

Surface Engineering of Specialty Steels

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SPECIALTY STEELS encompass a broad range of ferrous alloys noted for their special processing characteristics (powder metallurgy alloys), corrosion resistance (stainless steels), wear resistance and toughness (tool steels), high strength (maraging steels), or magnetic properties (electrical steels). Each of these material groups—with the exception of stainless steels, which were discussed in the previous article in this Section—will be reviewed below. Additional information on these materials can be found in Volumes 1 and 2 of the *ASM Handbook*.

Ferrous Powder Metallurgy Alloys

Powder metallurgy (P/M) in its simplest form consists of compressing metal powders in a shaped die to produce green compacts. These are then sintered, or diffusion bonded, at elevated temperatures in a furnace with a protective atmosphere. During sintering, the constituents usually do not melt, and the compacts become substantially strengthened by the development of bonds between individual particles.

For a specific metal powder and sintering condition, increased compact density results in improved mechanical properties. The density of sintered compacts may be increased by re-pressing. When re-pressing is performed primarily to increase dimensional accuracy rather than density, it is termed sizing. When re-pressing is intended to change the contour of the surface in contact with the punches, it is termed coining. For example, a sintered blank could be coined so that the surface is indented with small slots or letters and numbers. The re-pressing may be followed by re-sintering, which relieves the stresses due to cold work and may further strengthen the compact. More detailed information on consolidation practices for ferrous P/M parts can be found in Ref 1 and 2.

By pressing and sintering only, parts are produced at 80 to 93% of theoretical density. By re-pressing, with or without sintering, the materials may be further densified to 85 to 96% of theoretical density. High-temperature sintering will also produce parts at these high densities. The density of pressed parts is limited by the size and shape of the compact. The most common

P/M materials for structural parts are iron-copper-carbon, iron-nickel-carbon, and iron-carbon. Parts made from these materials respond to heat treatment with a defined hardenability band. Iron parts that are low in carbon and high in density can also be case hardened.

Designation of Ferrous P/M Materials

Ferrous P/M materials are customarily designated by the specifications or standards to which they are made, such as those listed in Table 1. Comparable standards are published by ASTM, SAE, and MPIF (Metal Powder Industries Federation).

The MPIF designations for ferrous P/M materials, described in detail in Ref 3, include a prefix of one or more letters (the first of which is F to indicate an iron-base material), four numerals, and a suffix. The second letter in the prefix identifies the principal alloying element (if one is specified); the percentage of the element is indicated by the first two digits. The third and fourth digits indicate the amount of carbon in the compacted and sintered part; the code designation 00 indicates less than 0.3%, 05 indicates 0.3 to 0.6%, and 08 indicates 0.6 to 0.9%. The suffix is used to indicate the minimum 0.2% yield strength of as-sintered parts and the minimum ultimate tensile strength of heat-treated materials in units of 1000 psi (6.894 MPa). The letters HT designate heat treated.

Commercially produced iron-base powders often contain controlled amounts of alloying elements other than those specified by any of the designations listed in Table 1. Manganese and molybdenum may be added to improve strength and the response to heat treatment. Sulfur may be added to enhance machinability. Additions of 0.45 to 0.80% P can improve the toughness of the part and reduce magnetic hysteresis losses. These powders are usually identified by the trade name of the producer even though the amounts of alloy additions are small enough that the designations listed in Table 1 could be applied to the powders. Commercially produced iron-base powders usually contain very little carbon because carbon lowers compressibility and the amount of carbon in the finished part is readily controlled by the

amount of admixed graphite and the composition of the sintering atmosphere.

Deburring P/M Parts (Ref 4)

Although cleaning and deburring generally are considered different operations, they are often accomplished simultaneously. Therefore, much of the discussion on deburring is applicable to the subsequent section of this article on cleaning.

The inherent porosity in P/M parts demands special considerations in all secondary operations. This is also true for cleaning and deburring; the relatively small size and complex shape of the parts also require special procedures and/or precautions that are not required for wrought or cast parts. The P/M parts shown in Fig. 1 are typical of small, intricate parts that frequently present deburring problems.

Deburring Methods. Due to the nature of the P/M process, burrs typically form on the edges and surfaces of P/M parts. In many simple shapes, deburring is almost automatic—that is, burrs are broken off during handling operations. If parts are surface hardened or steam treated, subsequent deburring may be unnecessary. However, for intricate parts such as those shown in Fig. 1, separate deburring operations generally are required.

The use of liquid deburring methods is not usually suitable, especially if such liquids are corrosive. Thus, acid pickling is not recommended, because acid may be entrapped in the pores, resulting in severe corrosion. Tumbling in a wet medium is used frequently as a deburring method, but removal of the liquid from the pores requires extra drying time. Preferred methods of deburring include:

- Rotary tumbling (self or with abrasive)
- Vibratory
- Abrasive blasting
- Centrifugal or high-energy methods

These methods, which are used for deburring and sometimes for cleaning, are described in the articles “Mechanical Cleaning Systems” and “Mass Finishing Methods” in this Volume. The discussions that follow are unique to P/M parts.

Table 1 Compositions of ferrous P/M structural materials

Description	Designation(a)			MPIF composition limits and ranges, % (b)				
	MPIF	ASTM	SAE	C	Ni	Cu	Fe	Mo
P/M iron	F-0000	B 783	853, Cl 1	0.3 max	...	...	97.7-100	...
P/M steel	F-0005	B 783	853, Cl 2	0.3-0.6	...	...	97.4-99.7	...
P/M steel	F-0008	B 783	853, Cl 3	0.6-1.0	...	...	97.0-99.1	...
P/M copper iron	FC-0200	B 783	...	0.3 max	...	1.5-3.9	93.8-98.5	...
P/M copper steel	FC-0205	B 783	...	0.3-0.6	...	1.5-3.9	93.5-98.2	...
P/M copper steel	FC-0208	B 783	864, Gr 1, Cl 3	0.6-1.0	...	1.5-3.9	93.1-97.9	...
P/M copper steel	FC-0505	B 783	...	0.3-0.6	...	4.0-6.0	91.4-95.7	...
P/M copper steel	FC-0508	B 783	864, Gr 2, Cl 3	0.6-1.0	...	4.0-6.0	91.0-95.4	...
P/M copper steel	FC-0808	B 783	864, Gr 3, Cl 3	0.6-1.0	...	6.0-11.0	86.0-93.4	...
P/M copper steel	...	...	864, Gr 4, Cl 3	0.6-0.9	...	18.0-22.0	75.1 min	...
P/M iron-copper	FC-1000	B 783	862	0.3 max	...	9.5-10.5	87.2-90.5	...
P/M prealloyed steel	FL-4205	B 783	...	0.4-0.7	0.35-0.45	...	95.9-98.7	0.50-0.85
P/M prealloyed steel	FL-4605	B 783	...	0.4-0.7	1.70-2.00	...	94.5-97.5	0.40-0.80
P/M iron-nickel	FN-0200	B 783	...	0.3 max	1.0-3.0	2.5 max	92.2-99.0	...
P/M nickel steel	FN-0205	B 783	...	0.3-0.6	1.0-3.0	2.5 max	91.9-98.7	...
P/M nickel steel	FN-0208	B 783	...	0.6-0.9	1.0-3.0	2.5 max	91.6-98.4	...
P/M iron-nickel	FN-0400	B 783	...	0.3 max	3.0-5.5	2.0 max	90.2-97.0	...
P/M nickel steel	FN-0405	B 783	...	0.3-0.6	3.0-5.5	2.0 max	89.9-96.7	...
P/M nickel steel	FN-0408	B 783	...	0.6-0.9	3.0-5.5	2.0 max	89.6-96.4	...
P/M iron-nickel	FN-0700	...	...	0.3 max	6.0-8.0	2.0 max	87.7-94.0	...
P/M nickel steel	FN-0705	...	...	0.3-0.6	6.0-8.0	2.0 max	87.4-93.7	...
P/M nickel steel	FN-0708	...	...	0.6-0.9	6.0-8.0	2.0 max	87.1-93.4	...
P/M infiltrated steel	FX-1000	B 783	...	0-0.3	...	8.0-14.9	82.8-92.0	...
P/M infiltrated steel	FX-1005	B 783	...	0.3-0.6	...	8.0-14.9	80.5-91.7	...
P/M infiltrated steel	FX-1008	B 783	...	0.6-1.0	...	8.0-14.9	80.1-91.4	...
P/M infiltrated steel	FX-2000	B 783	870	0.3 max	...	15.0-25.0	70.7-85.0	...
P/M infiltrated steel	FX-2005	B 783	...	0.3-0.6	...	15.0-25.0	70.4-84.7	...
P/M infiltrated steel	FX-2008	B 783	872	0.6-1.0	...	15.0-25.0	70.0-84.4	...

(a) Designations listed are nearest comparable designations; ranges and limits may vary slightly between comparable designations. (b) MPIF standards require that the total amount of all other elements be less than 2.0%, except in infiltrated steels, for which the total amount of other elements must be less than 4.0%.

Rotary Tumbling. Self-tumbling, tumbling with dry abrasive, and tumbling with abrasive in a liquid medium are suitable for deburring of P/M parts. Wet tumbling is not suitable for deburring P/M parts because of the difficulty of removing the tumbling liquid from the pores of the parts.

During self-tumbling, the workpieces are tumbled in a revolving barrel. This method provides an economical and efficient means of deburring, but is effective only on relatively simple parts. For parts such as those shown in Fig. 1, the internal surfaces and recesses are not completely deburred by this method. For more complete deburring, an abrasive is added. Size of the abrasive is important. At least a portion of the added abrasive should have a mesh size that is smaller than the smallest hole or recess in the workpiece; otherwise, not all surfaces will be reached.

Over-tumbling of P/M parts must be avoided, because it peens the surfaces and may partially close pores (not necessarily desirable). Over-tumbling also may damage gear teeth or other protrusions by removing too much metal or by excessive peening. Tumbling cycles should be based on the minimum time that will provide acceptable deburring.

Vibratory processing is similar to rotary tumbling in principle. However, the shaking involved in the vibratory method is faster and provides more uniform results compared to rotary tumbling. As in rotary tumbling, care must be taken to prevent over-tumbling.

Abrasive blasting, in which various materials are propelled by air or centrifugal force, offers another method of deburring. For practical reasons, it

is used less frequently than tumbling or vibrating. The abrasive must be selected carefully. Coarse shot or grit tends topeen the surfaces and close the pores. Also, abrasive blasting can "hammer" bits of abrasive into the workpiece, thus "charging" it.

Another disadvantage of conventional abrasive blasting is that, especially for large volumes of small workpieces, results are likely to be nonuniform. One type of blasting machine, which tumbles and blasts simultaneously, has been used successfully for deburring of P/M parts. Silica sand or a milder abrasive is suitable and is less likely to damage intricate workpieces. As with other deburring methods, overprocessing must be avoided.

Centrifugal or High-Energy Methods. Centrifugal finishing combines rotating action with high centrifugal force, which results in a more severe abrading action than can be obtained by conventional rotary tumbling. This action is obtained by revolving several rotating barrels around the periphery of a large carrier disk.

As a result, the action within one barrel consists of a combination of rotating motion and high centrifugal forces, which provides pressures up to 25 times the weight of the abrasive medium (if used) and the workpiece. As the disk rotates in one direction, the barrels rotate at a faster speed in the opposite direction. This counter movement within the entire mass accomplishes the desired results in a shorter time compared to other abrading processes. An advantage of this process is that it drives the abrasive into relatively inaccessible areas where burr removal may present problems.

Cleaning of P/M Parts (Ref 4)

Some of the deburring methods discussed above also may be considered as methods of cleaning. Frequently, however, methods such as tumbling and blasting are considered as preliminary cleaning operations to be followed by a more thorough cleaning, especially if the parts are to be coated.

Cleaning Methods. The inherent porosity in P/M parts imposes restrictions on selection of cleaning method. The use of a cleaning solution that is corrosive to the metal being cleaned is not recommended, because even the most thorough washing is not likely to remove all of the fluid, which presents a corrosion problem. Acid cleaning is therefore not recommended.

