral/organic acid that anodizes. It provides a non-chromate alternative for Type I and IB coatings where corrosion resistance, paint adhesion, and fatigue resistance are required. Type IIB is a thin sulfuric anodizing coating for use as non-chromate alternatives for Type I and IB coatings where corrosion resistance, paint adhesion, and fatigue resistance are required. Be sure to specify the class of anodic coating and any special sealing requirements.

Types I, IB, IC, and IIB shall have a thickness between 0.00002 and 0.0007 in. Type II shall have a thickness between 0.0007 and 0.0010 in.

Black Chrome, MIL-C-14538C: A hard, non-reflective, abrasion, heat and corrosion resistant coating approximately 0.0002 in. thick. Provides limited corrosion protection, but added protection can be obtained by specifying underplate such as nickel. Color is a dull dark gray, approaching black and may be waxed or oiled to darken.

Black chromium has poor throwing power, and conforming anodes are necessary for intricate shapes. Apply coating after heat treating and all mechanical operations are performed. Steel parts with hardness in excess of 40 Rc shall be stress relieved prior to plating by baking one hour or more (300 to 500°F) and baked after plating (375°F ± 25°F) for 3 hours.

Black Oxide Coating, MIL-C-13924C: A uniform, mostly decorative black coating for ferrous metals used to decrease light reflection. Only very limited corrosion protection under mild corrosion conditions. Black oxide coatings should normally be given a supplementary treatment.

Used for moving parts that cannot tolerate the dimensional change of a more corrosion resistant finish. Use alkaline oxidizing for wrought iron, cast and malleable irons, plain carbon, low alloy steel and corrosion resistant steel alloys. Alkaline-chromite oxidizing may be used on certain corrosion resistant steel alloys tempered at less than 900°F Salt oxidizing is suitable for corrosion resistant steel alloys that are tempered at 900°F or higher.

Cadmium, QQ-P-416F: Cadmium plating is required to be smooth, adherent, uniform in appearance, free from blisters, pits, nodules, burning, and other defects when examined visually without magnification. Unless otherwise specified in the engineering drawing or procurement documentation, the use of brightening agents in the plating solution to modify luster is prohibited on components with a specified heat treatment of 180 ksi minimum tensile strength (or 40 Rc) and higher. Either a bright (not caused by brightening agents) or dull luster shall be acceptable. Baking on Types II and III shall be done prior to application of supplementary coatings. For Classes 1, 2, and 3 the minimum thicknesses shall be 0.0005, 0.0003, and 0.0002 in. respectively.

Type I is to be used as plated. Types II and III require supplementary chromate and phosphate treatment respectively. Chromate treatment required for type II may be colored iridescent bronze to brown including olive drab, yellow and forest green. Type II is recommended for corrosion resistance. Type III is used as a paint base and is excellent for plating stainless steels that are to be used in conjunction with aluminum to prevent galvanic corrosion. For Types II and III the minimum cadmium thickness requirement shall be met after the supplementary treatment.

Chemical Films, MIL-C-5541E: The materials that qualify produce coatings that range in color from clear to iridescent yellow or brown. Inspection difficulties may arise with clear coatings because of their invisibility.

Class 1A chemical conversion coatings are intended to provide corrosion prevention when left unpainted as well as to improve adhesion of paint finish systems on aluminum and aluminum alloys. May be used on tanks, tubings, and component structures where paint finishes are not required for the exterior surfaces but are required for the interior surfaces.

Class 3 chemical conversion coatings are intended for use as a corrosive film for electrical and electronic applications where lower resistant contacts are required. The primary difference between Class 1A and Class 3 coating is thickness.

Chemical Finish: Black, MIL-F-495E: A uniform black corrosion retardant for copper. Coating has no abrasion resistance. Used to blacken color and reduce gloss on copper-alloy surfaces other than food service and water supply items. Also used as a base for subsequent coatings such as lacquer, varnish, oil, and wax.

