97

MOLD MATERIALS–STEEL

James T. Christensen

Crucible Steel, P.O. Box 977, Syracuse, NY 13201

97.1 DESCRIPTION

A wide range of steels are used for plastic molds for a variety of reasons. Many mold shops and mold designers have considerable experience with a particular grade of steel that works in a specific application, but there is not any one, all-purpose tool steel with the ideal combination of properties for every mold use. Necessarily, trade-offs must be made in choosing the mold steel because each grade offers advantages and disadvantages.

Table 97.1 identifies the four basic categories of tool steel that are most popular for plastic molds: prehardened grades, including a stainless prehardened grade; air hardening grades, including two particle metallurgy grades; stainless steels, with one particle metallurgy grade; and oil hardening grade. There are some other grades not listed in this table in limited use in the plastic industry; they also fall into these four basic categories.

Table 97.1 also ranks the different grades of tool steel by machinability, grindability, and polishability, based on the typical application hardness most often used. The ranking is numeric, with the higher numbers indicating superiority in that property.

All of the tool steels listed in Table 97.1, except the three CPM grades, are melted in an electric arc furnace and refined in an AOD vessel. This is done to control the heat-to-heat uniformity of chemistry and the cleanliness levels in the steel. After melting, ingots are cast, upset pressed, and rolled to produce blocks and bars that are alike in structure throughout the cross section. The blocks are machined and supplied either in the spherodized annealed or the heat-treated (prehard) condition.

The CPM process used to produce the three high-vanadium tool steels listed in Table 97.1 is discussed later in this section.

Table 97.2 shows physical and mechanical properties for selected mold steels. These properties are listed by grade and a typical hardness for each.

97.2 IDENTIFYING STEELS

97.2.1 Prehardened Tool Steels

These steels are supplied already heat treated in the range of 260–350 BHN to eliminate size changes and extra finishing operations associated with hardening molds. For cores and cavities, these steels machine in the medium range; they can be polished to lens mold applications. The resulfurized or sulfur-added modificiations to AISI 4140 or 4150 enhance machinability to the high area; however, these modified steels cannot take on a high polish because of the sulfur additions. They are usually used for shoes, holders, and mold bases.

TABLE 97.1. Tool Steel Nominal Chemistries for Plastic Mold Steels

Type	AISI Symbol	C	M_n	S_i	C_r	N_i	M_o	V	W	Machinability[a]	Grindability[a]	Polishability[a]	Typical Hardness, R_c
Prehardened													
	P20	0.30	0.75	0.50	1.65		0.40			8.5	10	10	31
	4140	0.40	0.90	0.30	1.00		0.20			8.5	10	8	28
	T414	0.02	0.50	0.50	11.75	2.90				6	8	10	30
Air Hardening													
	S7	0.50	0.70	0.35	3.25		1.40	0.25		7.5	8	10	55
	H13	0.40	0.35	1.05	5.00		1.35	1.05		7	8.5	10	47
	A-2	1.00	0.85	0.30	5.25		1.10	0.25		5	7	8	61
	A-6	0.70	2.00	0.30	1.00			1.35		6	8	9	56
	D-2	1.55	0.30	0.45	11.50		0.80	0.90		3.5	3.5	6	61
	A-11	2.45	0.50	0.90	5.25		1.30	9.75		4	3.5	7	61
	CPM10V[b]												
	CPM9V[b]	1.78	0.50	0.90	5.25		1.30	9.00		4.5	4.5	7	55
Stainless													
	T420	0.35	0.45	0.50	13.00					6.5	8	10	50
	T440C	1.05	1.00	1.00	17.00		0.75			3.5	4	8	58
	CPM T440V[b]	2.20	0.50	0.50	17.50		0.50	5.75		3.5	4	7.5	59
Oil Hardening													
	01	0.90	1.25	0.30	0.50				0.50	7	9	9	61

[a] Low number means property is poor. High number means property is good.

[b] Crucible trade name.

97.2. Physical and Mechanical Properties for Selected Plastic Mold Steels

	Tensile Strength, ksi (MPa)	Tensile Modulus × 10⁶ psi (GPa)	Yield Strength 2% Offset ksi (MPa)	Thermal Conductivity Btu-ft/(h-ft²-°F) °F			W/m/k	Density, lb/in.³ (g/cm³)	Coefficient of Thermal Expansion [illegible] °F	in./in./°F × 10⁻⁶	°C	mm/mm/°C × 10⁻⁶
	157 (1080)	30 (207)	136 (938)	200	24.7	93	42.7	0.284 (7.87)	100–500	5.84	38–260	10.5
IN)				400	27.5	204	47.6		68–800	7.10	20–427	12.8
	148 (1020)	30 (207)	95 (655)	200	24.4	93	42.2	0.282 (7.81)	68–212	6.84	20–100	12.3
IN)				400	26.5	204	45.8		68–752	7.62	20–400	13.7
	140 (966)	29 (200)	120 (828)	200	12.1	93	20.9	0.277 (7.67)	32–212	5.8	0–100	10.4
IN)									32–600	6.1	0–316	11.0
	93 (641)	30 (207)	55 (379)					0.283 (7.84)	75–750	7.3	24–400	13.1
IN)									75–1000	7.6	24–538	13.7
	225 (1550)	30 (207)	200 (1379)	68	14.2	20	24.6	0.280 (7.76)	100–800	6.88	38–427	12.4
						199	25.1		100–1000	7.00	38–538	12.6
	95 (655)	29 (200)	50 (345)	200	14.4	93	24.9	0.276 (7.65)	32–212	5.7	0–100	10.3
IN)									32–600	6.0	0–316	10.8
	110 (759)	29 (200)	65 (448)	200	14.0	93	24.2	0.276 (7.65)	32–212	5.7	0–100	10.3
IN)									32–600	6.0	0–316	10.8

