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High-Speed Tool Steels

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HIGH-SPEED TOOL STEELS and their requirements are defined by The American Society for Testing and Materials in Specification A600-79 as follows: High-speed tool steels are so named primarily because of their ability to machine materials at high cutting speeds. They are complex iron-base alloys of carbon, chromium, vanadium, molybdenum, or tungsten, or combinations thereof, and in some cases substantial amounts of cobalt. The carbon and alloy contents are balanced at levels to give high attainable hardening response, high wear resistance, high resistance to the softening effect of heat, and good toughness for effective use in industrial cutting operations. Commercial practice has developed two groups of cutting materials:

- The recognized standard high-speed tool steel, which serves almost all applications under mild to severe metal-cutting conditions
- A smaller group of intermediate steels, which are satisfactory for limited applications under mild to moderate metal-cutting conditions

The minimum requirements that must be met to be classed as a standard high-speed tool steel, and those for an intermediate high-speed tool steel, are listed in Table 1. To be acceptable for either group, an alloy must meet all of the requirements shown for that group.

A chronology of some of the significant developments in high-speed tool steels is given in Table 2. The research work in 1903 on a 14% tungsten alloy led to the development of the first high-speed tool steel, which is now designated T1.

Table 1 Requirements for high-speed tool steels per ASTM A 600

Requirement	Standard	Intermediate
Chemical requirements		
Minimum alloy content by major elements		
Carbon	0.65	0.70
Chromium	3.50	3.25
Vanadium	0.80	0.80
Tungsten + 1.8% molybdenum	11.75	6.50
Minimum total alloy content based on tungsten equivalents (⅓ Cr + 6.2 V + W + 1.8 Mo)		
Grades containing less than 5% cobalt	22.50	13.00
Grades containing 5% or more cobalt	21.00	12.00
Hardening response requirements		
Ability to be austenitized, and tempered at a temperature not less than 510 °C (950 °F) with a fine-grain structure (Snyder-Graff grain size 8 min) to	63 HRC	62 HRC

Table 2 Significant dates in the development of high-speed tool steels

Date	Development
1903	0.70% C, 14% W, 4% Cr prototype of modern high-speed tool steels
1904	0.30% V addition
1906	Introduction of electric furnace melting
1910	Introduction of first 18-4-1 composition (AISI T1)
1912	3 to 5% Co addition for improved hot hardness
1923	12% Co addition for increased cutting speeds
1939	Introduction of high-carbon high-vanadium super high-speed tool steels (M4 and T15)
1940–1952	Increasing substitution of molybdenum for tungsten
1953	Introduction of sulfurized free-machining high-speed tool steel
1961	Introduction of high-carbon high-cobalt super hard high-speed tool steels (M40 series)
1970	Introduction of powdered metal high-speed tool steels
1973	Addition of higher silicon/nitrogen content to M-7 to increase hardness
1980	Development of cobalt-free super high-speed tool steels
1982	Introduction of aluminum-modified high-speed tool steels for cutting tools

M and T Classification

There are presently more than 40 individual classifications of high-speed tool steels, according to the American Iron and Steel Institute (AISI). When these are compounded by the number of domestic manufacturers, the total number of individual steels in the high-speed tool steel category exceeds 150. The AISI established a classification system for the high-speed tool steels many years ago. That system consists of a T for those steels that have tungsten as one of their primary alloying elements and an M for those steels that have molybdenum additions as one of their primary alloying elements. In addition, there is a number that follows either the M or the T. Thus, there are high-speed tool steels designated M1, M2, M41, T1, T15, and so on. That number does not have any special significance other than to distinguish one from another. For example, M1 does not mean that it is more highly alloyed than M2 or has greater hardenability or poorer wear resistance, and so on. It merely separates the types and attempts to simplify selection for the user. Table 3 lists the nominal analyses of the common M and T types.

Effect of Alloying Elements

The T series contains 12 to 20% tungsten, with chromium, vanadium, and cobalt as the other major alloying elements. The M series contains approximately 3.5 to 10% molybdenum, with chromium, vanadium, tungsten, and cobalt as the other alloying elements. All types, whether molybdenum or tungsten, contain about 4% chromium; the carbon and vanadium contents vary. As a general rule, when the vanadium content is increased, the carbon content is usually increased (Ref 1).

The tungsten type T1 does not contain molybdenum or cobalt. Cobalt-base tungsten types range from T4 through T15 and contain various amounts of cobalt.

Molybdenum types M1 through M10 (except M6) contain no cobalt, but most contain some tungsten. The cobalt-base, molybdenum-tungsten, premium types are generally classified in the M30 and M40 series. Super high-speed steels normally range from M40 upward; they are capable of being heat treated to high hardnesses.

The M series steels generally have higher abrasion resistance than the T series steels and less distortion in heat treatment; also, they are less expensive (Ref 2). Tools made of high-speed tool steel can also be coated with titanium nitride, titanium carbide, and numerous other coatings by physical vapor deposition technique for improved performance and increased tool life.

Table 3 Composition of high-speed tool steels

AISI type	UNS designation	C	Si	Cr	V	W	Mo	Co
Molybdenum high-speed tool steels								
M1	T11301	0.83	0.35	3.75	1.18	1.75	8.70	...
M2								
Regular C	T11302	0.83	0.33	4.13	1.98	6.13	5.00	...
High C	...	1.00	0.33	4.13	1.98	6.13	5.00	...
M3								
Class 1	T11313	1.05	0.33	4.13	2.50	5.88	5.63	...
Class 2	T11323	1.20	0.33	4.13	3.00	5.88	5.63	...
M4	T11304	1.33	0.33	4.25	4.13	5.88	4.88	...
M6	T11306	0.80	0.33	4.13	1.50	4.25	5.00	12.00
M7	T11307	1.01	0.38	3.75	2.00	1.75	8.70	...
M10								
Regular C	T11310	0.89	0.33	4.13	2.00	...	8.13	...
High C	...	1.00	0.33	4.13	2.00	...	8.13	...
M15	T11315	1.50	0.33	4.00	5.00	6.50	3.50	5.00
M30	T11330	0.80	0.33	4.00	1.25	2.00	8.00	5.00
M33	T11333	0.89	0.33	3.75	1.18	1.70	9.50	8.25
M34	T11334	0.89	0.33	3.75	2.10	1.75	8.48	8.25
M35	T11335	0.80	0.33	4.00	2.00	6.00	5.00	5.00
M36	T11336	0.85	0.33	4.13	2.00	6.00	5.00	8.25
M41	T11341	1.10	0.33	4.13	2.00	6.63	3.75	8.25
M42	T11342	1.10	0.40	3.88	1.15	1.50	9.50	8.25
M46	T11346	1.26	0.53	3.95	3.15	2.05	8.25	8.30
M48	T11348	1.50	0.33	3.88	3.00	10.00	5.13	9.00
M50(a)	T11350	0.80	0.40	4.13	1.00	...	4.25	...
M52(a)	T11352	0.90	0.40	4.00	1.93	1.25	4.45	...
M62	T11362	1.30	0.28	3.88	2.00	6.25	10.50	...
Tungsten high-speed tool steels								
T1	T12001	0.73	0.30	4.13	1.10	18.00	...	...
T4	T12004	0.75	0.30	4.13	1.00	18.25	0.70	5.00
T5	T12005	0.80	0.30	4.38	2.10	18.25	0.88	8.25
T6	T12006	0.80	0.30	4.38	1.80	19.75	0.70	12.00
T8	T12008	0.80	0.30	4.13	2.10	14.00	0.70	5.00
T15	T12015	1.55	0.28	4.38	4.88	12.38	1.00	5.00

(a) Intermediate high-speed tool steel

Various elements are added to M and T series high-speed tool steels to impart certain properties to the tool steels. These elements and their effects are discussed below.