Chrome, QQ-C-320B: Has excellent hardness, wear resistance, and erosion resistance. In addition chrome has a low coefficient of friction, is resistant to heat, and can be rendered porous for lubrication purposes.

Types I and II have bright and satin appearances respectively.

Class 1 is used as plating for corrosion protection and Class 2, for engineering plating. Class 1 and 2 both shall have a minimum thickness of 0.00001 in. on all visible surfaces. If thickness is not specified use 0.002 in.

Class 2a will be plated to specified dimensions or processed to specified dimensions after plating. Class 2b will be used on parts below 40 Rc and subject to static loads or designed for limited life under dynamic loads. Class 2c will be used on parts below 40 Rc and designed for unlimited life under dynamic loads. Class 2d parts have hardness of 40 Rc or above, which are subject to static loads or designed for unlimited life under dynamic loads. Class 2e parts have hardness of 40 Rc or above, which are designed for unlimited life under dynamic loads.

All coated steel parts having a hardness of Rc 36 and higher shall be baked at a minimum of 375°F ± 25°F per the following conditions.With a tensile strength of 160-180 (ksi), the time at temperature will be 3 hr.; at 181-220 ksi, the time will be 8 hr.; and at 221 ksi and above, the time will be 12 hr.

Copper, MIL-C-14550B: Has good corrosion resistance when used as an undercoat. A number of copper processes are available, each designed for a specific purpose such as, to improve brightness (to eliminate the need for buffing), high speed (for electro-forming), and fine grain (to prevent case-hardening).

All steel parts having a hardness of Rc 35 and higher shall be baked at 375°F ± 25°F for 24 hours, within four hours after plating to provide hydrogen embrittlement relief. Plated springs and other parts subject to flexure shall not be flexed prior to baking operations.

Class 0 will have a thickness 0.001 - 0.005 in. and is used for heat treatment stop-off; Class 1 is 0.001 in. and is used to provide carburizing shield, also for plated through printed circuit boards. Class 2 is 0.0005 in. thick and is used as an undercoat for nickel and other platings. Class 3 is 0.0002 in. thick and is used to prevent basis metal migration into tin (prevents poisoning solderability). Class 4 is 0.0001 in. thick.

Tin Lead, MIL-P-81728A: It has excellent solderability. Either a matte or bright luster is acceptable. For electronics components, use only parts with a matte or flow brightened finish.

For brightened electronic components, the maximum thickness will be 0.0003 in. Tin 50 to 70% by weight and with a lead remainder, 0.0003-0.0005 in.

Magnesium Process, MIL-M-3171C: Process #1-A chrome pickle treatment for magnesium. Color varies from matte gray to yellow-red. Has only fair corrosion resistance (< 24 hours, 20% salt spray resistance).

#7-A dichromate treatment for magnesium. Color varies from light brown to gray depending on alloy. Only fair corrosion resistance (< 24 hours, 20% salt spray resistance).

#9-A galvanic anodize treatment for magnesium. Produces a dark brown to black coating. Designed to give a protective film on alloys which do not react to Dow No. 7 treatment. Only fair corrosion resistance (< 24 hours, 20% salt spray resistance).

Type/Class	Thickness (in.)	Comments
Type 1	Removes metal. (approx. 0.0006 for wrought, less for die castings.) No dimensional change	Used for protecting magnesium during shipment, storage and machining. Can be used as a paint base. NOTE: Must remove Type I coating before applying Type III and Type IV treatments.
Type III	…	*Note:* precleaning and pickling may result in dimensional changes due to metal loss.
Type IV	No dimensional change	Can be used as a paint base, and is applicable to all magnesium alloys. Used where optical properties (black) are required on close tolerance parts. NOTE: Precleaning and pickling may result in dimensional changes due to metal loss.

