TOOL STEELS

Overview

As the designation implies, tool steels serve primarily for making tools used in manufacturing and in the trades for the working and forming of metals, wood, plastics, and other industrial materials. Tools must withstand high specific loads, often concentrated at exposed areas, may have to operate at elevated or rapidly changing temperatures and in continual contact with abrasive types of work materials, and are often subjected to shocks, or may have to perform under other varieties of adverse conditions. Nevertheless, when employed under circumstances that are regarded as normal operating conditions, the tool should not suffer major damage, untimely wear resulting in the dulling of the edges, or be susceptible to detrimental metallurgical changes.

Tools for less demanding uses, such as ordinary handtools, including hammers, chisels, files, mining bits, etc., are often made of standard AISI steels that are not considered as belonging to any of the tool steel categories.

The steel for most types of tools must be used in a heat-treated state, generally hardened and tempered, to provide the properties needed for the particular application. The adaptability to heat treatment with a minimurn of harmful effects, which dependably results in the intended beneficial changes in material properties, is still another requirement that tool steels must satisfy.

To meet such varied requirements, steel types of different chemical composition, often produced by special metallurgical processes, have been developed. Due to the large number of tool steel types produced by the steel mills, which generally are made available with proprietary designations, it is rather difficult for the user to select those types that are most suitable for any specific application, unless the recommendations of a particular steel producer or producers are obtained.

Substantial clarification has resulted from the development of a classification system that is now widely accepted throughout the industry, on the part of both the producers and the users of tool steels. That system is used in the following as a base for providing concise information on tool steel types, their properties, and methods of tool steel selection.

The tool steel classification system establishes seven basic categories of tool and die steels. These categories are associated with the predominant applicational characteristics of the tool steel types they comprise. A few of these categories are composed of several groups to distinguish between families of steel types that, while serving the same general purpose, differ with regard to one or more dominant characteristics.

To provide an easily applicable guide for the selection of tool steel types best suited for a particular application, the subsequent discussions and tables are based on the previously mentioned application-related categories. As an introduction to the detailed surveys, a concise discussion is presented of the principal tool steel characteristics that govern the suitability for varying service purposes and operational conditions. A brief review of the major steel alloying elements and of the effect of these constituents on the significant characteristics of tool steels is also given in the following sections.

The Properties of Tool Steels.—Tool steels must possess certain properties to a higher than ordinary degree to make them adaptable for uses that require the ability to sustain heavy loads and perform dependably even under adverse conditions.

The extent and the types of loads, the characteristics of the operating conditions, and the expected performance with regard to both the duration and the level of consistency are the principal considerations, in combination with the aspects of cost, that govern the selection of tool steels for specific applications.

Although it is not possible to define and apply exact parameters for measuring significant tool steel characteristics, certain properties can be determined that may greatly assist in appraising the suitability of various types of tool steels for specific uses.

Because tool steels are generally heat-treated to make them adaptable to the intended use by enhancing the desirable properties, *the behavior of the steel during heat treatment* is of prime importance. The behavior of the steel comprises, in this respect, both the resistance to harmful effects and the attainment of the desirable properties. The following are considered the major properties related to heat treatment:

Safety in Hardening: This designation expresses the ability of the steel to withstand the harmful effects of exposure to very high heat and particularly to the sudden temperature changes during quenching, without harmful effects. One way of obtaining this property is by adding alloying elements that reduce the critical speed at which the quenching must be carried out, thus permitting the use of milder quenching media such as oil, salt, or just still air.

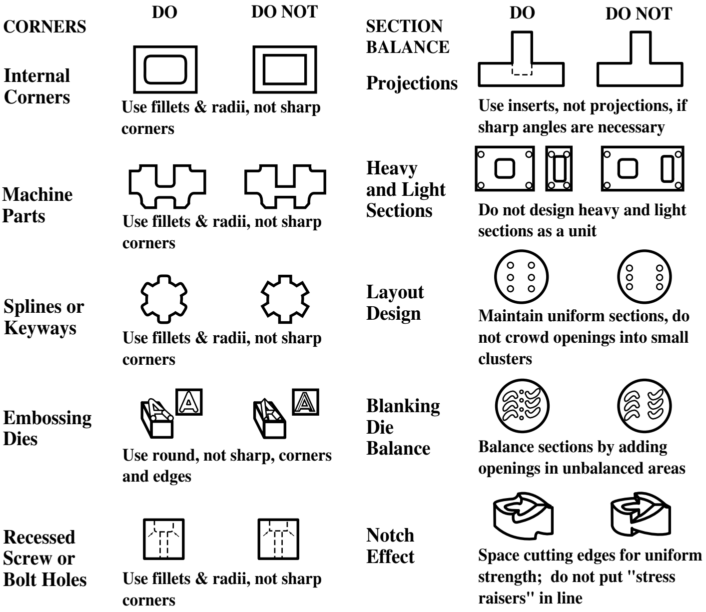

Fig. 1. Tool and die design tips to reduce breakage in heat treatment.
Courtesy of Society of Automotive Engineers, Inc.

The most common harm parts made of tool steel suffer from during heat treatment is the development of cracks. In addition to the composition of the steel and the applied heat-treating process, the configuration of the part can also affect the sensitivity to cracking. The preceding figure illustrates a few design characteristics related to cracking and warpage in heat treatment; the observation of these design tips, which call for generous filleting, avoidance of sharp angles, and major changes without transition in the cross-section, is particularly advisable when using tool steel types with a low index value for safety in hardening.

In current practice, the previously mentioned property of tool steels is rated in the order of decreasing safety (i.e., increasing sensitivity) as Highest, Very High, High, Medium, and Low safety, expressed in Tables 8 through 13 by the letters A, B, C, D, and E.

Distortions in Heat Treating: In parts made from tool steels, distortions are often a consequence of inadequate design (See Fig. 1.) or improper heat treatment (e.g., lack of stress relieving). However, certain types of tool steels display different degrees of sensitivity to distortion. Steels that are less stable require safer design of the parts for which they are used, more careful heat treatment, including the proper support for long and slender parts, or thin sections, and possibly greater grinding allowance to permit subsequent correction of the distorted shape. Some parts made of a type of steel generally sensitive to distortions can be heat-treated with very little damage when the requirements of the part call for a relatively shallow hardened layer over a soft core. However, for intricate shapes and large tools, steel types should be selected that possess superior nondeforming properties. The ratings used in Tables 8 through 13 express the nondeforming properties (stability of shape in heat treatment) of the steel types and start with the lowest distortion (the best stability) designated as A; the greatest susceptibility to distortion is designated as E.

Depth of Hardening: Hardening depth is indicated by a relative rating based on how deep the phase transformation penetrates from the surface and thus produces a hardened layer. Because of the effect of the heat-treating process, and particularly of the applied quenching medium, on the depth of hardness, reference is made in Tables 8 through 13 to the quench that results in the listed relative hardenability values. These values are designated by letters A, B, and C, expressing deep, medium, and shallow depth, respectively.

Resistance to Decarburization: Higher or lower sensitivity to losing a part of the carbon content of the surface exposed to heat depends on the chemistry of the steel. The sensitivity can be balanced partially by appropriate heat-treating equipment and processes. Also, the amount of material to be removed from the surface after heat treatment, usually by grinding, should be specified in such a manner as to avoid the retention of a decarburized layer on functional surfaces. The relative resistance of individual tool steel types to decarburization during heat treatment is rated in Tables 8 through 13 from High to Low, expressed by the letters A, B, and C.

Tool steels must be workable with generally available means, without requiring highly specialized processes. The tools made from these steels must, of course, perform adequately, often under adverse environmental and burdensome operational conditions. The ability of the individual types of tool steels to satisfy, to different degrees, such applicational requirements can also be appraised on the basis of significant properties, such as the following.

Machinability: Tools are precision products whose final shape and dimensions must be produced by machining, a process to which not all tool steel types lend themselves equally well. The difference in machinability is particularly evident in tool steels that, depending on their chemical composition, may contain substantial amounts of metallic carbides, beneficial to increased wear resistance, yet detrimental to the service life of tools with which the steel has to be worked. The microstructure of the steel type can also affect the ease of machining and, in some types, certain phase conditions, such as those due to low carbon content, may cause difficulties in achieving a fine surface finish. Certain types of tool steels have their machinability improved by the addition of small amounts of sulfur or lead. Machinability affects the cost of making the tool, particularly for intricate tool shapes, and must be considered in selection of the steel to be used. The ratings in Tables 8 through 13, starting with A for the greatest ease of machining to E for the lowest machinability, refer to working of the steel in an unhardened condition. Machinability is not necessarily identical with grindability, which expresses how well the steel is adapted to grinding after heat treating. The ease of grinding, however, may become an important consideration in tool steel selection, particularly for cutting tools and dies, which require regular sharpening involving extensive grinding. AVCO Bay State Abrasives Company compiled information on the relative grindability of frequently used types of tool steels. A simplified version of that information is presented in Table 1, which assigns the listed tool steel types to one of the following grindability grades: High (A), Medium (B), Low (C), and Very Low (D), expressing decreasing ratios of volume of metal removed to wheel wear.

Table 1. Relative Grindability of Selected Types of Frequently Used Tool Steels

AISI Tool Steel Type	H41	H42	H43	Other H	D2	D3	D5	D7	A Types	O Types	L Types	F Types
Relative Grindability Index	B	B	B	A	B	B	B	C	A	A	A	B

AISI High-Speed Tool Steel Type	M1	M2	M3 (1)	M3 (2)	M4	M7	M8	M10	M15	M36	M43	T1	T2	T3	T5	T6	T15
Relative Grindability Index	A	B	C	C	D	B	A	B	D	B	B	A	B	C	B	B	D

Hot Hardness: This property designates the steel's resistance to the softening effect of elevated temperature. This characteristic is related to the tempering temperature of the type of steel, which is controlled by various alloying elements such as tungsten, molybdenum, vanadium, cobalt, and chromium.

Hot hardness is a necessary property of tools used for hot work, like forging, casting, and hot extrusion. Hot hardness is also important in cutting tools operated at high-speed, which generate sufficient heat to raise their temperature well above the level where ordinary steels lose their hardness; hence the designation *high-speed steels*, which refers to a family of tool steels developed for use at high cutting speeds. Frequently it is the degree of the tool steel's resistance to softening at elevated temperature that governs important process data, such as the applicable cutting speed. In the ratings of Tables 8 through 13, tool steel types having the highest hot hardness are marked with A, subsequent letters expressing gradually decreasing capacity to endure elevated temperature without losing hardness.

Wear Resistance: The gradual erosion of the tool's operating surface, most conspicuously occurring at the exposed edges, is known as wear. Resistance to wear prolongs the useful life of the tool by delaying the degradation of its surface through abrasive contact with the work at regular operating temperatures; these temperatures vary according to the type of process. Wear resistance is observable experimentally and measurable by comparison. Certain types of metallic carbides embedded into the steel matrix are considered to be the prime contributing factors to wear resistance, besides the hardness of the heat-treated steel material. The ratings of Tables 8 through 13, starting with A for the best to E for poor, are based on conditions thought to be normal in operations for which various types of tool materials are primarily used.

Toughness: In tool steels, this property expresses ability to sustain shocks, suddenly applied and relieved loads, or major impacts, without breaking. Steels used for making tools must also be able to absorb such forces with only a minimum of elastic deformation and without permanent deformation to any extent that would interfere with the proper functioning of the tool. Certain types of tool steels, particularly those with high carbon content and without the presence of beneficial alloying constituents, tend to be the most sensitive to shocks, although they can also be made to act tougher when used for tools that permit a hardened case to be supported by a soft core. Tempering improves toughness, while generally reducing hardness. The rating indexes in Tables 8 through 13, A for the highest toughness through E for the types most sensitive to shocks, apply to tools heat treated to hardness values normally used for the particular type of tool steel.

Common Tool Faults and Failures.—The proper selection of the steel grade used for any particular type of tool is of great importance, but it should be recognized that many of the failures experienced in common practice originate from causes other than those related to the tool material.

To permit a better appraisal of the actual causes of failure and possible corrective action, a general, although not complete, list of common tool faults, resulting failures, and corrective actions is shown in Tables 2 through Tables 5. In this list, the potential failure causes are grouped into four categories. The possibility of more than a single cause being responsible for the experienced failure should not be excluded.

Finally, it must be remembered that the proper usage of tools is indispensable for obtaining satisfactory performance and tool life. Using the tools properly involves, for example, the avoidance of damage to the tool; overloading; excessive speeds and feeds; the application of adequate coolant when called for; a rigid setup; proper alignment; and firm tool and work holding.