Carbon is by far the most important of the elements and is very closely controlled. While the carbon content of any one high-speed tool steel is usually fixed within narrow limits, variations within these limits can cause important changes in the mechanical properties and the cutting ability. As the carbon concentration is increased, the working hardness also rises; the elevated temperature hardness is higher; and the number of hard, stable, complex carbides increases. The latter contribute much to the wear resistance and other properties of the high-speed tool steels.

Silicon. The influence of silicon on high-speed tool steel, up to about 1.00%, is slight. Increasing the silicon content from 0.15 to 0.45% gives a slight increase in maximum attainable tempered hardness and has some influence on carbide morphology, although there seems to be a concurrent slight decrease in toughness. Some manufacturers produce at least one grade with silicon up to 0.65%, but this level of silicon content requires a lower maximum austenitizing temperature than does a lower silicon level in the same grade, if overheating is to be avoided. In general, however, the silicon content is kept below 0.45% on most grades.

Manganese. Generally, manganese is not high in concentration in high-speed tool steels. This is because of its marked effect in increasing brittleness and the danger of cracking upon quenching.

Phosphorus has no effect on any of the desired properties of high-speed tool steels, but because of its well-known effect in causing cold shortness, or room-temperature brittleness, the concentration of phosphorus is kept to a minimum.

Chromium is always present in high-speed tool steels in amounts ranging from 3 to 5% and is mainly responsible for the hardenability. Generally, the addition is 4% because it appears that this concentration gives the best compromise between hardness and toughness. In addition, chromium reduces oxidation and scaling during heat treatment.

Tungsten. In the high-speed tool steels, tungsten is of vital importance. It is found in all T-type steels and in all but two of the M-type steels. The complex carbide of iron, tungsten, and carbon that is found in high-speed tool steels is very hard and significantly contributes to wear resistance. Tungsten improves hot hardness, causes secondary hardening, and imparts marked resistance to tempering. When the tungsten concentration is lowered in high-speed tool steels, molybdenum is usually added to make up for its loss.

Molybdenum forms the same double carbide with iron and carbon as tungsten does but has half the atomic weight of tungsten. As a consequence, molybdenum can be substituted for tungsten on the basis of approximately one part of molybdenum, by weight, for two parts of tungsten.

The melting point of the molybdenum steels is somewhat lower than that of the tungsten grades, and thus they require a lower hardening temperature and have a narrower hardening range. The M-type high-speed tool steels are tougher than the T-type high-speed tool steels, but the hot hardness is slightly lower. Compensation for this reduced hot hardness is partially accomplished by the addition of tungsten and, to a lesser extent, vanadium to the plain molybdenum grades. This is one important reason for the popularity of the tungsten-molybdenum grades (like M2, M3, M4): they afford good hot hardness, which is so desirable in high-speed tool steels.

Vanadium was first added to high-speed tool steels as a scavenger to remove slag impurities and to reduce nitrogen levels in the melting operation, but it was soon found that the element materially increased the cutting efficiency of tools. The addition of vanadium promotes the formation of very hard, stable carbides, which significantly increase wear resistance and, to a lesser extent, hot hardness. An increase in vanadium, when properly balanced by carbon additions, has relatively little effect on the toughness. For this reason, vanadium-bearing grades are a very good choice when very fast cutting operations are demanded, as in finishing cuts, or when the surface of the material is hard and scaly. The special characteristics of the high-speed tool steels that are due to high vanadium additions have given rise to several specially developed steels for very severe service requiring high toughness as well as exceptional hot hardness and wear resistance. The T15, M4, and M15 grades are in this category; their vanadium content is 4.88, 4.13, and 5.00%, respectively.

Cobalt. The main effect of cobalt in high-speed tool steel is to increase the hot hardness and thus to increase the cutting efficiency when high tool temperatures are attained during the cutting operation. Cobalt raises the heat-treating temperatures because it elevates the melting point. Hardening temperatures for cobalt high-speed tool steels can be 14 to 28 °C (25 to 50 °F) higher than would be normal for similar grades without cobalt. Cobalt additions slightly increase the brittleness of high-speed tool steels.

Cobalt steels are especially effective on rough or hogging cuts, but they are not usually suited to finishing cuts that do not involve high temperatures. Cobalt types usually perform quite well when cutting materials that have discontinuous chips such as cast iron or nonferrous metals.

The necessity of using deep cuts and fast speeds or of cutting hard and scaly materials justifies the use of cobalt high-speed tool steels.

Sulfur, in normal concentrations of 0.03% or less, has no effect on the properties of high-speed tool steels. However, sulfur is added to certain high-speed tool steels to contribute free-machining qualities, as it does in low-alloy steels. The amount of free-machining high-speed tool steels is a small but significant percentage of the total consumption of high-speed tool steels. One of the major areas for free-machining high-speed tool steels is in larger-diameter tools such as hobs, broaches, and so on.

Sulfur forms complex sulfides, containing chromium, vanadium, and manganese, which are distributed throughout the steel as stringer-type inclusions. The stringers interrupt the steel structure and act as notches, which aid the metal-removing action of a cutting tool when machining the high-speed steel, because the resulting chip is discontinuous, a characteristic of free-machining steels. Very high sulfur additions (up to 0.30%) are made to some powder metallurgy (P/M) high-speed tool steels for improved machinability/grindability by forming globular sulfides rather than stringers (see the article "P/M High-Speed Tool Steels" in this Volume).

Nitrogen is generally present in air-melted high-speed tool steel in amounts varying from approximately 0.02 to 0.03%. The nitrogen content of some high-speed tool steels is deliberately increased to about 0.04 to 0.05%, and this addition, when combined with higher than usual amounts of silicon, results in a slight increase of maximum attainable tempered hardness and some change of carbide morphology.

Properties of High-Speed Tool Steels

High-speed tool steels, regardless of whether they are an AISI M-type or T-type, have a rather striking similarity in their physical makeup:

- They all possess a high-alloy content
- They usually contain sufficient carbon to permit hardening to 64 HRC
- They harden so deeply that almost any section encountered commercially will have a uniform hardness from center to surface
- They are all hardened at high temperatures, and their rate of transformation is such that small sections can be cooled in still air and be near maximum hardness

All high-speed tool steels possess excess carbide particles, which in the annealed state contain a high proportion of the alloying elements. These carbide particles contribute materially to the wear resistance of hardened high-speed tool steel. By partially dissolving during heat treatment, these carbides provide the matrix of the steel with the necessary alloy and carbon content for hardenability, hot hardness, and resistance to tempering.

While all high-speed tool steels have many similar mechanical and physical characteristics, the properties may vary widely due to changes in chemical composition. Basically, the most important property of a high-speed tool steel is its cutting ability. Cutting ability depends on a combination of properties, the four most important of these being:

- *Hardness*: Resistance to penetration by diamond-hard indenter, measured at room temperature
- *Hot hardness*: The ability to retain high hardness at elevated temperatures
- *Wear resistance*: Resistance to abrasion, often measured by grindability, metal-to-metal, or various other types of tests to indicate a relative rating
- *Toughness*: Ability to absorb (impact) energy

The relative importance of these properties varies with every application. High machining speeds require a composition with a high initial hardness and a maximum resistance to softening at high temperatures. Certain materials may abrade the cutting edge of the tool excessively; hence, the wear resistance of the tool material may well be more important than its resistance to high cutting temperatures.