Because of porosity, thorough cleaning of P/M parts is more difficult than their wrought counterparts; P/M parts require more attention than is provided in many conventional cleaning systems. Preferred methods are hot caustic washing, ultrasonic degreasing, and electrolytic alkaline cleaning.

Ultrasonic Degreasing. Oils, greases, and other shop soil may be removed by vapor degreasing techniques such as vapor phase, vapor-spray-vapor, warm liquid-vapor, or boiling liquid-warm liquid-vapor techniques. For most P/M parts, especially if the degree of soiling is severe and/or part density is low, the boiling liquid-warm liquid-vapor process is preferred. This technique should be used in conjunction with an ultrasonic transducer, which literally shakes all entrapped contaminants out of

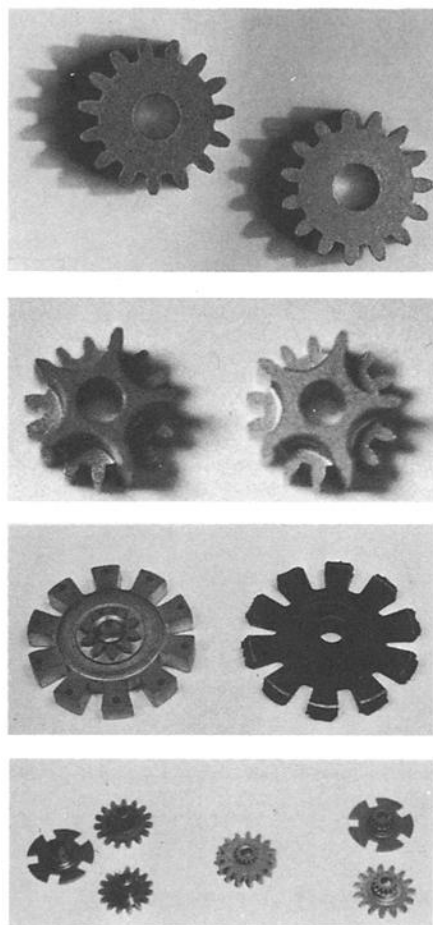


Fig. 1 Typical shapes of P/M parts that present deburring or cleaning difficulties

the pores, resulting in a thorough and safe method of cleaning.

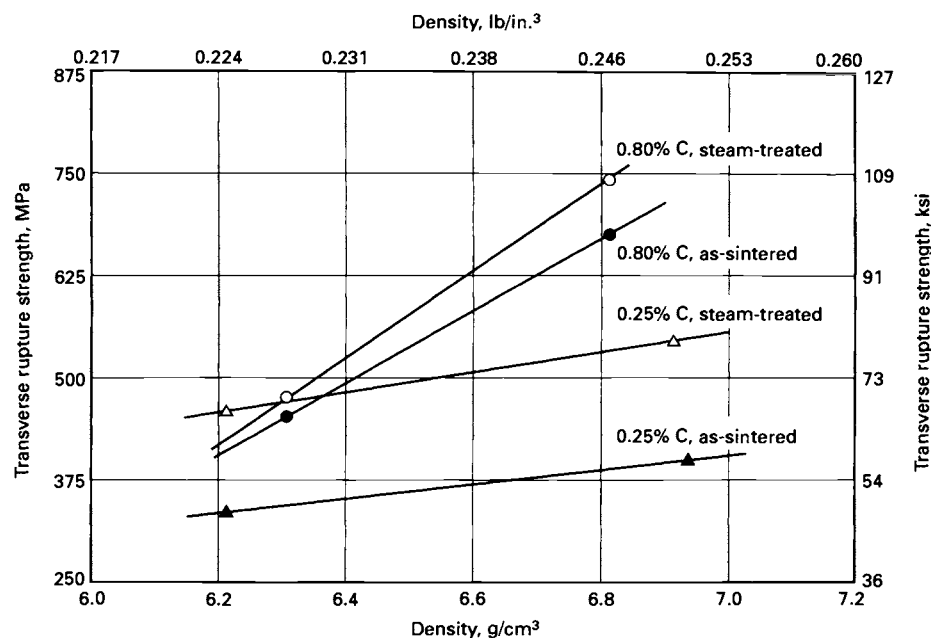
Electrolytic Alkaline Cleaning. Ferrous P/M parts can be cleaned, deoxidized, and stripped of nonmetallic coatings by subjecting them to electrolysis in a strongly alkaline aqueous solution. In this method the base metal is not attacked, and the possibility of rusting is minimal. Typical alkaline solutions are comprised of a:

- Source of caustic to aid cleaning
- Chelating agent to detach scale or rust
- Complexing agent to hold relatively large amounts of iron in solution

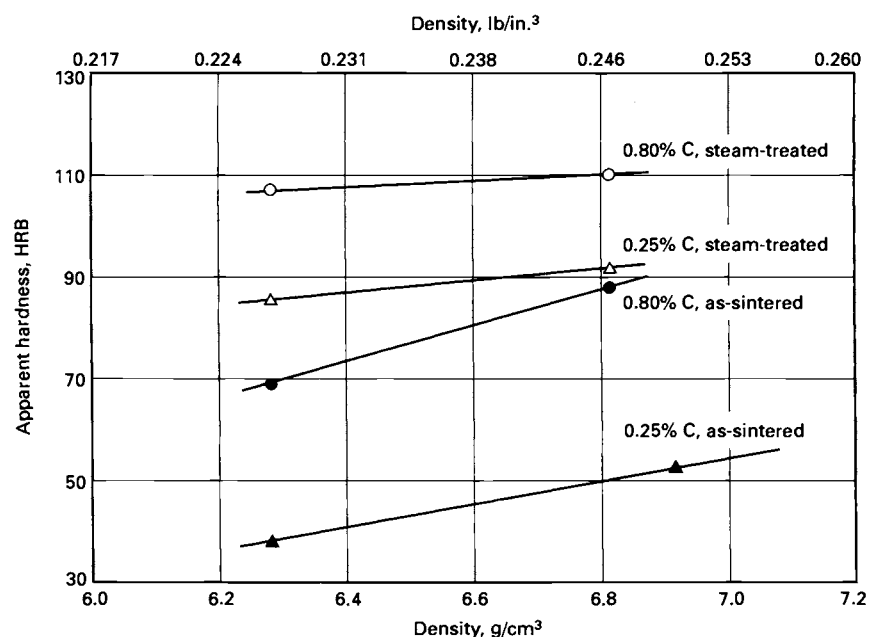
Electrolytic alkaline cleaning bath compositions and operating conditions are described in the article "Alkaline Cleaning" in this Volume. This cleaning process is well suited to cleaning of P/M parts, because the electrolytic action provides additional energy required to dislodge contaminants from pores or from relatively inaccessible areas.

Steam Treating of P/M Parts (Ref 5)

Ferrous P/M parts have traditionally been steam treated for improved wear resistance, corrosion resistance, and sealing capacity. Here, P/M parts are heated in a specific manner under a



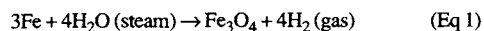
(a)



(b)

Fig. 2 Effect of steam treating on the mechanical properties of sintered carbon P/M steels as a function of density. (a) Transverse rupture strength. (b) Apparent hardness. Source: Ref 5

steam atmosphere at temperatures between 510 to 595 °C (950 to 1100 °F) to form a layer of black iron oxide (magnetite, or ferrous-ferrous oxide, FeO-Fe₂O₃) in the surface porosity according to the chemical reaction:



Steam treating cannot be described as a heat treatment because no structural changes occur in the matrix. In this process, magnetite (Fe₃O₄) is formed at the interconnecting surface porosity,

filling the porosity with a second phase. Magnetite has a microhardness equivalent to HRC 50.

The process itself is straightforward, the primary variables being temperature, time, and steam pressure. Caution must be used to prevent the formation of hydroxides and lower oxides such as ferrous oxide (FeO) and ferric oxide (Fe₂O₃), which is red rust.

The recommended procedure for steam treating is:

- Preclean parts to remove any oil or lubricants that may have been absorbed into the porosity

from prior machining, sizing, or finishing operations

- Load clean sintered parts in loosely packed baskets and place fixture into a furnace preheated to 315 °C (600 °F)
- Heat parts in air until the center of the load has stabilized at the set temperature
- Introduce superheated steam at a line pressure of 35 to 105 kPa (5 to 15 psi) and allow furnace to purge for at least 15 min
- Increase furnace temperature to desired set point and hold for no longer than 4 h at heat
- Upon completion of cycle, reduce furnace temperature to 315 °C (600 °F). When parts reach this temperature, the steam can be shut off and the parts unloaded

Caution should be used when opening the furnace door after the steam cycle. As shown in Equation 1, hydrogen is produced during this process and can ignite. It is recommended that a nitrogen purge be applied prior to unloading. This process, when correctly applied, can impart improved surface properties, and, depending upon steel composition, increased compressive yield strength.

In all steam-treated P/M steels, the ductility is significantly reduced due to the internal stresses created by the formation of the iron oxide. Care must be taken when treating high-carbon P/M steels because these internal stresses can initiate microcracking and cause severe loss of ductility. Many cases have been reported in which parts were accidentally dropped on the floor after being steam treated, and the parts subsequently shattered like glass. The best recommendation for preventing such an incident is to specify a 0.5% C (max) content on materials that are to be steam treated.

Figure 2(a) shows that transverse rupture strength increases proportionately with sintered density. Upon steam treating, low-carbon P/M steels exhibit a uniform increase in strength, whereas the high-carbon P/M steels show only a small incremental increase in strength.

Apparent hardness also is improved as shown in Fig. 2(b). By filling the porosity with a hard second phase, the P/M steel can offer better support to an indentation hardness test. As with rupture strength, the incremental increase in hardness of high-carbon steels is less than that of low-carbon steels. Additional information on the properties of steam-treated P/M steels can be found in Ref 6.

Coating of P/M Parts (Ref 4)

In addition to the surfaces provided by steam treatment, P/M parts are frequently coated by mechanical means, painting, or electroplating. The blue-black oxide-covered surface produced by exposure to steam is often the final finish for a variety of hardware items. It may also be used as a preliminary coating for a final finishing process, such as painting.

Regardless of the method used for coating, major emphasis must be placed on initial cleaning. If liquid contaminants are allowed to remain in the pores of parts, bleeding occurs, and defective coatings result. Steam treatment provides an excellent paint base.

Mechanical coating uses kinetic energy to deposit metallic coatings on parts. This process is also known as mechanical plating, or peen plating, when the coating is less than 25 µm (1 mil) thick. Coating is accomplished by placing the workpiece, glass beads, water, and the metal plating powder in a tumbling barrel.

Zinc is most commonly used as a plating material, although a wide range of metals and mixtures of metals can be mechanically plated on ferrous metal parts. For example, a mixture of 75% Zn and 25% Sn is commonly used. Metal powders are added to the mixtures to be tumbled. Complete details on the mechanical coating process may be found in the article "Mechanical Plating" in this Volume.

Powder metallurgy parts with densities not less than 83% can be mechanically plated without special considerations for porosity. When density drops below 83%, tests should be conducted to determine whether moisture is entrapped, which is detrimental to the finished parts. Generally, when density is below 83%, parts must be impregnated with wax or resin.

Painting. Usually, P/M parts are ideal candidates for coating by painting; the porosity enhances paint adhesion. Furthermore, P/M parts can be painted by spraying, dipping, or the contact transfer method. Air-drying types are suitable only for indoor protective coatings. Baking produces finishes of higher quality that are well suited for outdoor exposure.

Spray painting has several advantages over dipping, including improved control of dimensions and coating quality, and the ability to coat localized areas. However, higher labor costs and more paint loss from overspray are associated with spraying.

For spraying, baking types of alkyds are reduced with solvents to a spraying viscosity of 35 s through a No. 4 Ford Cup. Parts are sprayed and then air dried for 10 min, after which they may be baked for 30 min at a temperature compatible with the type of paint being used. This practice results in a dry film coating 38 to 46 µm (1.5 to 1.8 mils) thick.

In paint dipping, the parts to be coated are placed in baskets or on racks, immersed in the paint, and then allowed to drain. Dipping saves labor and paint, compared to spraying, but general quality of dipped parts is lower, notably because of edge buildup.