TABLE 97.3. Attainable Hardness of Carburized CSM 2[a]

Tempering Temperature °F	(°C)	Case Hardness, R_c	Core Hardness, R_c
600	(316)	57–58	47–48
650	(343)	57–58	46–47
700	(371)	55–56	45–46
750	(399)	54–55	44–45
800	(427)	53–55	43–44
900	(482)	52–53	39–40

[a] Gas carburized—1600°F (871°C).
Furnace cooled to 1475°F (802°C).
Oil quenched and tempered 4 + 4 hours.
Section size—4 in. (101.6 mm) diameter bar.

Note: Larger sections than those tested will show lower hardness values; smaller sections will show higher hardness values.

P20. P20 is the mold steel most widely used in the plastic industry for all types of machine-cut molds. P20 is most commonly supplied in the prehardened condition (around 300 BHN). High hard material is available in hardnesses up to 350 BHN for added strength and durability.

P20 is also supplied to the annealed condition at around 200 BHN. It can be heat treated, carburized, or nitrided to high hardness if mold wear is a problem or if it is easier at 200 BHN to acquire a high optical finish than at the standard hardness of 300 BHN.

Table 97.3 shows the attainable hardness of both the case and core of gas carburized CSM2R (P20) for different tempering temperatures.

Figure 97.1 shows the case depth vs the carburizing time. Figure 97.2 shows case depth vs the nitriding time for both 200 BHN and 300 BHN prehardened blocks of P20, nitrided at 975°F for 24, 36, 48, and 60 hour cycles.

P20 can be plated with chrome or nickel to provide added wear and corrosion resistance for molding PVC or other engineering plastics. It is available in blocks up to 75,000 lb (3400 kg) for use in large automotive or other applications. Prehardened P20 is used in injection and transfer molding; carburized P20, in compression molding for greater surface strength and wear resistance.

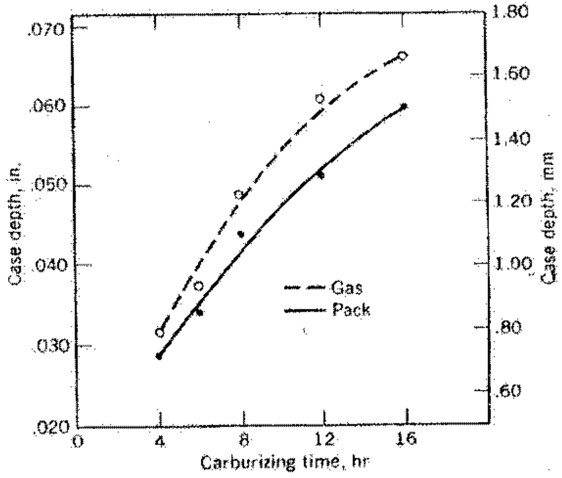


Figure 97.1. Carburizing CSM 2: depth of case vs time.

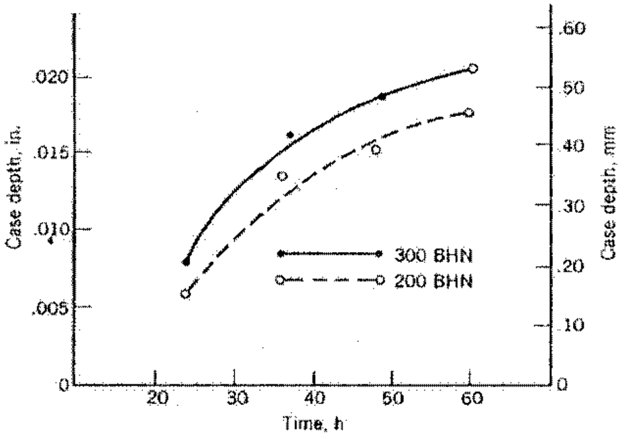


Figure 97.2. Nitriding 200 BHN and 300 BHN CSM2: depth of case vs time.

4140. 4140 is an alloy steel supplied in the prehardened condition (around 300 BHN) and used for holders, shoes, and mold bases. It usually holds the plastic mold, which is inserted. Blocks of 4140 used for cores and cavities, especially the resulfurized modifications, should only be employed to produce nondecorative parts. It has good fatigue, abrasion, and impact resistance as well as resistance to softening at elevated temperatures.

