HEAT-TREATING HIGH-SPEED STEELS

Heat Treating High-Speed Steels

Cobaltcrom Steel.—A tungstenless alloy steel or high-speed steel that contains approximately 1.5 per cent carbon, 12.5 per cent chromium, and 3.5 per cent cobalt. Tools such as dies and milling cutters, made from cobaltcrom steel can be cast to shape in suitable molds, the teeth of cutters being formed so that it is necessary only to grind them.

Before the blanks can be machined, they must be annealed; this operation is performed by pack annealing at the temperature of 1800 degrees F, for a period of from three to six hours, according to the size of the castings being annealed. The following directions are given for the hardening of blanking and trimming dies, milling cutters, and similar tools made from cobaltcrom steel: Heat slowly in a hardening furnace to about 1830 degrees F, and hold at this temperature until the tools are thoroughly soaked. Reduce the temperature about 50 degrees, withdraw the tools from the furnace, and allow them to cool in the atmosphere. As soon as the red color disappears from the cooling tool, place it in quenching oil until cold. The slight drop of 50 degrees in temperature while the tool is still in the hardening furnace is highly important to obtain proper results. The steel will be injured if the tool is heated above 1860 degrees F. In cooling milling cutters or other rotary tools, it is suggested that they be suspended on a wire to ensure a uniform rate of cooling.

Tools that are to be subjected to shocks or vibration, such as pneumatic rivet sets, shear blades, etc., should be heated slowly to 1650 degrees F, after which the temperature should be reduced to about 1610 degrees F, at which point the tool should be removed from the furnace and permitted to cool in the atmosphere. No appreciable scaling occurs in the hardening of cobaltcrom steel tools.

Preheating Tungsten High-Speed Steel.—Tungsten high-speed steel must be hardened at a very high temperature; consequently, tools made from such steel are seldom hardened without at least one preheating stage to avoid internal strain. This requirement applies especially to milling cutters, taps, and other tools having thin teeth and thick bodies and to forming tools of irregular shape and section. The tools should be heated slowly and carefully to a temperature somewhat below the critical point of the steel, usually in the range of 1500 to 1600 degrees F. Limiting the preheating temperature prevents the operation from being unduly sensitive, and the tool may be safely left in the furnace until it reaches a uniform temperature throughout its length and cross-section.

A single stage of preheating is customary for tools of simple form that are not more than from 1 to $1\frac{1}{2}$ inches in thickness. For large, intricate tools, two stages of preheating are frequently used. The first brings the tool up to a temperature of about 1100 to 1200 degrees F, and the second raises its temperature to 1550 to 1600 degrees F. A preheating time of 5 minutes for each $\frac{1}{4}$ inch in tool thickness has been recommended for a furnace temperature of 1600 degrees F. This is where a single stage of preheating is used and the furnace capacity should be sufficient to maintain practically constant temperature when the tools are changed. To prevent undue chilling, it is common practice to insert a single tool or a small lot in the hardening furnace whenever a tool or lot is removed, rather than to insert a full charge of cold metal at one time.

Preheating is usually done in a simple type of oven furnace heated by gas, electricity, or oil. Atmospheric control is seldom used, although for 18–4–1 steel a slightly reducing atmosphere (2 to 6 per cent carbon monoxide) has been found to produce the least amount of scale and will result in a better surface after final hardening.

Hardening of Tungsten High-Speed Steel.—All tungsten high-speed steels must be heated to a temperature close to their fusion point to develop their maximum efficiency as metal-cutting tools. Hardening temperatures ranging from 2200 to 2500 deg. F may be needed. The effects of changes in the hardening temperature on the cutting efficiency of several of the more common high-speed steels are shown in Table 1. The figures given are

ratios, the value 1.00 for each steel being assigned to the highest observed cutting speed for that steel. The figures for different steels, therefore, cannot be directly compared with each other, except to note changes in the point of maximum cutting efficiency.

Table 1. Relation of Hardening Temperature to Cutting Efficiency

Hardening Temperature, Deg. F	Typical Analyses of High-Speed Steels			
	18 – 4 – 1	14 – 4 – 2	18 – 4 –1 Cobalt	14 – 4 – 2 Cobalt
2200	0.86	0.83	0.84	0.85
2250	0.88	0.88	0.86	0.88
2300	0.90	0.93	0.90	0.91
2350	0.95	0.98	0.94	0.94
2400	0.99	0.98	0.98	0.98
2450	1.00	…	0.99	1.00
2500	0.98	…	1.00	0.97

The figures in the table refer to tools heated in an oven-type furnace in which a neutral atmosphere is maintained. The available data indicate that a steel reaches its best cutting qualities at a temperature approximately 50 deg. F lower than the figures in the table if it is hardened in a bath-type furnace. It is, however, desirable to use a hardening temperature approximately 50 deg. F lower than that giving maximum cutting qualities, to avoid the possibility of overheating the tool.

Length of Time for Heating: The cutting efficiency of a tool is affected by the time that it is kept at the hardening temperature, almost as much as by the hardening temperature itself. It has been common practice to heat a tool for hardening until a "sweat" appeared on its surface. This sweat is presumably a melting of the oxide film on the surface of a tool heated in an oxidizing atmosphere. It does not appear when the tool is heated in an inert atmosphere. This method of determining the proper heating time is at best an approximation and indicates only the temperature on the outside of the tool rather than the condition of the interior. As such, it cannot be relied upon to give consistent results.

The only safe method is to heat the tool for a definite predetermined time, based on the size and the thickness of metal that the heat must penetrate to reach the interior. The values given in Table 2 are based on a series of experiments to determine the relative cutting efficiency of a group of tools hardened in an identical manner, except for variations in the time the tools were kept at the hardening temperature. The time given is based on that required to harden throughout a tool resting on a conducting hearth; the tool receives heat freely from three sides, on its large top surface and its smaller side surfaces. (The table does not apply to a disk lying flat on the hearth.) For a tool having a projecting cutting edge, such as a tap, the thickness or depth of the projecting portion on which the cutting edge is formed should be used when referring to the table.

Table 2. Length of Heating Time for Through Hardening

High-Speed Steel Tool Thickness, in Inches	Time in Furnace at High Heat, in Minutes	High-Speed Steel Tool Thickness, in Inches	Time in Furnace at High Heat, in Minutes	High-Speed Steel Tool Thickness, in Inches	Time in Furnace at High Heat, in Minutes
1/4	2	1 1/2	7	5	18
1/2	3	2	8	6	20
3/4	4	3	12	8	25
1	5	4	15	10	30

The time periods given in Table 2 are based on complete penetration of the hardening effect. For very thick tools, the practical procedure is to harden to a depth sufficient to produce an adequate cutting edge, leaving the interior of the tool relatively soft.

Where atmosphere control is not provided, it often will be found impracticable to use both the temperature for maximum cutting efficiency, given in Table 1, and the heating time, given in Table 2, because abnormal scaling, grain growth, and surface decarburization of the tool will result. The principal value of an accurate control of the furnace atmosphere appears to lie in the fact that its use makes possible the particular heat treatment that produces the best structure in the tool without destruction of the tool surface or grain.

Quenching Tungsten High-Speed Steel.—High-speed steel is usually quenched in oil. The oil bath offers a convenient quench; it calls for no unusual care in handling and brings about a uniform and satisfactory rate of cooling, which does not vary appreciably with the temperature of the oil. Some authorities believe it desirable to withdraw the tool from the oil bath for a few seconds after it has reached a dull red. It is also believed desirable to move the tool around in the quenching oil, particularly immediately after it has been placed in it, to prevent the formation of a gas film on the tool. Such a film is usually a poor conductor of heat and slows the rate of cooling.