Hardness is necessary for cutting harder materials and generally gives increased tool life, but it must be balanced against the toughness required for the application.

The desired combination of properties in a high-speed tool steel may be obtained, first, by selection of the proper grade and,

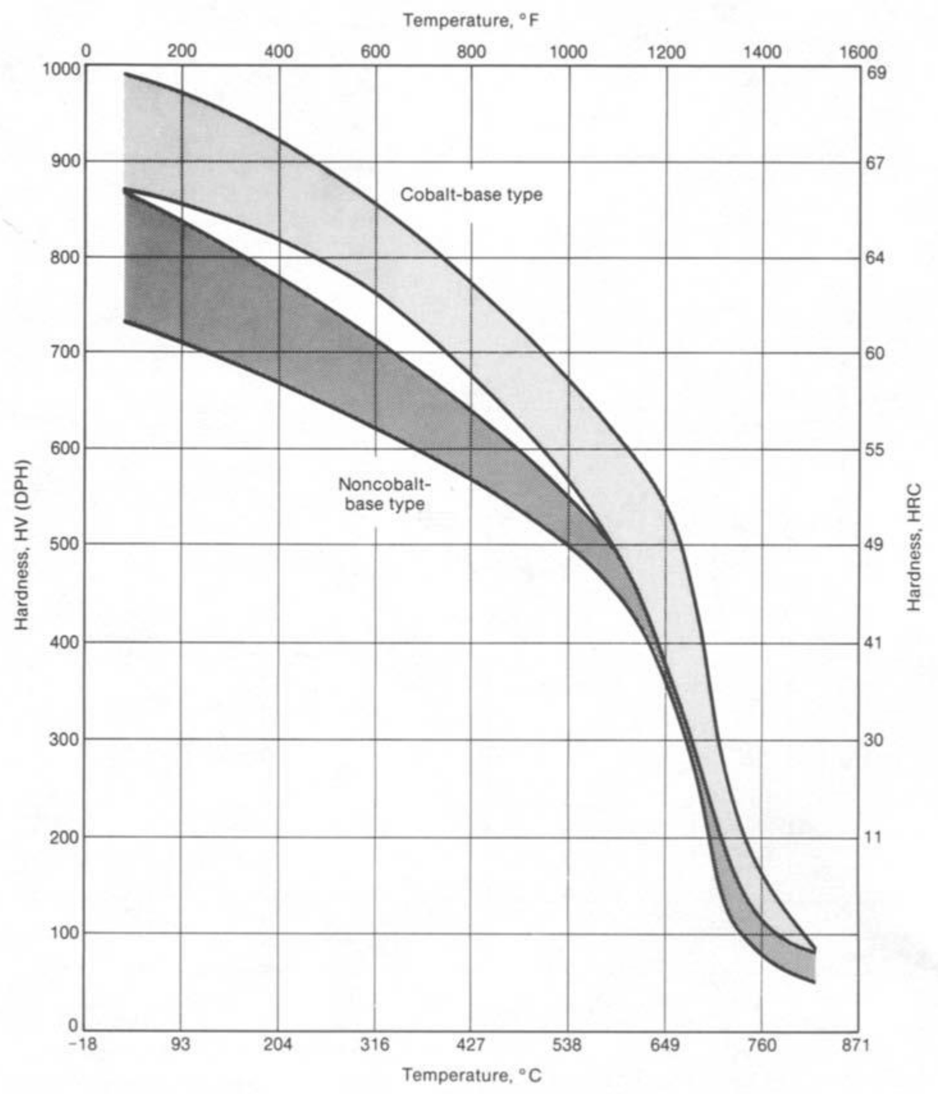

Fig. 1 Comparison of the hot hardness of cobalt-base (M33, M36, M4, and T15) type versus noncobalt-base (M1, M2, M4, M7, and T1) type high-speed tool steels

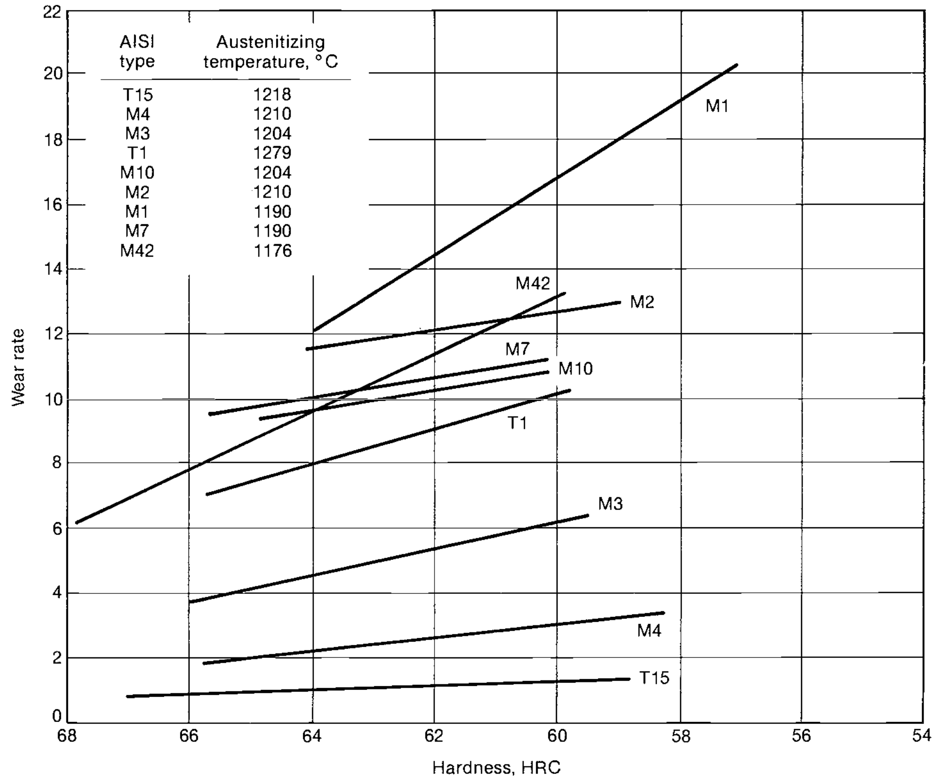

Fig. 2 Effect of hardness on wear rate for high-speed tool steels, each having been double tempered to the indicated hardness

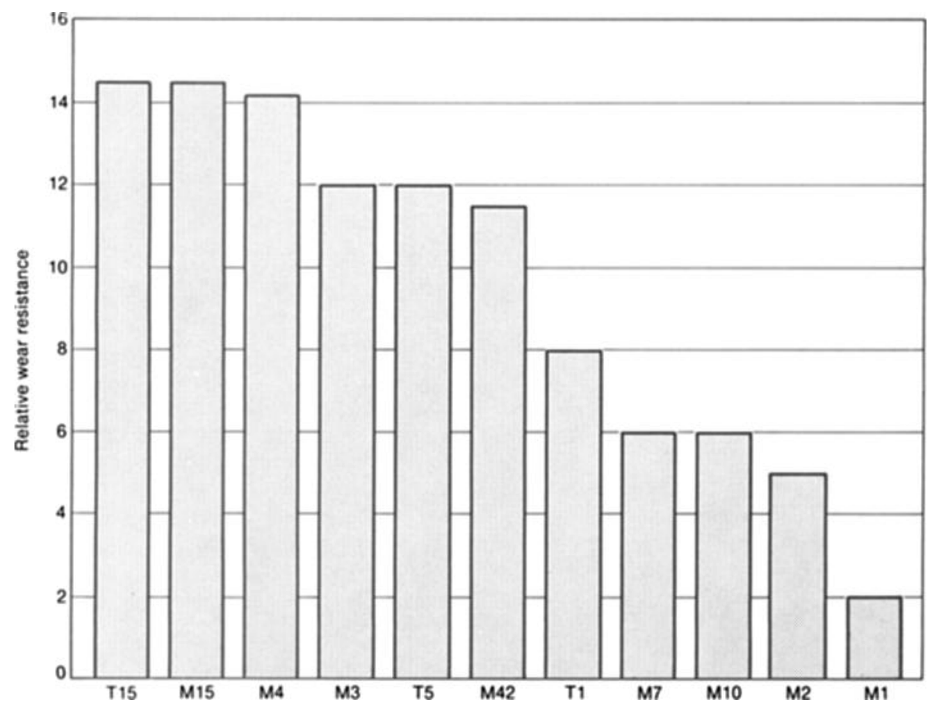

Fig. 3 Comparison of relative abrasion resistance at typical working hardness for high-speed tool steels