T414. T414 prehardened tool steel is supplied at 300 BHN. T414 is designed primarily for those applications where a tool steel more corrosion-resistant than P20 is needed for molding all plastics, including vinyl-base and other corrosive plastics. T414 will not rust when molds begin to sweat or during storage. Polishability is excellent for this prehardened grade, making it ideal for optical finishes. Its general corrosion resistance is excellent in a variety of corrosive environments and is superior to that of T410 stainless. T414 eliminates the need for chromium plating and the attendant problems of stripping for replating and pitting in the replating operation.

T414 can be texturized best by using a ferric chloride and water mixture; this produces depths acceptable for most texturing finishes in the same time that it takes to texturize P20.

97.2.2 Air Hardening Tool Steels

Air hardening tool steels are distinguished by the method of quenching (attaining the hardness) after the austenitizing temperature. In the hardening phase, this group of tool steels is cooled more slowly than the oil or water hardening grades. The result is less intense strains and less distortion.

The most important elements for making steels capable of air hardening are chromium and molybdenum, which, when combined with carbon, produce hard carbides with exceptional wear resistance.

To obtain the required hardness levels in large blocks, some of these steels are quenched in oil. To avoid excess scaling, air hardening tools are sometimes flash quenched in oil to about 1000–1200°F (538–649°C) and then cooled in air. Adequate space must be allowed for uniform movement of air around the parts being cooled. Although it is not good practice are large, creating machining and grinding difficulties in both the annealed and heat treated condition as well as toughness limitations in service. The particle metallurgy process has overcome these limitations by making very small, uniformly distributed carbides in the microstructural matrix.

Another advantage of the particle metallurgy process over the traditional slow ingot solidification process is the production of steels that evidence no alloy segregation macroscopically and exhibit small, uniformly distributed carbides and fine grain sizes microscopically. Since the sulfides also remain fine and uniformly distributed, the steels can be resulfurized without loosing toughness.

The particle metallurgy process can also produce higher alloyed tool steel compositions with much higher levels of vanadium. The small, uniformly distributed vanadium carbides permit conventional machining with carbide and ceramic inserts, even when heat treated to the low 60s HRc. These steels are used in applications requiring wear resistance superior to those available in conventionally produced steels.

A11 (CPM 10V). A11 (CPM 10V), which was commercially introduced in 1978, is designed for the exceptional combination of wear resistance and toughness. It is supplied in the annealed condition at about 260 BHN and can be heat treated to a maximum of 65 HRc. Normal application hardness for All is 60–62 HRc, where the combination of toughness and wear resistance are optimum. In the 63–65 HRc range, maximum wear resistance and compressive strength are achieved.

Figure 97.3 compares the wear resistance of A11 with other tool steels in laboratory crossed-cylinder wear tests. Figure 97.4 illustrates the impact toughness of A11 vs D2 and M2, showing they are comparable at similar hardnesses.

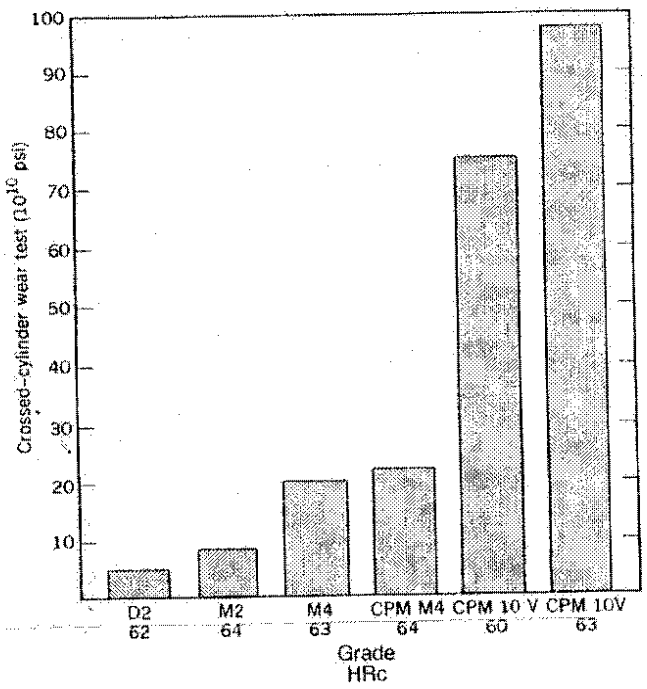


Figure 97.3. Wear resistance: A11 vs other tool steels.

air, a fluid uniform flow from electric fans is often used to speed up the cooling action.

S7. S7 is a chrome, molybdenum tool steel supplied in the annealed condition at about 200 BHN. It is usually used in the 52–56 Rockwell C hardness range. Larger sections more than 6 in. (152 mm) thick should be given an interrupted oil quench and tempered immediately to the temperature producing the desired hardness. This should be done when the block becomes warm to the touch. S7 offers the combination of high shock resistance and toughness usually required in compression and automatic molding operations.