Roll painting and lithographing (transfer coating) is a process in which paint is applied to external surfaces of cylindrical P/M parts, followed by the application of lithographing ink. Typically parts are roll coated and oven baked. The initial coating is usually a background color. Numbers of characters, as required, are then roll coated over the background coating, followed by baking dry.

Advantages of this painting procedure include:

- Precision painting can be achieved without applying paint to areas that do not require a coating
- With proper design of parts, areas can be painted with sharply defined edges
- Coating thickness can be closely controlled by varying the number of revolutions the part is permitted to make
- An unlimited number of character forms can be applied at relatively low cost

Principal limitations of the process are:

- Special handling is required
- Internal surfaces are not coated

Types of paint used in general procedures for painting of P/M parts are similar to those used for wrought counterparts, all of which are covered in detail in the article "Painting" in this Volume.

Electroplating. Powder metallurgy parts can be electroplated with various metals like their wrought counterparts. Methods used for plating of cast parts generally can be used for very dense parts (95% or more of theoretical). Plating of castings is described in the article "Surface Engineering of Cast Irons" in this Volume. For parts of lower densities, special preparation procedures are required.

During plating of P/M parts, the pores act as thermal pumps. Plating solutions are released from or absorbed by the pores, depending on the temperature differential between the workpiece and the solution. Interconnecting pores entrap solutions, which are then released slowly. Part density should be known before the sequence of cleaning and plating operations begins, and suitable precautions should be taken to prevent solution entrapment.

Entrapped solutions not only cause spotty plating and staining, which may develop within days, but also can cause contamination and depletion of all solutions used in the production process. It is therefore necessary that, if part density is below about 95%, pores must be closed before coating by electroplating.

Methods of closing pores that have proved successful include burnishing, buffing, rolling, heat treating, steam treating, and impregnation. All of these methods, except impregnation, provide varying degrees of closure. Mechanical methods are often excluded because of dimensional tolerances. Consequently, impregnation is the most suitable approach to closing pores.

Infiltration of iron compacts with metals such as copper is common practice and completely solves the porosity problem for subsequent electroplating. However, the cost of metal infiltration usually cannot be justified only to ensure satisfactory electroplating.

Impregnation with plastic seals P/M parts for further processing, such as electroplating. Pressure tightness and frequently an improvement in machining characteristics are added benefits derived from plastic impregnation. The process is not unlike the plastic impregnation process used to attain pressure tightness in porous castings.

Optimum results are obtainable with various types of plastic sealants, although the most commonly used are polyester resins and anaerobic sealants.

A typical processing cycle consists of:

- Cleaning thoroughly
- Baking at 120 to 150 °C (250 to 300 °F) to drive off all moisture or solvent
- Applying sealant under vacuum, such as in an autoclave
- Removing excess sealant by means of an emulsion cleaner
- Curing at 120 to 150 °C (200 to 250 °F)
- Tumbling, polishing, or abrasive blasting to remove excess cured sealant

Parts are now ready for routine cleaning and plating cycles, as required by the plating method used. Plating procedures are the same as those used for wrought parts (see the articles contained in the Section "Plating and Electroplating" in this Volume).

Case Hardening of P/M Parts (Ref 5)

Powder metallurgy parts can be case hardened by several processes, although various available processes are not equally suited to every application. Generally the best results (a clear case/core relationship) are obtained with P/M parts with densities exceeding 7.2 g/cm³ (90% of theoretical density). More detailed information on each of the processes described below can be found in *Heat Treating*, Volume 4 of the *ASM Handbook*.

Carburizing is normally specified in parts with a large cross-sectional thickness to attain maximum fatigue and impact properties. The material usually specified for carburizing contains hardenability agents such as nickel, molybdenum, and copper with relatively low carbon content. To develop optimum dynamic properties at porosity levels between 10 to 15%, a combined carbon level of 0.30 to 0.35% is recommended. As porosity is reduced below 10%, combined carbon can be reduced to 0.15 to 0.25% C. Because improved dynamic properties are also associated with high densities, it is recommended that combined carbon be adjusted to a level best suited for re-pressing after sintering.

In wrought steel, carburizing is normally characterized by a surface hardness range and an effective case depth. Microhardness measurements can accurately show the hardness profile in wrought steel but can be erratic when used on P/M steels. With P/M steels, however, subsurface porosity can influence the microhardness readings, resulting in false hardness readings. It is recommended that at least three hardness readings be taken at each level below the surface and averaged to determine effective case depth.

Carburizing of P/M steels is usually done at temperatures between 900 to 930 °C (1650 to 1705 °F). Time cycles are normally short because of the rapid diffusion of carbon through the interconnected porosity. Therefore, atmosphere carbon potentials need to be somewhat higher than those required for wrought steels of similar composition.

Carbonitriding is probably the more common case-hardening treatment used on P/M parts. Here process temperatures are lower (800 to 850 °C, or 1470 to 1560 °F) and ammonia additions to approximately 10% are made. Ammonia dissociates on the parts, allowing nitrogen to diffuse into the surfaces. This retards the critical cooling rate upon quenching and provides a more consistent martensite transformation. It also produces a more consistent surface hardness, which improves wear resistance and toughness of the P/M steel. Because lower temperatures can be used, carbonitriding provides better control of distortion compared to carburizing. Care must be taken when adding ammonia, however, since excessive nitrogen diffusion into the internal pore surfaces can cause embrittlement.

Carbonitriding is a shallow case-hardening treatment. Case depths greater than 0.50 mm (0.020 in.) deep are seldom specified. For this reason, cycle times are relatively short, usually on the order of 30 to 60 min. As in neutral hardening, carbon control is a critical aspect of the treatment. Normally carbon potentials of 1.0 to 1.2% are specified to maintain the carbon profile in the part.

Tempering is usually required after case hardening when densities exceed 90%. In this case, significantly high stresses that could initiate cracking are developed upon quenching. As porosity increases, this stress level is reduced to a level at which a posttemper is not necessary. However, judgment should be used when deciding whether tempering is required. If a substantial amount of retained austenite is formed upon carbonitriding, a temper is advisable.

If the part has thin cross sections, sharp corners, or undercuts that would act as stress raiser, then tempering would also be advisable. Recommended tempering temperatures for P/M parts range from 105 to 200 °C (220 to 390 °F). Above this temperature, entrained quench oil can ignite, creating a hazardous condition in the furnace. Tempering above 200 °C (390 °F) will result in improved toughness and fatigue properties of the heat-treated P/M steel. However, furnaces will need special adaptations to handle the high volume of smoke created by the ignition of the quench oil.

Induction Hardening. Spur gears, bevel gears, splined hubs, and cams are ideal components to utilize P/M production techniques. These parts usually require hard wear-resistant surfaces in some areas, with the retention of the ductility of the sintered matrix in the remainder of the part. Induction hardening is commonly specified for these applications.

This process can be placed in an automated machining line that can reduce handling and be a cost-effective hardening treatment when high volumes of parts are being produced. Because the inductance of P/M materials is typically reduced due to porosity, a higher power setting is normally required to reach a given depth of hardening compared to that used for a wrought material of similar composition. Furthermore, because the

heat is rapidly dissipated, a rapid transfer to the quench is mandatory.

As with wrought steels, the response to hardening by induction is dependent upon combined carbon content, alloy content, and surface decarburization. This latter variable can be a major concern with P/M parts. With today's conventional belt-type sintering furnaces using an endogas atmosphere, decarburizing can occur as the parts leave the hot zone and cool slowly through the 1100 to 800 °C (2010 to 1470 °F) temperature range.

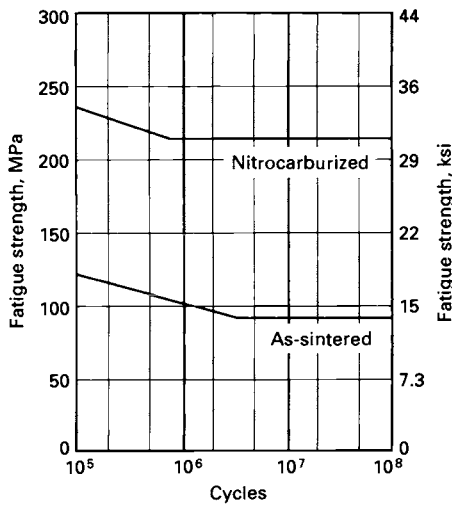
In most cases, P/M parts are quenched in a water-based solution containing some type of rust preventative to forestall internal corrosion. In those applications where induction hardening is considered, densities above 90% should be specified. With a decrease in density, the resistivity of the steel increases and permeability decreases. For this reason, integral quench coils using a high-velocity spray quench are generally used to attain maximum surface hardness in the P/M part.

Nitrocarburizing. This process is rapidly growing in popularity as a treatment for P/M parts. Here, nitrogen is diffused into the surfaces of the steel in sufficiently high concentration to form a thin layer of ϵ iron nitride on the surface of the part. This is done at temperatures ranging from 570 to 600 °C (1060 to 1110 °F). At these temperatures no austenite transformation occurs, thereby significantly reducing the dimensional changes and distortion.

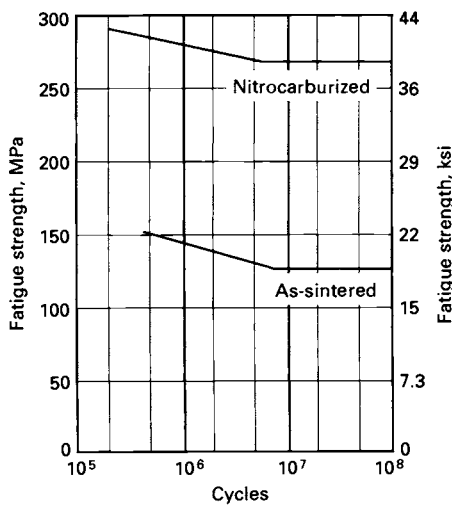
The process uses conventional integral quench atmosphere furnaces. The atmosphere usually consists of a 50/50 mixture of endothermic gas and anhydrous ammonia. Control of the nitrided layer thickness, as with the other treatments, is dependent on density. If the nitrided layer is allowed to form on the internal pore surfaces to any significant extent, a volume expansion can occur. For this reason, density of the P/M part should be above 90% of theoretical. This nitrided layer, when properly applied, can reduce the coefficient of friction at the surface of the part and provide improved wear resistance compared to conventional hardening to martensite. This process is best applied to applications where sliding wear and fretting are involved.

Because the hard nitrided layer is relatively thin, this process should not be applied where high indentation or impact loading is involved. The ϵ nitride layer that is formed can attain a file hardness in excess of HRC 60, depending on the alloy content of the steel. Indentation hardness testing is not recommended when evaluating this process. Since no transformation occurs, the P/M parts can be air cooled without loss of surface hardness. Also, no oil absorption occurs, which leaves the porosity open for impregnation if desired.

Nitrocarburizing also provides improved strength and reduced notch sensitivity in P/M parts. Figure 3 shows the fatigue improvement of two low-carbon P/M steels after nitrocarburizing. A typical nitrocarburized microstructure of an iron-copper-carbon P/M steel is shown in Fig. 4.