Salt Bath: Quenching in a lead or salt bath at from 1000 to 1200 deg. F has the advantage that cooling of the tool from hardening to room temperature is accomplished in two stages, thus reducing the possibility of setting up internal strains that may tend to crack the tool. The quenching temperature is sufficiently below the lower critical point for a tool so quenched to be allowed to cool to room temperature in still air. This type of quench is particularly advantageous for tools of complicated section that would easily develop hardening cracks. The salt quench has the advantage that the tool sinks and requires only a support, whereas the same tool will float in the lead bath and must be held under the surface. It is believed that the lead quench gives a somewhat higher matrix hardness, and is of advantage for tools that tend to fail by nose abrasion. Tools treated as described are brittle unless given a regular tempering treatment, because the 1000-deg. F quenching temperature is not a substitute for later tempering at the same temperature, after the tool has cooled to room temperature.

Air Cooling: Many high-speed steel tools are quenched in air, either in a stream of dry compressed air or in still air. Small sections harden satisfactorily in still air, but heavier sections should be subjected to air under pressure. One advantage of air cooling is that the tool can be kept straight and free from distortion, although it is likely that there will be more scale on a tool thus quenched than when oil, lead, or salt is used. Cooling between steel plates may help to keep thin flat tools straight and flat.

Straightening High-Speed Tools when Quenching.—The final straightness required in a tool must be considered when it is quenched. When several similar tools are to be hardened, a jig can be used to advantage for holding the tools while quenching. When long slender tools are quenched without holders, they frequently warp and must be straightened later. The best time for this straightening is during the first few minutes after the tools have been quenched, as the steel is then quite pliable and may be straightened without difficulty. The straightening must be done at once, as the tools become hard in a few minutes.

Anneal Before Rehardening.—Tools that are too soft after hardening must be annealed before rehardening. A quick anneal, such as previously described, is all that is required to put such a tool into the proper condition for rehardening. This treatment is absolutely essential. For milling cutters and forming tools of irregular section, a full anneal should be used.

Tempering or Drawing Tungsten High-Speed Steel.—The tempering or drawing temperature for high-speed steel tools usually varies from 900 to 1200 deg. F. This temperature is higher for turning and planing tools than for such tools as milling cutters, forming tools, etc. If the temperature is below 800 deg. F, the tool is likely to be too brittle. The general idea is to temper tools at the highest temperature likely to occur in service. Because this temperature ordinarily would not be known, the general practice is to temper at whatever temperature experience with that particular steel and tool has proved to be the best.

The furnace used for tempering usually is kept at a temperature of from 1000 to 1100 deg. F for ordinary high-speed steels and from 1200 to 1300 deg. F for steels of the cobalt type. These furnace temperatures apply to tools of the class used on lathes and planers. Such tools, in service, frequently heat to the point of visible redness. Milling cutters, forming tools, or any other tools for lighter duty may be tempered as low as 850 or 900 deg. F. When the tool has reached the temperature of the furnace, it should be held at this temperature for from one to several hours until it has been heated evenly throughout. It should then be allowed to cool gradually in the air and in a place that is dry and free from air drafts. In tempering, the tool should not be quenched, because quenching tends to produce strains that may result later in cracks.

Annealing Tungsten High-Speed Steel.—The following method of annealing high-speed steel has been used extensively. Use an iron box or pipe of sufficient size to allow at least $\frac{1}{2}$ inch of packing between the pieces of steel to be annealed and the sides of the box or pipe. It is not necessary that each piece of steel be kept separate from every other piece, but only that the steel be prevented from touching the sides of the annealing pipe or box. Pack carefully with powdered charcoal, fine dry lime, or mica (preferably charcoal), and cover with an airtight cap or lute with fire clay; heat slowly to 1600 to 1650 deg. F and keep at this heat from 2 to 8 hours, depending on the size of the pieces to be annealed. A piece measuring 2 by 1 by 8 inches requires about 3 hours. Cool as slowly as possible, and do not expose to the air until cold, because cooling in air is likely to cause partial hardening. A good method is to allow the box or pipe to remain in the furnace until cold.

Hardening Molybdenum High-Speed Steels.—Table 3 gives the compositions of several molybdenum high-speed steels that are widely used for general commercial tool applications. The general method of hardening molybdenum high-speed steels resembles that used for 18–4–1 tungsten high-speed steel except that the hardening temperatures are lower and more precautions must be taken to avoid decarburization, especially on tools made from Type I or Type II steels, when the surface is not ground after hardening. Either salt baths or atmosphere-controlled furnaces are recommended for hardening molybdenum high-speed steels.

Table 3. Compositions of Molybdenum High-Speed Steels

Element	Molybdenum–Tungsten		Molybdenum–Vanadium	Tungsten–Molybdenum
	Type Ia (Per Cent)	Type Ib[a] (Per Cent)	Type II (Per Cent)	Type III (Per Cent)
Carbon	0.70–0.85	0.76–0.82	0.70–0.90	0.75–0.90
Tungsten	1.25–2.00	1.60–2.30	…	5.00–6.00
Chromium	3.00–5.00	3.70–4.20	3.00–5.00	3.50–5.00
Vanadium	0.90–1.50	1.05–1.35	1.50–2.25	1.25–1.75
Molybdenum	8.00–9.50	8.00–9.00	7.50–9.50	3.50–5.50
Cobalt	See footnote	4.50–5.50	See footnote	See footnote

[a] Cobalt may be used in any of these steels in varying amounts up to 9 per cent, and the vanadium content may be as high as 2.25 percent. When cobalt is used in Type III steel, the vanadium content may be as high as 2.25 per cent. When cobalt is used in Type III steel, this steel becomes susceptible to decarburization. As an illustration of the use of cobalt, Type Ib steel is included. This is steel T10 in the U.S. Navy Specification 46S37, dated November 1, 1939.

The usual method is to preheat uniformly in a separate furnace to 1250 to 1550 deg. F then transfer to a high-heat furnace maintained within the hardening temperature range given in Table 4. Single-point cutting tools, in general, should be hardened at the upper end of the temperature range indicated by Table 4. Slight grain coarsening is not objectionable in such tools when they are properly supported in service and are not subjected to chattering; however, when these tools are used for intermittent cuts, it is better to use the middle of the temperature range. All other cutting tools, such as drills, countersinks, taps, milling

cutters, reamers, broaches, and form tools, should be hardened in the middle of the range shown. For certain tools, such as slender taps, cold punches, and blanking and trimming dies, where greater toughness to resist shocks is required, the lower end of the hardening temperature range should be used.

Table 4. Heat Treatment of Molybdenum High-Speed Steels

Heat-Treating Operation	Molybdenum–Tungsten Types Ia and Ib[a] (Temp., in Deg. F)	Molybdenum–Vanadium Type II (Temp., in Deg. F)	Tungsten–Molybdenum Type III (Temp., in Deg. F)
Forging	1850–2000	1850–2000	1900–2050
Not below	1600	1600	1600
Annealing	1450–1550	1450–1550	1450–1550
Strain relief	1150–1350	1150–1350	1150–1350
Preheating	1250–1500	1250–1500	1250–1550
Hardening[b]	2150–2250[a]	2150–2250	2175–2275
Salt	2150–2225	2150–2225	2150–2250
Tempering	950–1100	950–1100	950–1100

[a] For similar working conditions, Type Ib steel requires a slightly higher hardening heat than Type Ia.

[b] The higher side of the hardening range should be used for large sections, and the lower side for small sections.

Molybdenum high-speed steels can be pack-hardened following the same practice as is used for tungsten high-speed steels, but keeping on the lower side of the hardening range (approximately 1850 degrees F). Special surface treatments such as nitriding by immersion in molten cyanide that are used for tungsten high-speed steels are also applicable to molybdenum high-speed tools.