H13. H13 is a popular mold steel furnished in the annealed condition at about 210 BHN that must be heat treated after the mold is rough machined. This steel offers heat treatable hardnesses up to 53 HRc. It is often substituted for P20 in applications requiring higher hardness and better strength, such as compression molding. H13 resists softening at higher temperatures; its good heat check resistance is often useful in thermoset molding. To retard washing, high wear resistance applications can be handled by gas nitriding after finish grinding and polishing. Gas nitriding for 10 to 12 hours at 950°F (510°C) results in a case depth between 0.004 and 0.005 in. (0.10 to 0.13 mm) with a surface hardness of 65–70 HRc.

H13 is used for injection, compression, and transfer molds of intermediate hardness requiring good dimensional stability during heat treatment. H13 affords excellent polishability, which makes it a good candidate for lens mold applications.

A2. A2 is another air-hardening tool steel supplied in the annealed condition at 220 BHN. It can be heat treated to 60 HRc, making it suitable for compression molding and molding abrasive engineering resins. It is usually not available in large sections and is used for smaller molds. A2 has good dimensional stability during heat treatment, good toughness, fairly high abrasion resistance, and can be polished to an excellent finish. This makes A2 a good choice for smaller molds having complicated design.

A6. A6 is selected where high strength, good wear resistance, and good toughness are essential. It is supplied annealed at 220 BHN and requires a lower hardening temperature than A2, resulting in lower residual stresses and less chance of distortion in the furnished die. It can be hardened to 60 HRc and has excellent polishability at this maximum hardness range. It is used in injection, compression, and transfer molds.

D2. D2 is supplied annealed at around 235 BHN. It can be heat treated to a maximum of 62 HRc, at which it has low distortion and a high degree of safety. Its good abrasion resistance is important for molding reinforced plastics, although it is not usually available in large sections. D2 is used in small injection and compression molds and can be used to insert molds in abrasive applications. In its heat-treated condition, care in grinding is necessary to prevent abuse and grinding cracks.

Particle Metallurgy High-vanadium Tool Steels. Included among the air-hardening tool steels are two particle metallurgy high-vanadium tool steels (CPM 10V and CPM 9V). In the stainless steels is a third particle metallurgy grade, CPM T440V. These three grades are finding increased usage in molds, injection screws, barrel liners, and molding parts in such severe wear applications as glass-filled engineering resins.

The wear resistant properties in tool steels derive from both the heat treated hardness and the combination of hard, abrasion-resistant carbides in the microstructure. Of the carbides that are formed in most tool steels, vanadium carbides are the hardest and most wear-resistant. The others (in decreasing order) are tungsten, molybdenum, chromium, and iron carbides. Steels made with high vanadium levels do not represent a new developoment, but, in the past, they have had little success because of the size of the vanadium carbides

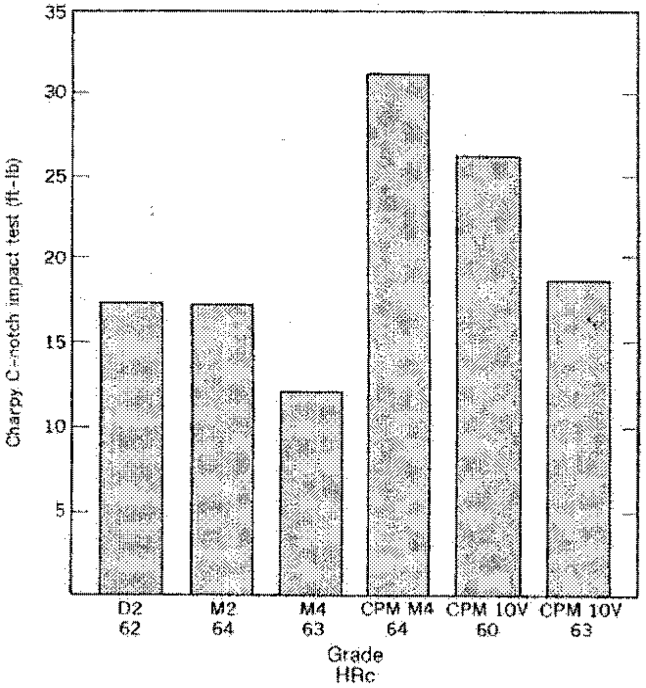


Figure 97.4. Toughness of All vs D2 and M2.

A11 is used for inserts in molds running glass-filled resins and other engineering plastics, where mold wear is a problem. It is employed in injection-molding equipment in screws, barrel liners, nozzles, nonreturnable check, rings, granulator/pelletizer blades, and other high-wear parts.

CPM 9V. CPM 9V is a high-vanadium tool steel whose chemistry is patterned after CPM 10V, although with less vanadium (9%) and carbon, to produce a high wearing tough tool. It is supplied in the annealed condition at about 240 BHN and can be heat treated to a maximum of 57 HRc. Normal application hardness range is 53–55 HRc. At this hardness, its wear properties are roughly half those of CPM 10V at 60 HRc but almost 10 times that of D2 at 62 HRc (see Figure 97.5).