(a)



(b)

Fig. 3 Increase in the notched axial fatigue strength of sintered low-carbon P/M steels after nitrocarburizing for 2 h at 570 °C (1060 °F). (a) F-0000 carbon steel. (b) FC-0205 copper-carbon steel. Metal powder density was 7.1 g/cm³ (0.256 lb/in.³). Source: Ref 5

Plasma nitrocarburizing is in essence a variant of the now well-established glow-discharge plasma (ion) nitriding method (see the discussion that follows on ion nitriding). A technical argument against the use of plasma nitrocarburizing has been the effect of retained lubricant on the character and stability of the glow-discharge plasma, thus effecting the reliability of the plasma technology when applied to sintered parts. Lubricants are added to powdered products in order to achieve optimum pressing conditions. A method by which the lubricant can be satisfactorily removed prior to the P/M parts entering the vacuum chamber of the plasma unit is described in Ref 7. Using this method, it is now routinely possible to plasma nitrocarburize in one batch up to 4500 components, such as chain gear wheels, that have been manufactured by P/M. The microstructure of such a plasma nitrocarburized component is shown in Fig. 5. It is interesting to note that detailed examination shows that pores within the

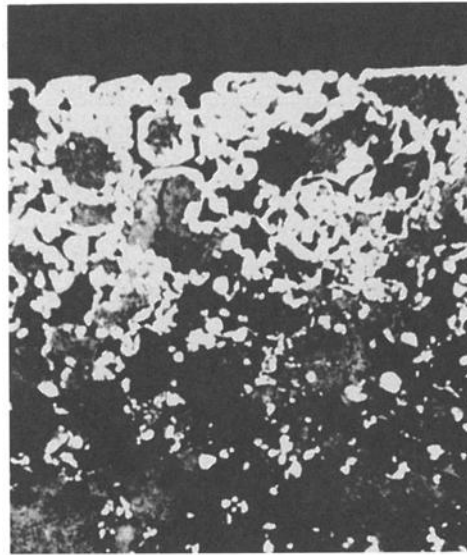


Fig. 4 Typical microstructure in a sintered ferritic nitrocarburized iron-copper-carbon P/M steel. 100x. Source: Ref 5

material, but close to the surface, also show the presence of the compound layer. The extent of the depth of such nitrocarburized pores is a function of the degree of interconnected porosity of the component, which is, in turn, a function of the pressing conditions.

Ion Nitriding. The hardness, wear resistance, and fatigue strength can also be improved by plasma, or ion, nitriding. This is a method of surface hardening using glow discharge technology to introduce nascent (elemental) nitrogen to the surface of a metal part for subsequent diffusion into the material. In a vacuum, high-voltage electrical energy is used to form a plasma, through which nitrogen ions are accelerated to impinge on the workpiece. This ion bombardment heats the workpiece, cleans the surface, and provides active nitrogen. Ion nitriding provides better control of case chemistry and uniformity and has other advantages, such as lower part distortion than conventional gas nitriding.

When ion nitriding of P/M steels, precleaning is more critical than with wrought alloys because of the porosity characteristic. A baking operation should precede the ion nitriding of P/M parts in order to break down or release agents and/or to evaporate any cleaning solvents.

Tool Steels

A tool steel is any steel used to make tools for cutting, forming, or otherwise shaping a material into a final part or component. These complex alloy steels, which contain relatively large amounts of tungsten, molybdenum, vanadium, manganese, and/or chromium, make it possible to meet increasingly severe service demands. In service, most tools are subjected to extremely high loads that are applied rapidly. The tools must withstand these loads a great number of times

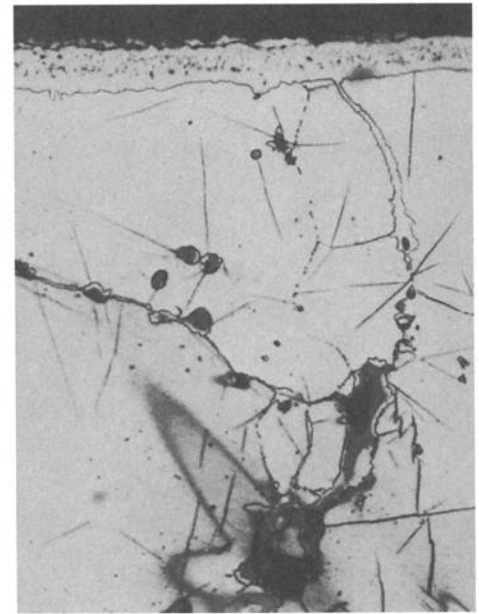


Fig. 5 Microstructure of a plasma nitrocarburized P/M steel with a compound surface layer thickness of 10 μm. Source: Ref 7

without breaking and without undergoing excessive wear or deformation. In many applications, tool steels must provide this capability under conditions that develop high temperatures in the tool. Most tool steels are wrought products, but precision castings can be used in some applications. The powder metallurgy process is also used in making tool steels. It provides, first, a more uniform carbide size and distribution in large sections and, second, special compositions that are difficult or impossible to produce in wrought or cast alloys.

Tool Steel Classifications

Tool steels are classified according to their composition, applications, or method of quenching. Each group is identified by a capital letter; individual tool steel types are assigned code numbers. Table 2 gives composition limits for the tool steels most commonly used. More detailed information on tool steels, including their processing, properties, and applications, can be found in Ref 8 and 9.

High-speed steels are tool materials developed largely for use in high-speed metal cutting applications. There are two classifications of high-speed steels; molybdenum high-speed steels, or group M, which contain from 0.75 to 1.52% C and 4.50 to 11.0% Mo, and tungsten high-speed steels, or group T, which have similar carbon contents but high (11.75 to 21.00%) tungsten contents. Group M steels constitute more than 95% of all high-speed steel produced in the United States.

Hot-work steels (group H) have been developed to withstand the combinations of heat, pressure, and abrasion associated with punching, shearing, or forming of metals at high temperatures.

Table 2 Composition limits of principal types of tool steels

AISI	Designations		Composition(a), %								
	SAE	UNS	C	Mn	Si	Cr	Ni	Mo	W	V	Co
Molybdenum high-speed steels											
M1	M1	T11301	0.78-0.88	0.15-0.40	0.20-0.50	3.50-4.00	0.30 max	8.20-9.20	1.40-2.10	1.00-1.35	...
M2	M2	T11302	0.78-0.88; 0.95-1.05	0.15-0.40	0.20-0.45	3.75-4.50	0.30 max	4.50-5.50	5.50-6.75	1.75-2.20	...
M3, class 1	M3	T11313	1.00-1.10	0.15-0.40	0.20-0.45	3.75-4.50	0.30 max	4.75-6.50	5.00-6.75	2.25-2.75	...
M3, class 2	M3	T11323	1.15-1.25	0.15-0.40	0.20-0.45	3.75-4.50	0.30 max	4.75-6.50	5.00-6.75	2.75-3.75	...
M4	M4	T11304	1.25-1.40	0.15-0.40	0.20-0.45	3.75-4.75	0.30 max	4.25-5.50	5.25-6.50	3.75-4.50	...
M6	...	T11306	0.75-0.85	0.15-0.40	0.20-0.45	3.75-4.50	0.30 max	4.50-5.50	3.75-4.75	1.30-1.70	11.00-13.00
M7	...	T11307	0.97-1.05	0.15-0.40	0.20-0.55	3.50-4.00	0.30 max	8.20-9.20	1.40-2.10	1.75-2.25	...
M10	...	T11310	0.84-0.94; 0.95-1.05	0.10-0.40	0.20-0.45	3.75-4.50	0.30 max	7.75-8.50	...	1.80-2.20	...
M30	...	T11330	0.75-0.85	0.15-0.40	0.20-0.45	3.50-4.25	0.30 max	7.75-9.00	1.30-2.30	1.00-1.40	4.50-5.50
M33	...	T11333	0.85-0.92	0.15-0.40	0.15-0.50	3.50-4.00	0.30 max	9.00-10.00	1.30-2.10	1.00-1.35	7.75-8.75
M34	...	T11334	0.85-0.92	0.15-0.40	0.20-0.45	3.50-4.00	0.30 max	7.75-9.20	1.40-2.10	1.90-2.30	7.75-8.75
M36	...	T11336	0.80-0.90	0.15-0.40	0.20-0.45	3.75-4.50	0.30 max	4.50-5.50	5.50-6.50	1.75-2.25	7.75-8.75
M41	...	T11341	1.05-1.15	0.20-0.60	0.15-0.50	3.75-4.50	0.30 max	3.25-4.25	6.25-7.00	1.75-2.25	4.75-5.75
M42	...	T11342	1.05-1.15	0.15-0.40	0.15-0.65	3.50-4.25	0.30 max	9.00-10.00	1.15-1.85	0.95-1.35	7.75-8.75
M43	...	T11343	1.15-1.25	0.20-0.40	0.15-0.65	3.50-4.25	0.30 max	7.50-8.50	2.25-3.00	1.50-1.75	7.75-8.75
M44	...	T11344	1.10-1.20	0.20-0.40	0.30-0.55	4.00-4.75	0.30 max	6.00-7.00	5.00-5.75	1.85-2.20	11.00-12.25
M46	...	T11346	1.22-1.30	0.20-0.40	0.40-0.65	3.70-4.20	0.30 max	8.00-8.50	1.90-2.20	3.00-3.30	7.80-8.80
M47	...	T11347	1.05-1.15	0.15-0.40	0.20-0.45	3.50-4.00	0.30 max	9.25-10.00	1.30-1.80	1.15-1.35	4.75-5.25
Tungsten high-speed steels											
T1	T1	T12001	0.65-0.80	0.10-0.40	0.20-0.40	3.75-4.00	0.30 max	...	17.25-18.75	0.90-1.30	...
T2	T2	T12002	0.80-0.90	0.20-0.40	0.20-0.40	3.75-4.50	0.30 max	1.00 max	17.50-19.00	1.80-2.40	...
T4	T4	T12004	0.70-0.80	0.10-0.40	0.20-0.40	3.75-4.50	0.30 max	0.40-1.00	17.50-19.00	0.80-1.20	4.25-5.75
T5	T5	T12005	0.75-0.85	0.20-0.40	0.20-0.40	3.75-5.00	0.30 max	0.50-1.25	17.50-19.00	1.80-2.40	7.00-9.50
T6	...	T12006	0.75-0.85	0.20-0.40	0.20-0.40	4.00-4.75	0.30 max	0.40-1.00	18.50-21.00	1.50-2.10	11.00-13.00
T8	T8	T12008	0.75-0.85	0.20-0.40	0.20-0.40	3.75-4.50	0.30 max	0.40-1.00	13.25-14.75	1.80-2.40	4.25-5.75
T15	...	T12015	1.50-1.60	0.15-0.40	0.15-0.40	3.75-5.00	0.30 max	1.00 max	11.75-13.00	4.50-5.25	4.75-5.25
Chromium hot-work steels											
H10	...	T20810	0.35-0.45	0.25-0.70	0.80-1.20	3.00-3.75	0.30 max	2.00-3.00	...	0.25-0.75	...
H11	H11	T20811	0.33-0.43	0.20-0.50	0.80-1.20	4.75-5.50	0.30 max	1.10-1.60	...	0.30-0.60	...
H12	H12	T20812	0.30-0.40	0.20-0.50	0.80-1.20	4.75-5.50	0.30 max	1.25-1.75	1.00-1.70	0.50 max	...
H13	H13	T20813	0.32-0.45	0.20-0.50	0.80-1.20	4.75-5.50	0.30 max	1.10-1.75	...	0.80-1.20	...
H14	...	T20814	0.35-0.45	0.20-0.50	0.80-1.20	4.75-5.50	0.30 max	...	4.00-5.25	...	...
H19	...	T20819	0.32-0.45	0.20-0.50	0.20-0.50	4.00-4.75	0.30 max	0.30-0.55	3.75-4.50	1.75-2.20	4.00-4.50
Tungsten hot-work steels											
H21	H21	T20821	0.26-0.36	0.15-0.40	0.15-0.50	3.00-3.75	0.30 max	...	8.50-10.00	0.30-0.60	...
H22	...	T20822	0.30-0.40	0.15-0.40	0.15-0.40	1.75-3.75	0.30 max	...	10.00-11.75	0.25-0.50	...
H23	...	T20823	0.25-0.35	0.15-0.40	0.15-0.60	11.00-12.75	0.30 max	...	11.00-12.75	0.75-1.25	...
H24	...	T20824	0.42-0.53	0.15-0.40	0.15-0.40	2.50-3.50	0.30 max	...	14.00-16.00	0.40-0.60	...
H25	...	T20825	0.22-0.32	0.15-0.40	0.15-0.40	3.75-4.50	0.30 max	...	14.00-16.00	0.40-0.60	...
H26	...	T20826	0.45-0.55(b)	0.15-0.40	0.15-0.40	3.75-4.50	0.30 max	...	17.25-19.00	0.75-1.25	...
Molybdenum hot-work steels											
H42	...	T20842	0.55-0.70(b)	0.15-0.40	...	3.75-4.50	0.30 max	4.50-5.50	5.50-6.75	1.75-2.20	...
Air-hardening medium-alloy cold-work steels											
A2	A2	T30102	0.95-1.05	1.00 max	0.50 max	4.75-5.50	0.30 max	0.90-1.40	...	0.15-0.50	...
A3	...	T30103	1.20-1.30	0.40-0.60	0.50 max	4.75-5.50	0.30 max	0.90-1.40	...	0.80-1.40	...
A4	...	T30104	0.95-1.05	1.80-2.20	0.50 max	0.90-2.20	0.30 max	0.90-1.40	...	...	...
A6	...	T30106	0.65-0.75	1.80-2.50	0.50 max	0.90-1.20	0.30 max	0.90-1.40	...	...	...
A7	...	T30107	2.00-2.85	0.80 max	0.50 max	5.00-5.75	0.30 max	0.90-1.40	0.50-1.50	3.90-5.15	...
A8	...	T30108	0.50-0.60	0.50 max	0.75-1.10	4.75-5.50	0.30 max	1.15-1.65	1.00-1.50	...	...
A9	...	T30109	0.45-0.55	0.50 max	0.95-1.15	4.75-5.50	1.25-1.75	1.30-1.80	...	0.80-1.40	...
A10	...	T30110	1.25-1.50(c)	1.60-2.10	1.00-1.50	...	1.55-2.05	1.25-1.75	...	...	...
High-carbon, high-chromium cold-work steels											
D2	D2	T30402	1.40-1.60	0.60 max	0.60 max	11.00-13.00	0.30 max	0.70-1.20	...	1.10 max	1.00 max
D3	D3	T30403	2.00-2.35	0.60 max	0.60 max	11.00-13.50	0.30 max	...	1.00 max	1.00 max	...
D4	...	T30404	2.05-2.40	0.60 max	0.60 max	11.00-13.00	0.30 max	0.70-1.20	...	1.00 max	...
D5	D5	T30405	1.40-1.60	0.60 max	0.60 max	11.00-13.00	0.30 max	0.70-1.20	...	1.00 max	2.50-3.50
D7	D7	T30407	2.15-2.50	0.60 max	0.60 max	11.50-13.50	0.30 max	0.70-1.20	...	3.80-4.40	...
Oil-hardening cold-work steels											
O1	O1	T31501	0.85-1.00	1.00-1.40	0.50 max	0.40-0.60	0.30 max	...	0.40-0.60	0.30 max	...
O2	O2	T31502	0.85-0.95	1.40-1.80	0.50 max	0.35 max	0.30 max	0.30 max	...	0.30 max	...
O6	O6	T31506	1.25-1.55(c)	0.30-1.10	0.55-1.50	0.30 max	0.30 max	0.20-0.30	...	...	...
O7	...	T31507	1.10-1.30	1.00 max	0.60 max	0.35-0.85	0.30 max	0.30 max	1.00-2.00	0.40 max	...