When heated in an open fire or in furnaces without atmosphere control, these steels do not sweat like 18–4–1 steels; consequently, determining the proper time in the high-heat chamber is a matter of experience. This time approximates that used with 18–4–1 steels, although it may be slightly longer when the lower part of the hardening range is used. Much can be learned by preliminary hardening of test pieces and checking on the hardness fracture and structure. It is difficult to give the exact heating time, because it is affected by temperature, type of furnace, size and shape, and furnace atmosphere. Rate of heat transfer is most rapid in salt baths, and slowest in controlled-atmosphere furnaces with high carbon monoxide content.

Quenching and Tempering of Molybdenum High-Speed Tools.—Quenching may be done in oil, air, or molten bath. To reduce the possibility of breakage and undue distortion of intricately shaped tools, it is advisable to quench in a molten bath at approximately 1100 degrees F. The tool also may be quenched in oil and removed while still red, or at approximately 1100 degrees F. The tool is then cooled in air to room temperature, and tempered immediately to avoid cracking.

When straightening is necessary, it should be done after quenching and before cooling to room temperature prior to tempering.

To temper, the tools should be reheated slowly and uniformly to 950 to 1100 degrees F. For general work, 1050 degrees F is most common. The tools should be held at this temperature at least 1 hour. Two hours is a safer minimum, and 4 hours is maximum. The time and temperature depend on the hardness and toughness required. Where tools are subjected to more or less shock, multiple temperings are suggested.

Protective Coatings for Molybdenum Steels.—To protect the surface from oxidation during heat treatment, borax may be applied by sprinkling it lightly over the steel when the latter is heated in a furnace to a low temperature (1200 to 1400 deg. F). Small tools may be rolled in a box of borax before heating. Another method more suitable for finished tools is

to apply the borax or boric acid in the form of a supersaturated water solution. The tools are then immersed in the solution at 180 to 212 deg. F, or the solution may be applied with a brush or spray. Pieces so treated are heated as usual, taking care in handling to ensure good adherence of the coating. Special protective coatings or paints, when properly applied, have been found extremely useful. These materials do not fuse or run at the temperatures used, and therefore do not affect the furnace hearth. When applying these coatings, it is necessary to have a surface free from scale or grease to ensure good adherence. Coatings may be sprayed or brushed on, and usually one thin coat is sufficient. Heavy coats tend to pit the surface of the tool and are difficult to remove. Tools covered with these coatings should be allowed to dry before they are charged into the preheat furnace. After hardening and tempering, the coating can be easily removed by light blasting with sand or steel shot. When tools are lightly ground, these coatings come off immediately. Protection may also be obtained by wrapping pieces in stainless steel foil.

Nitriding High-Speed Steel Tools.—Nitriding is applied to high-speed steel for the purpose of increasing tool life by producing a very hard skin or case, the thickness of which ordinarily is from 0.001 to 0.002 inch. Nitriding is done after the tool has been fully heat treated and finish-ground. (The process differs entirely from that which is applied to surface harden certain alloy steels by heating in an atmosphere of nitrogen or ammonia gas.) The temperature of the high-speed steel nitriding bath, which is a mixture of sodium and potassium cyanides, is equal to or slightly lower than the tempering temperature. For ordinary tools, this temperature usually varies from about 1025 to 1050 deg. F; but if the tools are exceptionally fragile, the range may be reduced to 950 or 1000 deg. F. Accurate temperature control is essential to prevent exceeding the final tempering temperature. The nitriding time may vary from 10 or 15 minutes to 30 minutes or longer, and should be determined by experiment. The shorter periods are applied to tools for iron or steel, or any shock-resisting tools, and the longer periods are for tools used in machining nonferrous metals and plastics. This nitriding process is applied to tools such as hobs, reamers, taps, box tools, form tools, and milling cutters. Nitriding may increase tool life 50 to 200 per cent, or more, but it should always be preceded by correct heat treatment.

Nitriding Bath Mixtures and Temperatures: A mixture of 60 per cent sodium cyanide and 40 per cent potassium cyanide is commonly used for nitriding. This mixture has a melting point of 925 deg. F, which is gradually reduced to 800 deg. F as the cyanate content of the bath increases. A more economical mixture of 70 per cent sodium cyanide and 30 per cent potassium cyanide may be used if the operating temperature of the bath is only 1050 deg. F. Nitriding bath temperatures should not exceed 1100 deg. F because higher temperatures accelerate the formation of carbonate at the expense of the essential cyanide. A third mixture suitable for nitriding consists of 55 per cent sodium cyanide, 25 per cent potassium chloride, and 20 per cent sodium carbonate. This mixture melts at 930 deg. F.

Equipment for Hardening High-Speed Steel.—Equipment for hardening high-speed steel consists of a hardening furnace capable of maintaining a temperature of 2350 to 2450 deg. F; a preheating furnace capable of maintaining a temperature of 1700 to 1800 deg. F, and of sufficient size to hold a number of pieces of the work; a tempering (drawing) furnace capable of maintaining a temperature of 1000 to 1200 deg. F as a general rule; and a water-cooled tank of quenching oil.

High-speed steels usually are heated for hardening either in some type of electric furnace or in a gas-fired furnace of the muffle type. The small furnaces used for high-speed steel seldom are oil-fired. It is desirable to use automatic temperature control and, where an oven type of furnace is employed, a controlled atmosphere is advisable because of the variations in cutting qualities caused by hardening under uncontrolled conditions. Some furnaces of both electric and fuel-fired types are equipped with a salt bath suitable for high-speed steel hardening temperatures. Salt baths have the advantage of providing protection against the atmosphere during the heating period. A type of salt developed for commercial use is water-soluble, so that all deposits from the hardening bath may be removed by

immersion in water after quenching in oil or salt, or after air cooling. One type of electric furnace heats the salt bath internally by electrodes immersed in it. The same type of furnace is also applied to various heat-treating operations, such as cyanide hardening, liquid carburizing, tempering, and annealing.

An open-forge fire has many disadvantages, especially in hardening cutters or other tools that cannot be ground all over after hardening. The air blast decarburizes the steel and lack of temperature control makes it impossible to obtain uniform results. Electric and gas furnaces provide continuous uniform heat, and the temperature may be regulated accurately, especially when pyrometers are used. In shops equipped with only one furnace for carbon steel and one for high-speed steel, the tempering can be done in the furnace used for hardening carbon steel after the preheating is finished and the steel has been removed for hardening.

Heating High-Speed Steel for Forging.—Care should be taken not to heat high-speed steel for forging too abruptly. In winter, the steel may be extremely cold when brought into the forge shop. If the steel is put directly into the hot forge fire, it is likely to develop cracks that will show up later in the finished tool. The steel, therefore, should be warmed gradually before heating for forging.

Subzero Treatment of Steel

Subzero treatment consists of subjecting the steel, after hardening and either before or after tempering, to a subzero temperature (that usually ranges from -100 to -120 deg. F) and for a period of time varying with the size or volume of the tool, gage, or other part. Commercial equipment is available for obtaining these low temperatures.

The subzero treatment is employed by most gage manufacturers to stabilize precision gages and prevent subsequent changes in size or form. Subzero treatment is also applied to some high-speed steel cutting tools. The object here is to increase the durability or life of the tools; however, up to the present time, the results of tests by metallurgists and tool engineers often differ considerably and in some instances are contradictory. Methods of procedure also vary, especially with regard to the order and number of operations in the complete heat-treating and cooling cycle.

Changes Resulting From Subzero Treatment.—When steel is at the hardening temperature it contains a solid solution of carbon and iron known as *austenite*. When the steel is hardened by sudden cooling, most of the austenite, which is relatively soft, tough, and ductile even at room temperatures, is transformed into martensite, a hard and strong constituent. If all the austenite were changed to martensite upon reaching room temperature, this process would be an ideal hardening operation, but many steels retain some austenite. In general, the higher the carbon and alloy contents and the higher the hardening temperature, the greater the tendency to retain austenite. When steel is cooled to subzero temperatures, the stability of the retained austenite is reduced so that it is more readily transformed. To obtain more complete transformation, the subzero treatment may be repeated. The ultimate transformation of austenite to martensite may take place in carbon steel without the aid of subzero treatment, but this natural transformation might require 6 months or longer, whereas by refrigeration this change occurs in a few hours.