Figure 97.6 displays another advantage of CPM 9V, its superior toughness as compared to A2, D2, and CPM 10V.

Although CPM 9V is fairly new grade to the plastics industry, it is expected to have a significant impact in tooling applications where heat check resistance, good toughness, and wear resistance are required.

97.2.3 Stainless Mold Steels

Stainless steels are selected for molds because of their corrosion resistance to PVC and other corrosive resins. Stainless molds will not corrode in the water lines or in storage between production runs. They eliminate the need to chrome plate and all the problems associated with stripping and rechrome plating. As a group, their polishability is excellent especially at higher hardnesses, which makes them ideally [illegible]

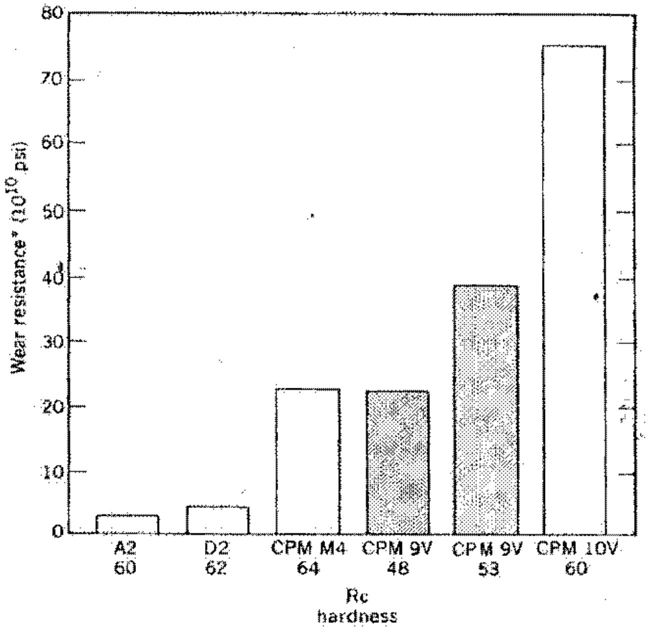
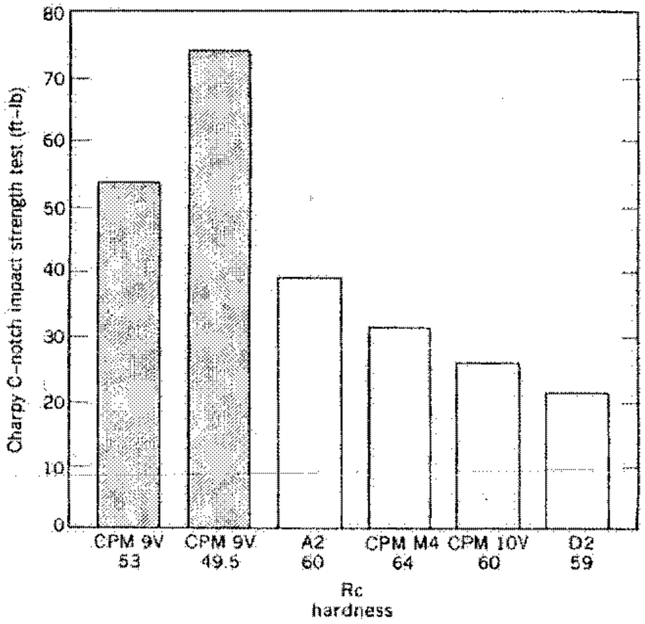


Figure 97.5. Wear resistance: CPM 9V.



T420. T420 is a popular stainless mold steel furnished in the annealed condition at about 215 BHN for molds for all plastics. It can be readily machined in the annealed condition and has good dimensional stability in heat treatment. T420 can be heat treated to a maximum of 53 HRc. It is used frequently to eliminate corrosion problems associated with rusting water lines and mold surface pitting caused by condensation in operation or storage. T420 can be selected for injection, compression, and transfer molds used for PVC or other corrosive resins. It is also chosen for lens and glass molds because of its polishability.

T440C. T440C is another stainless steel selected for plastic mold applications and supplied in the annealed condition at 230 BHN. It can be hardened to the 60 HRc range, which results in higher strength and abrasion resistance than T420 but slightly lower corrosion resistance. This relates to its higher carbon content, forming more chromium carbides, which reduces the chromium remaining in solution. The result is slightly lower corrosion resistance than T420. T440C is used for smaller compression and injection molds.

CPM T440V. CPM T440V is the stainless version of the CPM high-vanadium tool steels. Its chemistry is patterned after T440C with almost 6% vanadium added for wear resistance. It is supplied in the annealed condition at about 260 BHN. Small molds and machinery parts that process corrosive, abrasive resins are excellent applications for CPM T440V. This grade can be heat treated to a maximum of 62 HRc, with recommended usage in the 58–60 HRc range. Typical applications include injection screws, bushings, nonreturn check ring valves, pelletizer blades, and mold inserts.