Table 2. Common Tool Faults, Failures, and Cures
Improper Tool Design

Fault Description	Probable Failure	Possible Cure
Drastic section changes—widely different thicknesses of adjacent wall sections or protruding elements	In liquid quenching, the thin section will cool and then harden more rapidly than the adjacent thicker section, setting up stresses that may exceed the strength of the steel.	Make such parts of two pieces or use an air-hardening tool steel that avoids the harsh action of a liquid quench.
Sharp corners on shoulders or in square holes	Cracking can occur, particularly in liquid quenching, due to stress concentrations.	Apply fillets to the corners and/or use an air-hardening tool steel.
Sharp cornered keyways	Failure may arise during service, and is usually considered to be caused by fatigue.	The use of round keyways should be preferred when the general configuration of the part makes it prone to failure due to square keyways.
Abrupt section changes in battering tools	Due to impact in service, pneumatic tools are particularly sensitive to stress concentrations that lead to fatigue failures.	Use taper transitions, which are better than even generous fillets.
Functional inadequacy of tool design—e.g., insufficient guidance for a punch	Excessive wear or breakage in service may occur.	Assure solid support, avoid unnecessary play, adapt travel length to operational conditions (e.g., punch to penetrate to four-fifths of thickness in hard work material).
Improper tool clearance, such as in blanking and punching tools	Deformed and burred parts may be produced, excessive tool wear or breakage can result.	Adapt clearances to material conditions and dimensions to reduce tool load and to obtain clean sheared surfaces.

Table 3. Common Tool Faults, Failures, and Cures
Faulty Condition or Inadequate Grade of Tool Steel

Fault Description	Probable Failure	Possible Cure
Improper tool steel grade selection	Typical failures: Chipping—insufficient toughness. Wear—poor abrasion resistance. Softening—inadequate "red hardness."	Choose the tool steel grade by following recommendations and improve selection when needed, guided by property ratings.
Material defects—voids, streaks, tears, flakes, surface cooling cracks, etc.	When not recognized during material inspection, tools made of defective steel often prove to be useless.	Obtain tool steels from reliable sources and inspect tool material for detectable defects.

Table 3. *(Continued)* Common Tool Faults, Failures, and Cures
Faulty Condition or Inadequate Grade of Tool Steel

Fault Description	Probable Failure	Possible Cure
Decarburized surface layer ("bark") in rolled tool steel bars	Cracking may originate from the decarburized layer or it will not harden ("soft skin").	Provide allowance for stock to be removed from all surfaces of hot-rolled tool steel. Recommended amounts are listed in tool steel catalogs and vary according to section size, generally about 10 per cent for smaller and 5 per cent for larger diameters.
Brittleness caused by poor carbide distribution in high-alloy tool steels	Excessive brittleness can cause chipping or breakage during service.	Bars with large diameter (above about 4 inches) tend to be prone to nonuniform carbide distribution. Choose upset forged discs instead of large-diameter bars.
Unfavorable grain flow	Improper grain flow of the steel used for milling cutters and similar tools can cause teeth to break out.	Upset forged discs made with an upset ratio of about 2 to 1 (starting to upset thickness) display radial grain flow. Highly stressed tools, such as gear-shaper cutters, may require the cross forging of blanks.

Table 4. Common Tool Faults, Failures, and Cures
Heat-Treatment Faults

Fault Description	Probable Failure	Possible Cure
Improper preparation for heat treatment. Certain tools may require stress relieving or annealing, and often preheating, too	Tools highly stressed during machining or forming, unless stress relieved, may aggravate the thermal stresses of heat treatment, thus causing cracks. Excessive temperature gradients developed in nonpreheated tools with different section thicknesses can cause warpage.	Stress relieve, when needed, before hardening. Anneal prior to heavy machining or cold forming (e.g., hobbing). Preheat tools (a) having substantial section thickness variations or (b) requiring high quenching temperatures, as those made of high-speed tool steels.
Overheating during hardening; quenching from too high a temperature	Causes grain coarsening and a sensitivity to cracking that is more pronounced in tools with drastic section changes.	Overheated tools have a characteristic microstructure that aids recognition of the cause of failure and indicates the need for improved temperature control.
Low hardening temperature	The tool may not harden at all, or in its outer portion only, thereby setting up stresses that can lead to cracks.	Controlling both the temperature of the furnace and the time of holding the tool at quenching temperature will prevent this not too frequent deficiency.
Inadequate composition or condition of the quenching media	Water-hardening tool steels are particularly sensitive to inadequate quenching media, which can cause soft spots or even violent cracking.	For water-hardening tool steels, use water free of dissolved air and contaminants, also assure sufficient quantity and proper agitation of the quench.
Improper handling during and after quenching	Cracking, particularly of tools with sharp corners, during the heat treatment can result from holding the part too long in the quench or incorrectly applied tempering.	Following the steel producer's specifications is a safe way to assure proper heat-treatment handling. In general, the tool should be left in the quench until it reaches a temperature of 150 to 200°F, and should then be transferred promptly into a warm tempering furnace.
Insufficient tempering	Omission of double tempering for steel types that require it may cause early failure by heat checking in hot-work steels or make the tool abnormally sensitive to grinding checks.	Double temper highly alloyed tool steel of the high-speed, hot-work, and high-chromium categories, to remove stresses caused by martensite formed during the first tempering phase. Second temper also increases hardness of most high-speed steels.

Table 4. *(Continued)* Common Tool Faults, Failures, and Cures
Heat-Treatment Faults

Fault Description	Probable Failure	Possible Cure
Decarburization and carburization	Unless hardened in a neutral atmosphere the original carbon content of the tool surface may be changed: Reduced carbon (decarburization) causes a soft layer that wears rapidly. Increased carbon (carburization) when excessive may cause brittleness.	Heating in neutral atmosphere or well-maintained salt bath and controlling the furnace temperature and the time during which the tool is subjected to heating can usually keep the carbon imbalance within acceptable limits.

Table 5. Common Tool Faults, Failures, and Cures
Grinding Damages

Fault Description	Probable Failure	Possible Cure
Grinding Damages		
Excessive stock removal rate causing heating of the part surface beyond the applied tempering temperature	Scorched tool surface displaying temper colors varying from yellow to purple, depending on the degree of heat, causes softening of the ground surface. When coolant is used, a local rehardening can take place, often resulting in cracks.	Prevention: by reducing speed and feed, or using coarser, softer, more open-structured grinding wheel, with ample coolant. Correction: eliminate the discolored layer by subsequent light stock removal. Not always a cure, because the effects of abusive grinding may not be corrected.
Improper grinding wheel specifications; grain too fine or bond too hard	Intense localized heating during grinding may set up surface stresses causing grinding cracks. These cracks are either parallel but at right angles to the direction of grinding or, when more advanced, form a network. May need cold etch or magnetic particle testing to become recognizable.	Prevention: by correcting the grinding wheel specifications. Correction: in shallow (0.002- to 0.004-inch) cracks, by removing the damaged layer, when permitted by the design of the tool, using very light grinding passes.
Incorrectly dressed or loaded grinding wheel	Heating of the work surface can cause scorching or cracking. Incorrect dressing can also cause a poor finish of the ground work surface.	Dress wheel with sharper diamond and faster diamond advance to produce coarser wheel surface. Alternate dressing methods, like crush-dressing, can improve wheel surface conditions. Dress wheel regularly to avoid loading or glazing of the wheel surface.
Inadequate coolant, with regard to composition, amount, distribution, and cleanliness	Introducing into the tool surface heat that is not adequately dissipated or absorbed by the coolant can cause softening, or even the development of cracks.	Improve coolant supply and quality, or reduce stock removal rate to reduce generation of heat in grinding.
Damage caused by abusive abrasive cutoff	The intensive heat developed during this process can cause a hardening of the steel surface, or may even result in cracks.	Reduce rate of advance; adopt wheel specifications better suited for the job. Use ample coolant or, when harmful effect not eliminated, replace abrasive cutoff by some cooler-acting stock separation method (e.g., sawing or lathe cutoff) unless damaged surface is being removed by subsequent machining.

Note: Illustrated examples of tool failures from causes such as listed above may be found in “The Tool Steel Trouble Shooter” handbook, published by Bethlehem Steel Corporation.

The Effect of Alloying Elements on Tool Steel Properties.—*Carbon (C):* The presence of carbon, usually in excess of 0.60 per cent for nonalloyed types, is essential for raising the hardenability of steels to the levels needed for tools. Raising the carbon content by different amounts up to a maximum of about 1.3 per cent increases the hardness slightly and the wear resistance considerably. The amount of carbon in tool steels is designed to attain certain properties (such as in the water-hardening category where higher carbon content may be chosen to improve wear resistance, although to the detriment of toughness) or, in the alloyed types of tool steels, in conformance with the other constituents to produce well-balanced metallurgical and performance properties.

Manganese (Mn): In small amounts, to about 0.60 per cent, manganese is added to reduce brittleness and to improve forgeability. Larger amounts of manganese improve hardenability, permitting oil quenching for nonalloyed carbon steels, thus reducing deformation, although with regard to several other properties, manganese is not an equivalent replacement for the regular alloying elements.

Silicon (Si): In itself, silicon may not be considered an alloying element of tool steels, but it is needed as a deoxidizer and improves the hot-forming properties of the steel. In combination with certain alloying elements, the silicon content is sometimes raised to about 2 per cent to increase the strength and toughness of steels used for tools that have to sustain shock loads.

Tungsten (W): Tungsten is one of the important alloying elements of tool steels, particularly because of two valuable properties: it improves “hot hardness,” that is, the resistance of the steel to the softening effect of elevated temperature, and it forms hard, abrasion-resistant carbides, thus improving the wear properties of tool steels.

Vanadium (V): Vanadium contributes to the refinement of the carbide structure and thus improves the forgeability of alloy tool steels. Vanadium has a very strong tendency to form a hard carbide, which improves both the hardness and the wear properties of tool steels. However, a large amount of vanadium carbide makes the grinding of the tool very difficult (causing low grindability).

Molybdenum (Mo): In small amounts, molybdenum improves certain metallurgical properties of alloy steels such as deep hardening and toughness. It is used often in larger amounts in certain high-speed tool steels to replace tungsten, primarily for economic reasons, often with nearly equivalent results.

Cobalt (Co): As an alloying element of tool steels, cobalt increases hot hardness and is used in applications where that property is needed. Substantial addition of cobalt, however, raises the critical quenching temperature of the steel with a tendency to increase the decarburization of the surface, and reduces toughness.

Chromium (Cr): This element is added in amounts of several per cent to high-alloy tool steels, and up to 12 per cent to types in which chromium is the major alloying element. Chromium improves hardenability and, together with high carbon, provides both wear resistance and toughness, a combination valuable in certain tool applications. However, high chromium raises the hardening temperature of the tool steel, and thus can make it prone to hardening deformations. A high percentage of chromium also affects the grindability of the tool steel.

Nickel (Ni): Generally in combination with other alloying elements, particularly chromium, nickel is used to improve the toughness and, to some extent, the wear resistance of tool steels.

The addition of more than one element to a steel often produces what is called a synergistic effect. Thus, the combined effects of two or more alloy elements may be greater than the sum of the individual effects of each element.

Classification of Tool Steels.—Steels for tools must satisfy a number of different, often conflicting requirements. The need for specific steel properties arising from widely varying applications has led to the development of many compositions of tool steels, each intended to meet a particular combination of applicational requirements. The resultant diversity of tool steels, their number being continually expanded by the addition of new developments, makes it extremely difficult for the user to select the type best suited to his needs, or to find equivalent alternatives for specific types available from particular sources.

As a cooperative industrial effort under the sponsorship of AISI and SAE, a tool classification system has been developed in which the commonly used tool steels are grouped into seven major categories. These categories, several of which contain more than a single group, are listed in the following with the letter symbols used for their identification. The individual types of tool steels within each category are identified by suffix numbers following the letter symbols.

Category Designation	Letter Symbol	Group Designation
High-Speed Tool Steels	M	Molybdenum types
	T	Tungsten types
Hot-Work Tool Steels	H1–H19	Chromium types
	H20–H39	Tungsten types
	H40–H59	Molybdenum types
Cold-Work Tool Steels	D	High-carbon, high-chromium types
	A	Medium-alloy, air-hardening types
	O	Oil-hardening types
Shock-Resisting Tool Steels	S	…
Mold Steels	P	…
Special-Purpose Tool Steels	L	Low-alloy types
	F	Carbon–tungsten types
Water-Hardening Tool Steels	W	…

The following detailed discussion of tool steels will be in agreement with these categories, showing for each type the percentages of the major alloying elements. However, these values are for identification only; elements in tool steels of different producers in the mean analysis of the individual types may deviate from the listed percentages.

The Selection of Tool Steels for Particular Applications.—Although the advice of the specialized steel producer is often sought as a reliable source of information, the engineer is still faced with the task of selecting the tool steel. It must be realized that frequently the designation of the tool or of the process will not define the particular tool steel type best suited for the job. For that reason, tool steel selection tables naming a single type for each listed application cannot take into consideration such often conflicting work factors as ease of tool fabrication and maintenance (resharpening), productivity, product quality, and tooling cost.

When data related to past experience with tool steels for identical or similar applications are not available, a tool steel selection procedure may be followed, based on information in this Handbook section as follows:

1) Identify the AISI category that contains the sought type of steel by consulting the Quick Reference Table on starting on page 455.

Within the defined category

a) find from the listed applications of the most frequently used types of tool steels the particular type that corresponds to the job on hand; or

b) evaluate from the table of property ratings the best compromise between any conflicting properties (e.g., compromising on wear resistance to obtain better toughness).

For those willing to refine even further the first choice or to improve on it when there is not entirely satisfactory experience in one or more meaningful respects, the identifying analyses of the different types of tool steels within each general category may provide additional guidance. In this procedure, the general discussion of the effects of different alloying elements on the properties of tool steels, in a previous section, will probably be found useful.