The thorough, uniform heating that is always recommended in heat-treating operations should be accompanied by thorough, uniform cooling when the subzero treatment is applied. To ensure uniform cooling, the subzero cooling period should be increased for the larger tools and it may range from 2 to 6 hours. The tool or other part is sometimes surrounded by one or more layers of heavy wrapping or asbestos paper to delay the cooling somewhat and ensure uniformity. After the cooling cycle is started, it should continue without interruption.

Subzero treatment may sometimes cause cracking. Normally, the austenite in steel provides a cushioning effect that may prevent cracking or breakage resulting from treatments

involving temperature and dimensional changes; but if this cushioning effect is removed, particularly at very low temperatures as in subzero treatments, there may be danger of cracking, especially with tools having large or irregular sections and sharp corners offering relatively low resistance to stresses. This effect is one reason why subzero treatments may differ in regard to the cooling and tempering cycle.

Stabilizing Dimensions of Gages or Precision Parts by Subzero Cooling.—Transformation of austenite into martensite is accompanied by an increase in volume; consequently, the transformation of austenite, that may occur naturally over a period of months or years, tends to change the dimensions and form of steel parts, and such changes may be serious in the case of precision gages, close-fitting machine parts, etc. To prevent such changes, the subzero treatment has proved effective. Gage-blocks, for example, may be stabilized by hardening followed by repeated cycles of chilling and tempering, to transform a large percentage of the austenite into martensite.

Order of Operations for Stabilizing Precision Gages: If precision gages and sine-bars, are heat-treated in the ordinary manner and then are finished without some stabilizing treatment, dimensional changes and warpage are liable to occur. Sub-zero cooling provides a practical and fairly rapid method of obtaining the necessary stabilization by transforming the austenite into martensite. In stabilization treatments of this kind, tempering is the final operation. One series of treatments that has been recommended after hardening and rough-grinding is as follows:

A) Cool to −120 degrees F. (This cooling period may require from one to six hours, depending on the size and form of the gage.)

B) Place gage in boiling water for two hours (oil or salt bath may also be used).

Note: Steps (a) and (b) may be repeated from two to six times, depending on the size and form of the gage. These repeated cycles will eventually transform practically all the austenite into martensite. Two or three cooling and drawing operations usually are sufficient for such work as thread gages and gage-blocks.

C) Follow with regular tempering or drawing operation and finish gage by lapping.

Series of Stabilizing Treatments for Chromium Steel: The following series of treatments has proved successful in stabilizing precision gage-blocks made from SAE 52100 chromium steel.

A) Preheat to 600 degrees F and then heat to 1575 degrees F for a period of four minutes.

B) Quench in oil at 85 degrees F. (Uniform quenching is essential.)

C) Temper at 275 degrees F for one hour.

D) Cool in tempering furnace to room temperature.

E) Continue cooling in atmosphere of industrial refrigerator for six hours with temperature of atmosphere at −120 degrees F.

F) Allow gage-blocks to return to room temperature and again temper.

Note: The complete treatment consists of six subzero cooling periods, each followed by a tempering operation. The transformation to martensite is believed to be complete even after the fifth cooling period. The hardness is about 66 Rockwell C. Transformation is checked by magnetic tests based upon the magnetism of martensite and the nonmagnetic qualities of austenite.

Stabilizing Dimensions of Close-Fitting Machine Parts.—Subzero treatment will always cause an increase in size. Machine parts subjected to repeated and perhaps drastic changes in temperature, as in aircraft, may eventually cause trouble due to growth or warpage as the austenite gradually changes to martensite. In some instances, the sizes of close-fitting moving parts have increased sufficiently to cause seizure. Such treatment, for example, may be applied to precision bearings made from SAE 52100 or alloy carburizing steels for stabilizing or aging them. *Time* aging of 52100 steels after hardening has been found to cause changes as large as 0.0025 inch in medium size sections. A practical remedy is to apply the subzero treatment before the final grinding or other machining operation.

Subzero Treatment of Carburized Parts to Improve Physical Properties.—The sub-zero treatment has been applied to carburized machine parts. For example, the amount of retained austenite in carburized gears may be sufficient to reduce the life of the gears. In one component, the Rockwell hardness was increased from 55 C to 65 C without loss of impact resistance qualities; in fact, impact and fatigue resistance may be increased in some examples.

Application of Subzero Treatments to High-Speed Steel.—The subzero treatment has been applied to such tools as milling cutters, hobs, taps, broaches, and drills. It is applicable to different classes of high-speed steels, such as the 18–4–1 tungsten, 18–4–14 cobalt, and the molybdenum high-speed steels. This *cold* treatment is applied preferably in conjunction with the heat treatment, both being combined in a continuous cycle of operations. The general procedure is either to harden the steel, cool it to a subzero temperature, and then temper; or, especially if there is more than one tempering operation, the first one may *precede* subzero cooling. The cooling and tempering cycle may be repeated two or more times. The number and order of the operations, or the complete cycle, may be varied to suit the class of work and, to minimize the danger of cracking, particularly if the tool has large or irregular sections, sharp corners or edges, or a high cobalt content. A subzero treatment of some kind with a final tempering operation for stress relief, is intended to increase strength and toughness without much loss in hardness; consequently, if there is greater strength at a given hardness, tools subjected to subzero treatment can operate with a higher degree of hardness than those heat treated in the ordinary manner, or, if greater toughness is preferred, it can be obtained by tempering to the original degree of hardness.

Order of Cooling and Tempering Periods for High-speed Steel.—The order or cycle for the cooling and tempering periods has not been standardized. The methods that follow have been applied to high-speed steel tools. They are given as examples of procedure and are subject to possible changes due to subsequent developments. The usual ranges of pre-heating and hardening temperatures are given; but for a particular steel, the recommended temperatures should be obtained from the manufacturer.

1) *Double Subzero Treatment:* (For rugged simple tool forms without irregular sections, sharp corners or edges where cracks might develop during the subzero treatment).

  a) Preheat between 1400 and 1600 degrees F (double preheating is preferable, the first preheating ranging from 700 to 1000 degrees F).

  b) Heat to the hardening temperature. (*Note:* Tests indicate that the effect of subzero treatment on high-speed steel may be influenced decidedly by the hardening temperature. If this temperature is near the lower part of the range, the results are unsatisfactory. Effective temperatures for ordinary high-speed steels appear to range from 2300 to 2350 degrees F).

  c) Quench in oil, salt, lead, or air, down to a workpiece temperature of 150–200 degrees F. (*Note:* One method is to quench in oil; a second method is to quench in oil to about 200–225 degrees F and then air cool; a third method is to quench in salt bath at 1050–1100 degrees F and then air cool.)

  d) Cool in refrigerating unit to temperature of −100 to −120 degrees F *right after quenching*. (*Note:* Tests have shown that a delay of one hour has a detrimental effect, and in ten hours the efficiency of the subzero treatment is reduced 50 per cent. This is because the austenite becomes more and more stabilized when the subzero treatment is delayed; consequently, the austenite is more difficult to transform into martensite.) The refrigerating period usually varies from two to six hours, depending on the size of the tool. Remove the tool from the refrigerating unit and allow it to return to room temperature.

  e) Temper to required hardness for a period of two and one-half to three hours. The tempering temperature usually varies from a minimum of 1000 to 1100 degrees F for ordinary high-speed steels. Tests indicate that if this first tempering is less than two and one-half hours at 1050 degrees F, there will not be sufficient precipitation of car-

bides at the tempering temperature to allow complete transformation of the retained austenite on cooling, whereas more than three hours causes some loss in room temperature hardness, hot hardness, strength, and toughness.

f) Repeat subzero treatment, step (d).

g) Repeat the tempering operation, step (e). (*Note:* The time for the second tempering operation is sometimes reduced to about one-half the time required for the first tempering.)