second, by the proper heat treatment, two equally important decisions.

Hardness. Hardness is the most commonly stipulated requirement of a high-speed tool steel and is used as an acceptance check of a heat-treated tool. All high-speed tool steels can be hardened to room temperature hardness of 64 HRC, while the M40 series, some of the M30 series, and T15 can reach nearly 69 HRC.

Hot Hardness. A related and important component of cutting ability is hot hardness. It is simply the ability to retain hardness at elevated temperatures. This property is important because room temperature hardness values are not the same values that exist at the elevated temperature produced by friction between the tool and workpiece.

Hot hardness values of some representative grades are plotted in Fig. 1. It is noteworthy that the cobalt-base types as a group exhibit higher hot hardness than non-cobalt-base types. For a comparison of the hot hardness of other metals, alloys, carbides, and ceramics to that of high-speed tool steels, see Fig. 1 in the article "Cast Cobalt Alloys" in this Volume.

Wear Resistance. The third component of cutting ability is resistance to wear. Wear resistance of high-speed tool steels is affected by the matrix hardness and composition, by precipitated M_2C and MC carbides responsible for secondary hardness, by the volume of excess alloy carbides, and by the nature of these excess carbides. In practically any given high-speed tool steels, wear resistance strongly depends on hardness of the steel, and higher hardness, however achieved, is an aim when highly abrasive cutting conditions are encountered (Fig. 2).

For the ultimate in wear resistance, carbon content has been increased simultaneously with vanadium content, to permit the introduction of a greater quantity of total carbide and a greater percentage of extremely hard vanadium carbide in high-speed tool steel. Examples of this effect are given when discussing the effect of vanadium on the properties of high-speed tool steels. Steels T15, M3 (class 2), M4, and M15 are in this category, and all have extremely high wear resistance.

Laboratory tests for wear resistance are diverse, making comparisons between different procedures difficult. Therefore, production tests on actual tools are used to a great extent. However, laboratory tests can produce valuable data on the relative wear resistance for these steels (Fig. 3). The data given in Fig. 3 were generated by measuring the volume loss of a high-speed tool steel sample against the volume loss of a known vitrified abrasive wheel after a predetermined grinding procedure.

Toughness. The fourth component of cutting ability mentioned above is toughness, which is defined as a combination of two factors:

- The ability to deform before breaking (ductility)
- The ability to resist permanent deformation (elastic strength)

If either of these factors is to be used to describe toughness (a practice not to be condoned), the second appears more practical for high-steel tool steel because rarely are large degrees of flow or deformation

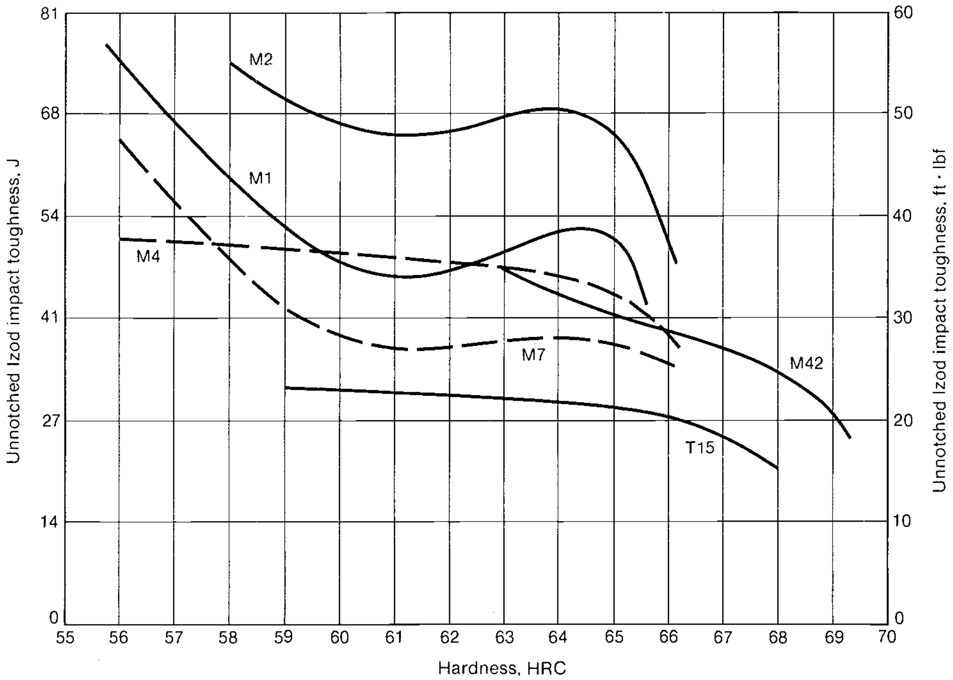

Fig. 4 Plot of impact toughness versus hardness for high-speed tool steels

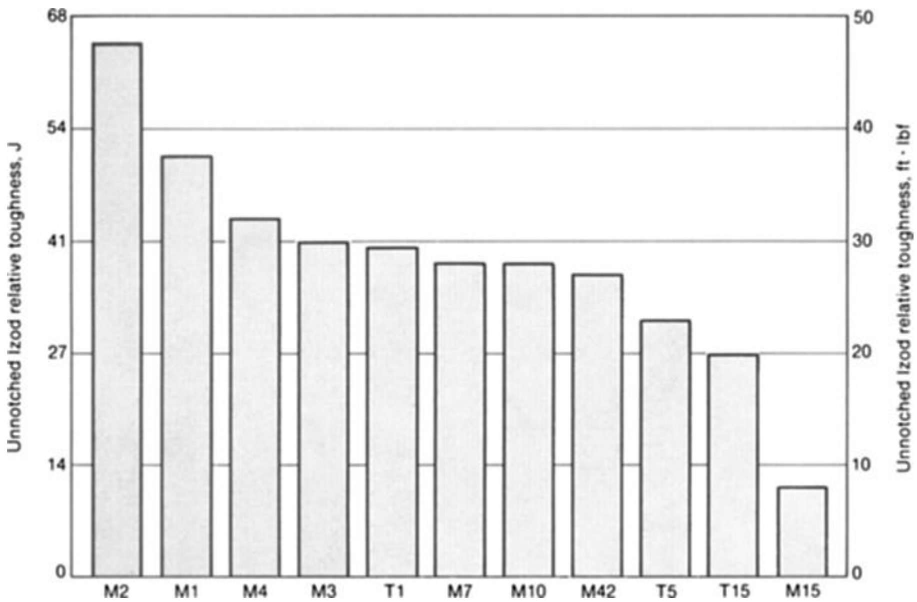

Fig. 5 Relative toughness of high-speed tool steels at typical working hardness

permissible with fine-edge tools. The first, however, cannot be ignored, as frequently the stress applied to a tool (through overloads, shock, notches, and sharp corners) exceeds the elastic strength.