The following two examples illustrate the procedure for refining an original choice with the purpose of adopting a tool steel grade best suited to a particular set of conditions:

Table 6. Classification, Approximate Compositions, and Properties Affecting Selection of Tool andDie Steels

(From SAE Recommended Practice)

Type of Tool Steel	Chemical Composition[a]								Non-warping Prop.	Safety in Hardening	Toughness	Depth of Hardening	Wear Resistance
	C	Mn	Si	Cr	V	W	Mo	Co					
Water Hardening													
0.80 Carbon	70–0.85	[b]	[b]	[b]	…	…	…	…	Poor	Fair	Good[c]	Shallow	Fair
0.90 Carbon	0.85–0.95	[b]	[b]	[b]	…	…	…	…	Poor	Fair	Good[c]	Shallow	Fair
1.00 Carbon	0.95–1.10	[b]	[b]	[b]	…	…	…	…	Poor	Fair	Good[c]	Shallow	Good
1.20 Carbon	1.10–1.30	[b]	[b]	[b]	…	…	…	…	Poor	Fair	Good[c]	Shallow	Good
0.90 Carbon–V	0.85–0.95	[b]	[b]	[b]	0.15–0.35	…	…	…	Poor	Fair	Good	Shallow	Fair
1.00 Carbon–V	0.95–1.10	[b]	[b]	[b]	0.15–0.35	…	…	…	Poor	Fair	Good	Shallow	Good
1.00 Carbon–VV	0.90–1.10	[b]	[b]	[b]	0.35–0.50	…	…	…	Poor	Fair	Good	Shallow	Good
Oil Hardening													
Low Manganese	0.90	1.20	0.25	0.50	0.20[d]	0.50	…	…	Good	Good	Fair	Deep	Good
High Manganese	0.90	1.60	0.25	0.35[d]	0.20[d]	…	0.30[d]	…	Good	Good	Fair	Deep	Good
High-Carbon, High-Chromium[e]	2.15	0.35	0.35	12.00	0.80[d]	0.75[d]	0.80[d]	…	Good	Good	Poor	Through	Best
Chromium	1.00	0.35	0.25	1.40	…	…	0.40	…	Fair	Good	Fair	Deep	Good
Molybdenum Graphitic	1.45	0.75	1.00	…	…	…	0.25	…	Fair	Good	Fair	Deep	Good
Nickel–Chromium[f]	0.75	0.70	0.25	0.85	0.25[d]	…	0.50[d]	…	Fair	Good	Fair	Deep	Fair
Air Hardening													
High-Carbon, High-Chromium	1.50	0.40	0.40	12.00	0.80[d]	…	0.90	0.60[d]	Best	Best	Fair	Through	Best
5 Per Cent Chromium	1.00	0.60	0.25	5.25	0.40[d]	…	1.10	…	Best	Best	Fair	Through	Good
High-Carbon, High-Chromium–Cobalt	1.50	0.40	0.40	12.00	0.80[d]	…	0.90	3.10	Best	Best	Fair	Through	Best
Shock-Resisting													
Chromium–Tungsten	0.50	0.25	0.35	1.40	0.20	2.25	0.40[d]	…	Fair	Good	Good	Deep	Fair
Silicon–Molybdenum	0.50	0.40	1.00	…	0.25[d]	…	0.50	…	Poor[g]	Poor[h]	Best	Deep	Fair
Silicon–Manganese	0.55	0.80	2.00	0.30[d]	0.25[d]	…	0.40[d]	…	Poor[g]	Poor[h]	Best	Deep	Fair
Hot Work													
Chromium–Molybdenum–Tungsten	0.35	0.30	1.00	5.00	0.25[d]	1.25	1.50	…	Good	Good	Good	Through	Fair
Chromium–Molybdenum–V	0.35	0.30	1.00	5.00	0.40	…	1.50	…	Good	Good	Good	Through	Fair
Chromium–Molybdenum–VV	0.35	0.30	1.00	5.00	0.90	…	1.50	…	Good	Good	Good	Through	Fair
Tungsten	0.32	0.30	0.20	3.25	0.40	9.00	…	…	Good	Good	Good	Through	Fair

Table 6. *(Continued)* **Classification, Approximate Compositions, and Properties Affecting Selection of Tool andDie Steels**
(From SAE Recommended Practice)

Type of Tool Steel	Chemical Composition[a]								Non-warping Prop.	Safety in Hardening	Toughness	Depth of Hardening	Wear Resistance
	C	Mn	Si	Cr	V	W	Mo	Co					
High Speed													
Tungsten, 18–4–1	0.70	0.30	0.30	4.10	1.10	18.00	…	…	Good	Good	Poor	Through	Good
Tungsten, 18–4–2	0.80	0.30	0.30	4.10	2.10	18.50	0.80	…	Good	Good	Poor	Through	Good
Tungsten, 18–4–3	1.05	0.30	0.30	4.10	3.25	18.50	0.70	…	Good	Good	Poor	Through	Best
Cobalt–Tungsten, 14–4–2–5	0.80	0.30	0.30	4.10	2.00	14.00	0.80	5.00	Good	Fair	Poor	Through	Good
Cobalt–Tungsten, 18–4–1–5	0.75	0.30	0.30	4.10	1.00	18.00	0.80	5.00	Good	Fair	Poor	Through	Good
Cobalt–Tungsten, 18–4–2–8	0.80	0.30	0.30	4.10	1.75	18.50	0.80	8.00	Good	Fair	Poor	Through	Good
Cobalt–Tungsten, 18–4–2–12	0.80	0.30	0.30	4.10	1.75	20.00	0.80	12.00	Good	Fair	Poor	Through	Good
Molybdenum, 8–2–1	0.80	0.30	0.30	4.00	1.15	1.50	8.50	…	Good	Fair	Poor	Through	Good
Molybdenum–Tungsten, 6–6–2	0.83	0.30	0.30	4.10	1.90	6.25	5.00	…	Good	Fair	Poor	Through	Good
Molybdenum–Tungsten, 6–6–3	1.15	0.30	0.30	4.10	3.25	5.75	5.25	…	Good	Fair	Poor	Through	Best
Molybdenum–Tungsten, 6–6–4	1.30	0.30	0.30	4.25	4.25	5.75	5.25	…	Good	Fair	Poor	Through	Best
Cobalt–Molybdenum–Tungsten, 6–6–2–8	0.85	0.30	0.30	4.10	2.00	6.00	5.00	8.00	Good	Fair	Poor	Through	Good

[a] C = carbon; Mn = manganese; Si = silicon; Cr = chromium; V = vanadium; W = tungsten; Mo = molybdenum; Co = cobalt.

[b] Carbon tool steels are usually available in four grades or qualities: *Special (Grade 1)*—The highest quality water-hardening carbon tool steel, controlled for hardenability, chemistry held to closest limits, and subject to rigid tests to ensure maximum uniformity in performance; *Extra (Grade 2)*—A high-quality water-hardening carbon tool steel, controlled for hardenability, subject to tests to ensure good service; *Standard (Grade 3)*—A good-quality water-hardening carbon tool steel, not controlled for hardenability, recommended for application where some latitude with respect to uniformity is permissible; *Commercial (Grade 4)*—A commercial-quality water-hardening carbon tool steel, not controlled for hardenability, not subject to special tests. On *special* and *extra* grades, limits on manganese, silicon, and chromium are not generally required if Shepherd hardenability limits are specified. For *standard* and *commercial* grades, limits are 0.35 max. each for Mn and Si; 0.15 max. Cr for standard; 0.20 max. Cr for commercial.

[c] Toughness decreases somewhat when increasing depth of hardening.

[d] Optional element. Steels have found satisfactory application either with or without the element present. In silicon–manganese steel listed under Shock-Resisting Steels, if chromium, vanadium, and molybdenum are not present, then hardenability will be affected.

[e] This steel may have 0.50 per cent nickel as an optional element. The steel has been found to give satisfactory application either with or without the element present.

[f] Approximate nickel content of this steel is 1.50 per cent.

[g] Poor when water quenched, fair when oil quenched.

[h] Poor when water quenched, good when oil quenched.

Table 7. Quick Reference Guide for Tool Steel Selection

Application Areas	Tool Steel Categories and AISI Letter Symbol						
	High-Speed Tool Steels, M and T	Hot-Work Tool Steels, H	Cold-Work Tool Steels, D, A, and O	Shock-Resisting Tool Steels, S	Mold Steels, P	Special-Purpose Tool Steels, L and F	Water-Hardening Tool Steels, W
Examples of Typical Applications							
Cutting Tools Single-point types (lathe, planer, boring) Milling cutters Drills Reamers Taps Threading dies Form cutters	General-purpose production tools: M2, T1 For increased abrasion resistance: M3, M4, and M10 Heavy-duty work calling for high hot hardness: T5, T15 Heavy-duty work calling for high abrasion resistance: M42, M44		Tools with keen edges (knives, razors) Tools for operations where no high-speed is involved, yet stability in heat treatment and substantial abrasion resistance are needed	Pipe cutter wheels			Uses that do not require hot hardness or high abrasion resistance. Examples with carbon content of applicable group: Taps (1.05/1.10% C) Reamers (1.10/1.15% C) Twist drills (1.20/1.25% C) Files (1.35/1.40% C)
Hot Forging Tools and Dies Dies and inserts Forging machine plungers and pierces	For combining hot hardness with high abrasion resistance: M2, T1	Dies for presses and hammers: H20, H21 For severe conditions over extended service periods: H22 to H26, also H43	Hot trimming dies: D2	Hot trimming dies Blacksmith tools Hot swaging dies			Smith's tools (1.65/0.70% C) Hot chisels (0.70/0.75% C) Drop forging dies (0.90/1.00% C) Applications limited to short-run production
Hot Extrusion Tools and Dies Extrusion dies and mandrels, Dummy blocks Valve extrusion tools	Brass extrusion dies: T1	Extrusion dies and dummy blocks: H20 to H26 For tools that are exposed to less heat: H10 to H19		Compression molding: S1			

Table 7. *(Continued)* Quick Reference Guide for Tool Steel Selection

Application Areas	Tool Steel Categories and AISI Letter Symbol						
	High-Speed Tool Steels, M and T	Hot-Work Tool Steels, H	Cold-Work Tool Steels, D, A, and O	Shock-Resisting Tool Steels, S	Mold Steels, P	Special-Purpose Tool Steels, L and F	Water-Hardening Tool Steels, W
	Examples of Typical Applications						
Cold-Forming Dies Bending, forming, drawing, and deep drawing dies and punches	Burnishing tools: M1, T1	Cold heading: die casting dies: H13	Drawing dies: 01 Coining tools: O1, D2 Forming and bending dies: A2 Thread rolling dies: D2	Hobbing and short-run applications: S1, S7 Rivet sets and rivet busters		Blanking, forming, and trimmer dies when toughness has precedence over abrasion resistance: L6	Cold-heading dies: W1 or W2 (C ≅ 1.00%) Bending dies: W1 (C ≅ 1.00%)
Shearing Tools Dies for piercing, punching, and trimming Shear blades	Special dies for cold and hot work: T1 For work requiring high abrasion resistance: M2, M3	For shearing knives: H11, H12 For severe hot shearing applications: M21, M25	Dies for medium runs: A2, A6 also O1 and O4 Dies for long runs: D2, D3 Trimming dies (also for hot trimming): A2	Cold and hot shear blades Hot punching and piercing tools Boilermaker's tools		Knives for work requiring high toughness: L6	Trimming dies (0.90⁄0.95% C) Cold blanking and punching dies (1.00% C)
Die Casting Dies and Plastics Molds		For zinc and lead: H11 For aluminum: H13 For brass: H21	A2 and A6 O1		Plastics molds: P2 to P4, and P20		
Structural Parts for Severe Service Conditions	Roller bearings for high-temperature environment: T1 Lathe centers: M2 and T1	For aircraft components (landing gear, arrester hooks, rocket cases): H11	Lathe centers: D2, D3 Arbors: O1 Bushings: A4 Gages: D2	Pawls Clutch parts		Spindles, clutch parts (where high toughness is needed): L6	Spring steel (1.10⁄1.15% C)
Battering Tools for Hand and Power Tool Use				Pneumatic chisels for cold work: S5 For higher performance: S7			For intermittent use: W1 (0.80% C)

Example 1, Workpiece—Trimming Dies: For the manufacture of a type of trimming die, the first choice was grade A2, because for the planned medium rate of production, the lower material cost was considered an advantage.

A subsequent rise in the production rate indicated the use of a higher-alloy tool steel, such as D2, whose increased abrasion resistance would permit longer runs between regrinds.

A still further increase in the abrasion-resistant properties was then sought, which led to the use of D7, the high carbon and high chromium content of which provided excellent edge retainment, although at the cost of greatly reduced grindability. Finally, it became a matter of economic appraisal, whether the somewhat shorter tool regrind intervals (for D2) or the more expensive tool sharpening (for D7) constituted the lesser burden.

Example 2, Workpiece—Circular form cutter made of high-speed tool steel for use on multiple-spindle automatic turning machines: The first choice from the Quick Reference Guide may be the classical tungsten-base high-speed tool steel T1, because of its good performance and ease of heat treatment, or its alternate in the molybdenum high-speed tool steel category, the type M2.