2) *Single Subzero Treatment:* This treatment is the same as procedure No. 1 except that a second subzero cooling is omitted; hence, the cycle consists of hardening, subzero cooling, and double tempering. Procedure No. 3, which follows, also has one subzero cooling period in the cycle, but this *follows* the first tempering operation.

3) *Tempering Followed by Subzero Treatment:* (This treatment is for tools having irregular sections, sharp corners, or edges where cracks might develop if the hardening operation were followed immediately by subzero cooling.)

a) Preheat and heat for hardening.

b) Preheat and heat for hardening.

c) Quench as described under Procedure No. I.

d) Temper to required hardness.

e) Cool to subzero temperature −100 to −120 degrees F and then allow the tool to return to room temperature.

f) Repeat tempering operation.

Testing the Hardness of Metals

Brinell Hardness Test.—The Brinell test for determining the hardness of metallic materials consists in applying a known load to the surface of the material to be tested through a hardened steel ball of known diameter. The diameter of the resulting permanent impression in the metal is measured and the Brinell Hardness Number (BHN) is then calculated from the following formula in which D = diameter of ball in millimeters, d = measured diameter at the rim of the impression in millimeters, and P = applied load in kilograms.

$$\text{BHN} = \frac{\text{load on indenting tool in kilograms}}{\text{surface area of indentation in sq. mm.}} = \frac{P}{\frac{\pi D}{2}(D - \sqrt{D^2 - d^2})}$$

If the steel ball were not deformed under the applied load and if the impression were truly spherical, then the preceding formula would be a general one, and any combination of applied load and size of ball could be used. The impression, however, is not quite a spherical surface because there must always be some deformation of the steel ball and some recovery of form of the metal in the impression; hence, for a standard Brinell test, the size and characteristics of the ball and the magnitude of the applied load must be standardized. In the standard Brinell test, a ball 10 millimeters in diameter and a load of 3000, 1500, or 500 kilograms is used. It is desirable, although not mandatory, that the test load be of such magnitude that the diameter of the impression be in the range of 2.50 to 4.75 millimeters. The following test loads and approximate Brinell numbers for this range of impression diameters are: 3000 kg, 160 to 600 BHN; 1500 kg, 80 to 300 BHN; 500 kg, 26 to 100 BHN. In making a Brinell test, the load should be applied steadily and without a jerk for at least 15 seconds for iron and steel, and at least 30 seconds in testing other metals. A minimum period of 2 minutes, for example, has been recommended for magnesium and magnesium alloys. (For the softer metals, loads of 250, 125, or 100 kg are sometimes used.)

According to the American Society for Testing and Materials Standard E10-66, a steel ball may be used on material having a BHN not over 450, a Hultgren ball on material not over 500, or a carbide ball on material not over 630. The Brinell hardness test is not recommended for material having a BHN over 630.

Rockwell Hardness Test.—The Rockwell hardness tester is essentially a machine that measures hardness by determining the depth of penetration of a penetrator into the specimen under certain fixed conditions of test. The penetrator may be either a steel ball or a diamond spheroconical penetrator. The hardness number is related to the depth of indentation and the number is higher the harder the material. A minor load of 10 kg is first applied, causing an initial penetration; the dial is set at zero on the black-figure scale, and the major load is applied. This major load is customarily 60 or 100 kg when a steel ball is used as a penetrator, but other loads may be used when necessary. The ball penetrator is $\frac{1}{16}$ inch in diameter normally, but other penetrators of larger diameter, such as $\frac{1}{8}$ inch, may be employed for soft metals. When a diamond spheroconical penetrator is employed, the load usually is 150 kg. Experience decides the best combination of load and penetrator for use. After the major load is applied and removed, according to standard procedure, the reading is taken while the minor load is still applied.

The Rockwell Hardness Scales.—The various Rockwell scales and their applications are shown in the following table. The type of penetrator and load used with each are shown in Tables 1 and 2, which give comparative hardness values for different hardness scales.

Scale	Testing Application
A	For tungsten carbide and other extremely hard materials. Also for thin, hard sheets.
B	For materials of medium hardness such as low- and medium-carbon steels in the annealed condition.
C	For materials harder than Rockwell B-100.
D	Where a somewhat lighter load is desired than on the C scale, as on case-hardened pieces.
E	For very soft materials such as bearing metals.
F	Same as the E scale but using a $\frac{1}{16}$-inch ball.
G	For metals harder than tested on the B scale.
H & K	For softer metals.
15–N; 30–N; 45–N	Where a shallow impression or a small area is desired. For hardened steel and hard alloys.
15–T; 30–T; 45-T	Where a shallow impression or a small area is desired for materials softer than hardened steel.

Shore's Scleroscope.—The scleroscope is an instrument that measures the hardness of the work in terms of elasticity. A diamond-tipped hammer is allowed to drop from a known height on the metal to be tested. As this hammer strikes the metal, it rebounds, and the harder the metal, the greater the rebound. The extreme height of the rebound is recorded, and an average of a number of readings taken on a single piece will give a good indication of the hardness of the work. The surface smoothness of the work affects the reading of the instrument. The readings are also affected by the contour and mass of the work and the depth of the case, in carburized work, the soft core of light-depth carburizing, pack-hardening, or cyanide hardening, absorbing the force of the hammer fall and decreasing the rebound. The hammer weighs about 40 grains, the height of the rebound of hardened steel is in the neighborhood of 100 on the scale, or about $6\frac{1}{4}$ inches, and the total fall is about 10 inches or 255 millimeters.

Vickers Hardness Test.—The Vickers test is similar in principle to the Brinell test. The standard Vickers penetrator is a square-based diamond pyramid having an included point angle of 136 degrees. The numerical value of the hardness number equals the applied load in kilograms divided by the area of the pyramidal impression: A smooth, firmly supported, flat surface is required. The load, which usually is applied for 30 seconds, may be 5, 10, 20, 30, 50, or 120 kilograms. The 50-kilogram load is the most usual. The hardness number is based upon the diagonal length of the square impression. The Vickers test is considered to be very accurate, and may be applied to thin sheets as well as to larger sections with proper load regulation.

Knoop Hardness Numbers.—The Knoop hardness test is applicable to extremely thin metal, plated surfaces, exceptionally hard and brittle materials, very shallow carburized or nitrided surfaces, or whenever the applied load must be kept below 3600 grams. The Knoop indentor is a diamond ground to an elongated pyramidal form and it produces an indentation having long and short diagonals with a ratio of approximately 7 to 1. The longitudinal angle of the indentor is 172 degrees, 30 minutes, and the transverse angle 130 degrees. The Tukon Tester in which the Knoop indentor is used is fully automatic under electronic control. The Knoop hardness number equals the load in kilograms divided by the projected area of indentation in square millimeters. The indentation number corresponding to the long diagonal and for a given load may be determined from a table computed for a theoretically perfect indentor. The load, which may be varied from 25 to 3600 grams, is applied for a definite period and always normal to the surface tested. Lapped plane surfaces free from scratches are required.

Monotron Hardness Indicator.—With this instrument, a diamond-ball impressor point $\frac{3}{4}$ mm in diameter is forced into the material to a depth of $\frac{9}{500}$ inch and the pressure required to produce this constant impression indicates the hardness. One of two dials shows the pressure in kilograms and pounds, and the other shows the depth of the impression in millimeters and inches. Readings in Brinell numbers may be obtained by means of a scale designated as *M*–1.