(a) All steels except group W contain 0.25 max Cu, 0.03 max P, and 0.03 max S; group W steels contain 0.20 max P, and 0.025 max S. Where specified, sulfur may be increased to 0.06 to 0.15% to improve machinability of group H, M, and T steels. (b) Available in several carbon ranges. (c) Contains free graphite in the microstructure. (d) Optional. (e) Specified carbon ranges are designated by suffix numbers.

(continued)

Table 2 Composition limits of principal types of tool steels (continued)

AISI	Designations		Composition(a), %								
	SAE	UNS	C	Mn	Si	Cr	Ni	Mo	W	V	Co
Shock-resisting steels											
S1	S1	T41901	0.40-0.55	0.10-0.40	0.15-1.20	1.00-1.80	0.30 max	0.50 max	1.50-3.00	0.15-0.30	...
S2	S2	T41902	0.40-0.55	0.30-0.50	0.90-1.20	...	0.30 max	0.30-0.60	...	0.50 max	...
S5	S5	T41905	0.50-0.65	0.60-1.00	1.75-2.25	0.35 max	...	0.20-1.35	...	0.35 max	...
S6	...	T41906	0.40-0.50	1.20-1.50	2.00-2.50	1.20-1.50	...	0.30-0.50	...	0.20-0.40	...
S7	...	T41907	0.45-0.55	0.20-0.80	0.20-1.00	3.00-3.50	...	1.30-1.80	...	0.20-0.30(d)	...
Low-alloy special-purpose tools steels											
L2	...	T61202	0.45-1.00(b)	0.10-0.90	0.50 max	0.70-1.20	...	0.25 max	...	0.10-0.30	...
L6	L6	T61206	0.65-0.75	0.25-0.80	0.50 max	0.60-1.20	1.25-2.00	0.50 max	...	0.20-0.30(d)	...
Low-carbon mold steels											
P2	...	T51602	0.10 max	0.10-0.40	0.10-0.40	0.75-1.25	0.10-0.50	0.15-0.40	...	...	...
P3	...	T51603	0.10 max	0.20-0.60	0.40 max	0.40-0.75	1.00-1.50	...	...	...	...
P4	...	T51604	0.12 max	0.20-0.60	0.10-0.40	4.00-5.25	...	0.40-1.00	...	...	...
P5	...	T51605	0.10 max	0.20-0.60	0.40 max	2.00-2.50	0.35 max	...	...	...	...
P6	...	T51606	0.05-0.15	0.35-0.70	0.10-0.40	1.25-1.75	3.25-3.75	...	...	...	...
P20	...	T51620	0.28-0.40	0.60-1.00	0.20-0.80	1.40-2.00	...	0.30-0.55	...	...	...
P21	...	T51621	0.18-0.22	0.20-0.40	0.20-0.40	0.20-0.30	3.90-4.25	...	...	0.15-0.25	1.05-1.25Al
Water-hardening tool steels											
W1	W108, W109, W110, W112	T72301	0.70-1.50(e)	0.10-0.40	0.10-0.40	0.15 max	0.20 max	0.10 max	0.15 max	0.10 max	...
W2	W209, W210	T72302	0.85-1.50(e)	0.10-0.40	0.10-0.40	0.15 max	0.20 max	0.10 max	0.15 max	0.15-0.35	...
W5	...	T72305	1.05-1.15	0.10-0.40	0.10-0.40	0.40-0.60	0.20 max	0.10 max	0.15 max	0.10 max	...

(a) All steels except group W contain 0.25 max Cu, 0.03 max P, and 0.03 max S; group W steels contain 0.20 max P, and 0.025 max S. Where specified, sulfur may be increased to 0.06 to 0.15% to improve machinability of group H, M, and T steels. (b) Available in several carbon ranges. (c) Contains free graphite in the microstructure. (d) Optional. (e) Specified carbon ranges are designated by suffix numbers.

Group H steels usually have medium carbon contents (0.35 to 0.45%) and combined chromium, tungsten, molybdenum, and vanadium contents of 6 to 25%. H steels are divided into chromium hot-work steels, tungsten hot-work steels, and molybdenum hot-work steels.

Cold-work steels are restricted in application to those uses that do not involve prolonged or repeated heating above 205 to 260 °C (400 to 500 °F). There are three categories of cold-work steels: air-hardening steels, or group A; high-carbon, high-chromium steels, or group D; and oil-hardening steels, or group O.

Shock-resisting, or group S, steels contain manganese, silicon, chromium, tungsten, and molybdenum, in various combinations; carbon content is about 1.50%. Group S steels are used primarily for chisels, rivet sets, punches, and other applications requiring high toughness and resistance to shock loading.

The low-alloy special purpose, or group L, tool steels contain small amounts of chromium, vanadium, nickel, and molybdenum. Group L steels are generally used for machine parts and other special applications requiring good strength and toughness.

Mold steels, or group P, contain chromium and nickel as principal alloying elements. Because of their low resistance to softening at elevated temperatures, group P steels are used almost exclusively in low-temperature die casting dies and in molds for injection or compression molding of plastics.

Water-hardening, or group W, tool steels contain carbon as the principal alloying element (0.70 to 1.50% C). Group W steels, which also have low resistance to softening at elevated temperatures, are suitable for cold heading, coining, and emboss-

ing tools, woodworking tools, metal-cutting tools, and wear-resistant machine tool components.

Surface Treatments for Tool Steels (Ref 10)

Most surface treatments are employed to increase surface hardness and/or wear resistance, minimize adhesion (reduce friction), or improve the corrosion resistance of the tool steel base. The processes discussed below are described in greater detail elsewhere in this Volume or in *Heat Treating*, Volume 4 of the *ASM Handbook*.

Carburizing. The processes of case hardening and carburizing are of limited use in tool steel applications, because of the relatively high carbon contents of the tool steels. Carburizing can be accomplished in many ways, and essentially consists of heating the final machined tool into the austenite region in the presence of carbonaceous solids, liquids, or gases.

Low-carbon plastic mold steels (P type) are often carburized after hubbing or machining of the cavity in the mold. In this application, the tool steel is intentionally lean in carbon content to improve hubbing or machining, and must be carburized in order to have sufficient surface hardness for the end use.

Nitriding is a frequently used surface treatment that increases surface hardness, adds to the corrosion resistance of the tool, and reduces friction. Basically, the process involves heating the finished tool in the presence of a nitrogen-containing liquid or gas and allowing nitrogen to diffuse into the tool. Gas nitriding is usually accomplished at a lower temperature (about 527 °C, or 980 °F) and longer time (10 to 90 h) than liquid nitriding, which occurs at temperatures ranging from 538 to 552 °C (1000

to 1025 °F) for 2 to 4 h. A nitrided depth that ranges from 13 to 76 μm (0.0005 to 0.003 in.) is desired.

Because of decreased wear and die pickup, cold-extrusion punches experience a two to three-fold improvement in life. Nitriding is often used whenever mold wash is a problem in the die casting of zinc or aluminum alloys. Galling of sheet metal working dies can be alleviated by nitriding these dies before use.

Steels that will be nitrided should contain one or more of the nitride-forming elements (chromium, vanadium, or aluminum) in order to prevent the easy spalling and chipping that results when iron nitride is formed. Commonly nitrided tool steels include H11, H12, H13, A2, O2, and the high-speed tool steels.

Ion or plasma nitriding has many of the same characteristics of liquid or gas nitriding. This process relies on a nitrogen gas being ionized by glow discharge conditions between the tool (cathode) and the furnace wall or shield (anode). The primary advantages are the reductions in time and temperature, which save money and reduce the distortion and softening of prehardened tools. Usually, treatment times vary between 0.5 and 36 h.

Boriding. In this process, boron atoms from a solid, liquid, gas, or plasma atmosphere surrounding the finished part are diffused into the surface, creating a hard, water-resistant iron boride layer. Metal-to-metal wear testing demonstrated a three-fold improvement in wear resistance of borided O1 and O2 tool steels and over a two-fold increase in A2 tool steel (Ref 11). Borided A2 tool steel showed twice the life of uncoated O2 tool steel in a deep-drawing operation in which low-carbon steel cups were manufactured (Ref 11). An H13 roller designed to flange milk cans was borided and pro-

Table 3 Machining tool life improvements due to steam oxidation

Tool	Application	Tool life	
		Before steam treating	After steam treating
M2 broachers	Cutting AISI 1010 latch	20 h per grind	70 h per grind
M2 drills	Drilling Bakelite plastic insulating blocks	10 holes	25 holes
	Phenolic terminal plates	1700 holes per grind	8500 holes per grind
M7 end mill tools	Drilling AISI 4030 steel 25 mm (1 in.) thick	17 holes	81 holes
	Cutting 8740 steel forgings	30 pieces	200 pieces
A6 hobs	Cutting teeth on AISI 3140 forged gear	...	62.2% increased life
M2 milling cutters	Two slots in 1020 steel	150 cuts per grind	306 cuts per grind
	Slotting 1020 steel bars	2000 per grind	7000 per grind
M2 saw blades	Cutting 75 mm (3 in.) rods, austenitic steel	100% endurance at 0.52 m/s (102 sfm)	120% endurance at 0.57 m/s (112 sfm)
M2 taps	Cutting SAE 52100 steel	1800 pieces	3000 pieces

Source: Ref 13

Table 4 Effect of steam oxidation on tool life in forming various carbon steel nuts and bolts

Tool	Application	Tool life	
		Before steam treating(a)	After steam treating(b)
M2 4th station punch	Castle nut 1030 material	21,000 nuts	42,000 nuts
M2 4th station punch	Slotted insert nut 1030 material	22,000 nuts	38,000 nuts
M2 4th station punch	Castle nut 1030 material	29,000 nuts	80,000 nuts
M2 3rd station punch	Castle nut 1110 material	20,000 nuts	35,000 nuts
M2 4th station punch	Castle nut 1110 material	15,000 nuts	35,000 nuts
M2 trim die	Bolt head 1335 material	7,000 bolts	16,000 bolts

(a) Hardened and triple tempered. (b) Hardened, triple tempered and steam treated. Source: Ref 13

duced three times as many cans before it wore out (Ref 12).