In practice, neither of these grades provided a tool that could hold its edge and profile over the economical tool change time, because of the abrasive properties of the work material and the high cutting speeds applied in the cycle. An overrating of the problem resulted in reaching for the top of the scale, making the tool from T15, a high-alloy high-speed tool steel (high vanadium and high cobalt).

Although the performance of the tools made of T15 was excellent, the cost of this steel type was rather high, and the grinding of the tool, both for making it and in the regularly needed resharpening, proved to be very time-consuming and expensive. Therefore, an intermediate tool steel type was tried, the M3 that provided added abrasion resistance (due to increased carbon and vanadium content), and was less expensive and much easier to grind than the T15.

High-Speed Tool Steels

The primary application of high-speed steels is to tools used for the working of metals at high cutting speeds. Cutting metal at high speed generates heat, the penetration of the cutting tool edge into the work material requires great hardness and strength, and the continued frictional contact of the tool with both the parent material and the detached chips can only be sustained by an abrasion-resistant tool edge.

Accordingly, the dominant properties of high-speed steel are B) resistance to the softening effect of elevated temperature; C) great hardness penetrating to substantial depth from the surface; and D) excellent abrasion resistance.

High-speed tool steels are listed in the AISI specifications in two groups: molybdenum types and tungsten types, these designations expressing the dominant alloying element of the respective group.

Molybdenum-Type High-Speed Tool Steels.—Unlike the traditional tungsten-base high-speed steels, the tool steels listed in this category are considered to have molybdenum as the principal alloying constituent, this element also being used in the designation of the group. Other significant elements like tungsten and cobalt might be present in equal, or even greater amounts in several types listed in this category. The available range of types also includes high-speed tool steels with higher than usual carbon and vanadium content. Amounts of these alloying elements have been increased to obtain better abrasion resistance although such a change in composition may adversely affect the machinability and the grindability of the steel. The series in whose AISI identification numbers the number 4 is the first digit was developed to attain exceptionally high hardness in heat treatment that, for these types, usually requires triple tempering rather than the double tempering generally applied for high-speed tool steels.

Properties and Applications of Frequently Used Molybdenum Types: AISI M1: This alloy was developed as a substitute for the classical T1 to save on the alloying element tungsten by replacing most of it with molybdenum. In most uses, this steel is an acceptable substitute, although it requires greater care or more advanced equipment for its heat treatment than the tungsten alloyed type it replaces. The steel is often selected for cutting tools like drills, taps, milling cutters, reamers, lathe tools used for lighter cuts, and for shearing dies.

AISI M2: Similar to M1, yet with substantial tungsten content replacing a part of the molybdenum. This is one of the general-purpose high-speed tool steels, combining the economic advantages of the molybdenum-type steels with greater ease of hardening, excellent wear resistance, and improved toughness. It is a preferred steel type for the manufacture of general-purpose lathe tools; of most categories of multiple-edge cutting tools, like milling cutters, taps, dies, reamers, and for form tools in lathe operations.

AISI M3: A high-speed tool steel with increased vanadium content for improved wear resistance, yet still below the level where vanadium would interfere with the ease of grinding. This steel is preferred for cutting tools requiring improved wear resistance, like broaches, form tools, milling cutters, chasers, and reamers.

AISI M7: The chemical composition of this type is similar to that of M1, except for the higher carbon and vanadium content that raises the cutting efficiency without materially reducing the toughness. Because of sensitivity to decarburization, heat treatment in a salt bath or a controlled atmosphere is advisable. Used for blanking and trimming dies, shear blades, lathe tools, and thread rolling dies.

AISI M10: Although the relatively high vanadium content assures excellent wear and cutting properties, the only slightly increased carbon does not cause brittleness to an extent that is harmful in many applications. Form cutters and single-point lathe tools, broaches, planer tools, punches, blanking dies, and shear blades are examples of typical uses.

AISI M42: In applications where high hardness both at regular and at elevated temperatures is needed, this type of high-speed steel with high cobalt content can provide excellent service. Typical applications are tool bits, form tools, shaving tools, fly cutters, roll turning tools, and thread rolling dies. Important uses are found for M42, and for other types of the "M40" group in the working of "difficult-to-machine" alloys.

Tungsten-Type High-Speed Tool Steels.—For several decades following their introduction, the tungsten-base high-speed steels were the only types available for cutting operations involving the generation of substantial heat, and are still preferred by users who do not have the kind of advanced heat-treating equipment that efficient hardening of the molybdenum-type high-speed tool steels requires. Most tungsten high-speed steels display excellent resistance to decarburization and can be brought to good hardness by simple heat treatment. However, even with tungsten-type high-speed steels, heat treatment using modern methods and furnaces can appreciably improve the metallurgical qualities of the hardened material and the performance of the cutting tools made from these steels.

Properties and Applications of Frequently Used Tungsten Types: AISI T1: Also mentioned as the 18–4–1 type with reference to the nominal percentage of its principal alloying elements (W–Cr–V), it is considered to be the classical type of high-speed tool steel. The chemical composition of T1 was developed in the early 1900s, and has changed very little since. T1 is still considered to be perhaps the best general-purpose high-speed tool steel because of the comparative ease of its machining and heat treatment. It combines a high degree of cutting ability with relative toughness. T1 steel is used for all types of multiple-edge cutting tools like drills, reamers, milling cutters, threading taps and dies, light- and medium-duty lathe tools, and is also used for punches, dies, and machine knives, as well as for structural parts that are subjected to elevated temperatures, like lathe centers, and certain types of antifriction bearings.

AISI T2: Similar to T1 except for somewhat higher carbon content and twice the vanadium contained in the former grade. Its handling ease, both in machining and heat treating,

Table 8. Molybdenum High-Speed Steels

Identifying Chemical Composition and Typical Heat-Treatment Data																					
	AISI Type			M1	M2	M3 Cl. 1	M3 Cl. 2	M4	M6	M7	M10	M30	M33	M34	M36	M41	M42	M43	M44	M46	M47
Identifying Chemical Elements in Per Cent	C			0.80	0.85; 1.00	1.05	1.20	1.30	0.80	1.00	0.85; 1.00	0.80	0.90	0.90	0.80	1.10	1.10	1.20	1.15	1.25	1.10
	W			1.50	6.00	6.00	6.00	5.50	4.00	1.75	…	2.00	1.50	2.00	6.00	6.75	1.50	2.75	5.25	2.00	1.50
	Mo			8.00	5.00	5.00	5.00	4.50	5.00	8.75	8.00	8.00	9.50	8.00	5.00	3.75	9.50	8.00	6.25	8.25	9.50
	Cr			4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.25	3.75	3.75	4.25	4.00	3.75
	V			1.00	2.00	2.40	3.00	4.00	1.50	2.00	2.00	1.25	1.15	2.00	2.00	2.00	1.15	1.60	2.25	3.20	1.25
	Co			…	…	…	…	…	12.00	…	…	5.00	8.00	8.00	8.00	5.00	8.00	8.25	12.00	8.25	5.00
Heat-Treat. Data	Hardening Temperature Range, °F			2150–2225	2175–2225	2200–2250	2200–2250	2200–2250	2150–2200	2150–2225	2150–2225	2200–2250	2200–2250	2200–2250	2225–2275	2175–2220	2175–2210	2175–2220	2190–2240	2175–2225	2150–2200
	Tempering Temperature Range, °F			1000–1100	1000–1160	1000–1100	1000–1100	1000–1100	1000–1100	1000–1100	1000–1100	1000–1100	1000–1100	1000–1100	1000–1100	1000–1100	950–1100	950–1100	1000–1160	975–1050	975–1100
	Approx. Tempered Hardness, Rc			65–60	65–60	66–61	66–61	66–61	66–61	66–61	65–60	65–60	65–60	65–60	65–60	70–65	70–65	70–65	70–62	69–67	70–65
Relative Ratings of Properties (A = greatest to E = least)																					
Characteristics in Heat Treatment	Safety in Hardening			D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
	Depth of Hardening			A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
	Resistance to Decarburization			C	B	B	B	B	C	C	C	C	C	C	C	C	C	C	C	C	C
	Stability of Shape in Heat Treatment	Quenching Medium	Air or Salt	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
			Oil	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
Service Properties	Machinability			D	D	D	D/E	D	D	D	D	D	D	D	D	D	D	D	D	D	D
	Hot Hardness			B	B	B	B	B	A	B	B	A	A	A	A	A	A	A	A	A	A
	Wear Resistance			B	B	B	B	A	B	B	B	B	B	B	B	B	B	B	B	B	B
	Toughness			E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E

is comparable to that of T1, although it should be held at the quenching temperature slightly longer, particularly when the heating is carried out in a controlled atmosphere furnace. The applications are similar to that of T1, however, because of its increased wear resistance T2 is preferred for tools required for finer cuts, and where the form or size retention of the tool is particularly important, such as for form and finishing tools.

AISI T5: The essential characteristic of this type of high-speed steel, its superior red hardness, stems from its substantial cobalt content that, combined with the relatively high amount of vanadium, provides this steel with excellent wear resistance. In heat treatment, the tendency for decarburization must be considered, and heating in a controlled, slightly reducing atmosphere is recommended. This type of high-speed tool steel is mainly used for single-point tools and inserts; it is well adapted for working at high-speeds and feeds, for cutting hard materials and those that produce discontinuous chips, also for nonferrous metals and, in general, for all kinds of tools needed for hogging (removing great bulks of material).

AISI T15: The performance qualities of this high-alloy tool steel surpass most of those found in other grades of high-speed tool steels. The high vanadium content, supported by uncommonly high carbon assures superior cutting ability and wear resistance. The addition of high cobalt increases the “hot hardness,” and therefore tools made of T15 can sustain cutting speeds in excess of those commonly applicable to tools made of steel. The machining and heat treatment of T15 does not cause extraordinary problems, although for best results, heating to high temperature is often applied in its heat treatment, and double or even triple tempering is recommended. On the other hand, T15 is rather difficult to grind because of the presence of large amounts of very hard metallic carbides; therefore, it is considered to have a very low “grindability” index. The main uses are in the field of high-speed cutting and the working of hard metallic materials, T15 being often considered to represent in its application a transition from the regular high-speed tool steels to cemented carbides. Lathe tool bits, form cutters, and solid and inserted blade milling cutters are examples of uses of this steel type for cutting tools; excellent results may also be obtained with such tools as cold-work dies, punches, blanking, and forming dies, etc. The low toughness rating of the T15 steel excludes its application for operations that involve shock or sudden variations in load.

Hot-Work Tool Steels

A family of special tool steels has been developed for tools that in their regular service are in contact with hot metals over a shorter or longer period of time, with or without cooling being applied, and are known as hot-work steels. The essential property of these steels is their capability to sustain elevated temperature without seriously affecting the usefulness of the tools made from them. Depending on the purpose of the tools for which they were developed, the particular types of hot-work tool steels have different dominant properties and are assigned to one of three groups, based primarily on their principal alloying elements.

Hot-Work Tool Steels, Chromium Types.—As referred to in the group designation, the chromium content is considered the characteristic element of these tool steels. Their predominant properties are high hardenability, excellent toughness, and great ductility, even at the cost of wear resistance. Some members of this family are made with the addition of tungsten, and in one type, cobalt as well. These alloying elements improve the resistance to the softening effect of elevated temperatures, but reduce ductility.

Properties and Applications of Frequently Used Chromium Types: AISI H11: This hot-work tool steel of the Chromium–molybdenum–vanadium type has excellent ductility, can be machined easily, and retains its strength at temperatures up to 1000 degrees F.

Table 9. Tungsten High-Speed Tool Steels

Identifying Chemical Composition and Typical Heat-Treatment Data										
Identifying Chemical Elements in Per Cent	AISI Type			T1	T2	T4	T5	T6	T8	T15
	C			0.75	0.80	0.75	0.80	0.80	0.75	1.50
	W			18.00	18.00	18.00	18.00	20.00	14.00	12.00
	Cr			4.00	4.00	4.00	4.00	4.50	4.00	4.00
	V			1.00	2.00	1.00	2.00	1.50	2.00	5.00
	Co			…	…	5.00	…	…	5.00	5.00
Heat-Treat. Data	Hardening Temperature Range, °F			2300–2375	2300–2375	2300–2375	2325–2375	2325–2375	2300–2375	2200–2300
	Tempering Temperature Range, °F			1000–1100	1000–1100	1000–1100	1000–1100	1000–1100	1000–1100	1000–1200
	Approx. Tempered Hardness, R_c			65–60	66–61	66–62	65–60	65–60	65–60	68–63
Relative Ratings of Properties (A = greatest to E = least)										
Characteristics in Heat Treatment	Safety in Hardening			C	C	D	D	D	D	D
	Depth of Hardening			A	A	A	A	A	A	A
	Resistance to Decarburization			A	A	B	C	C	B	B
	Stability of Shape in Heat Treatment	Quenching Medium	Air or Salt	C	C	C	C	C	C	C
			Oil	D	D	D	D	D	D	D
Service Properties	Machinability			D	D	D	D	D/E	D	D/E
	Hot Hardness			B	B	A	A	A	A	A
	Wear Resistance			B	B	B	B	B	B	A
	Toughness			E	E	E	E	E	E	E

These properties, combined with relatively good abrasion and shock resistance, account for the varied fields of application of H11, which include the following typical uses:

E) structural applications where high strength is needed at elevated operating temperatures, as for gas turbine engine components; and F) hot-work tools, particularly of the kind whose service involves shocks and drastic cooling of the tool, such as in extrusion tools, pierce and draw punches, bolt header dies, etc.