Magnesium Anodic Treatment, MIL-M-45202C: The HAE anodic finish is probably the hardest coating currently available for magnesium. It exhibits stability at high temperatures and has good dielectric strength. It serves as an excellent paint base. It requires resin seal or paint for maximum corrosion protection.

Type/Class	Typical Thickness	Comments
Type I, Light coating.		
Class A	0.2 mil	Tan coating (HAE)
Grade 1	…	Without post treatment (dyed)
Grade 2	…	With biflouride-dichromate post treatment
Class C	0.3 mil	Light green coating (Dow #17)
Type II, Heavy coating		
Class A	1.5 mil	Hard brown coating (HAE)
Grade 1	…	Without post treatment
Grade 3	…	With biflouride-dichromate post treatment
Grade 4	…	With biflouride-dichromate post treatment including moist heat aging
Grade 5		With double application of biflouride-dichromate post treatment including moist heat aging.
Class D	1.2 mil	Dark green coating (Dow #17)

Coatings range from thin clear to light gray-green, to thick dark-green coatings. The clear coatings are used as a base for subsequent clear lacquers or paints to produce a final appearance similar to clear anodizing on aluminum. The light gray-green coatings are used in most applications which are to be painted. The thick, dark-green coating offers the best combination of abrasion resistance, protective value and paint base characteristics.

Electroless Nickel, AMS 2404C, AMS 2405B, AMS 2433B: Is typically used as a coating to provide a hard-ductile, wear-resistant, and corrosion-resistant surface for operation in service up to 1000°F, to provide uniform build-up on complex shapes.

AMS 2404C, is deposited directly on the basis metal without a flash coating of other metal, unless otherwise specified. AMS 2405B, is deposited directly on the basis metal except where parts fabricated from corrosion resistant steels or alloys where a "strike" coating of nickel or other suitable metal is required, unless otherwise specified. AMS 2433B, is a type of electroless nickel typically used to enhance the solderability of surfaces, but usage is not limited to such applications. Generally, the plate shall be placed directly on the basis metal. However, aluminum alloys shall be zinc immersion coated per ASTM B253 followed by copper flash; corrosion resistant steels and nickel and cobalt alloys or other basis metals may use a nickel or copper flash undercoat when the purchaser permits.

Electroless Nickel Preparation: Parts having a hardness higher than Rc 40 and have been machined or ground after heat treatment shall be suitably stress-relieved before cleaning and plating.

After treatment, parts having a hardness of Rc 33 and over shall be heated to 375°F ± 15°F for three hours. If such treatment is injurious to the parts, bake at 275°F ± 15°F for four hours.

Electroless Nickel, Low-Phosphorous

Note: If permitted by drawing, the maximum hardness and wear resistance are obtained by heating parts for 30-60 minutes, preferably in an inert atmosphere, at 750°F ± 15°F except aluminum parts shall be baked at 450°F ± 15°F for four hours. If such heating is not specified, bake at 375°F ± 15°F for three hours. If this treatment is injurious to parts or assemblies, bake at 275°F for five hours.

Plating: nickel-thallium-boron (Electroless Deposition) and nickel-boron (Electroless Deposition)

Preparation: All fabrication-type operations shall be completed.

Post-treatment: Cold worked or heat treated parts and aluminum alloys and other parts requiring special thermal treatment shall be post treated as agreed upon by purchaser and vendor. Other plated parts within four hours after plating shall be heat treated for 90 ± 10 minutes at 675°F ± 15°F.

Electropolishing, (No MIL-SPEC No.): This process electrolytically removes or diminishes scratches, burrs, and unwanted sharp edges from most metals. Finishes from satin to mirror-bright are produced by controlling time, temperature, or both.

Typically the thickness loss is 0.0002 in. This process is not recommended for close tolerance surfaces.