Boriding takes place at temperatures as low as 600 °C (1100 °F), but usual practice involves a period from 1 to 6 h at temperatures from 800 to 900 °C (1470 to 1650 °F) (Ref 11, 12). The resultant layer is between 13 and 130 μm (0.0005 and 0.005 in.), and tends to be dull because of the microroughness of the surface. This high process temperature requires that the boron treatment act as the austenitization step, or else the process must be followed by re-austenitization. This necessarily limits the process to applications where tolerances of about 25 μm (0.001 in.) can be tolerated.

Carbide Coating by Toyota Diffusion Process. Good surface covering and strongly bonding carbide coatings, such as VC, NbC, and Cr₇C₃, can be formed on die steel surfaces by a coating method developed at Toyota Central Research and Development Laboratory, Inc. of Japan.

In the Toyota Diffusion (TD) process, metal dies to be treated are degreased, immersed in a carbide salt bath for a specific time period, quenched for core hardening, tempered, and washed in hot water for the removal of any residual salt. The borax salt bath contains compounds (usually ferroalloys) with carbide-forming elements such as vanadium, niobium, and chromium. The bath temperature is selected to conform to the hardening temperature of the die steel. For example, the borax bath temperature would be between 1000 and 1050 °C (1830 and 1920 °F) for H13 die steel.

The carbide layer is formed on the die surface through a chemical reaction between carbide-forming elements dissolved in the fused borax

and carbon in the substrate. The carbide layer thickens due to reaction between the carbide-forming element atoms in the salt bath and the carbon atoms diffusing into the outside surface layer from the interior of the substrate.

The thickness of the carbide layer is varied by controlling the bath temperature and immersion time. An immersion time of 4 to 8 h is needed for H13 steel to produce carbide layers with satisfactory thickness (5 to 10 μm) for die-casting applications. Dies are then removed from the bath and cooled in oil and salt or air for core hardening followed by tempering.

Coated tool steels, such as H12 and H13 steels, exhibit high hardness and excellent resistance to wear, seizure, corrosion, and oxidation. In addition, resistance to cracking, flaking, and heat checking is claimed. Hardness of the coating depends on layer composition: 3500 HV for vanadium carbide, 2800 HV for niobium carbide, and 1700 HV for chromium carbide.

Oxidation is a well-established process used for high-speed steel cutting tools. Increases in tool life of up to 100% are mostly due to a decrease in friction, because of the hard oxide coating and the ability of the porous oxide to entrap lubricant and draw it to the tool-workpiece interface. Steam oxidation of a finished tool is accomplished either by exposure to steam at a temperature of about 566 °C (1050 °F) or by treating in liquid sodium hydroxide and sodium nitrate salts at approximately 140 °C (285 °F) for periods of time ranging from 5 to 20 min. These treatments result in a black oxidized layer that is less than 5 μm (0.0002 in.) thick and will not peel, chip, nor crack, even when the tool is bent or cut. Tool life improvements due to steam oxidation are listed in Tables 3 and 4.

Bright Finish. Most high-speed cutting 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.

Plating. Three different kinds of plating are used on tool steels. Cadmium plating is used for appearance purposes and to reduce corrosion of the tool. It also has some usefulness in preventing adhesion. Nickel plating is commonly used for appearance purposes and to prevent corrosion.

The most commonly practiced tool steel plating process is hard chromium plating. Plating thickness varies between 2 and 13 μm (0.0001 and 0.0005 in.) and, because it is very hard, it prolongs life by increasing abrasive wear resistance. More important than plating hardness is its very low friction coefficient, which effectively prevents adhesive wear.

However, hard chromium plating is not without problems. Tool steels may be hydrogen embrittled when plated, and the plating has a tendency to spall and flake. These wear debris can actually accelerate abrasive wear.

Chemical vapor deposition (CVD), a process conducted in a vacuum chamber, relies on a deposition from reacted gas onto the tool steel surface. Many different materials can be used as coatings. Chromium, Al₂O₃, TiC, CrC, Fe₄N, and TiN are commonly used, and other materials are being studied. This process utilizes high temperatures, usually above 800 °C (1472 °F), which means that tool steels must be tempered after the CVD coating is applied. The most popular wear-resistant coatings are TiC and TiN, which are used to coat high-speed, cold-work die and hot-work die tool steels. These coatings commonly range in thickness from 2 to 20 μm (0.0001 to 0.001 in.). Using CVD coating with TiC and TiN, the primary mechanism of wear reduction is the extremely high hardness, which leads to excellent abrasion resistance, although some decrease in friction coefficient can often be realized. The chlorine content of the coating must carefully be maintained at a level below 5% to avoid degradation of the wear resistance (Ref 14).

Tool steels that can be successfully CVD coated include the AISI A, S, D, H, M, and T steel types. The lower-alloyed S type and all of the W and O types are either very difficult or impossible to properly coat, because of their low austenitization temperatures.

Physical vapor deposition (PVD), which is also conducted in a vacuum chamber, can be accomplished in several different ways. The process relies on plasma-aided precipitation of either TiC or TiN onto tool steel at temperatures ranging from 200 to 550 °C (400 to 1025 °F) (Ref 14). This temperature range is much more suitable for the coating of

high-speed tool steels than the temperatures required for CVD.

Tool steel wear is reduced in about the same proportions (2 to 6 times less wear), whether the TiC or TiN is applied by CVD or PVD. TiN coatings on H13 pins reduced the friction coefficient in pin-on-disk tests from 0.7 to less than 0.2 (Ref 15). Modified ASTM G65-10 abrasive wear testing of D3 steel showed that wear of the TiN-coated samples was between 4 and 23% of the uncoated samples, depending on their initial surface roughness (Ref 15). This result led Sundquist et al. to propose that increases in tool life that are due to TiN coating can only be expected when the surface roughness is less than the coating thickness (Ref 15). Specific examples of the use of PVD coatings for improving the life of high-speed steel tools are listed in Table 5.

Ion implantation is a process by which atoms of virtually any element can be injected into the near-surface region of any solid. The implantation process involves forming a beam of charged ions of the desired element and then accelerating them at high energies towards the surface of the solid, which is held under high vacuum. The atoms penetrate into the solid to a depth of 0.25 to 25 nm (2.5 to 250 Å). This process differs from coating processes in that it does not produce a discrete coating; rather, it alters the chemical composition near the surface of the solid. The most common element implanted in tool steels in order to improve tribological properties, specifically adhesive and sliding wear, is nitrogen. Examples of ion implantation in metal forming and cutting applications are listed in Table 6. Ion implantation of titanium and carbon has also improved the service life of stamping and cutting tools.

Laser surface processing methods, such as laser melting, have also been applied to tool steels. Hsu and Molian (Ref 18) reported that the tool life of laser-melted M2 steel tool bits was from 200 to 500% higher than if they were conventionally hardened using catastrophic failure criterion (Fig. 6). For laser-melted M35 steel tool bits, the tool life was from 20 to 125% higher than if they were conventionally hardened using flank wear failure criterion (Fig. 6). High-alloy martensite, fine austenite grain size, and finely dispersed carbides all contributed to high hardness, good toughness, and low coefficient of friction.

Maraging Steels (Ref 19)

Maraging steels comprise a special class of high-strength steels that differ from conventional steels in that they are hardened by a metallurgical reaction that does not involve carbon. Instead, these steels are strengthened by the precipitation of intermetallic compounds at temperatures of about 480 °C (900 °F). The term maraging is derived from martensite age hardening and denotes the age hardening of low-carbon, iron-nickel lath martensite matrix. The physical metallurgy and properties of maraging steels are described in Ref 19.

Commercial maraging steels are designed to provide specific levels of yield strength from

Table 5 Increased tool life attained with PVD coated cutting tools

Type	Cutting tool		Workpiece material	Workpieces machined before resharpening	
	High-speed tool steel, AISI type	Coating		Uncoated	Coated
End mill	M7	TiN	1022 steel, 35 HRC	325	1200
End mill	M7	TiN	6061-T6 aluminum alloy	166	1500
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	3400
Broach	M2	TiN	Type 410 stainless steel	10,000-12,000	31,000
Pipe tap	M2	TiN	Gray iron	3000	9000
Tap	M2	TiN	1050 steel, 30-33 HRC	60-70	750-800
Form tool	T15	TiC	1045 steel	5000	23,000
Form tool	T15	TiN	Type 303 stainless steel	1840	5890
Cutoff tool	M2	TiC-TiN	Low-carbon steel	150	1000
Drill	M7	TiN	Low-carbon steel	1000	4000
Drill	M7	TiN	Titanium alloy 662 layered with D6AC tool steel, 48-50 HRC	9	86

Source: Ref 16

Table 6 Examples of ion implantation in metalforming and cutting applications

Part	Part material	Process	Work material	Ion	Energy, keV	Benefit
Tool inserts	TiN-coated tool steel	Machining	4140	N	80	3× life
Taps	HSS	Tapping	4140	N	80	3× life
	HSS	Tapping	4130	N	80	5× life
	HSS	Tapping	4140	N	50	10× life
	M35	Tapping	...	N ₂	200	4× life
	M7	Tapping	...	N	100	2× life
Cutting blade	M2	Cutting	1050	N	100	2× life
	M2	Cutting	SAE 950	N	100	4× life
	D2	Forming	321 SS	N	80	2× life
Dies	M2	Forming	Steel	N	100	2-12× life
	M2	Forming	1020	N	100	Negligible effect
	D6	Forming	TiO ₂ and rubber	N	100	6× life
	Molds	D2	Forming	Polymers	N	50	5× life
Rollers	H13	Rolling	Steel	N	100	5× life

Note: HSS, high-speed steel; SS, stainless steel. Source: Ref 17

1030 to 2420 MPa (150 to 350 ksi). Some experimental maraging steels have yield strengths as high as 3450 MPa (500 ksi). These steels typically have very high nickel, cobalt, and molybdenum contents and very low carbon contents. Carbon, in fact, is an impurity in these steels and is kept as low as commercially feasible in order to minimize the formation of titanium carbide (TiC), which can adversely affect strength, ductility, and toughness.

Table 7 lists the chemical compositions of the more common grades of maraging steel. The nomenclature that has become established for these steels is nominal yield strength (ksi units) in parentheses. Thus, for example, 18Ni (200) steel is normally age hardened to a yield strength of 1380 MPa (200 ksi). The first three steels in Table 7—18Ni (200), 18Ni (250), and 18Ni (300)—are the most widely used and most commonly available grades. The 18Ni (350) grade is an ultrahigh-strength variety made in limited quantities for special applications. Two 18Ni (350) compositions have been produced (see the footnote in Table 7). The 18Ni (Cast) grade was developed specifically as a cast composition.

A number of cobalt-free maraging steels and a low-cobalt bearing maraging steel have recently been developed. The driving force for the development of these particular alloys was the cobalt shortage and resultant price escalation of cobalt during the late 1970s and early 1980s. The nominal compositions for these alloys are also listed in Table 7.