Keep's Test.—With this apparatus, a standard steel drill is caused to make a definite number of revolutions while it is pressed with standard force against the specimen to be tested. The hardness is automatically recorded on a diagram on which a dead soft material gives a horizontal line, and a material as hard as the drill itself gives a vertical line, intermediate hardness being represented by the corresponding angle between 0 and 90 degrees.

Comparison of Hardness Scales.—Tables 1 and 2 show comparisons of various hardness scales. All such tables are based on the assumption that the metal tested is homogeneous to a depth several times that of the indentation. To the extent that the metal being tested is not homogeneous, errors are introduced because different loads and different shapes of penetrators meet the resistance of metal of varying hardness, depending on the depth of indentation. Another source of error is introduced in comparing the hardness of different materials as measured on different hardness scales. This error arises from the fact that in any hardness test, metal that is severely cold-worked actually supports the penetrator, and different metals, different alloys, and different analyses of the same type of alloy have different cold-working properties. In spite of the possible inaccuracies introduced by such factors, it is of considerable value to be able to compare hardness values in a general way.

The data shown in Table 1 are based on extensive tests on carbon and alloy steels mostly in the heat-treated condition, but have been found to be reliable on constructional alloy steels and tool steels in the as-forged, annealed, normalized, quenched, and tempered conditions, providing they are homogeneous. These hardness comparisons are not as accurate for special alloys such as high manganese steel, 18–8 stainless steel and other austenitic steels, nickel-base alloys, constructional alloy steels, and nickel-base alloys in the cold-worked condition.

The data shown in Table 2 are for hardness measurements of unhardened steel, steel of soft temper, grey and malleable cast iron, and most nonferrous metals. Again these hardness comparisons are not as accurate for annealed metals of high Rockwell B hardness such as austenitic stainless steel, nickel and high nickel alloys, and cold-worked metals of low B-scale hardness such as aluminum and the softer alloys.

Table 1. Comparative Hardness Scales for Steel

Rockwell C-Scale Hardness Number	Diamond Pyramid Hardness Number Vickers	Brinell Hardness Number 10-mm Ball, 3000-kgf Load			Rockwell Hardness Number		Rockwell Superficial Hardness Number Superficial Diam. Penetrator			Shore Scleroscope Hardness Number
		Standard Ball	Hultgren Ball	Tungsten Carbide Ball	A-Scale 60-kgf Load Diam. Penetrator	D-Scale 100-kgf Load Diam. Penetrator	15-N Scale 15-kgf Load	30-N Scale 30-kgf Load	45-N Scale 45-kgf Load	
68	940	…	…	…	85.6	76.9	93.2	84.4	75.4	97
67	900	…	…	…	85.0	76.1	92.9	83.6	74.2	95
66	865	…	…	…	84.5	75.4	92.5	82.8	73.3	92
65	832	…	…	739	83.9	74.5	92.2	81.9	72.0	91
64	800	…	…	722	83.4	73.8	91.8	81.1	71.0	88
63	772	…	…	705	82.8	73.0	91.4	80.1	69.9	87
62	746	…	…	688	82.3	72.2	91.1	79.3	68.8	85
61	720	…	…	670	81.8	71.5	90.7	78.4	67.7	83
60	697	…	613	654	81.2	70.7	90.2	77.5	66.6	81
59	674	…	599	634	80.7	69.9	89.8	76.6	65.5	80
58	653	…	587	615	80.1	69.2	89.3	75.7	64.3	78
57	633	…	575	595	79.6	68.5	88.9	74.8	63.2	76
56	613	…	561	577	79.0	67.7	88.3	73.9	62.0	75
55	595	…	546	560	78.5	66.9	87.9	73.0	60.9	74
54	577	…	534	543	78.0	66.1	87.4	72.0	59.8	72
53	560	…	519	525	77.4	65.4	86.9	71.2	58.6	71
52	544	500	508	512	76.8	64.6	86.4	70.2	57.4	69
51	528	487	494	496	76.3	63.8	85.9	69.4	56.1	68
50	513	475	481	481	75.9	63.1	85.5	68.5	55.0	67
49	498	464	469	469	75.2	62.1	85.0	67.6	53.8	66
48	484	451	455	455	74.7	61.4	84.5	66.7	52.5	64
47	471	442	443	443	74.1	60.8	83.9	65.8	51.4	63
46	458	432	432	432	73.6	60.0	83.5	64.8	50.3	62
45	446	421	421	421	73.1	59.2	83.0	64.0	49.0	60
44	434	409	409	409	72.5	58.5	82.5	63.1	47.8	58
43	423	400	400	400	72.0	57.7	82.0	62.2	46.7	57
42	412	390	390	390	71.5	56.9	81.5	61.3	45.5	56
41	402	381	381	381	70.9	56.2	80.9	60.4	44.3	55
40	392	371	371	371	70.4	55.4	80.4	59.5	43.1	54
39	382	362	362	362	69.9	54.6	79.9	58.6	41.9	52
38	372	353	353	353	69.4	53.8	79.4	57.7	40.8	51
37	363	344	344	344	68.9	53.1	78.8	56.8	39.6	50
36	354	336	336	336	68.4	52.3	78.3	55.9	38.4	49
35	345	327	327	327	67.9	51.5	77.7	55.0	37.2	48
34	336	319	319	319	67.4	50.8	77.2	54.2	36.1	47
33	327	311	311	311	66.8	50.0	76.6	53.3	34.9	46
32	318	301	301	301	66.3	49.2	76.1	52.1	33.7	44
31	310	294	294	294	65.8	48.4	75.6	51.3	32.5	43
30	302	286	286	286	65.3	47.7	75.0	50.4	31.3	42
29	294	279	279	279	64.7	47.0	74.5	49.5	30.1	41
28	286	271	271	271	64.3	46.1	73.9	48.6	28.9	41
27	279	264	264	264	63.8	45.2	73.3	47.7	27.8	40
26	272	258	258	258	63.3	44.6	72.8	46.8	26.7	38
25	266	253	253	253	62.8	43.8	72.2	45.9	25.5	38
24	260	247	247	247	62.4	43.1	71.6	45.0	24.3	37
23	254	243	243	243	62.0	42.1	71.0	44.0	23.1	36
22	248	237	237	237	61.5	41.6	70.5	43.2	22.0	35

Table 1. *(Continued)* **Comparative Hardness Scales for Steel**

Rockwell C-Scale Hardness Number	Diamond Pyramid Hardness Number Vickers	Brinell Hardness Number 10-mm Ball, 3000-kgf Load			Rockwell Hardness Number		Rockwell Superficial Hardness Number Superficial Diam. Penetrator			Shore Sclero-scope Hard-ness Num-ber
		Standard Ball	Hultgren Ball	Tungsten Carbide Ball	A-Scale 60-kgf Load Diam. Penetra-tor	D-Scale 100-kgf Load Diam. Penetra-tor	15-N Scale 15-kgf Load	30-N Scale 30-kgf Load	45-N Scale 45-kgf Load	
21	**243**	**231**	**231**	**231**	**61.0**	**40.9**	**69.9**	**42.3**	**20.7**	35
20	**238**	**226**	**226**	**226**	**60.5**	**40.1**	**69.4**	**41.5**	**19.6**	34
(18)	230	219	219	219	…	…	…	…	…	33
(16)	222	212	212	212	…	…	…	…	…	32
(14)	213	203	203	203	…	…	…	…	…	31
(12)	204	194	194	194	…	…	…	…	…	29
(10)	196	187	187	187	…	…	…	…	…	28
(8)	188	179	179	179	…	…	…	…	…	27
(6)	180	171	171	171	…	…	…	…	…	26
(4)	173	165	165	165	…	…	…	…	…	25
(2)	166	158	158	158	…	…	…	…	…	24
(0)	160	152	152	152	…	…	…	…	…	24

Note: The values in this table shown in **boldface** type correspond to those shown in American Society for Testing and Materials Specification E140-67.