97.2.4 Oil Hardening Tool Steels

Oil hardening tool steels have substantial amounts of manganese and other alloys, which permit these steels to be hardened in oil. There is no case condition on these steels as there is in water hardening grades, and they will harden all the way through, even in relatively large sections (up to 2.5 in. (64 mm) round].

O1. O1 is supplied in the annealed condition at about 200 BHN. It can be heat treated to high hardnesses (61–63 HRc) and is used primarily for smaller molds or mold inserts where strength is a consideration over toughness. This steel may be hardened from fairly low temperatures with minimal size changes. O1 is considered a general-purpose tool steel used for injection, compression, and transfer molds.

97.3 HEAT TREATMENT

Molds are heat treated to produce combinations of strength, wear resistance, and toughness in the particular grade of steel selected so that it will perform in a specific way. (This applies to nitrided and carburized cases as well as the deep and through hardening grades.) Table 97.4 shows the annealing, hardening, and tempering temperatures with the expected results of heat treatment. Although heat treating represents a relatively small cost to a mold tooling project, if it is improperly done catastrophic failures can result. Before reviewing the actual steps in heat treating, two areas of concern must be identified—stress relieving and the furnace atmosphere.

97.3.1 Stress Relieving

Most mold steels are supplied in the annealed condition and are relatively low in residual stresses. Severe machining operations, such as hogging out a cavity or cutting, cause these

TABLE 97.4. Tool Steel Heat Treatment for Plastic Mold Steels

Steel	Annealing Temperature, °F (°C)	Hardness Annealed, BHN	Hardening Temperature, °F (°C)	Quenching Medium	Tempering Temperatures, °F (°C)	Hardness Heat-Treated R_c
P20	1425–1450 (774–788)	180–210	1500–1550 (815–843)	Oil	1075–1150 (579–621)	30–36
4140	1550–1600 (843–871)	180–210	1550–1600 (843–871)	Oil	1100–1200 (593–649)	29–34
T414	1200–1300 (649–704)	210–230	1475–1550 (802–843)	Air	700–750 (371–399)	28–30
S-7	1500–1550 (815–843)	182–223	1725–1750 (940–954)	Air or air/oil	500–700 (260–371)	52–56
H-13	1575–1625 (857–885)	192–235	1800–1850 (982–1010)	Air	1000–1100 (538–593)	46–52
A-2	1550–1600 (843–871)	207–235	1750–1800 (954–982)	Air or air/oil	400–650 (204–343)	58–62
A-6	1400–1425 (760–774)	210–230	1500–1625 (815–885)	Air	400–600 (204–316)	55–59
D-2	1600–1650 (871–899)	217–255	1825–1875 (996–1024)	Air or air/oil	900–1000 (482–538)	54–60
CPM 10V	1600–1650 (871–899)	248–269	1950–2150 (1066–1177)	Air, salt or air/oil	1000–1025 (532–552)	58–65
CPM 9V	1625–1650 (885–899)	223–255	1850–2100 (1010–1149)	Air, salt or air/oil	1000–1100 (538–593)	46–57
T420	1550–1650 (843–899)	192–241	1800–1900 (982–1038)	Air or air/oil	400–750 (204–399)	48–54
T440C	1550–1650 (843–899)	190–215	1850–1900 (1010–1038)	Air or air/oil	300–500 (149–260)	55–58
CPM T440V	1625–1650 (885–899)	240–260	1850–2050 (1010–1121)	Air, salt or air/oil	300–500 (149–260)	52–62
O1	1400–1440 (760–782)	183–212	1450–1500 (788–815)	Oil	350–450 (177–232)	58–63

After such severe machining operations, stress relieving is recommended to reduce the residual stresses and thereby keep the distortion during heat treatment to the level planned. If a deep cavity is being formed in a piece of mold steel, stress relieving is recommended after 80–90% of the material has been removed.

A mold should also be stress relieved after finishing, especially if this has involved much of grinding and polishing, to reduce the residual stress level of the mold going into service. Intermittent stress relieving can prevent premature cracking of a mold after a certain number of parts have been produced. For example, it can be done after a mold is taken out of service and is waiting for the next customer order. Stress relieving for annealed material should be done at 1200–1300°F (649–704°C) and held at this temperature for as many hours as the largest inch-thickness (25 mm) dimension. For example, a mold 5 in. (127 mm) thick should be held at this temperature for five hours and then air cooled. Prehardened or hardened material should be heated to 50–100°F (10–38°C) below the last tempering temperature and held at this temperature for an appropriate time before air cooling. If the stress relieving is done above the tempering temperatures, there will be a reduction in the hardness of the mold and some dimensional changes.

97.3.2 Furnace Atmospheres

these stages, it is important to consider design and mass; these two factors determine the important relationship of time and temperature. Furnace atmospheres used in the heat treatment process must also be considered because of decarburization.