Toughness tests on high-steel tool steel are usually conducted at room temperature. Tool failures that occur from spalling of the tool edge generally occur during the initial contact of the tool with the work, and once the tool becomes heated, its performance in this respect is much superior. Therefore, room temperature tests are perhaps of greater value when toughness is considered than when hardness is in question. Laboratory tests for the measurement of toughness of hardened high-speed tool steel include bend, unnotched or C-notch impact, static torsion, and torsion impact tests. Figures 4 and 5 compare relative unnotched impact values for representative high-speed tool steels. Modest improvements in toughness (within a grade) can be made by lowering the tempered hardness. Lower austenitizing temperatures enhance the toughness for a given hardness and grade.

Heat Treatment of High-Speed Tool Steels

Proper heat treatment is as critical to the success of the cutting tool as material selection itself. Often the highest-quality steel made into the most precise tools does not perform because of improper heat treatment.

The object of the heat treating or hardening operation is to transform a fully annealed high-speed tool steel consisting mainly of ferrite (iron) and alloy carbides into a hardened and tempered martensitic structure having carbides that provide the cutting tool properties (see Fig. 6 and 7).

The heat treatment process can be divided into four primary areas, preheating, austenitizing, quenching, and tempering. Figure 8 outlines graphically these four heat treatment steps.

Preheating. From a metallurgical standpoint, preheating plays no part in the hardening reaction; however, it performs three important functions. The first of these is to reduce thermal shock, which always results when a cold tool is placed into a warm or hot furnace. Minimizing thermal shock reduces the danger of excessive distortion or cracking. It also relieves some of the stresses developed during machining and/or forming, although conventional stress relieving is more effective.

The second major benefit of preheating is to increase equipment productivity by decreasing the amount of time required in the high-heat furnace. Thirdly, if the high-heat furnace is not neutral to the surface of the tool or part, preheating will reduce the amount of carburization and decarburization that would result if no preheat were employed. In commercial salt bath hardening, a two-step preheat is typically used for high-speed tool steels. The first preheat is carried out between 650 and 760 °C (1200 and 1400 °F); the second preheat cycle is carried out between 815 and 900 °C (1500 and 1650 °F). In atmosphere or vacuum heat treating, the furnace is usually heated slowly to a single preheat of 790 to 845 °C (1450 to 1550 °F). Preheat duration is of little importance as long as the part is heated throughout its cross section.

Austenitizing (hardening) is the second step of the heat treatment operation. Austenitizing is a time/temperature dependent reaction. High-speed tool steels depend upon the dissolving of various complex alloy carbides during austenitizing to develop their properties. These alloy carbides do not dissolve to any appreciable extent unless the steel is heated to a temperature within 28 to 56 °C (50 to 100 °F) of their melting point. This temperature is dependent upon the particular high-speed tool steel being treated and is in the range of 1150 to 1290 °C (2100 to 2350 °F). The generally recommended hold time for high-speed tool steel is approximately 2 to 6 min, depending upon

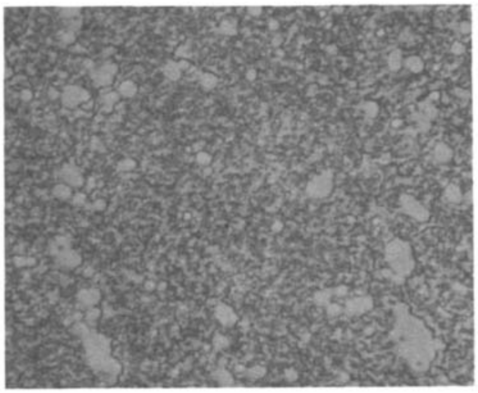

Fig. 6 Microstructure of fully annealed high-speed tool steel consisting of ferrite (iron) and alloy carbides. 1000×

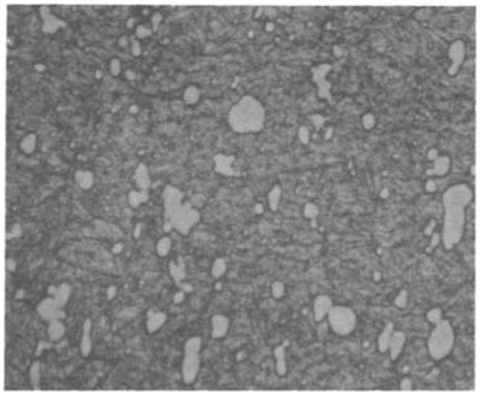

Fig. 7 Microstructure of hardened, tempered high-speed tool steel having martensitic structure with carbides. 1000×

high-speed tool steel type, tool configuration, and cross-sectional size.

Lowering the hardening temperature (underhardening) generally improves the impact toughness while lowering the hot hardness. Raising the hardening temperature increases heat-treated room-temperature hardness and also increases the hot hardness.

Quenching. The quenching or cooling of the workpiece from the austenitizing temperature is designed to transform the austenite that forms at the high temperature to a hard martensitic structure. The rate of cooling, which must be controlled, is dictated by the analysis of the particular steel. Sometimes high-speed steels are two-step quenched, initially in a molten salt bath maintained at approximately 540 to 595 °C (1000 to 1100 °F) or an oil quench, followed by air cooling to near ambient temperature. The least drastic form of quenching is cooling in air, although only in the smaller and/or thinner cross sections would high-speed tool steels air quench rapidly enough to transform the majority of the structure into the desirable martensitic condition. The austenite-martensite transformation is exemplified in Fig. 9 illustrating a time-temperature-transformation curve.

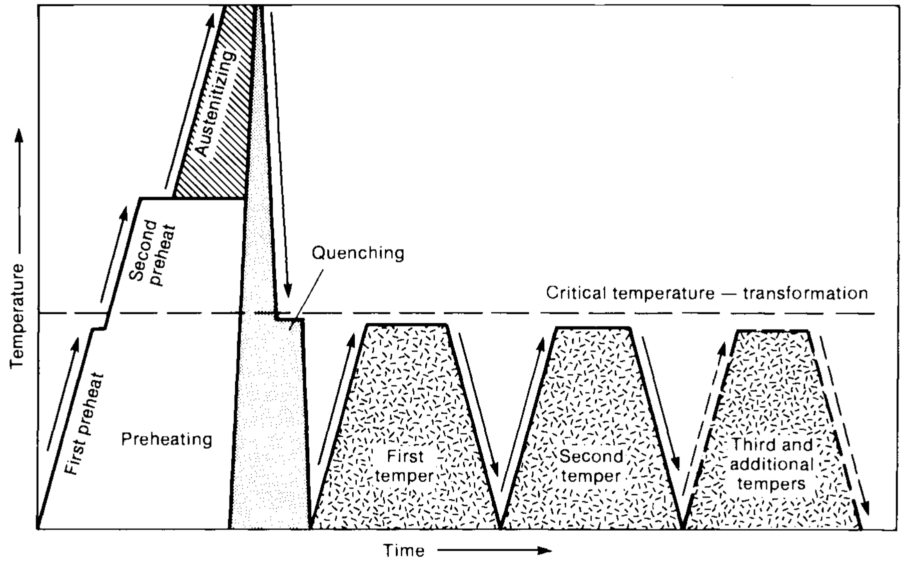

Fig. 8 Time versus temperature plot illustrating sequences required to properly heat treat high-speed tool steels

Tempering. Following austenitizing and quenching, the steel is in a highly stressed state and therefore is very susceptible to cracking. Tempering (or drawing) increases the toughness of the steel and also provides secondary hardness, as illustrated by the peak on the right of the tempering curve in Fig. 10. Tempering involves reheating the steel to an intermediate temperature range (always below the critical transformation temperature), soaking, and air cooling.