Gold, MIL-G-45204C: Has a yellow to orange color depending on the proprietary process used. Will range from matte to bright finish depending on basis metal. It has good corrosive resistance and a high tarnish resistance. It provides a low contact resistance, is a good conductor of electricity, and has excellent solderability. If the hardness grade for the gold coating is not specified, Type I shall be furnished at a hardness of Grade A, and Type II furnished at a hardness of Grade C.

For soldering, a thin pure soft gold coating is preferred. A minimum and maximum thickness 0.00005 and 0.00010 in., respectively, shall be plated.

Unless otherwise specified, gold over silver underplate combinations shall be excluded from electronics hardware. Silver or copper plus silver may not be used as an underplate unless required by the item specification. When gold is applied to brass bronze or beryllium copper, or a copper plate or strike, an antidiffusion underplate such as nickel shall be applied.

Type I is 99.7% gold minimum (Grades A, B, or C); Type II is 99.0% (Grades B, C, or D); and Type III is 99.9% (Grade A only).

Grade A is 90 Knoop maximum; Grade B is 91-129 Knoop; Grade C is 130-200 Knoop; and Grade D is 201 Knoop and over.

Class 00 has a thickness of 0.00002 in. minimum; Class 0, 0.00003 in.; Class 1, 0.00005 in.; Class 2, 0.0001 in.; Class 3, 0.0002 in.; Class 4, 0.0003 in.; Class 5, 0.0005 in.; and Class 6, 0.0015 in.

Hard Anodize, MIL-A-8625F: The color will vary from light tan to black depending on alloy and thickness. Can be dyed in darker colors depending on the thickness. Coating penetrates base metal as much as builds up on the surface. The term thickness includes both the buildup and penetration. It provides a very hard ceramic type coating. Abrasion resistance will vary with alloy and thickness of coating. Has good dielectric properties.

Do not seal coatings where the main function is to obtain maximum abrasion or wear resistance. When used for exterior applications requiring corrosion resistance but permitting reduced abrasion, the coating shall be sealed (boiling deionized water or hot 5% sodium dichromate solution, or other suitable chemical solutions).

Type III will have a thickness specified on the contract or applicable drawing. If not specified use a nominal thickness of 0.002 in. Hard coatings may vary in thickness from 0.0005 - 0.0045 in.

Class 1 shall be not dyed or pigmented. Class 2 shall be dyed and the color specified on the contract. The process can be controlled to very close thickness tolerances. Where maximum serviceability or special properties are required, consult metal finisher for best alloy choice. Thick coatings (those over 0.004 in.) will tend to break down sharp edges. Can be used as an electrical insulation coating. “Flash” hard anodize may be used instead of conventional anodize for corrosion resistance and may be more economical in conjunction with other hard anodized areas.

Lubrication, Solid Film MIL-L-46010D: The Military Plating Specification establishes the requirements for three types of heat cured solid film lubricants that are intended to reduce wear and prevent galling, corrosion, and seizure of metals. For use on aluminum, copper, steel, stainless steel, titanium, and chromium, and nickel bearing surfaces.

Types I, II, and III have a thicknesses of 0.008 - 0.013 mm. No single reading less than 0.005 mm or greater than 0.018 mm.

Type I has a curing temperature of 150 ± 15°C and an endurance life of 250 minutes; Type II, 204 ± 15°C and 450 minutes; and Type III is a low volatile organic compound (VOC) content lubricant with cure cycles of 150 ± 15°C for two hours, or 204 ± 15°C for one hour with an endurance life of 450 minutes. Color 1 has a natural product color and Color 2 has a black color.

Nickel, QQ-N-290A: There is a nickel finish for almost any need. Nickel can be deposited soft, hard-dull, or bright, depending on process used and conditions employed in plating. Thus, hardness can range from 150-500 Vickers. Nickel can be similar to stainless steel in color, or can be a dull gray (almost white) color. Corrosion resistance is a function of thickness. Nickel has a low coefficient of thermal expansion.

All steel parts having a tensile strength of 220,000 or greater shall not be a nickel plate without specific approval of procuring agency.