Decarburization occurs on steel surfaces heated above 1300°F (704°C) in oxidizing atmospheres and results in the loss of carbon on these surfaces. Carbon loss actually results in a two-toned steel, with a lower carbon outside area covering the desired inner composition. When this happens, a softer working surface is produced that usually leads to poor tool performance. Some tool steels have a greater tendency to decarburize than others, but those with higher carbon contents are more susceptible to this phenomenon.

To prevent decarburization, the furnace atmosphere can be an inert gas, a high-temperature salt bath, or no atmosphere (vacuum).

97.3.3 Preheating

Preheating is the first step in the heat-treatment process. It serves a number of purposes including minimizing decarburization, avoiding heavy scaling, and relieving stress caused by cold working. Preheating allows more uniform heating between the surface and the center of the mold because it equalizes the mold temperature before the mold is exposed to the high heat furnace. The preheat temperature varies with each grade but is generally above 1000°F (538°C) and seldom over 1600°F (871°C).

In large or complicated molds two preheats are recommended to reduce temperature differentials and thermal stress gradients.

97.3.4 High Heat

The high heat cycle is the most important step because during it the final conditioning of the steel is accomplished. Both the temperature and the time must be carefully monitored. Excessive temperature or time will cause grain coarsening and decarburization. Low temperatures or short times bring about inadequate solution of carbides or nonuniform structural conditions.

The high-heat time period is called the soak. The proper soak ensures that the entire section is thoroughly heated and that the steel will respond to the heat treatment in a uniform manner. Soak times depend on the grade of steel and the overall size of the piece being heat treated. Good operators know their furnace capabilities and make adjustments to make certain that the actual steel temperature is proper for the heat treatment of that grade.

97.3.5 Quenching

After austenitizing, the mold is quenched. During the quench, the actual hardening of the steel takes place. Different compositions of steels require different cooling rates to achieve full hardness. The decision to use a particular quenching medium is based on its ability to remove heat at the rate required by the particular steel and the mass of the section. The ideal medium will reduce the temperature quickly at first and then more slowly to accommodate the stresses, which develop in the lower temperature range, from hardening.

97.3.6 Tempering

Tempering is performed after the quench and involves a precisely controlled time–temperature relationship. Furthermore, control of the time between the quench and tempering is most vital. Since hardening takes place gradually at the end of the quench cycle, tempering too soon interrupts proper cooling and puts a stop to further hardening. In large sections with a significant temperature gradient, cracking may occur, the stresses from hardening continue to build up to a point where rupture may occur. The general rule is to begin tempering as soon as the work can be held with the bare hands [between 125 and 150°F (52 and 66°C)].

The usual temperature range for tempering extends from 300 to 1200°F (149–649°C), depending on the grade and the hardness desired. At a minimum, the time period should be two hours; usually, an hour per inch (25 mm) at the smallest cross section.

97.4 SURFACE TREATMENT

There are several surface treatments used to prepare the mold surface for the final ordered part. These include polishing, electrical discharge machining (EDM), texturing (photoetching), and plating/coating.

97.4.1 Polishing

Polishing is the oldest and still most widely used technique for finishing the required surfaces. In most molds, a certain amount of polishing is required, even if other finishes are applied through texturing and plating. In general, the harder the steel surface is, the easier it is to bring it up to the required polished surface. The prehardened steel P20 and stainless steel T414 have excellent polishability and are used for lens mold applications. Occasionally orange peel or pitting problems are associated with these softer steels, but care in polishing can prevent this phenomenon. With certain grades, experience is the best guide in attaining the desired surface finish. In general, it is important to go slow; not use mechanical polishers; not skip any steps—through the paper grits, stones, and diamond polish; and avoid extreme pressures.

Orange peel and/or pitting can occur on any steel and usually appears as the surface is brought up with the diamond compounds to a mirror finish. These problems occur when the yield/tensile strength of the surface is exceeded. When this happens, the surface moves and actual pieces of the matrix are pulled out, causing pits. To correct this condition, the affected area must be stoned off to remove the pits, with the last stone before diamond polishing, stress relieving, and restoning making sure not to skip any steps. Hand polishing is recommended at light pressures.

97.4.2 Electrical Discharge Machining (EDM)

EDM can produce surface quality equal or better to that obtained with conventional machining. EDM often eliminates the need for secondary finishing operations. In the EDM operation, the EDM pulse actually melts away the surface of the steel being contacted by the spark. The recast "white" layer, which remains on the surface, contains brittle, untempered martensite. The newer generation of EDM pulse-generated power supplies reduces this white layer to less than 0.0005 in. (0.0127 mm). It is always a good idea to remove this white layer with subsequent stoning and polishing. If this layer is not removed, the work piece should be at least stress relieved.

97.4.3 Texturing

Texturing or photoetching is performed to give the surface of the molded part a different look. These different surfaces are made to look like leather, wood grain, and other common materials simulated by plastics. Most steels used for molds can be textured. Steels high in nickel are more difficult to etch because nickel resists acids used in the etching process. The stainless steels, which are high in chrome (12–15%), are etched successfully using different in these applications. PVC materials generate corrosion of molds and molding equipment. Stainless grades are chosen in these molding applications to resist corrosion.