Tempering serves to stress relieve and to transform retained austenite from the quenching step to fresh martensite. Some precipitation of complex carbide also occurs, further enhancing secondary hardness. It is this process of transforming retained austenite and tempering of newly formed martensite that dictates a multiple tempering procedure. High-speed tool steels require 2 to 4 tempers at a soak time of 2 to 4 h each. As with austenitizing temperatures and quenching rates, the number of tempers is dictated by the specific grade. High-speed tool steels should be multiple tempered at 540 °C (1000 °F) minimum for most grades. It is essential to

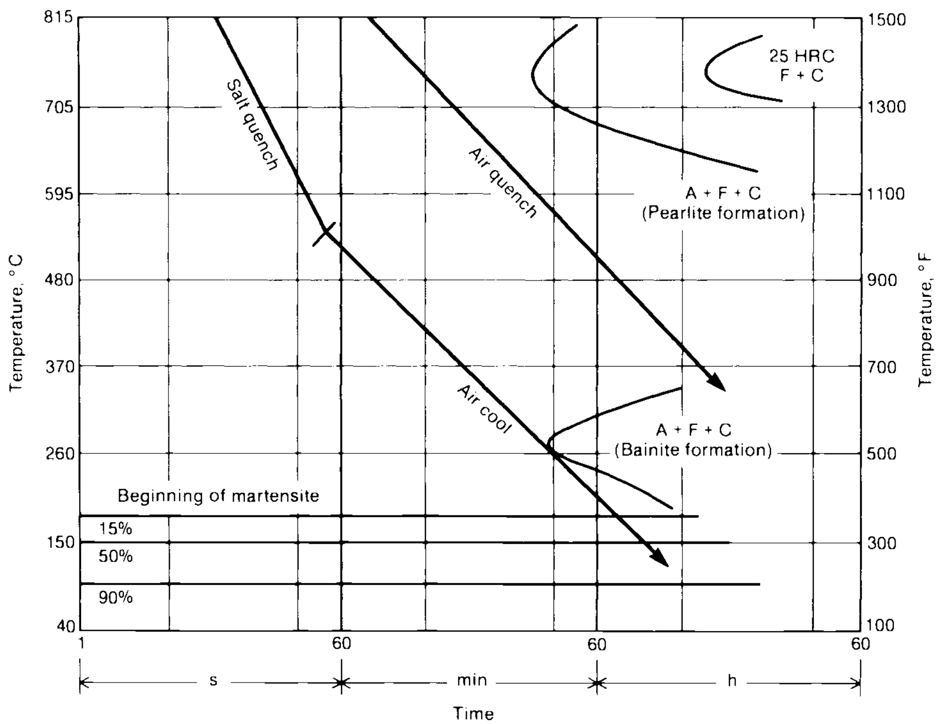

Fig. 9 Time-temperature-transformation diagram for M2 high-speed tool steel that was annealed prior to quenching. Austenitizing temperature was 1230 °C (2250 °F), and critical temperature was 830 °C (1530 °F).

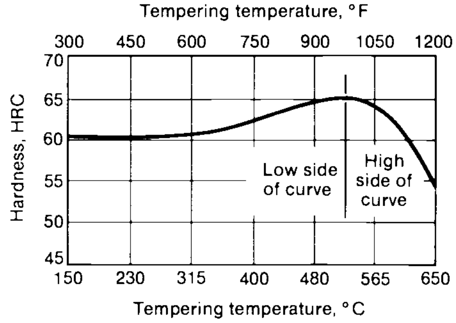

Fig. 10 Tempering curve for M2 high-speed tool steel. To optimize the transformation of retained austenite to fresh martensite during the tempering sequence, the high (right) side of the secondary hardness peak curve is preferred, and the low (left) side should be avoided.

favor the right (high) side of the secondary hardness peak of the tempering curve in order to optimize the above-described transformations.

Subzero treatments are sometimes used in conjunction with tempering in order to continue the transformation of austenite to martensite. Numerous tests have been run on the effect of cold treatments, and the findings generally prove that cold treatments used after quenching and first temper enhance the transformation to martensite, in much the same way that multiple tempering causes transformation. Cold treatments administered to high-speed tool steels immediately after quenching can result in cracking or distortion because the accompanying size change is not accommodated by the newly formed, brittle martensite. It is generally accepted that subzero treatments are not necessary if the steel is properly hardened and tempered.

Surface Treatments

Tools made of high-speed tool steel are available with either a bright, black oxide or nitride finish or they can be coated with titanium nitride and other coatings using a vapor disposition process that greatly increases tool life.

Bright Finish. Most tools are finished with a ground or mechanically polished surface that would be categorized as a bright finish. Bright finished tools are often preferred to tools with an oxide finish for machining nonferrous work material. The smooth or bright finish tends to resist galling, a type of welding or buildup associated with many nonferrous alloys. However, work materials of ferrous alloys tend to adhere to similar, iron-base tools having a bright finish. This buildup on the cutting edges leads to increased frictional heat, poor surface finish, and increased load at the cutting edge.

Black Oxide Finish. This characteristic black finish is typically applied to drills and other cutting tools by oxidizing in a steam atmosphere at approximately 540 °C (1000 °F). The black oxide surface has little or no effect on hardness, but serves as a partial barrier to galling of similar ferrous metals. The surface texture also permits retention of lubricant.

Nitride Finish. Nitriding is a method of introducing nitrogen to the surface of high-speed tool steels at a typical temperature of 480 to 595 °C (900 to 1100 °F) and is accomplished either by the dissociation of ammonia gas, exposure to sodium cyanide salt mixtures, or bombardment with nitrogen ions in order to liberate nascent nitrogen, which combines with the steel to form a hard iron nitride. Nitriding improves wear resistance of high-speed steel, at the expense of notch toughness.

Coated High-Speed Tool Steels. The addition of wear-resistant coatings to high-speed tool steel cutting tools lagged behind the coating of carbide inserts by approximately 10 years until the development of the low-temperature physical vapor deposition (PVD) process, an innovation, which is much more suitable for coating high-speed tool steels than is the older chemical vapor deposition (CVD) process, and which also eliminates the need for subsequent heat treatment (Ref 3). As described in Ref 4, titanium nitride is the most commonly used and most durable coating available, although substitutes such as other nitrides (hafnium nitride and zirconium nitride) and carbides (titanium carbide, zirconium carbide, and hafnium carbide) are being developed. These other coatings are expected to equal or surpass the desired properties of titanium nitrides in future years. The hard thin (2 to 5 μm, or 80 to 200 μin. thick) deposit of high-density titanium nitride, which has 2500 HV hardness and imparts a characteristic gold color to high-speed tool steels, provides excellent wear resistance, minimizes heat buildup, and prevents welding of the workpiece material, while improving the surface finish of high-speed tool steels (Ref 5).

The initial use, in 1980, of titanium nitride coatings was to coat gear cutting tools. Subsequent applications include the coating of both single-point and multipoint tools such as lathe tools, drills, reamers, taps, milling cutters, end mills, and broaches (Ref 3). Today, titanium nitride coated hobs and shapers dominate high-production applications in the automotive industry to such an extent that 80% of such tools use this coating.