Surface Treatments for Maraging Steels (Ref 19)

Cleaning. Grit blasting is the most efficient technique for removing oxide films formed by heat treatment. Maraging steels can be chemically cleaned by pickling in sulfuric acid or by duplex pickling in hydrochloric acid and then in nitric acid plus hydrofluoric acid (see Tables 7 and 11 in the article "Surface Engineering of Stainless Steels" in this Volume). As with conventional steels, care must be taken to avoid overpickling. The sodium hydride cleaning of maraging steels should be avoided to minimize problems with crack formation. Grease

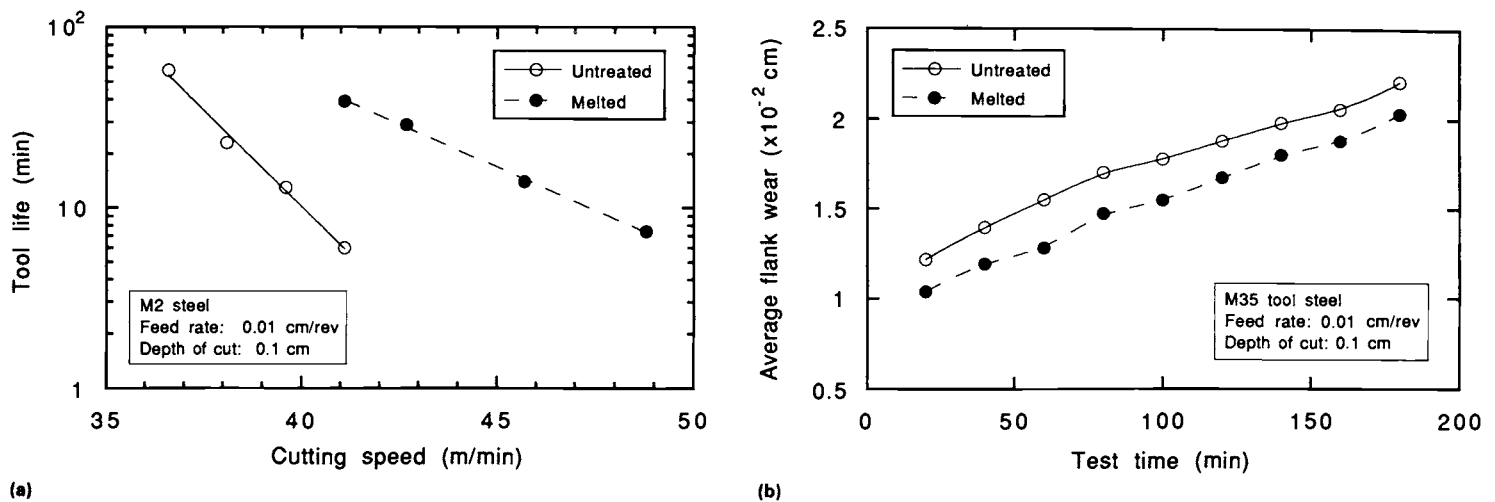


Fig. 6 Tool life of conventionally heat-treated and laser-melted tool bits. (a) M2 tool steel. (b) M35 tool steel. Source: Ref 18

Table 7 Nominal compositions of commercial maraging steels

Grade	Composition, % (a)					
	Ni	Mo	Co	Ti	Al	Nb
Standard grades						
18Ni(200)	18	3.3	8.5	0.2	0.1	...
18Ni(250)	18	5.0	8.5	0.4	0.1	...
18Ni(300)	18	5.0	9.0	0.7	0.1	...
18Ni(350)	18	4.2(b)	12.5	1.6	0.1	...
18Ni(Cast)	17	4.6	10.0	0.3	0.1	...
12-5-3(180)(c)	12	3	...	0.2	0.3	...
Cobalt-free and low-cobalt bearing grades						
Cobalt-free 18Ni(200)	18.5	3.0	...	0.7	0.1	...
Cobalt-free 18Ni(250)	18.5	3.0	...	1.4	0.1	...
Low-cobalt 18Ni(250)	18.5	2.6	2.0	1.2	0.1	0.1
Cobalt-free 18Ni(300)	18.5	4.0	...	1.85	0.1	...

(a) All grades contain no more than 0.03% C. (b) Some producers use a combination of 4.8% Mo and 1.4% Ti, nominal. (c) Contains 5% Cr

and oils can be removed by cleaning in trichloroethane-type solutions.

Nickel Plating. Maraging steels can be nickel plated in chloride baths provided that proper surface-activation steps are followed. Heavy chromium deposits can be plated on top of nickel electrodeposits. Maraging steels are less susceptible to hydrogen embrittlement during plating than conventional quenched and tempered steels of comparable hardness. They are not immune to hydrogen, however, and baking after plating is recommended. Baking should be done at temperatures of about 150 to 205 °C (300 to 400 °F) for periods of 3 to 10 h, depending on size and baking temperature. Baking cannot be combined with age hardening, because considerable hydrogen remains in the steel after heat treating at the higher temperatures.

Nitriding. Considerable surface hardening can be achieved by nitriding maraging steels in dissociated ammonia. Hardness levels equivalent to 65 to 70 HRC can be achieved at depths of up to 0.15 mm (0.006 in.) after nitriding for 24 to 48 h at 455 °C (850 °F). Nitriding at this temperature allows age hardening to occur during nitriding; therefore, the two processes can be accomplished simultaneously.

Salt bath nitriding for 90 min at 540 °C (1000 °F) has been done successfully. Such treatment must be very carefully controlled to avoid excessive overaging. Both the fatigue strength and the wear resistance (Fig. 7) of maraging steels are improved by nitriding.

Maraging steels can also be surface hardened by ion nitriding. Ozbaysal and Inal (Ref 20) have demonstrated that the surface hardening of maraging steels without a reduction in core hardness is possible using the ion nitriding process. Their studies on 18Ni(250), 18Ni(300), and 18Ni(350) showed that the highest surface hardness and the highest core hardness for all three grades were achieved by nitriding at approximately 440 °C (825 °F). Figure 8 shows the surface and core hardness as functions of ion nitriding time and temperature for 300-grade maraging alloy.

Electrical Steels (Ref 21)

Electrical steels are flat-rolled silicon-containing alloys used for soft magnetic applications such as components (magnetic cores) for motors,

generators, and transformers. The beneficial effects of silicon additions to iron include:

- Increase of electrical resistivity
- Suppression of the γ loop enabling desirable grain growth
- Development of preferred orientation grain structure

The addition of silicon also reduces magneto-crystalline anisotropy energy, and at ~6.5% Si content reduces the magnetostriction constants to nearly zero. High-permeability and low hysteresis losses can therefore be attained at the 6.5Si-Fe composition. On the negative side, the addition of silicon to iron lowers magnetic saturation, lowers Curie temperature, and seriously decreases mechanical ductility. At silicon levels above ~4%, the alloy becomes brittle and difficult to process by cold-rolling methods; thus, few commercial steels contain more than ~3.5% Si.

The commercial grades of silicon steel in common use are made mostly in electric or basic oxygen furnaces. Continuous casting and/or vacuum degassing (V-D) may be employed. Flat-rolled silicon-iron sheet and strip has low sulfur content, typically below 0.25%, with better grades below 0.01%. Carbon contents are frequently less than 0.04%. Manganese may be present up to approximately 0.70%. Residual elements such as chromium, molybdenum, nickel, copper, and phosphorus may also be present. The major alloying addition is silicon plus up to 0.6% Al (optional). These alloys are not generally sold on the basis of their composition, but rather are sold based upon controlled magnetic properties, particularly at core losses.

Electrical sheet grades are divided into two general classifications, (1) oriented steels and (2) nonoriented steels. The oriented steels are given mill treatments designed to yield exceptionally good magnetic properties in the rolling, or lengthwise, direction of the steel. Nonoriented grades are made with a mill treatment that yields a grain structure, or texture, of a random nature and,

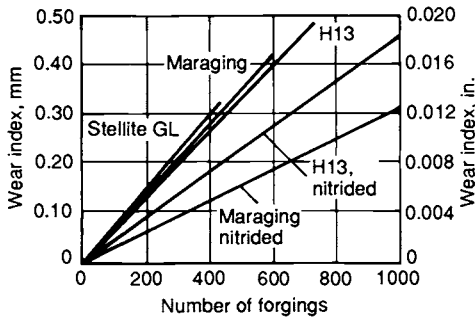


Fig. 7 Relative wear rates of nitrided and non-nitrided tool steels and maraging steels used in extrusion forging

core loss is obtained with higher silicon contents, larger grain size optimization, lower impurity levels, thinner gages, and insulating coatings.

The AISI designations are still in common use, but the newer ASTM designations provide more specific information regarding the grade identified. A typical ASTM designation is 47S200. The first two digits of the ASTM designation indicate the thickness in mm ($\times 100$). Following these digits is a letter (C, D, F, S, G, H, or P) that indicates the material type and the respective magnetic test conditions. The last three digits provide an indication of the maximum allowable core loss in units of either (watts/kg) $\times 100$, or (watts/lb) \times

100. If the core-loss value is expressed in watts/kg, the grade designation takes the suffix M, indicating an ASTM metric standard. Several ASTM flat-rolled products specifications are written in English and metric versions, such as A 677-84 and its companion metric specification A 677M-83.

Surface Treatments for Electrical Steels

The purpose of the core metal in a motor, generator, or transformer is to offer the best path for the magnetic lines of flux, and its success in this respect is measured by its permeability. Cores are usually composed of a larger number of thin

therefore, the magnetic properties in the rolling direction of the steel are not significantly better than those in the transverse direction. Subdivisions of these steels include semiprocessed grades and the fully processed grades. The former must be given a heat treatment by the purchaser. Fully processed grades are process annealed by the manufacturer.

Table 8 gives examples of properties specified by ASTM and American Iron and Steel Institute (AISI) for standard grades of nonoriented and oriented electrical steel. The AISI designations were adopted in 1946 to eliminate the wide variety in nomenclature formerly used. When originally adopted, the AISI designation number approximated ten times the maximum core loss,* in watts per pound, exhibited by 29 gage (0.36 mm, or 0.014 in.) samples when tested at a flux density of 1.5 T (15 kG) and a magnetic circuit frequency of 60 Hz. Note that fully processed M-36 tested as 0.36 mm (0.14 in.) strip now has a maximum allowable core loss of 4.2 W/kg (1.9 W/lb), not an approximate level of 7.9 W/kg (3.6 W/lb). Low

* The term *core loss*, as applied to electrical steel, is a quantitative measure of the rate at which electrical energy is converted to thermal energy during 50 or 60 cycle ac magnetization. Core loss is separated into two components: hysteresis loss and eddy current loss.

Table 8 Properties of selected electrical steels

AISI type (approximate equivalent)	Nominal (Si + Al) content, %	Thickness		ASTM designation	Maximum core loss at 60 Hz and B = 1.5 T (15 kG)	
		mm	in.		W/kg	W/lb
Nonoriented						
Semiprocessed (ASTM A 683)(a)						
M-47	1.10	0.64	0.025	64S350	7.71	3.50
	1.10	0.47	0.019	47S300	6.61	3.00
M-45	1.70	0.64	0.025	64S280	6.17	2.80
	1.70	0.47	0.019	47S250	5.51	2.50
M-43	2.00	0.64	0.025	64S260	5.73	2.60
	2.00	0.47	0.019	47S230	5.07	2.30
M-36	2.40	0.64	0.025	64S230	5.07	2.30
	2.40	0.47	0.019	47S200	4.41	2.00
M-27	2.70	0.64	0.025	64S213	4.69	2.13
	2.70	0.47	0.019	47S188	4.14	1.88
...	3.00	0.64	0.025	64S194	4.28	1.94
...	3.00	0.47	0.019	47S178	3.92	1.78
Fully processed (ASTM A 677)(b)						
...	0.50	0.64	0.025	64F600	13.22	6.00
...	0.80	0.47	0.019	47F450	9.92	4.50
M-47	1.05	0.64	0.025	64F470	10.36	4.70
	1.05	0.47	0.019	47F380	8.38	3.80
M-45	1.85	0.64	0.025	64F340	7.49	3.40
	1.85	0.47	0.019	47F290	6.39	2.90
M-43	2.35	0.64	0.025	64F270	5.95	2.70
	2.35	0.47	0.019	47F230	5.07	2.30
M-36	2.65	0.64	0.025	64F240	5.29	2.40
	2.65	0.47	0.019	47F205	4.52	2.05
	2.65	0.36	0.014	36F190	4.19	1.90
M-27	2.8	0.64	0.025	64F225	4.96	2.25
	2.8	0.47	0.019	47F190	4.19	1.90
	2.8	0.36	0.014	36F180	3.97	1.80
M-22	3.2	0.64	0.025	64F218	4.80	2.18
	3.2	0.47	0.019	47F185	4.08	1.85
	3.2	0.36	0.014	36F168	3.70	1.68
M-19	3.3	0.64	0.025	64F208	4.58	2.08
	3.3	0.47	0.019	47F174	3.83	1.74
	3.3	0.36	0.014	36F158	3.48	1.58
M-15	3.5	0.47	0.019	47F168	3.70	1.68
	3.5	0.36	0.014	36F145	3.20	1.45
Oriented						
Fully processed (ASTM A 876)(c)						
M-6	3.15	0.35	0.014	35G066	1.45	0.66
	3.15	0.35	0.014	35H094	2.07(d)	0.94
M-5	3.15	0.30	0.012	30G058	1.28	0.58
	3.15	0.30	0.012	30H083	1.83(d)	0.83
M-4	3.15	0.27	0.011	27G051	1.12	0.51
	3.15	0.27	0.011	27H074	1.63(d)	0.74
...	3.15	0.23	0.009	23G046	1.01	0.46
...	3.15	0.23	0.009	23H071	1.56(d)	0.71
...	3.15	0.27	0.011	27P066	1.45(d)	0.66
...	3.15	0.30	0.012	30P070	1.54(d)	0.70