Class 1 is used for corrosion protection. Plating shall be applied over an underplating of copper or yellow brass on zinc and zinc based alloys. In no case, shall the copper underplate be substituted for any part of the specified nickel thickness. Class 2 is used in engineering applications.

Grade A has a thickness of 0.0016 in.; Grade B, 0.0012 in.; Grade C, 0.001 in.; Grade D, 0.0008 in.; Grade E, 0.0006 in.; Grade F, 0.0004 in.; and Grade G, 0.002 in.

Palladium, MIL-P-45209B: A gray, dense deposit good for undercoats. Has good wear characteristics, corrosion resistance, catalytic properties, and good conductivity.

The thickness shall be 0.00005 in. unless otherwise specified.

Steel springs and other steel parts subject to flexure or repeated impact and of hardness greater than Rc 40 shall be heated to 375°F ± 25°F for three hours after plating.

Passivate, QQ-P-35C: Intended to improve the corrosion resistance of parts made from austentic, ferritic, and martensitic corrosion-resistant steels of the 200, 300, and 400 series and precipitation hardened corrosion resistant steels. 440C grades may be exempt from passivation treatments of the procuring activity.

Type II is a medium temperature nitric acid solution with sodium dichromate additive. Type VI, a low temperature nitric acid solution; Type VII, a medium temperature nitric acid solution; and Type VIII, a medium temperature high concentration nitric acid solution.

Phosphate Coating: Light, TT-C-490D: This specification covers cleaning methods and pretreatment processes.

Methods /Types	Typical Thickness (in.)	Comments
Cleaning Methods		
	–	Light coating for use as a paint base.
Method I	…	Mechanical or abrasive cleaning (for ferrous surfaces only).
Method II	…	Used for solvent cleaning.
Method III	…	Used for hot alkalines (for ferrous surfaces only).
Method IV	…	Emulsion.
Method V	…	Used for alkaline derusting (for ferrous surfaces only).
Method VI	…	Phosphoric acid.
Pretreatment Coatings		
Type I	…	Zinc phosphate. Class 1-spray application: Class 2A and 2B-Immersion or Dip application
Type II	…	Aqueous Iron Phosphate
Type III	0.0003 – 0.0005	Is an organic pretreatment coating
Type IV	…	Non-aqueous iron phosphate
Type V	…	Zinc phosphate

Type I is intended as a general all-purpose pretreatment prior to painting. Type II and IV are intended primarily for use where metal parts are to be formed after painting. Type III is intended for use where size and shape preclude using Type I, II, or IV and where items containing mixed metal components are assembled prior to treatment.

Phosphate Coating: Heavy, DOD-P-16232-F: The primary differences are that Type M is used as a heavy manganese phosphate coating for corrosion and wear resistance and Type Z is used as a Zinc phosphate coating.

Type M has a thickness from 0.0002-0.0004 in. and Type Z, 0.0002-0.0006 in. Class 1, for both types has a supplementary preservative treatment or coating as specified; Class 2, has a supplementary treatment with lubricating oil; and Class 3, no supplementary treatment is required. For Type M, Class 4 is chemically converted (may be dyed to color as specified) with no supplementary coating or supplementary coating as specified. For Type Z, Class 4 is the same as Class 3.

This coating is for medium and low alloy steels. The coatings range from gray to black in color. The "heavy" phosphate coatings covered by this specification are intended as a base for holding/retaining supplemental coatings which provide the major portion of the corrosion resistance. "Light" phosphate coatings used for a paint base are covered by other specifications. Heavy zinc phosphate coatings may be used when paint and supplemental oil coatings are required on various parts or assemblies.

Rhodium, MIL-R-46085B: Rhodium is metallic and similar to stainless steel in color, has excellent corrosion and abrasion resistance, is almost as hard as chromium, and has a high reflectivity. Thicker coatings of Rhodium are very brittle.