As described in Ref 6, significant cost savings are possible because the titanium nitride coating improves tool life up to 400% and increases feed and speed rates by 30%. This is primarily attributable to the increased lubricity of the coating because its coefficient of friction is one-third that of the bare metal surface of a tool.

Examples of increased tool life obtained when using coated versus uncoated single-point and multipoint cutting tools are listed in Table 4. The increased production obtained with a coated tool justifies the application of the coating despite the resulting 20 to 30% increase in the base price of the tool (Ref 3).

Coated tools can meet close-tolerance requirements and significantly improve the machining of carbon and alloy steels, stainless steels (especially the 300 series, where galling can be a problem), and aluminum alloys (especially aircraft grades). Coated high-speed tool steels are less of a factor in the machining of certain titanium alloys and some high-nickel alloys because of chemical reactions between the coatings and the workpiece materials (Ref 3).

High-Speed Tool Steel Applications

High-speed tool steels are used for most of the common types of cutting tools including single-point lathe tools, drills, reamers, taps, milling cutters, end mills, hobs, saws, and broaches.

Single-Point Cutting Tools

The simplest cutting tools are single-point cutting tools, which are often referred to as tool bits, lathe tools, cutoff tools, or inserts. They have only one cutting surface or edge in contact with the work material at any given time. Such tools are used for turning, threading, boring, planing, or shaping, and most are mounted in a toolholder that is made of some type of tough alloy steel. The performance of such tools is dependent on the tool material as well as factors such as the material being cut, the speeds and feeds, the cutting fluid, and fixturing. Following is a discussion of material characteristics and recommendations for the most popular lathe tools.

M1, M2, and T1 are suitable for all-purpose tool bits. They offer excellent strength and toughness and are suitable for both roughing and finishing and can be used for machining wrought steel, cast steel, cast iron, brass, bronze, copper, aluminum, and so on (see the Section "Machining of Specific Metals and Alloys" in this Volume). These are good economical grades for general shop purposes.

M3 class 2 and M4 high-speed tool steels have high-carbon and high-vanadium contents. The wear resistance is several times that of standard high-speed steels. These bits are hard and tough, withstanding intermittent cuts even under heavy feeds. They are useful for general applications and especially recommended for cast steels, cast iron, plastics, brass, and heat-treated steels. On tool bit applications where failure occurs from rapid wearing of the cutting edge, M3 class 2 and M4 will be found to surpass the performance of regular tool bits.

T4, T5, and T8 combine wear resistance resulting from the higher carbon and vanadium contents together with a higher hot hardness, resulting from a cobalt content.

Table 4 Increased tool life attained with coated cutting tools

Cutting tool				Workpieces machined before resharpening	
Type	High-speed tool steel, AISI type	Coating	Workpiece material	Uncoated	Coated
End mill	M7	TiN	1022 steel, 35 HRC	325	1 200
End mill	M7	TiN	6061-T6 aluminum alloy	166	1 500
End mill	M3	TiN	7075T aluminum alloy	9	53
Gear hob	M2	TiN	8620 steel	40	80
Broach insert	M3	TiN	Type 303 stainless steel	100 000	300 000
Broach	M2	TiN	48% nickel alloy	200	3 400
Broach	M2	TiN	Type 410 stainless steel	10 000–12 000	31 000
Pipe tap	M2	TiN	Gray iron	3 000	9 000
Tap	M2	TiN	1050 steel, 30-33 HRC	60–70	750–800
Form tool	T15	TiC	1045 steel	5 000	23 000
Form tool	T15	TiN	Type 303 stainless steel	1 840	5 890
Cutoff tool	M2	TiC-TiN	Low-carbon steel	150	1 000
Drill	M7	TiN	Low-carbon steel	1 000	4 000
Drill	M7	TiN	Titanium alloy 662 layered with D6AC tool steel, 48-50 HRC	9	86

Source: Ref 3

Because of the good resistance to abrasion and high hot hardness, these steels should be applied to the cutting of hard, scaly, or gritty materials. They are well adapted for making hogging cuts, for the cutting of hard materials, and for the cutting of materials that throw a discontinuous chip, such as cast iron and nonferrous materials. The high degree of hot hardness permits T4, T5, and T8 to cut at greater speeds and feeds than most high-speed tool steels. They are much more widely used for single-point cutting tools, such as lathe, shaper, and planer tools, than for multiple-edge tools.

Superhard tool bits made from the M40 series offer the highest hardness available for high-speed tool steels. The M40 steels are economical cobalt alloys that can be treated to reach a hardness as high as 69 HRC. Tool bits made from them are easy to grind and offer top efficiency on the difficult-to-machine space-age materials (titanium and nickel-base alloys, for example) and heat-treated high-strength steels requiring high hot hardness.

T15 tool bits are made from a steel capable of being treated to a high hardness, with outstanding hot hardness and wear resistance. The exceptional wear resistance of T15 has made it the most popular high-speed tool steel for lathe tools. It has higher hardness than most other steels, and wear resistance surpassing that of all other conventional high-speed tool steels as well as certain cast cutting tool materials. It has ample toughness for most types of cutting tool applications, and will withstand intermittent cuts. These bits are especially adapted for machining materials of high-tensile strength such as heat-treated steels and for resisting abrasion encountered with hard cast iron, cast steel, brass, aluminum, and plastics. Tool bits of T15 can cut ordinary materials at speeds 15 to 100% higher than average.

Often an engineer will specify a grade that is not necessary for a given application. For example, selecting M42 for a general application that could be satisfied with M2 does not always prove to be beneficial. The logic is that the tool can be run faster and therefore generate a higher production rate. What happens many times is that the M42 will chip because of its lower toughness level, whereas the M2 will not.

Multipoint Cutting Tools

Applications of high-speed tool steels for other cutting tool applications such as drills, end mills, reamers, taps, threading dies, milling cutters, circular saws, broaches, and hobs are based on the same parameters of hot hardness, wear resistance, toughness, and economics of manufacture. Some of the cutting tools that require extensive grinding have been produced of P/M high-speed tool steels (see the article "P/M High-Speed Tool Steels" in this Volume).

General-purpose drills, other than those made from low-alloy steels for low production on wood or soft materials, are made from high-speed tool steels, typically M1, M2, M7, and M10. For lower cost hardware quality drills, intermediate high-speed tool steels M50 and M52 are sometimes used although they cannot be expected to perform as well as standard high-speed tool steels in production work. For high hot hardness required in the drilling of the more difficult-to-machine alloys such as nickel-base or titanium product, M42, M33, or T15 are used.

High-speed tool steel twist drills are not currently being coated as extensively as gear cutting tools because many drills are not used for production applications. Also, the cost of coating (predominantly with titanium nitride) is prohibitive because it represents a higher percentage of the total tool cost.

Drills coated with titanium nitride reduce cutting forces (thrust and torque) and improve the surface finishes to the point that they eliminate the need for prior core drilling and/or subsequent reaming. Coated drills have been found especially suitable for cutting highly abrasive materials, hard nonferrous alloys, and difficult-to-machine materials such as heat-resistant alloys. These tools are not recommended for drilling titanium alloys because of possible chemical bonding of the coating to the workpiece material. When drilling gummy materials (1018 and 1020 steels, for example) with coated tools, it may be necessary to provide for chipbreaking capabilities in the tool design (Ref 3).