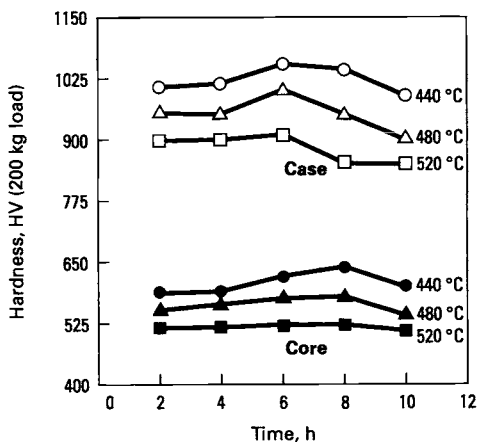


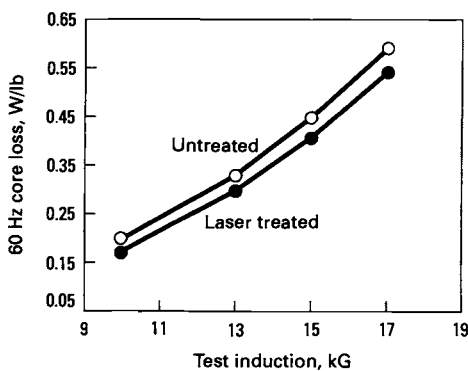
Fig. 8 Surface (case) and core hardness as functions of ion nitriding time and temperature for 18Ni (300) maraging steel. Source: Ref 20

(a) Refer to ASTM A 683-84 and companion specification A 683M-84 (metric) for detailed information. (b) Refer to ASTM A 677-84 and companion specification A 677M-83 (metric) for detailed information. (c) Refer to ASTM A 876-87 and companion specification A 876M-87 for detailed information. (d) B (magnetic induction) = 1.7 T (17 kG).

Table 9 Types of core plate coatings used for lowering core losses in electrical steels

Core plate designation	Description
C-1	An organic enamel or varnish coating sometimes used for cores not immersed in oil. It enhances punchability and is resistant to ordinary operating temperatures. It will not withstand stress-relief annealing.
C-2	An inorganic insulation consisting of a glass-like film formed during the high-temperature annealing of electrical steel, particularly grain-oriented electrical steel, as the result of the reaction of an applied coating of MgO and silicates in the surface of the steel. This insulation is intended for air-cooled or oil-immersed cores. It will withstand stress-relief annealing and has sufficient interlamination resistance for wound cores of narrow-width strip such as in distribution transformers. It is not intended for stamped lamination because it is abrasive to dies.
C-3	An enamel or varnish coating intended for air-cooled or oil-immersed cores. C-3 enhances punchability and is resistant to normal operating temperatures. It will not withstand stress-relief annealing.
C-4	Consists of a chemically treated or phosphated surface useful for air-cooled or oil-immersed cores. It will withstand stress-relief annealing in relatively neutral atmospheres.
C-5	An inorganic insulation similar to C-4 but with ceramic fillers (such as colloidal silica) added to increase the electrical insulation properties. C-5 can be used in air-cooled or oil-immersed cores and will endure stress-relief annealing.

Source: ASTM A 345

**Fig. 9** Effect of laser scribing on the core loss of a high-permeability grain-oriented electrical steel. Source: Ref 23

metal laminations that are fabricated by punching from thin sheets of metal, and which are subsequently assembled to form a core.

Interlaminar insulation is necessary for high electrical efficiency in the magnetic core, whether the application is static or rotating. For small cores used in fractional-horsepower motors, an oxide surface on the laminations may insulate the core adequately. Insulations of AISI types C-1, C-2, C-3, C-4, and C-5 are used for more rigorous requirements. Table 9 describes the characteristics of these various core coatings.

Organic-Type Insulation. Types C-1 and C-3 are organic and cannot be successfully applied to laminations before annealing. They are unsuitable for electrical equipment operated at high temperatures or for power transformers with certain types of coolants. However, they improve the punchability of the sheet steel.

Inorganic-Type Insulation. Inorganic types C-4 and C-5 are used when insulation requirements are severe and when annealing temperatures up to 790 °C (1450 °F) must be withstood. Typical values of interlaminar resistance for these two types are between 3 and 100 Ω · cm/lamination under a pressure of 2070 kPa (300 psi). These coatings also can be made to impart residual tensile stresses in the steel substrate, which can improve magnetic properties.

Core insulation must be sufficiently thin and uniform so as to have no more than 2.0% effect on the lamination factor (solidity of the core). To calculate the required insulation for most operations at power frequency, the square of the resistivity, in ohm-centimeters per lamination, should at least equal the square of the width of the magnetic path, in inches. This usually ensures a negligible interlaminar loss that is less than 1.0% of the core loss.

Ceramic Films. Japanese electrical steel producers have reported significant improvement in core loss as a result of ion plating of TiN and CrN ceramic coatings (Ref 22). Application of these ceramic films on chemically polished grain-oriented electrical steel sheet increased the magnetic flux density by 0.004 to 0.015 T (0.04 to 0.15 kG) and lowered the core loss by 0.12 to 0.20 W/kg (0.05 to 0.09 W/lb). By laser domain refining (see discussion below), it was possible to further improve the core loss by 0.04 to 0.09 W/kg (0.02 to 0.04 W/lb). Using this dual ceramic film/laser treatment, electrical steels with original core losses of 0.88 W/kg (0.4 W/lb) were improved to an ultralow core loss of 0.55 W/kg (0.25 W/lb), which corresponds to an improvement of about 40% (Ref 22).

Laser Magnetic Domain Refinement. Core loss improvements of 2 to 14% can be achieved by rapid scanning (typically 100 m/s, or 325 ft/s) a high-powered focused laser beam across the surface (transverse to the rolling direction) of grain-oriented glass-coated (Si-Mg-P-Al glass) 3% silicon-irons (Ref 23). There is no flame, spark, or smoke generated during this process, which is also referred to as laser scribing, and the material/coating shows no visible surface change. The improvement in core loss is due to a thermal shock imparted to the microstructure which causes slip plane dislocations to form, thereby producing new magnetic domain wall boundaries (Ref 23). By adjusting the spacing of the scanned laser lines, the energy lost due to moving domain walls back and forth under the action of the applied ac field in the transformer is minimized. The laser lines restrict the length of the domains and also act to control the width of the domains. Thus by adjusting the spacing of the laser lines, the domain sizes can be controlled, i.e., refined. Figure 9 illustrates the improvement in core loss as a function of

applied field strength for a 0.26 mm (0.0104 in.) thick silicon steel sheet.

REFERENCES

1. L.F. Pease III, *Ferrous Powder Metallurgy Materials, Properties and Selection: Irons, Steels, and High-Performance Alloys*, Vol 1, ASM Handbook, ASM International, 1990, p 801-821
2. W.B. James, M.J. McDermott, and R.A. Powell, *Powder Forging, Forming and Forging*, Vol 14, ASM Handbook (formerly 9th ed., *Metals Handbook*), ASM International, 1988, p 188-211
3. *Materials Standards for P/M Structural Parts*, MPlF Standard 35, Metal Powder Industries Federation, 1990
4. H.E. Boyer, *Secondary Operations Performed on P/M Parts and Products*, *Powder Metallurgy*, Vol 7, ASM Handbook (formerly 9th ed., *Metals Handbook*), ASM International, 1984, p 451-462
5. H.A. Ferguson, *Heat Treating of Powder Metallurgy Steels*, *Heat Treating*, Vol 4, ASM Handbook, 1991, p 229-236
6. L.F. Pease III, *Mechanical Properties of Steam Blackened P/M Materials*, in *Modern Developments in Powder Metallurgy: Proceedings of the International Powder Metallurgy Conference*, Metal Powder Industries Federation, 1988
7. W. Rembes, *Ion Nitriding Applications Grow for Automotive Components*, *Heat Treat.*, March 1990
8. A.M. Bayer, *Wrought Tool Steels*, *Properties and Selection: Irons, Steels, and High-Performance Alloys*, Vol 1, ASM Handbook (formerly 10th ed., *Metals Handbook*), ASM International, 1990, p 757-779
9. K.E. Pinnow and W. Stasko, *P/M Tool Steels*, *Properties and Selection: Irons, Steels, and High-Performance Alloys*, Vol 1, ASM Handbook (formerly 10th ed., *Metals Handbook*), ASM International, 1990, p 780-792
10. J.L. Maloney III, *Friction and Wear of Tool Steels*, *Friction, Lubrication, and Wear Technology*, Vol 18, ASM Handbook, ASM International, 1992, p 734-740
11. H.C. Fiedler and R.J. Sieraski, *Boriding Steels for Wear Resistance*, *Met. Prog.*, Feb 1971, p 102-103
12. O.N. Guy, *Boronizing—A Surface Heat Treatment for Critical Wear Surfaces*, *New Developments in Tool Materials and Applications*, Illinois Institute of Technology, 1977
13. T.D. Deming, *Steam Treating Emerges as Important Cog in Metal Surface Engineering*, *Industrial Heating*, Jan 1990, p 28-30
14. F. Wendl, *Current Trends in Surface Treatment of Tools Used for Plastics Processing*, *Thyssen Edelstahl Tech. Ber.*, special issue, May 1990, p 82-99
15. H.A. Sundquist, E.H. Sirvio, and M.T. Kurkinen, *Wear of Metalworking Tools Ion Plated With Titanium Nitride*, *Met. Tech.*, Vol 10, 1983, p 130-134

16. C. Wick, HSS Cutting Tools Gain a Productivity Edge, *Manufacturing Engineering*, May 1987, p 38
17. G.R. Fenske, Ion Implantation, *Friction, Lubrication, and Wear Technology*, Vol 18, *ASM Handbook*, ASM International, 1992, p 850-860
18. M. Hsu and P.A. Molian, *Wear*, Vol 127, 1988, p 253
19. K. Rohrbach and M. Schmidt, Maraging Steels, *Properties and Selection: Irons, Steels, and High-Performance Alloys*, Vol 1, *ASM Handbook* (formerly 10th ed., *Metals Handbook*), ASM International, 1990, p 793-800
20. K. Ozbaysal and O.T. Inal, Surface Hardening of Marage Steels by Ion Nitriding without Reduction in Core Hardness, in *Ion Nitriding*, ASM International, 1986, p 97-115
21. D.W. Dietrich, Magnetically Soft Materials, *Properties and Selection: Nonferrous Alloys and Special-Purpose Materials*, Vol 2, *ASM Handbook* (formerly 10th ed., *Metals Handbook*), ASM International, 1990, p 761-781
22. Y. Inokuti, K. Suzuki, and Y. Kobayashi, Grain Oriented Silicon Steel Sheet With New Ceramic Films Characterized by Ultra-Low Iron Loss, *Materials Transactions, JIM*, Vol 33 (No. 10), 1992, p 946-952
23. G.L. Neiheisel, Laser Magnetic Domain Refinement, *LIA Vol 44, Proc. Conf. ICALEO 1984*, p 102-111