Class/Types	Thickness (in.)	Comments
Type I	–	Over nickel, silver, gold, or platinum.
Type II	–	Over other metals, requires nickel undercoat.
Class 1	0.000002	Used on silver for tarnish resistance.
Class 2	0.00001	Applications range from electronic to nose cones -wherever wear, corrosion resist solderability and reflectivity are important.
Class 3	0.00002	
Class 4	0.00010	
Class 5	0.00025	

Parts having a hardness of Rc 33 or above shall be baked at 375°F for three hours prior to cleaning. Parts having hardness of 40 Rc and above shall be baked within four hours after plating at 375°F for three hours.

Silver, QQ-S-365D: Silver has an increasing use in both decorative and engineering fields, including electrical and electronic fields.

Silver is white matte to very bright in appearance. Has good corrosion resistance, depending on base metal and will tarnish easily. Its hardness varies from about 90-135 Brinell depending on process and plating conditions. Solderability is excellent, but decreases with age. Silver is the best conductor of electricity. Has excellent lubricity and smear characteristics for antigalling uses on static seals, bushing, etc. Stress relief steel parts at a minimum 375°F ± 25°F or more prior to cleaning and plating if they contain or are suspected of having damaging residual tensile stresses.

All types and grades will have a minimum thickness of 0.0005 in. unless otherwise specified. Type I is matte, Type II is semi-bright, and Type III is bright. Grade A has a chromate post-treatment to improve tarnish resistance. In contrast Grade B has no supplementary treatment.

Tin, MIL-T-10727C: There are two different types of coating methods used, electrodeposited (based on Use ASTM B545 standard specification for electrodeposited coatings of tin) and hot dipped.

Thickness as specified on drawing (thickness is not part of the specification) is 0.0001-0.0025 in., flash for soldering; 0.0002-0.0004 in., to prevent galling and seizing; 0.0003 in. minimum, where corrosion resistance is important; and 0.0002-0.0006 to prevent formation of case during nitriding.

Color is a gray-white color in plated condition. Tin is soft, but very ductile. It has good corrosion resistance, and has excellent solderability. Tin is not good for low temperature applications.

If a bright finish is desired to be used in lieu of fused tin, specify Bright Tin plate. Thickness can exceed that of fused tin and deposit shows excellent corrosion resistance and solderability.

Vacuum Cadmium, MIL-C-8837B: Is used primarily to provide corrosion resistance to ferrous parts free from hydrogen contamination and possible embrittlement. Recommended on steels with a strength of 2.2x105 psi or above.

Coating is applied after all machining, brazing, welding, and forming has been completed. Prior to coating, all steel parts shall be stress relieved by baking at 375°F ± 25 for three hours if suspected of having residual tensile stresses. Immediately prior to coating, lightly dry abrasive blast areas are to be coated.

Type I shall be as plated; and Types II and III require supplementary chromate and phosphate treatments respectively.

Classes 1, 2, and 3 have thicknesses of 0.0005, 0.0003, and 0.0002 in. respectively.

Cadmium coating shall not be used, if in service, temperature reaches 450°F.

A salt spray test is required for type II and is 96 hours.

Zinc, ASTM-B633: This specification covers requirements for electrodeposited zinc coatings applied to iron or steel articles to protect them from corrosion. It does not cover zinc-coated wire or sheets.

Type I will be as plated; Type II will have colored chromate conversion coatings; Type III will have colorless chromate conversion coatings; and Type IV will have phosphate conversion coatings.

High strength steels (tensile strength over 1700 Mpa) shall not be electroplated.

Stress relief: All parts with ultimate tensile strength 1000 Mpa and above at minimum 190°C for three hours or more before cleaning and plating.

Hydrogen embrittlement relief: All electroplated parts 1200 Mpa or higher shall be baked at 190°C for three hours or more within four hours after electroplating.

Corrosion Resistance Requirements	
Types	Test Period Hr.
II	96
III	12