AISI H12: The properties of this type of steel are comparable to those of H11, with increased abrasion resistance and hot hardness, resulting from the addition of tungsten, yet in an amount that does not affect the good toughness of this steel type. The applications, based on these properties, are hot-work tools that often have to withstand severe impact, such as various punches, bolt header dies, trimmer dies, and hot shear blades. H12 is also used to make aluminum extrusion dies and die-casting dies.

AISI H13: This type of tool steel differs from the preceding ones particularly in properties related to the addition of about 1 per cent vanadium, which contributes to increased hot hardness, abrasion resistance, and reduced sensitivity to heat checking. Such properties are needed in die casting, particularly of aluminum, where the tools are subjected to drastic heating and cooling at high operating temperatures. Besides die-casting dies, H13 is also widely used for extrusion dies, trimmer dies, hot gripper and header dies, and hot shear blades.

AISI H19: This high-alloyed hot-work tool steel, containing chromium, tungsten, cobalt, and vanadium, has excellent resistance to abrasion and shocks at elevated temperatures. It is particularly well adapted to severe hot-work uses where the tool, to retain its size and shape, must withstand wear and the washing-out effect of molten work material. Typical applications include brass extrusion dies and dummy blocks, inserts for forging and valve extrusion dies, press forging dies, and hot punches.

Hot-Work Tool Steels, Tungsten Types.—Substantial amounts of tungsten, yet very low-carbon content characterize the hot-work tool steels of this group. These tool steels have been developed for applications where the tool is in contact with the hot-work material over extended periods of time; therefore, the resistance of the steel to the softening effect of elevated temperatures is of prime importance. even to the extent of accepting a lower degree of toughness.

Properties and Applications of Frequently Used Tungsten Types: AISI H21: This medium-tungsten alloyed hot-work tool steel has substantially increased abrasion resistance over the chromium alloyed types, yet possesses a degree of toughness that represents a transition between the chromium and the higher-alloyed tungsten-steel types. The principal applications are for tools subjected to continued abrasion, yet to only a limited amount of shock loads, like tools for the extrusion of brass, both dies and dummy blocks, pierces for forging machines, inserts for forging tools, and hot nut tools. Another typical application is dies for the hot extrusion of automobile valves.

AISI H24: The comparatively high tungsten content (about 14 per cent) of this steel results in good hardness, great compression strength, and excellent abrasion resistance, but makes it sensitive to shock loads. By taking these properties into account, the principal applications include extrusion dies for brass in long-run operations, hot-forming and gripper dies with shallow impressions, punches that are subjected to great wear yet only to moderate shocks, and hot shear blades.

AISI H20: The composition of this high-alloyed tungsten-type hot-work steel resembles the tungsten-type high-speed steel AISI T1, except for the somewhat lower carbon content for improved toughness. The high amount of tungsten provides the maximum resistance to the softening effect of elevated temperature and assures excellent wear-resistant properties, including withstanding the washing-out effect of certain processes. However, this steel is less resistant to thermal shocks than the chromium hot-work steels. Typical applications comprise extrusion dies for long production runs, extrusion mandrels operated

Table 10. Hot-Work Tool Steels

Identifying Chemical Composition and Typical Heat-Treatment Data																		
AISI	Group			Chromium Types						Tungsten Types						Molybdenum Types		
	Type			H10	H11	H12	H13	H14	H19	H21	H22	H23	H24	H25	H26	H41	H42	H43
Identifying Chemical Elements in Per Cent	C			0.40	0.35	0.35	0.35	0.40	0.40	0.35	0.35	0.35	0.45	0.25	0.50	0.65	0.60	0.55
	W			…	…	1.50	…	5.00	4.25	9.00	11.00	12.00	15.00	15.00	18.00	1.50	6.00	…
	Mo			2.50	1.50	1.50	1.50	…	…	…	…	…	…	…	…	8.00	5.00	8.00
	Cr			3.25	5.00	5.00	5.00	5.00	4.25	3.50	2.00	12.00	3.00	4.00	4.00	4.00	4.00	4.00
	V			0.40	0.40	0.40	1.00	…	2.00	…	…	…	…	…	1.00	1.00	2.00	2.00
	Co			…	…	…	…	…	4.25	…	…	…	…	…	…	…	…	…
Heat-Treat. Data	Hardening Temperature Range, °F			1850–1900	1825–1875	1825–1875	1825–1900	1850–1950	2000–2200	2000–2200	2000–2200	2000–2300	2000–2250	2100–2300	2150–2300	2000–2175	2050–2225	2000–2175
	Tempering Temperature Range, °F			1000–1200	1000–1200	1000–1200	1000–1200	1100–1200	1000–1300	1100–1250	1100–1250	1200–1500	1050–1200	1050–1250	1050–1250	1050–1200	1050–1200	1050–1200
	Approx. Tempered Hardness, Rc			56–39	54–38	55–38	53–38	47–40	59–40	54–36	52–39	47–30	55–45	44–35	58–43	60–50	60–50	58–45
Relative Ratings of Properties (A = greatest to D = least)																		
Characteristics in Heat Treatment	Safety in Hardening			A	A	A	A	A	B	B	B	B	B	B	B	C	C	C
	Depth of Hardening			A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
	Resistance to Decarburization			B	B	B	B	B	B	B	B	B	B	B	B	C	B	C
	Stability of Shape in Heat Treatment	Quenching Medium	Air or Salt	B	B	B	B	C	C	C	C	…	C	C	C	C	C	C
			Oil	…	…	…	…	…	D	D	D	D	D	D	D	D	D	D
Service Properties	Machinability			C/D	C/D	C/D	C/D	D	D	D	D	D	D	D	D	D	D	D
	Hot Hardness			C	C	C	C	C	C	C	C	B	B	B	B	B	B	B
	Wear Resistance			D	D	D	D	D	C/D	C/D	C/D	C/D	C	D	C	C	C	C
	Toughness			C	B	B	B	C	C	C	C	D	D	C	D	D	D	D

without cooling, hot piercing punches, hot forging dies and inserts. It is also used as special structural steel for springs operating at elevated temperatures.

Hot-Work Tool Steels, Molybdenum Types.—These steels are closely related to certain types of molybdenum high-speed steels and possess excellent resistance to the softening effect of elevated temperature but their ductility is rather low. These steel types are generally available on special orders only.

Properties and Applications of Frequently Used Molybdenum Types: AISI H43: The principal constituents of this hot-work steel, chromium, molybdenum, and vanadium, provide excellent abrasion- and wear-resistant properties at elevated temperatures. H43 has a good resistance to the development of heat checks and a toughness adequate for many different purposes. Applications include tools and operations that tend to cause surface wear in high-temperature work, like hot headers, punch and die inserts, hot heading and hot nut dies, as well as different kinds of punches operating at high temperature in service involving considerable wear.

Cold-Work Tool Steels

Tool steels of the cold-working category are primarily intended for die work, although their use is by no means restricted to that general field. Cold-work tool steels are extensively used for tools whose regular service does not involve elevated temperatures. They are available in chemical compositions adjusted to the varying requirements of a wide range of different applications. According to their predominant properties, characterized either by the chemical composition or by the quenching medium in heat treatment, the cold-work tool steels are assigned to three different groups, as discussed in what follows.

Cold-Work Tool Steels, High-Carbon, High-Chromium Types.—The chemical composition of tool steels of this family is characterized by the very high chromium content, to the order of 12 to 13 per cent, and the uncommonly high carbon content, in the range of about 1.50 to 2.30 per cent. Additional alloying elements that are present in different amounts in some of the steel types of this group are vanadium, molybdenum, and cobalt, each of which contributes desirable properties.

The predominant properties of the whole group are: 1) excellent dimensional stability in heat treatment, where, with one exception, air quench is used; 2) great wear resistance, particularly in the types with the highest carbon content; and 3) rather good machinability.

Properties and Applications of Frequently Used High-Carbon, High-Chromium Types:

AISI D2: An air-hardening die steel with high-carbon, high-chromium content having several desirable tool steel properties, such as abrasion resistance. high hardness, and nondeforming characteristics. The carbon content of this type, although relatively high, is not particularly detrimental to its machining. The ease of working can be further improved by selecting the same basic type with the addition of sulfur. Several steel producers supply the sulfurized version of D2, in which the uniformly distributed sulfide particles substantially improve the machinability and the resulting surface finish. The applications comprise primarily cold-working press tools for shearing (blanking and stamping dies, punches, shear blades), for forming (bending, seaming), also for thread rolling dies, solid gages, and wear-resistant structural parts. Dies for hot trimming of forgings are also made of D2 which is then heated treated to a lower hardness for the purpose of increasing toughness.

AISI D3: The high carbon content of this high-chromium tool steel type results in excellent resistance to wear and abrasion and provides superior compressive strength as long as the pressure is applied gradually, without exerting sudden shocks. In hardening, an oil quench is used, without affecting the excellent nondeforming properties of this type. Its deep-hardening properties make it particularly suitable for tools that require repeated regrinding during their service life, such as different types of dies and punches. The more important applications comprise blanking, stamping, and trimming dies and punches for

Table 11. Cold-Work Tool Steels

Identifying Chemical Composition and Typical Heat-Treatment Data																		
AISI	Group	High-Carbon, High-Chromium Types					Medium-Alloy, Air-Hardening Types								Oil-Hardening Types			
	Types	D2	D3	D4	D5	D7	A2	A3	A4	A6	A7	A8	A9	A10	O1	O2	O6	O7
Identifying Chemical Elements in Per Cent	C	1.50	2.25	2.25	1.50	2.35	1.00	1.25	1.00	0.70	2.25	0.55	0.50	1.35	0.90	0.90	1.45	1.20
	Mn	…	…	…	…	…	…	…	2.00	2.00	…	…	…	1.80	1.00	1.60	…	…
	Si	…	…	…	…	…	…	…	…	…	…	…	…	1.25	…	…	1.00	…
	W	…	…	…	…	…	…	…	…	…	1.00	1.25	…	…	0.50	…	…	1.75
	Mo	1.00	…	1.00	1.00	1.00	1.00	1.00	1.00	1.25	1.00	1.25	1.40	1.50	…	…	0.25	…
	Cr	12.00	12.00	12.00	12.00	12.00	5.00	5.00	1.00	1.00	5.25	5.00	5.00	…	0.50	…	…	0.75
	V	1.00	…	…	…	4.00	…	1.00	…	…	4.75	…	1.00	…	…	…	…	…
	Co	…	…	…	3.00	…	…	…	…	…	…	…	…	…	…	…	…	…
Heat-Treatment Data	Ni	…	…	…	…	…	…	…	…	…	…	…	1.50	1.80	…	…	…	…
	Hardening Temperature Range, °F	1800–1875	1700–1800	1775–1850	1800–1875	1850–1950	1700–1800	1750–1850	1500–1600	1525–1600	1750–1800	1800–1850	1800–1875	1450–1500	1450–1500	1400–1475	1450–1500	1550–1525
	Quenching Medium	Air	Oil	Air	Air	Air	Air	Air	Air	Air	Air	Air	Air	Air	Oil	Oil	Oil	Oil
	Tempering Temperature Range, °F	400–1000	400–1000	400–1000	400–1000	300–1000	350–1000	350–1000	350–800	300–800	300–1000	350–1100	950–1150	350–800	350–500	350–500	350–600	350–550
	Approx. Tempered Hardness, Rc	61–54	61–54	61–54	61–54	65–58	62–57	65–57	62–54	60–54	67–57	60–50	56–35	62–55	62–57	62–57	63–58	64–58
Relative Ratings of Properties (A = greatest to E = least)																		
Characteristics in Heat Treatment	Safety in Hardening	A	C	A	A	A	A	A	A	A	A	A	A	A	B	B	B	B
	Depth of Hardening	A	A	A	A	A	A	A	A	A	A	A	A	A	B	B	B	B
	Resistance to Decarburization	B	B	B	B	B	B	B	A/B	A/B	B	B	B	A/B	A	A	A	A
	Stability of Shape in Heat Treatment	A	B	A	A	A	A	A	A	A	A	A	A	A	B	B	B	B
Service Properties	Machinability	E	E	E	E	E	D	D	D/E	D/E	E	D	D	C/D	C	C	B	C
	Hot Hardness	C	C	C	C	C	C	C	D	D	C	C	C	D	E	E	E	E
	Wear Resistance	B/C	B	B	B/C	A	C	B	C/D	C/D	A	C/D	C/D	C	D	D	D	D
	Toughness	E	E	E	E	E	D	D	D	D	E	C	C	D	D	D	D	C

long production runs; forming, bending and drawing tools; and structural elements like plug and ring gages, and lathe centers, in applications where high wear resistance is important.

Cold-Work Tool Steels, Oil-Hardening Types.—With a relatively low percentage of alloying elements, yet with a substantial amount of manganese, these less expensive types of tool steels attain good depth of hardness in an oil quench, although at the cost of reduced resistance to deformation. Their good machinability supports general-purpose applications, yet because of relatively low wear resistance, they are mostly selected for comparatively short-run work.