Values in ( ) are beyond the normal range and are given for information only.

Turner's Sclerometer.—In making this test a weighted diamond point is drawn, once forward and once backward, over the smooth surface of the material to be tested. The hardness number is the weight in grams required to produce a standard scratch.

Mohs's Hardness Scale.—Hardness, in general, is determined by what is known as Mohs's scale, a standard for hardness that is applied mainly to nonmetallic elements and minerals. In this hardness scale, there are ten degrees or steps, each designated by a mineral, the difference in hardness of the different steps being determined by the fact that any member in the series will scratch any of the preceding members.

This scale is as follows: 1) talc; 2) gypsum; 3) calcite; 4) fluor spar; 5)   apatite;

6) orthoclase; 7) quartz; 8) topaz; 9) sapphire or corundum; and 10) diamond.

These minerals, arbitrarily selected as standards, are successively harder, from talc, the softest of all minerals, to diamond, the hardest. This scale, which is now universally used for nonmetallic minerals, is not applied to metals.

Relation Between Hardness and Tensile Strength.—The approximate relationship between the hardness and tensile strength is shown by the following formula:

Tensile strength = $Bhn \times 515$ (for Brinell numbers up to 175).

Tensile strength = $Bhn \times 490$ (for Brinell numbers larger than 175).

The above formulas give the tensile strength in pounds per square inch for steels. These approximate relationships between hardness and tensile strength do not apply to nonferrous metals with the possible exception of certain aluminum alloys.

Durometer Tests.—The durometer is a portable hardness tester for measuring hardness of rubber, plastics, and some soft metals. The instrument is designed to apply pressure to the specimen and the hardness is read from a scale while the pressure is maintained. Various scales can be used by changing the indentor and the load applied.

**Table 2. Comparative Hardness Scales for Unhardened Steel,
Soft-Temper Steel, Grey and Malleable Cast Iron, and Nonferrous Alloys**

Rockwell Hardness Number			Rockwell Superficial Hardness Number			Rockwell Hardness Number			Brinell Hardness Number	
Rockwell B scale 1/16″ Ball Penetrator 100-kg Load	Rockwell F scale 1/16″ Ball Penetrator 60-kg Load	Rockwell G scale 1/16″ Ball Penetrator 150-kg Load	Rockwell Superficial 15-T scale 1/16″ Ball Penetrator 15-kg Load	Rockwell Superficial 30-T scale 1/16″ Ball Penetrator 30-kg Load	Rockwell Superficial 45-T scale 1/16″ Ball Penetrator 45-kg Load	Rockwell E scale 1/8″ Ball Penetrator 100-kg Load	Rockwell K scale 1/8″ Ball Penetrator 150-kg Load	Rockwell A scale "Brale" Penetrator 60-kg Load	Brinell Scale 10-mm Standard Ball 500-kg Load	Brinell Scale 10-mm Standard Ball 3000-kg Load
100	…	82.5	93.0	82.0	72.0	…	…	61.5	201	240
99	…	81.0	92.5	81.5	71.0	…	…	61.0	195	234
98	…	79.0	…	81.0	70.0	…	…	60.0	189	228
97	…	77.5	92.0	80.5	69.0	…	…	59.5	184	222
96	…	76.0	…	80.0	68.0	…	…	59.0	179	216
95	…	74.0	91.5	79.0	67.0	…	…	58.0	175	210
94	…	72.5	…	78.5	66.0	…	…	57.5	171	205
93	…	71.0	91.0	78.0	65.5	…	…	57.0	167	200
92	…	69.0	90.5	77.5	64.5	…	100	56.5	163	195
91	…	67.5	…	77.0	63.5	…	99.5	56.0	160	190
90	…	66.0	90.0	76.0	62.5	…	98.5	55.5	157	185
89	…	64.0	89.5	75.5	61.5	…	98.0	55.0	154	180
88	…	62.5	…	75.0	60.5	…	97.0	54.0	151	176
87	…	61.0	89.0	74.5	59.5	…	96.5	53.5	148	172
86	…	59.0	88.5	74.0	58.5	…	95.5	53.0	145	169
85	…	57.5	…	73.5	58.0	…	94.5	52.5	142	165
84	…	56.0	88.0	73.0	57.0	…	94.0	52.0	140	162
83	…	54.0	87.5	72.0	56.0	…	93.0	51.0	137	159
82	…	52.5	…	71.5	55.0	…	92.0	50.5	135	156
81	…	51.0	87.0	71.0	54.0	…	91.0	50.0	133	153
80	…	49.0	86.5	70.0	53.0	…	90.5	49.5	130	150
79	…	47.5	…	69.5	52.0	…	89.5	49.0	128	147
78	…	46.0	86.0	69.0	51.0	…	88.5	48.5	126	144
77	…	44.0	85.5	68.0	50.0	…	88.0	48.0	124	141
76	…	42.5	…	67.5	49.0	…	87.0	47.0	122	139
75	99.5	41.0	85.0	67.0	48.5	…	86.0	46.5	120	137
74	99.0	39.0	…	66.0	47.5	…	85.0	46.0	118	135
73	98.5	37.5	84.5	65.5	46.5	…	84.5	45.5	116	132
72	98.0	36.0	84.0	65.0	45.5	…	83.5	45.0	114	130
71	97.5	34.5	…	64.0	44.5	100	82.5	44.5	112	127
70	97.0	32.5	83.5	63.5	43.5	99.5	81.5	44.0	110	125
69	96.0	31.0	83.0	62.5	42.5	99.0	81.0	43.5	109	123
68	95.5	29.5	…	62.0	41.5	98.0	80.0	43.0	107	121
67	95.0	28.0	82.5	61.5	40.5	97.5	79.0	42.5	106	119
66	94.5	26.5	82.0	60.5	39.5	97.0	78.0	42.0	104	117
65	94.0	25.0	…	60.0	38.5	96.0	77.5	…	102	116
64	93.5	23.5	81.5	59.5	37.5	95.5	76.5	41.5	101	114
63	93.0	22.0	81.0	58.5	36.5	95.0	75.5	41.0	99	112
62	92.0	20.5	…	58.0	35.5	94.5	74.5	40.5	98	110
61	91.5	19.0	80.5	57.0	34.5	93.5	74.0	40.0	96	108
60	91.0	17.5	…	56.5	33.5	93.0	73.0	39.5	95	107
59	90.5	16.0	80.0	56.0	32.0	92.5	72.0	39.0	94	106

Table 2. *(Continued)* **Comparative Hardness Scales for Unhardened Steel, Soft-Temper Steel, Grey and Malleable Cast Iron, and Nonferrous Alloys**