End mills are produced in a variety of sizes and designs, usually with two, four, or six cutting edges on the periphery. This shank-type milling cutter is typically made from general-purpose high-speed tool steels M1, M2, M7, and M10. For workpieces made from hardened materials (over 300 HB), a grade such as T15, M42, or M33 is more effective. Increased cutting speeds can be used with these cobalt-containing high-speed tool steels because of their improved hot hardness.

One manufacturer realized a fourfold increase in the tool life of end mill wear lands when he switched to a titanium-nitride coated tool (Fig. 11). Titanium nitride coated end mills also outperform uncoated solid carbide tools. When machining valves made from type 304 stainless steel, a switch from solid carbide end mills to titanium nitride coated end mills resulted in a fivefold increase in tool life, that is, 150 parts compared to 30 finished with the carbide tools (Ref 3). Furthermore, the cost of the coated high-speed steel end mills was only one-sixth that of the carbide tools. Both types of 19 mm (¾ in.) fluted end mills were used to machine a 1.6 mm (1/16 in.) deep slot at a speed of 300 rev/min and a feed of 51 mm/min (2 in./min).

Reamers are designed to remove only small amounts of metal and therefore require very little flute depth for the removal of chips. For this reason, reamers are designed as rigid tools, requiring less toughness from the high-speed tool steel than a deeply fluted drill. The general-purpose grades M1, M2, M7, M10, and T1 are typically used at maximum hardness levels. For applications requiring greater wear resistance, grades such as M3, M4, and T15 are appropriate.

Milling Cutters. The size, style, configuration, complexity, and capacity of milling cutters is almost limitless. There are staggered-tooth and straight-tooth, form-re-

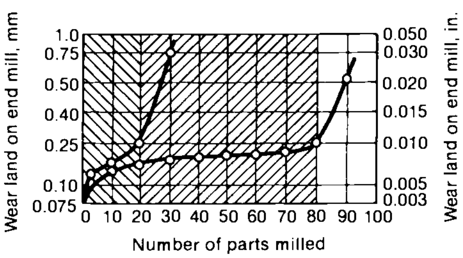

Fig. 11 Wear lands developed with uncoated and titanium nitride coated end mills show a 4:1 increase in tool life with coated tools. The crosshatched area at left (extending from 0 to 20 parts) indicates the number of pieces produced by uncoated end mill after 0.25 mm (0.010 in.) wear land on the tool; the crosshatched area at right represents quantity produced by titanium nitride coated end mill after 0.25 mm (0.010 in.) wear land on tool. Source: Ref 3

lieved and formed milling cutters with sizes that range from 51 to 305 mm (2 to 12 in.) and are used to machine slots, grooves, racks, sprockets, gears, splines, and so on. They cut a wide variety of materials, including plastics, aluminum, steel, cast iron, superalloys, titanium, and graphite structures. The general-purpose high-speed tool steel used for more than 70% of milling cutter applications is M2, usually the free-machining type. It has a good balance of wear resistance, hot hardness, toughness, and strength and works well on carbon, alloy, and stainless steels, aluminum, cast iron, and some plastics (generally any material that is under 30 HRC in hardness). When higher hardness materials or more wear-resistant materials need to be milled, M3 or M4 are selected. The higher carbon and vanadium content in those materials improves wear resistance and allows for the machining of materials greater than 35 HRC in hardness. For workpiece hardness levels above that and as high as 50 HRC, either M42 with its high hardness and high hot hardness properties or T15 with its high wear resistance and high hardness characteristics are desirable. The powder metallurgy grades in M4 and T15 are increasing in popularity for milling cutters because of their ease of grinding and regrinding.

Hobs are a type of milling cutter that operates by cutting a repeated form about a center, such as gear teeth. The hob cuts by meshing and rotating about the workpiece, forming a helical pattern. This type of metal cutting creates less force at the cutting edge (less chip load on the teeth) than do ordinary milling cutters. Accordingly, less toughness and edge strength is required of hob materials; wear is more commonly a mode of failure. Most hobs are made from a high-carbon version of M2, although normal carbon levels are also used. M2 with a sulfur addition or P/M product for improved machinability and surface finish is often used for hobs.

Saws are quite similar to milling cutters in style and application, but they are usually thinner and tend to be smaller in diameter. Sizes range from 0.076 mm (0.003 in.) thick by 13 mm (½ in.) outside diameter to more than 6.4 mm (¼ in.) thick by 203 mm (8 in.) outside diameter. Used for cutting, slitting, and slotting, saws are available with straight-tooth, staggered-tooth, and side-tooth configurations and are made from alloys similar to those used for milling cutters. Again, M2 high-speed tool steel is the general-purpose saw material, but, because of the typical thinness of these products, toughness is optimized with lower hardness. There are relatively few saws that are made from M3 or M4 high-speed tool steel because generally T15 and M42 are the two alternative materials to the standard M2 steel. M42 is often used to machine stainless steels, aluminum, and brass because it increases saw production life and can be run at considerably higher speeds. T15 is used for very specialized applications. Saws made of high-speed tool steel are used to cut, slit, and slot everything from steel, aluminum, brass, pipe, and titanium to gold jewelry, fish, frozen foods, plastics, rubber, and paper.

Broaches. M2 high-speed tool steel is the most frequently used material for broaches. This includes the large or circular broaches that are made in large quantities as well as the smaller keyway and shape broaches. Sometimes the higher-carbon material is used, but generally free-machining M2 is used because it results in a better surface finish. P/M products are very popular for broaches in both M2 as well as M3 class 2 and M4 when they are used to improve wear resistance. M4 is probably the second most widely used material for this application. M42 and T15 are often used for difficult-to-machine materials such as the nickel-base alloys and other aerospace-type alloys.

A high-nickel (48%) alloy magnet manufacturer using a 3.2 × 13 × 305 mm (⅛ × ½ × 12 in.) flat broach made of M2 increased tool life from 200 pieces to 3400 pieces when a titanium nitride coating was added, and also obtained a smoother surface finish. Replacing the flat broach with an uncoated 11.99 mm (0.472 in.) diam by 660 mm (26 in.) long round broach increased the production to about 7000 pieces, and coating the round broach with titanium nitride further increased the magnet production to about 19 000 pieces (Ref 3). Thus, going from an uncoated flat broach to a coated round broach increased production by a factor of 95.

Factors in Selecting High-Speed Tool Steels

No one composition of high-speed tool steel can meet all cutting tool requirements. The general-purpose molybdenum steels such as M1, M2, and M7 and tungsten steel T1 are more commonly used than other high-speed tool steels. They have the highest toughness and good cutting ability, but they possess the lowest hot hardness and wear resistance of all the high-speed tool steels. The addition of vanadium offers the advantage of greater wear resistance and hot hardness, and steels with intermediate vanadium contents are suited for fine and roughing cuts on both hard and soft materials. The 5% V steel (T15) is especially suited for cutting hard metals and alloys or high-strength steels, and is particularly suitable for the machining of aluminum, stainless steels, austenitic alloys, and refractory metals. Wrought high-vanadium high-speed tool steels are more difficult to grind than their P/M product counterparts. The addition of cobalt in various amounts allows still higher hot hardness, the degree of hot hardness being proportional to the cobalt content. Although cobalt steels are more brittle than the noncobalt types, they give better performance on hard, scaly materials that are machined with deep cuts at high speeds.

High-speed tool steels have continued to be of importance in industrial commerce for 70 to 80 years despite the inroads made by competitive cutting tool materials such as cast cobalt alloys, cemented carbides, ceramics, and cermets. The superior toughness of high-speed tool steels guarantees its niche in the cutting tool materials marketplace.

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