Properties and Applications of Frequently Used Oil-Hardening Types: AISI O1: A low-alloy tool steel that is hardened in oil and exhibits only a low tendency to shrinking or warping. It is used for cutting tools, the operation of which does not generate high heat, such as taps and threading dies, reamers, and broaches, and for press tools like blanking, trimming, and forming dies in short- or medium-run operations.

AISI O2: Manganese is the dominant alloying element in this type of oil-hardening tool steel that has good nondeforming properties, can be machined easily, and performs satisfactorily in low-volume production. The low hardening temperature results in good safety in hardening, both with regard to form stability and freedom from cracking. The combination of handling ease, including free-machining properties, with good wear resistance, makes this type of tool steel adaptable to a wide range of common applications such as cutting tools for low- and medium-speed operations; forming tools including thread rolling dies; structural parts such as bushings and fixed gages, and for plastics molds.

AISI O6: This oil-hardening type of tool steel belongs to a group often designated as graphitic because of the presence of small particles of graphitic carbon that are uniformly dispersed throughout the steel. Usually, about one-third of the total carbon is present as free graphite in nodular form, which contributes to the uncommon ease of machining. In the service of parts made of this type of steel, the free graphite acts like a lubricant, reducing wear and galling. The ease of hardening is also excellent, requiring only a comparatively low quenching temperature. Deep hardness penetration is produced and the oil quench causes very little dimensional change. The principal applications of the O6 tool steel are in the field of structural parts, like arbors, bushings, bodies for inserted tool cutters, and shanks for cutting tools, jigs, and machine parts, and fixed gages like plugs, rings, and snap gages. It is also used for blanking, forming, and trimming dies and punches, in applications where the stability of the tool material is more important than high wear resistance.

Cold-Work Tool Steels, Medium-Alloy, Air-Hardening Types.—The desirable nondeforming properties of the high-chromium types are approached by the members of this family, with substantially lower alloy content that, however, is sufficient to permit hardening by air quenching. The machinability is good, and the comparatively low wear resistance is balanced by relatively high toughness, a property that, in certain applications, may be considered of prime importance.

Properties and Applications of Frequently Used Medium-Alloy, Air-Hardening Types:

AISI A2: The lower chromium content, about 5 per cent, makes this air-hardening tool steel less expensive than the high-chromium types, without affecting its nondeforming properties. The somewhat reduced wear resistance is balanced by greater toughness, making this type suitable for press work where the process calls for tough tool materials. The machinability is improved by the addition of about 0.12 percent sulfur, offered as a variety of the basic composition by several steel producers. The prime uses of this tool steel type are punches for blanking and forming, cold and hot trimming dies (the latter heat treated to a lower hardness), thread rolling dies, and plastics molds.

AISI A6: The composition of this type of tool steel makes it adaptable to air hardening from a relatively low temperature, comparable to that of oil-hardening types, yet offering improved stability in heat treating. Its reduced tendency to heat-treatment distortions makes this tool steel type well adapted for die work, forming tools, and gages, which do not require the highest degree of wear resistance.

Shock-Resisting, Mold, and Special-Purpose Tool Steels

There are fields of tool application in which specific properties of the tool steels have dominant significance, determining to a great extent the performance and the service life of tools made of these materials. To meet these requirements, special types of tool steels have been developed. These individual types grew into families with members that, while similar in their major characteristics, provide related properties to different degrees. Originally developed for a specific use, the resulting particular properties of some of these tool steels made them desirable for other uses as well. In the tool steel classification system, they are shown in three groups, as discussed in what follows.

Shock-Resisting Tool Steels.—These steels are made with low-carbon content for increased toughness, even at the expense of wear resistance, which is generally low. Each member of this group also contains alloying elements, different in composition and amount, selected to provide properties particularly adjusted to specific applications. Such varying properties are the degree of toughness (generally, high in all members), hot hardness, abrasion resistance, and machinability.

Properties and Applications of Frequently Used Shock-Resisting Types: AISI S1: This Chromium–tungsten alloyed tool steel combines, in its hardened state, great toughness with high hardness and strength. Although it has a low-carbon content for reasons of good toughness, the carbon-forming alloys contribute to deep hardenability and abrasion resistance. When high wear resistance is also required, this property can be improved by carburizing the surface of the tool while still retaining its shock-resistant characteristics. Primary uses are for battering tools, including hand and pneumatic chisels. The chemical composition, particularly the silicon and tungsten content, provides good hot hardness, too, up to operating temperatures of about 1050 °F, making this tool steel type also adaptable for such hot-work tool applications involving shock loads, as headers, pierces, forming tools, drop forge die inserts, and heavy shear blades.

AISI S2: This steel type serves primarily for hand chisels and pneumatic tools, although it also has limited applications for hot work. Although its wear-resistance properties are only moderate, S2 is sometimes used for forming and thread rolling applications, when the resistance to rupturing is more important than extended service life. For hot-work applications, this steel requires heat treatment in a neutral atmosphere to avoid either carburization or decarburization of the surface. Such conditions make this tool steel type particularly susceptible to failure in hot-work uses.

AISI S5: This composition is essentially a Silicon–manganese type tool steel with small additions of chromium, molybdenum, and vanadium for the purpose of improved deep hardening and refinement of the grain structure. The most important properties of this steel are its high elastic limit and good ductility, resulting in excellent shock-resisting characteristics, when used at atmospheric temperatures. Its recommended quenching medium is oil, although a water quench may also be applied as long as the design of the tools avoids sharp corners or drastic sectional changes. Typical applications include pneumatic tools in severe service, like chipping chisels, also shear blades, heavy-duty punches, and bending rolls. Occasionally, this steel is also used for structural applications, like shanks for carbide tools and machine parts subject to shocks.

Table 12. Shock-Resisting, Mold, and Special-Purpose Tool Steels

Identifying Chemical Composition and Typical Heat-Treatment Data																			
AISI	Category			Shock-Resisting Tool Steels				Mold Steels							Special-Purpose Tool Steels				
	Types			S1	S2	S5	S7	P2	P3	P4	P5	P6	P20	P21[a]	L2[b]	L3[b]	L6	F1	F2
Identifying Elements in Per Cent	C			0.50	0.50	0.55	0.50	0.07	0.10	0.07	0.10	0.10	0.35	0.20	0.50/ 1.10	1.00	0.70	1.00	1.25
	Mn			…	…	0.80	…	…	…	…	…	…	…	…	…	…	…	…	…
	Si			…	1.00	2.00	…	…	…	…	…	…	…	…	…	…	…	…	…
	W			2.50	…	…	…	…	…	…	…	…	…	…	…	…	…	1.25	3.50
	Mo			…	0.50	0.40	1.40	0.20	…	0.75	…	…	0.40	…	…	…	0.25	…	…
	Cr			1.50	…	…	3.25	2.00	0.60	5.00	2.25	1.50	1.25	…	1.00	1.50	0.75	…	…
	V			…	…	…	…	…	…	…	…	…	…	…	0.20	0.20	…	…	…
	Ni			…	…	…	…	0.50	1.25	…	…	3.50	…	4.00	…	…	1.50	…	…
Heat-Treat. Data	Hardening Temperature, °F			1650–1750	1550–1650	1600–1700	1700–1750	1525–1550[c]	1475–1525[c]	1775–1825[c]	1550–1600[c]	1450–1500[c]	1500–1600[c]	Soln. treat.	1550–1700	1500–1600	1450–1550	1450–1600	1450–1600
	Tempering Temp. Range, °F			400–1200	350–800	350–800	400–1150	350–500	350–500	350–900	350–500	350–450	900–1100	Aged	350–1000	350–600	350–1000	350–500	350–500
	Approx. Tempered Hardness, Rc			58–40	60–50	60–50	57–45	64–58[d]	64–58[d]	64–58[d]	64–58[d]	61–58[d]	37–28[d]	40–30	63–45	63–56	62–45	64–60	65–62
Relative Ratings of Properties (A = greatest to E = least)																			
Characteristics in Heat Treatment	Safety in Hardening			C	E	C	B/C	C	C	C	C	C	C	A	D	D	C	E	E
	Depth of Hardening			B	B	B	A	B[e]	B[e]	B[e]	B[e]	A[e]	B	A	B	B	B	C	C
	Resist. to Decarb.			B	C	C	B	A	A	A	A	A	A	A	A	A	A	A	A
	Stability of Shape in Heat Treatment	Quench. Med.	Air	…	…	…	A	…	…	B	…	B	C	A	…	…	…	…	…
			Oil	D	…	D	C	C	C	…	C	C	…	A	D	D	C	…	…
			Water[f]	…	E	…	…	…	…	…	E	…	…	…	E	E	…	E	E
Service Properties	Machinability			D	C/D	C/D	D	C/D	D	D/E	D	D	C/D	D	C	C	D	C	D
	Hot Hardness			D	E	E	C	E	E	D	E	E	E	D	E	E	E	E	E
	Wear Resistance			D/E	D/E	D/E	D/E	D	D	C	D	D	D/E	D	D/E	D	D	D	B/C
	Toughness			B	A	A	B	C	C	C	C	C	C	D	B	D	B	E	E

[a] Contains also about 1.20 per cent A1. Solution treated in hardening.

[b] Quenched in oil.

[c] After carburizing.

[d] Carburized case.

[e] Core hardenability.

[f] Sometimes brine is used.

Mold Steels.—These materials differ from all other types of tool steels by their very low-carbon content, generally requiring carburizing to obtain a hard operating surface. A special property of most steel types in this group is the adaptability to shaping by impression (hobbing) instead of by conventional machining. They also have high resistance to decarburization in heat treatment and dimensional stability, characteristics that obviate the need for grinding following heat treatment. Molding dies for plastics materials require an excellent surface finish, even to the degree of high luster; the generally high-chromium content of these types of tool steels greatly aids in meeting this requirement.

Properties and Applications of Frequently Used Mold Steel Types: AISI P3 and P4:

Essentially, both types of tool steels were developed for the same special purpose, that is, the making of plastics molds. The application conditions of plastics molds require high core strength, good wear resistance at elevated temperature, and excellent surface finish. Both types are carburizing steels that possess good dimensional stability. Because hobbing, that is, sinking the cavity by pressing a punch representing the inverse replica of the cavity into the tool material, is the process by which many plastics mold cavities are produced, good “hobbability” of the tool steels used for this purpose is an important requirement. The different chemistry of these two types of mold steels is responsible for the high core hardness of the P4, which makes it better suited for applications requiring high strength at elevated temperature.

AISI P6: This nickel–chromium-type plastics mold steel has exceptional core strength and develops a deep carburized case. Due to the high nickel–chromium content, the cavities of molds made of this steel type are produced by machining rather than by hobbing. An outstanding characteristic of this steel type is the high luster that is produced by polishing of the hard case surface.

AISI P20: This general-type mold steel is adaptable to both through hardening and carburized case hardening. In through hardening, an oil quench is used and a relatively lower, yet deeply penetrating hardness is obtained, such as is needed for zinc die-casting dies and injection molds for plastics. After the direct quenching and tempering, carburizing produces a very hard case and comparatively high core hardness. When thus heat treated, this steel is particularly well adapted for making compression, transfer, and plunger-type plastics molds.

Special-Purpose Tool Steels.—These steels include several low-alloy types of tool steels that were developed to provide transitional types between the more commonly used basic types of tool steels, and thereby contribute to the balancing of certain conflicting properties such as wear resistance and toughness; to offer intermediate depth of hardening; and to be less expensive than the higher-alloyed types of tool steels.

Properties and Applications of Frequently Used Special-Purpose Types: AISI L6: This material is a low-alloy-type special-purpose tool steel. The comparatively safe hardening and the fair nondeforming properties, combined with the service advantage of good toughness in comparison to most other oil-hardening types, explains the acceptance of this steel with a rather special chemical composition. The uses of L6 are for tools whose toughness requirements prevail over abrasion-resistant properties, such as forming rolls and forming and trimmer dies in applications where combinations of moderate shock- and wear-resistant properties are sought. The areas of use also include structural parts, like clutch members, pawls, and knuckle pins, that must withstand shock loads and still display good wear properties.

AISI F2: This carbon–tungsten type is one of the most abrasion-resistant of all water-hardening tool steels. However, it is sensitive to thermal changes, such as are involved in heat treatment and it is also susceptible to distortions. Consequently, its use is limited to tools of simple shape in order to avoid cracking in hardening. The shallow hardening characteristics of F2 result in a tough core and are desirable properties for certain tool types that, at the same time, require excellent wear-resistant properties.

Water-Hardening Tool Steels.—Steel types in this category are made without, or with only a minimum amount of alloying elements and, their heat treatment needs the harsh quenching action of water or brine, hence the general designation of the category.

Water-hardening steels are usually available with different percentages of carbon, to provide properties required for different applications; the classification system lists a carbon range of 0.60 to 1.40 per cent. In practice, however, the steel mills produce these steels in a few varieties of differing carbon content, often giving proprietary designations to each particular group. Typical carbon content limits of frequently used water-hardening tool steels are 0.70–0.90, 0.90–1.10, 1.05–1.20, and 1.20–1.30 per cent. The appropriate group should be chosen according to the intended use, as indicated in the steel selection guide for this category, keeping in mind that whereas higher carbon content results in deeper hardness penetration, it also reduces toughness.