Rockwell Hardness Number			Rockwell Superficial Hardness Number			Rockwell Hardness Number				Brinell
B scale 1/16" Ball Penetrator 100-kg Load	F scale 1/16" Ball Penetrator 60-kg Load	G scale 1/16" Ball Penetrator 150-kg Load	Superficial 15-T scale 1/16" Ball Penetrator 15-kg Load	Superficial 30-T scale 1/16" Ball Penetrator 30-kg Load	Superficial 45-T scale 1/16" Ball Penetrator 45-kg Load	E scale 1/8" Ball Penetrator 100-kg Load	H scale 1/8" Ball Penetrator 60-kg Load	K scale 1/8" Ball Penetrator 150-kg Load	A scale "Brale" Penetrator 60-kg Load	Brinell Scale 10-mm Standard Ball 500-kg Load
58	90.0	14.5	79.5	55.0	31.0	92.0	…	71.0	38.5	92
57	89.5	13.0	…	54.5	30.0	91.0	…	70.5	38.0	91
56	89.0	11.5	79.0	54.0	29.0	90.5	…	69.5	…	90
55	88.0	10.0	78.5	53.0	28.0	90.0	…	68.5	37.5	89
54	87.5	8.5	…	52.5	27.0	89.5	…	68.0	37.0	87
53	87.0	7.0	78.0	51.5	26.0	89.0	…	67.0	36.5	86
52	86.5	5.5	77.5	51.0	25.0	88.0	…	66.0	36.0	85
51	86.0	4.0	…	50.5	24.0	87.5	…	65.0	35.5	84
50	85.5	2.5	77.0	49.5	23.0	87.0	…	64.5	35.0	83
49	85.0	1.0	76.5	49.0	22.0	86.5	…	63.5	…	82
48	84.5	…	…	48.5	20.5	85.5	…	62.5	34.5	81
47	84.0	…	76.0	47.5	19.5	85.0	…	61.5	34.0	80
46	83.0	…	75.5	47.0	18.5	84.5	…	61.0	33.5	…
45	82.5	…	…	46.0	17.5	84.0	…	60.0	33.0	79
44	82.0	…	75.0	45.5	16.5	83.5	…	59.0	32.5	78
43	81.5	…	74.5	45.0	15.5	82.5	…	58.0	32.0	77
42	81.0	…	…	44.0	14.5	82.0	…	57.5	31.5	76
41	80.5	…	74.0	43.5	13.5	81.5	…	56.5	31.0	75
40	79.5	…	73.5	43.0	12.5	81.0	…	55.5	…	74
39	79.0	…	…	42.0	11.0	80.0	…	54.5	30.5	74
38	78.5	…	73.0	41.5	10.0	79.5	…	54.0	30.0	73
37	78.0	…	72.5	40.5	9.0	79.0	…	53.0	29.5	72
36	77.5	…	…	40.0	8.0	78.5	100	52.0	29.0	…
35	77.0	…	72.0	39.5	7.0	78.0	99.5	51.5	28.5	71
34	76.5	…	71.5	38.5	6.0	77.0	99.0	50.5	28.0	70
33	75.5	…	…	38.0	5.0	76.5	…	49.5	…	69
32	75.0	…	71.0	37.5	4.0	76.0	98.5	48.5	27.5	…
31	74.5	…	…	36.5	3.0	75.5	98.0	48.0	27.0	68
30	74.0	…	70.5	36.0	2.0	75.0	…	47.0	26.5	67
29	73.5	…	70.0	35.5	1.0	74.0	97.5	46.0	26.0	…
28	73.0	…	…	34.5	…	73.5	97.0	45.0	25.5	66
27	72.5	…	69.5	34.0	…	73.0	96.5	44.5	25.0	…
26	72.0	…	69.0	33.0	…	72.5	…	43.5	24.5	65
25	71.0	…	…	32.5	…	72.0	96.0	42.5	…	64
24	70.5	…	68.5	32.0	…	71.0	95.5	41.5	24.0	…
23	70.0	…	68.0	31.0	…	70.5	…	41.0	23.5	63
22	69.5	…	…	30.5	…	70.0	95.0	40.0	23.0	…
21	69.0	…	67.5	29.5	…	69.5	94.5	39.0	22.5	62
20	68.5	…	…	29.0	…	68.5	…	38.0	22.0	…
19	68.0	…	67.0	28.5	…	68.0	94.0	37.5	21.5	61
18	67.0	…	66.5	27.5	…	67.5	93.5	36.5	…	…
17	66.5	…	…	27.0	…	67.0	93.0	35.5	21.0	60
16	66.0	…	66.0	26.0	…	66.5	…	35.0	20.5	…
15	65.5	…	65.5	25.5	…	65.5	92.5	34.0	20.0	59
14	65.0	…	…	25.0	…	65.0	92.0	33.0	…	…
13	64.5	…	65.0	24.0	…	64.5	…	32.0	…	58
12	64.0	…	64.5	23.5	…	64.0	91.5	31.5	…	…
11	63.5	…	…	23.0	…	63.5	91.0	30.5	…	…
10	63.0	…	64.0	22.0	…	62.5	90.5	29.5	…	57
9	62.0	…	…	21.5	…	62.0	…	29.0	…	…
8	61.5	…	63.5	20.5	…	61.5	90.0	28.0	…	…
7	61.0	…	63.0	20.0	…	61.0	89.5	27.0	…	56
6	60.5	…	…	19.5	…	60.5	…	26.0	…	…
5	60.0	…	62.5	18.5	…	60.0	89.0	25.5	…	55
4	59.5	…	62.0	18.0	…	59.0	88.5	24.5	…	…
3	59.0	…	…	17.0	…	58.5	88.0	23.5	…	…
2	58.0	…	61.5	16.5	…	58.0	…	23.0	…	54
1	57.5	…	61.0	16.0	…	57.5	87.5	22.0	…	…
0	57.0	…	…	15.0	…	57.0	87.0	21.0	…	53

Not applicable to annealed metals of high B-scale hardness such as austenitic stainless steels, nickel and high-nickel alloys nor to cold-worked metals of low B-scale hardness such as aluminum and the softer alloys. (Compiled by Wilson Mechanical Instrument Co.)

Creep.—Continuing changes in dimensions of a stressed material over time is called creep, and it varies with different materials and periods under stress, also with temperature. Creep tests may take some time as it is necessary to apply a constant tensile load to a specimen under a selected temperature. Measurements are taken to record the resulting elongation at time periods sufficiently long for a relationship to be established. The data are then plotted as elongation against time. The load is applied to the specimen only after it has reached the testing temperature, and causes an initial elastic elongation that includes some plastic deformation if the load is above the proportional limit for the material.

Some combinations of stress and temperature may cause failure of the specimen. Others show initial high rates of deformation, followed by decreasing, then constant, rates over long periods. Generally testing times to arrive at the constant rate of deformation are over 1000 hours.

Creep Rupture.—Tests for creep rupture are similar to creep tests but are prolonged until the specimen fails. Further data to be obtained from these tests include time to rupture, amount of elongation, and reduction of area. Stress-rupture tests are performed without measuring the elongation, so that no strain data are recorded, time to failure, elongation and reduction of area being sufficient. Sometimes, a V-notch is cut in the specimen to allow measurement of notch sensitivity under the testing conditions.

Stress Analysis.—Stresses, deflections, strains, and loads may be determined by application of strain gages or lacquers to the surface of a part, then applying loads simulating those to be encountered in service. Strain gages are commercially available in a variety of configurations and are usually cemented to the part surface. The strain gages are then calibrated by application of a known moment, load, torque, or pressure. The electrical characteristics of the strain gages change in proportion to the amount of strain, and the magnitude of changes in these characteristics under loads to be applied in service indicate changes caused by stress in the shape of the components being tested.

Lacquers are compounded especially for stress analysis and are applied to the entire part surface. When the part is loaded, and the lacquer is viewed under light of specific wavelength, stresses are indicated by color shading in the lacquer. The presence and intensity of the strains can then be identified and measured on the part(s) or on photographs of the setup. From such images, it is possible to determine the need for thicker walls, strengthening ribs and other modifications to component design that will enable the part to withstand stresses in service.

Most of these tests have been standardized by the American Society for Testing and Materials (ASTM), and are published in their *Book of Standards* in separate sections for metals, plastics, rubber, and wood. Many of the test methods are also adopted by the American National Standards Institute (ANSI).

Identifying Metals.—When it is necessary to sort materials, several rough methods may be used without elaborate chemical analysis. The most obvious of these is by using a magnet to pick out those materials that contain magnetic elements. To differentiate various levels of carbon and other elements in a steel bar, hold the bar in contact with a grinding wheel and observe the sparks. With high levels of carbon, for instance, sparks are produced that appear to split into several bright tracers. Patterns produced by several other elements, including small amounts of aluminum and titanium, for instance, can be identified with the aid of Data Sheet 13, issued by the American Society for Metals (ASM), Metals Park, OH.