The general system distinguishes the following four grades: 1) special; 2) extra;

3) standard; and 4) commercial.

listed in the order of decreasing quality. The differences between these grades, which are not offered by all steel mills, are defined in principle only. The distinguishing characteristics are purity and consistency, resulting from different degrees of process refinement and inspection steps applied in making the steel. Higher qualities are selected for assuring dependable uniformity and performance of the tools made from the steel.

The groups with higher carbon content are more sensitive to heat-treatment defects and are generally used for the more demanding applications, so the better grades are usually chosen for the high-carbon types and the lower grades for applications where steels with lower carbon content only are needed.

Water-hardening tool steels, although the least expensive, have several drawbacks, but these are quite acceptable in many types of applications. Some limiting properties are the tendency to deformation in heat treatment due to harsh effects of the applied quenching medium, the sensitivity to heat during the use of the tools made of these steels, the only fair degree of toughness, and the shallow penetration of hardness. However, this last-mentioned property may prove a desirable characteristic in certain applications, such as cold-heading dies, because the relatively shallow hard case is supported by the tough, although softer core.

The AISI designation for water-hardening tool steels is W, followed by a numeral indicating the type, primarily defined by the steel's chemical composition, as shown in the Table 13.

Recommended Applications of Water-Hardening Type W1 (Plain Carbon) Tool Steels:

Group I (C-0.70 to 0.90%): This group is relatively tough and therefore preferred for tools that are subjected to shocks or abusive treatment. Used for such applications as: hand tools, chisels, screwdriver blades, cold punches, and nail sets, and fixture elements, vise jaws, anvil faces, and chuck jaws.

Group II (C-0.90 to 1.10%): This group combines greater hardness with fair toughness, resulting in improved cutting capacity and moderate ability to sustain shock loads. Used for such applications as: hand tools, knives, center punches, pneumatic chisels, cutting tools, reamers, hand taps, and threading dies, wood augers; die parts, drawing and heading dies, shear knives, cutting and forming dies; and fixture elements, drill bushings, lathe centers, collets, and fixed gages.

Group III (C-1.05 to 1.20%): The higher carbon content of this group increases the depth of hardness penetrations, yet reduces toughness, thus the resistance to shock loads. Preferred for applications where wear resistance and cutting ability are the prime considerations. Used for such applications as: hand tools, woodworking chisels, paper knives, cutting tools (for low-speed applications), milling cutters, reamers, planer tools, thread chasers, center drills, die parts, cold blanking, coining, bending dies.

Group IV (C-1.20 to 1–30%): The high carbon content of this group produces a hard case of considerable depth with improved wear resistance yet sensitive to shock and concentrated stresses. Selected for applications where the capacity to withstand abrasive wear is needed, and where the retention of a keen edge or the original shape of the tool is important. Used for such applications as: cutting tools for finishing work, like cutters and reamers, and for cutting chilled cast iron and forming tools, for ferrous and nonferrous metals, and burnishing tools.

By adding small amounts of alloying elements to W-steel types 2 and 5, certain characteristics that are desirable for specific applications are improved. The vanadium in type 2 contributes to retaining a greater degree of fine-grain structure after heat treating. Chromium in type 5 improves the deep-hardening characteristics of the steel, a property needed for large sections, and assists in maintaining the keen cutting edge that is desirable in cutting tools like broaches, reamers, threading taps, and dies.

Table 13. Water-Hardening Tool Steels—Identifying Chemical Composition and Heat-Treatment Data

Chemical Composition in Per Cent	AISI Types		
	W1	W2	W5
C	0.60–1.40	0.60–1.40	1.10
	Varying carbon content may be available		
V	…	0.25	…
Cr	These elements are adjusted to satisfy the hardening requirements		0.50
Mn			
Si			

Heat-Treatment Data		
Hardening Temperature Ranges, °F Varying with Carbon Content	0.60–0.80%	1450–1500
	0.85–1.05%	1425–1550
	1.10–1.40%	1400–1525
Quenching Medium		Brine or Water
Tempering Temperature Range, °F		350–650
Approx. Tempered Hardness, Rc		64–50

Relative Ratings of Properties (A = greatest to E = least)							
Characteristics in Heat Treatment				Service Properties			
Safety in Hardening	Depth of Hardening	Resistance to Decarburization	Stability of Shape in Heat Treatment	Machinability	Hot Hardness	Wear Resistance	Toughness
D	C	A	E	A	E	D/E	C/D

Mill Production Forms of Tool Steels

Tool steels are produced in many different forms, although not all those listed in the following are always readily available; certain forms and shapes are made for special orders only.

Hot-Finished Bars and Cold-Finished Bars.—These bars are the most commonly produced forms of tool steels. Bars can be furnished in many different cross-sections, the round shape being the most common. Sizes can vary over a wide range, with a more limited number of standard stock sizes. Various conditions may also be available, however, technological limitations prevent all conditions applying to every size, shape, or type of steel. Tool steel bars may be supplied in one of the following conditions and surface finishes:

Conditions: Hot-rolled or forged (natural); hot-rolled or forged and annealed; hot-rolled or forged and heat-treated; cold- or hot-drawn (as drawn); and cold- or hot-drawn and annealed.

Finishes: Hot-rolled finish (scale not removed); pickled or blast-cleaned; cold-drawn; turned or machined; rough ground; centerless ground or precision flat ground; and polished (rounds only).

Other forms in which tool steels are supplied are the following:

Rolled or Forged Special Shapes: These shapes are usually produced on special orders only, for the purpose of reducing material loss and machining time in the large-volume manufacture of certain frequently used types of tools.

Forgings: All types of tool steels may be supplied in the form of forgings, which are usually specified for special shapes and for dimensions that are beyond the range covered by bars.

Wires: Tool steel wires are produced either by hot or cold drawing and are specified when special shapes, controlled dimensional accuracy, improved surface finish, or special mechanical properties are required. Round wire is commonly produced within an approximate size range of 0.015 to 0.500 inch, and these dimensions also indicate the limits within which other shapes of tool steel wires, like oval, square, or rectangular, may be produced.

Drill Rods: Rods are produced in round, rectangular, square, hexagonal, and octagonal shapes, usually with tight dimensional tolerances to eliminate subsequent machining, thereby offering manufacturing economies for the users.

Hot-Rolled Plates and Sheets, and Cold-Rolled Strips: Such forms of tool steel are generally specified for the high-volume production of specific tool types.

Tool Bits: These pieces are semifinished tools and are used by clamping in a tool holder or shank in a manner permitting ready replacement. Tool bits are commonly made of high-speed types of tool steels, mostly in square, but also in round, rectangular, andother shapes. Tool bits are made of hot rolled bars and are commonly, yet not exclusively, supplied in hardened and ground form, ready for use after the appropriate cutting edges are ground, usually in the user's plant.

Hollow Bars: These bars are generally produced by trepanning, boring, or drilling of solid round rods and are used for making tools or structural parts of annular shapes, like rolls, ring gages, bushings, etc.

Tolerances of Dimensions.—Such tolerances have been developed and published by the American Iron and Steel Institute (AISI) as a compilation of available industry experience that, however, does not exclude the establishment of closer tolerances, particularly for hot rolled products manufactured in large quantities. The tolerances differ for various categories of production processes (e.g., forged, hot-rolled, cold-drawn, centerless ground) and of general shapes.

Allowances for Machining.—These allowances provide freedom from soft spots and defects of the tool surface, thereby preventing failures in heat treatment or in service. After a layer of specific thickness, known as the allowance, has been removed, the bar or other form of tool steel material should have a surface without decarburization and other surface defects, such as scale marks or seams. The industry wide accepted machining allowance values for tool steels in different conditions, shapes, and size ranges are spelled out in AISI specifications and are generally also listed in the tool steel catalogs of the producer companies.

Decarburization Limits.—Heating of steel for production operation causes the oxidation of the exposed surfaces resulting in the loss of carbon. That condition, called decarburization, penetrates to a certain depth from the surface, depending on the applied process, the shape and the dimensions of the product. Values of tolerance for decarburization must be considered as one of the factors for defining the machining allowances, which must also compensate for expected variations of size and shape, the dimensional effects of heat treatment, and so forth. Decarburization can be present not only in hot-rolled and forged, but also in rough turned and cold-drawn conditions.

Advances in Tool Steel Making Technology.—Significant advances in processes for tool steel production have been made that offer more homogeneous materials of greater density and higher purity for applications where such extremely high quality is required. Two of these methods of tool steel production are of particular interest.

Vacuum-melted tool steels: These steels are produced by the consumable electrode method, which involves remelting of the steel originally produced by conventional processes. Inside a vacuum-tight shell that has been evacuated, the electrode cast of tool steel of the desired chemical analysis is lowered into a water-cooled copper mold where it strikes a low-voltage, high-amperage arc causing the electrode to be consumed by gradual melting. The undesirable gases and volatiles are drawn off by the vacuum, and the inclusions float on the surface of the pool, accumulating on the top of the produced ingot, to be removed later by cropping. In the field of tool steels, the consumable-electrode vacuum-melting (CVM) process is applied primarily to the production of special grades of hot-work and high-speed tool steels.

High-speed tool steels produced by powder metallurgy: The steel produced by conventional methods is reduced to a fine powder by a gas atomization process. The powder is compacted by a hot isostatic method with pressures in the range of 15,000 to 17,000 psi. The compacted billets are hot-rolled to the final bar size, yielding a tool-steel material which has 100 per cent theoretical density. High-speed tool steels produced by the P/M method offer a tool material providing increased tool wear life and high impact strength, of particular advantage in interrupted cuts.

Physical Properties

Physical Properties of Heat-Treated Steels.—Steels that have been "fully hardened" to the same hardness when quenched will have about the same tensile and yield strengths regardless of composition and alloying elements. When the hardness of such a steel is known, it is also possible to predict its reduction of area and tempering temperature. The accompanying figures illustrating these relationships have been prepared by the Society of Automotive Engineers.

Fig. 1 gives the range of Brinell hardnesses that could be expected for any particular tensile strength or it may be used to determine the range of tensile strengths that would correspond to any particular hardness. Fig. 2 shows the relationship between the tensile strength or hardness and the yield point. The solid line is the normal-expectancy curve. The dotted-line curves give the range of the variation of scatter of the plotted data. Fig. 3 shows the relationship that exists between the tensile strength (or hardness) and the reduction of area. The curve to the left represents the alloy steels and that on the right the carbon steels. Both are normal-expectancy curves and the extremities of the perpendicular lines that intersect them represent the variations from the normal-expectancy curves that may be caused by quality differences and by the magnitude of parasitic stresses induced by quenching. Fig. 4 shows the relationship between the hardness (or approximately equivalent tensile strength) and the tempering temperature. Three curves are given, one for fully hardened steels with a carbon content between 0.40 and 0.55 per cent, one for fully hardened steels with a carbon content between 0.30 and 0.40 per cent, and one for steels that are not fully hardened.

From Fig. 1, it can be seen that for a tensile strength of, say, 200,000 pounds per square inch, the Brinell hardness could range between 375 and 425. By taking 400 as the mean hardness value and using Fig. 4, it can be seen that the tempering temperature of fully hardened steels of 0.40 to 0.55 per cent carbon content would be 990 degrees F and that of fully hardened steels of 0.30 to 0.40 per cent carbon would be 870 degrees F. This chart also shows that the tempering temperature for a steel not fully hardened would approach 520 degrees F. A yield point of 0.9 × 200,000, or 180,000, pounds per square inch is indicated (Fig. 2) for the fully hardened steel with a tensile strength of 200,000 pounds per square inch. Most alloy steels of 200,000 pounds per square inch tensile strength would probably have a reduction in area of close to 44 per cent (Fig. 3) but some would have values in the range of 35 to 53 per cent. Carbon steels of the same tensile strength would probably have a reduction in area of close to 24 per cent but could possibly range from 17 to 31 per cent.

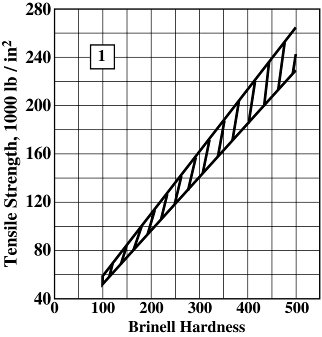

Fig. 1.

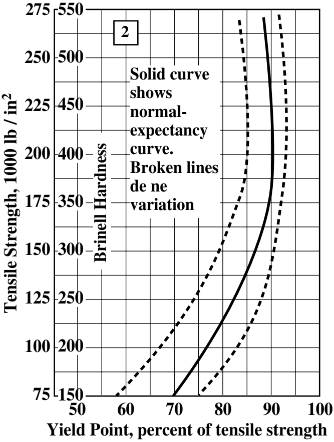

Fig. 2.

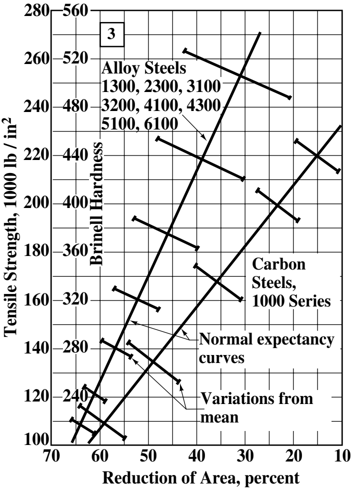

Fig. 3.

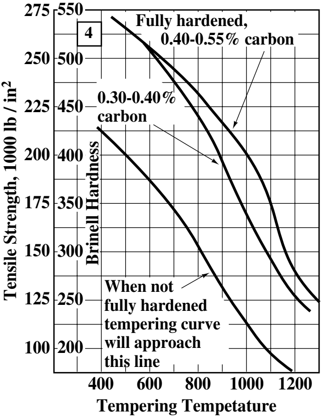

Fig. 4.

Figs. 2 and 3 represent steel in the quenched and tempered condition and Fig. 1 represents steel in the hardened and tempered, as-rolled, annealed, and normalized conditions.

These charts give a good general indication of mechanical properties; however, more exact information when required should be obtained from tests on samples of the individual heats of steel under consideration.

Strength Data for Ferrous Metals.—The accompanying Table 1 gives ultimate strengths, yield points, and moduli of elasticity for various ferrous metals. Values are given as ranges, minimum values, and average values. Ranges of values are due to differences in size and shape of sections, heat treatments undergone, and composition, where several slightly different materials are listed under one general classification. The values in the table are meant to serve as a guide in the selection of ferrous materials and should not be used to write specifications. More specific data should be obtained from the supplier.

Strength Data for Nonferrous Metals.—The ultimate tensile, shear, and yield strengths and moduli of elasticity of many nonferrous metals are given in Table 2. Values for the most part are given in ranges rather than as single values because of differences in composition, forms, sizes, and shapes for the aluminum alloys plus differences in heat treatments undergone for the other nonferrous metals. The values in the table are meant to serve as a guide, not as specifications. More specific data should be obtained from the supplier.

Effect of Temperature on Strength and Elasticity of Metals.—Most ferrous metals have a maximum strength at approximately 400 degrees F, whereas the strength of nonferrous alloys is a maximum at about room temperature. The table on page 478 gives general data for variation in metal strength with temperature.

The modulus of elasticity of metals decreases regularly with increasing temperatures above room temperature until at some elevated temperature it falls off rapidly and reaches zero at the melting point.

Table 1. Strength Data for Iron and Steel

	Ultimate Strength				Modulus of Elasticity	
Material	Tension, Thousands of Pounds per Square Inch, T	Compression, in terms of T	Shear, in terms of T	Yield Point, Thousands of Pounds per Square Inch	Tension, Millions of psi, E	Shear,[a] in terms of E
Cast iron, gray, class 20	20[b]	3.6T to 4.4T	1.6T	…	11.6	0.40E
class 25	25[b]	3.6T to 4.4T	1.4T	…	14.2	0.40E
class 30	30[b]	3.7T	1.4T	…	14.5	0.40E
class 35	35[b]	3.2T to 3.9T	1.4T	…	16.0	0.40E
class 40	40[b]	3.1T to 3.4T	1.3T	…	17	0.40E
class 50	50[b]	3.0T to 3.4T	1.3T	…	18	0.40E
class 60	60[b]	2.8T	1.0T	…	19.9	0.40E
malleable	40 to 100[c]	…	…	30 to 80[c]	25	0.43E
nodular (ductile iron)	60 to 120[d]	…	…	40 to 90[d]	23	…
Cast steel, carbon	60 to 100	T	0.75T	30 to 70	30	0.38E
low-alloy	70 to 200	T	0.75T	45 to 170	30	0.38E
Steel, SAE 950 (low-alloy)	65 to 70	T	0.75T	45 to 50	30	0.38E
1025 (low-carbon)	60 to 103	T	0.75T	40 to 90	30	0.38E
1045 (medium-carbon)	80 to 182	T	0.75T	50 to 162	30	0.38E
1095 (high-carbon)	90 to 213	T	0.75T	20 to 150	30	0.39E
1112 (free-cuttting)*	60 to 100	T	0.75T	30 to 95	30	0.38E
1212 (free-cuttting)	57 to 80	T	0.75T	25 to 72	30	0.38E
1330 (alloy)	90 to 162	T	0.75T	27 to 149	30	0.38E
2517 (alloy)[e]	88 to 190	T	0.75T	60 to 155	30	0.38E
3140 (alloy)	93 to 188	T	0.75T	62 to 162	30	0.38E
3310 (alloy)[e]	104 to 172	T	0.75T	56 to 142	30	0.38E
4023 (alloy)[e]	105 to 170	T	0.75T	60 to 114	30	0.38E
4130 (alloy)	81 to 179	T	0.75T	46 to 161	30	0.38E
4340 (alloy)	109 to 220	T	0.75T	68 to 200	30	0.38E
4640 (alloy)	98 to 192	T	0.75T	62 to 169	30	0.38E
4820 (alloy)[e]	98 to 209	T	0.75T	68 to 184	30	0.38E
5150 (alloy)	98 to 210	T	0.75T	51 to 190	30	0.38E
52100 (alloy)	100 to 238	T	0.75T	81 to 228	30	0.38E
6150 (alloy)	96 to 228	T	0.75T	59 to 210	30	0.38E
8650 (alloy)	110 to 228	T	0.75T	69 to 206	30	0.38E
8740 (alloy)	100 to 179	T	0.75T	60 to 165	30	0.38E
9310 (alloy)[e]	117 to 187	T	0.75T	63 to 162	30	0.38E
9840 (alloy)	120 to 285	T	0.75T	45 to 50	30	0.38E
Steel, stainless, SAE						
30302[f]	85 to 125	T	…	35 to 95	28	0.45E
30321[f]	85 to 95	T	…	30 to 60	28	…
30347[f]	90 to 100	T	…	35 to 65	28	…
51420[g]	95 to 230	T	…	50 to 195	29	0.40E
51430[h]	75 to 85	T	…	40 to 70	29	…
51446[h]	80 to 85	T	…	50 to 70	29	…
51501[g]	70 to 175	T	…	30 to 135	29	…
Steel, structural						
common	60 to 75	T	0.75T	33[b]	29	0.41E
rivet	52 to 62	T	0.75T	28[b]	29	…
rivet, high-strength	68 to 82	T	0.75T	38[b]	29	…
Wrought iron	34 to 54	T	0.83T	23 to 32	28	…

[a] Synonymous in other literature to the modulus of elasticity in torsion and the modulus of rigidity, G.

[b] Minimum specified value of the American Society for Testing and Materials. The specifications for the various materials are as follows: Cast iron, ASTM A48; structural steel for bridges and structures, ASTM A7; structural rivet steel, ASTM A141; high-strength structural rivet steel, ASTM A195.

[c] Range of minimum specified values of the ASTM (ASTM A47, A197, and A220).

[d] Range of minimum specified values of the ASTM (ASTM A339) and the Munitions Board Standards Agency (MIL-I-17166A and MIL-I-11466).

[e] Carburizing grades of steel.

[f] Nonhardenable nickel–chromium and Chromium–nickel–manganese steel (austenitic).

[g] Hardenable chromium steel (martensitic).

[h] Nonhardenable chromium steel (ferritic).

Table 2. Strength Data for Nonferrous Metals

	Ultimate Strength, Thousands of Pounds per Square Inch		Yield Strength (0.2 per cent offset), Thousands of Pounds per Square Inch	Modulus of Elasticity, Millions of Pounds per Square Inch	
Material	in Tension	in Shear		in Tension, *E*	in Shear, *G*
Aluminum alloys, cast,					
sand-cast	19 to 35	14 to 26	8 to 25	10.3	…
heat-treated	20 to 48	20 to 34	16 to 40	10.3	…
permanent-mold-cast,	23 to 35	16 to 27	9 to 24	10.3	…
heat-treated	23 to 48	15 to 36	8.5 to 43	10.3	…
die-cast	30 to 46	19 to 29	16 to 27	10.3	…
Aluminum alloys, wrought,					
annealed	10 to 42	7 to 26	4 to 22	10.0 to 10.6	…
cold-worked	12 to 63	8 to 34	11 to 59	10.0 to 10.3	…
heat-treated	22 to 83	14 to 48	13 to 73	10.0 to 11.4	…
Aluminum bronze, cast,	62 to 90	…	25 to 37	15 to 18	…
heat-treated	80 to 110	…	32 to 65	15 to 18	…
Aluminum bronze, wrought,					
annealed	55 to 80	…	20 to 40	16 to 19	…
cold-worked	71 to 110	…	62 to 66	16 to 19	…
heat-treated	101 to 151	…	48 to 94	16 to 19	…
Brasses, leaded, cast	32 to 40	29 to 31	12 to 15	12 to 14	…
flat products, wrought	46 to 85	31 to 45	14 to 62	14 to 17	5.3 to 6.4
wire, wrought	50 to 88	34 to 46	…	15	5.6
Brasses, nonleaded,					
flat products, wrought	34 to 99	28 to 48	10 to 65	15 to 17	5.6 to 6.4
wire, wrought	40 to 130	29 to 60	…	15 to 17	5.6 to 6.4
Copper, wrought,					
flat products	32 to 57	22 to 29	10 to 53	17	6.4
wire	35 to 66	24 to 33	…	17	6.4
Inconel, cast	70 to 95	…	30 to 45	23	…
flat products, wrought	80 to 170	…	30 to 160	31	11
wire, wrought	80 to 185	…	25 to 175	31	11
Lead	2.2 to 4.9	…	…	0.8 to 2.0	…
Magnesium, cast,					
sand & permanent mold	22 to 40	17 to 22	12 to 23	6.5	2.4
die-cast	33	20	22	6.5	2.4
Magnesium, wrought,					
sheet and plate	35 to 42	21 to 23	20 to 32	6.5	2.4
bars, rods, and shapes	37 to 55	19 to 27	26 to 44	6.5	2.4
Monel, cast	65 to 90	…	32 to 40	19	…
flat products, wrought	70 to 140	…	25 to 130	26	9.5
wire, wrought	70 to 170	…	25 to 160	26	9.5
Nickel, cast,	45 to 60	…	20 to 30	21.5	…
flat products, wrought	55 to 130	…	15 to 115	30	11
wire, wrought	50 to 165	…	10 to 155	30	11
Nickel silver, cast	40 to 50	…	24 to 25	…	…
flat products, wrought	49 to 115	41 to 59	18 to 90	17.5 to 18	6.6 to 6.8
wire, wrought	50 to 145	…	25 to 90	17.5 to 18	6.6 to 6.8
Phosphor bronze, wrought,					
flat products	40 to 128	…	14 to 80	15 to 17	5.6 to 6.4
wire	50 to 147	…	20 to 80	16 to 17	6 to 6.4
Silicon bronze, wrought,					
flat products	56 to 110	42 to 63	21 to 62	15	5.6
wire	50 to 145	36 to 70	25 to 70	15 to 17	5.6 to 6.4
Tin bronze, leaded, cast	21 to 38	23 to 43	15 to 18	10 to 14.5	…
Titanium	50 to 135	…	40 to 120	15.0 to 16.5	…
Zinc, commercial rolled	19.5 to 31	…	…	…	…
Zirconium	22 to 83	…	…	9 to 14.5	4.8

Consult the index for data on metals not listed and for more data on metals listed.

Average Ultimate Strength of Common Materials other than Metals
(pounds per square inch)

Material	Compression	Tension
Bricks, best hard	12,000	400
Bricks, light red	1,000	40
Brickwork, common	1,000	50
Brickwork, best	2,000	300
Cement, Portland, 1 month old	2,000	400
Cement, Portland, 1 year old	3,000	500
Concrete, Portland	1,000	200
Concrete, Portland, 1 year old	2,000	400
Granite	19,000	700
Limestone and sandstone	9,000	300
Trap rock	20,000	800
Slate	14,000	500
Vulcanized fiber	39,000	13,000

Influence of Temperature on the Strength of Metals

	Degrees Fahrenheit							
	210	400	570	750	930	1100	1300	1475
Material	Strength in Per Cent of Strength at 70 Degrees F							
Wrought iron	104	112	116	96	76	42	25	15
Cast iron	…	100	99	92	76	42	…	…
Steel castings	109	125	121	97	57	…	…	…
Structural steel	103	132	122	86	49	28	…	…
Copper	95	85	73	59	42	…	…	…
Bronze	101	94	57	26	18	…	…	…

Strength of Copper–Zinc–Tin Alloys
(U.S. Government Tests)

Percentage of			Tensile Strength, lb/in^2	Percentage of			Tensile Strength, lb/in^2	Percentage of			Tensile Strength, lb/in^2
Copper	Zinc	Tin		Copper	Zinc	Tin		Copper	Zinc	Tin	
45	50	5	15,000	60	20	20	10,000	75	20	5	45,000
50	45	5	50,000	65	30	5	50,000	75	15	10	45,000
50	40	10	15,000	65	25	10	42,000	75	10	15	43,000
55	43	2	65,000	65	20	15	30,000	75	5	20	41,000
55	40	5	62,000	65	15	20	18,000	80	15	5	45,000
55	35	10	32,500	65	10	25	12,000	80	10	10	45,000
55	30	15	15,000	70	25	5	45,000	80	5	15	47,500
60	37	3	60,000	70	20	10	44,000	85	10	5	43,500
60	35	5	52,500	70	15	15	37,000	85	5	10	46,500
60	30	10	40,000	70	10	20	30,000	90	5	5	42,000