Certain pressures in the molding process, as in injection and compression molding, require higher strength tool steels. Operating temperatures and designed cycle times must be considered by the tool designer to evaluate the steel's heat check resistance and thermal conductivity. Heat treatment and surface treatment are other important decisions made by the mold designer to ensure that the tool lasts for the entire anticipated production schedule.

All these factors influence the life of a mold tool. A successful tool design achieves an intricate balance of the desired part design and material, the mold steel capabilities, and die making techniques.

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The following simple precautions should be used when selecting a steel for molds to be textured:

- Use a good mold steel.
- Use the same steel for all components of the mold for uniform chemistry.
- Avoid nonuniform machining stresses.
- When welding, use welding rods of the same chemistry as the mold.
- Retemper thoroughly after welding heat treated molds.

The key word in successful texturing of molds is uniformity. The steel selected should be as alike as possible in all characteristics. Ideally, the steel for all molds in a family should be made from the same steel bar with the steel cut so that the grain runs in the same direction. The same processing methods and tools should be used on all molds when matching texture is desired.

97.4.4 Plating/Coating

Molds are given many plating or coating treatments to increase wear and corrosion resistance and aid in reducing release problems. There is no one plating or coating treatment that solves all these problems. The molder must decide which problem is causing the greatest loss in production and choose the plating or coating treatment designed to help solve that problem.

The following chart lists the plating or coating treatments for steels used for plastic molds and the reasons for choosing this treatment.

Plating or Coating Treatment	Purpose
Hard chrome	Reduce wear and corrosion.
Nickel (electroless and electrolyte)	Resist corrosion, improve wear; used to build up worn or undersized molds.
Nitriding	Increases surface hardness for increased wear, adds some corrosion resistance, and aids in polishing.
TiN (titanium nitride)	Increases surface hardness for increased wear and lubricity for faster part removal.
Ion implantation	Increases surface hardness for increased wear, adds some corrosion resistance, and improves mold-release characteristics.

97.5 INDUSTRY PRACTICES

When tool steels are selected for plastic molding, the mold designer must analyze all the requirements associated with each mold before choosing the steel with the best combination of properties.

Glass-filled or fiber-reinforced resins cause abrasion of the mold surface and wear feed customized for cost-effective adaptation to specific application requirements. Unlike thermosets, they are in most cases reprocessable without serious losses of properties.

But they do have limitations of heat-distortion temperatures, cold flow and creep, and are more likely to be damaged by chemical solvent attack from paints, glues, and cleaners. When injection-molded, dimensional integrity and ultimate strength are more dependent on sound tool and part design and molding parameters than is generally the case with thermosets (where cross-linking of the polymer chains tends to offset such problems). Common thermoplastics include the following:

Acrylonitrile–Butadiene–Styrene. (ABS) is a terpolymer that provides a tough, hard, rigid plastic with adequate chemical, electrical and weathering characteristics, low water absorption, and resistance to hot-and-cold water cycles. Used for telephones, sports gear, automotive grilles, electronic instrument housings and furniture. It is electro-platable, good as a structural foam, and available as a tinted transparent.

Acetal. This crystalline polymer (and copolymer) is strong, stiff, and has exceptional resistance to abrasion, heat, chemicals, creep and fatigue. With a low coefficient of surface friction, it is especially useful for mechanical parts such as gears, pawls, latches, cams, cranks, plumbing parts, etc. It is chrome platable.

Acrylic. High optical clarity, the best weatherability, broadest color range and hardest surface of any untreated thermoplastic. Chemical, thermal and impact properties are good to fair. Normally an exterior material, used as optical lenses, automotive taillights, decorative nameplates, aircraft glazing, illuminated signs, medical devices, etc. A new use is as opaque colored sheeting thermoformed to produce an outer coating behind which glass-fiber-reinforced polyester resins are sprayed to produce camper tops, swimming-pool steps, plumbing fixtures with weatherability and repairability reported superior to polyester gel coats.

Cellulosics. Cellulosics are tough, transparent, hard or flexible polymers made from plant cellulose feedstock. With exposure to light, heat, weather and aging, they tend to dry out, deform, embrittle and lose gloss. Molding applications include: tool handles, control knobs, eyeglass frames. Extrusion uses: blister packaging, toys, holiday decorations, etc.

Fluoroplastics. Fluoroplastics have superior heat and chemical resistance, excellent electrical properties, but only moderate strength. Variations include PTFE, FEP, PFA, CTFE, ECTFE, ETFE, and PVDF. Used for bearings, valves, pumps handling concentrated corrosive chemicals, skillet linings, and as a film over textile webs for inflatables such as blimps and pneumatic sheds. Excellent human-tissue compatibility allows its use for implants.

Nylon (Polyamide). Nylon is a crystalline plastic and the first engineering-grade thermoplastic. Tough, slippery, with good electrical properties, but hygroscopic and with dimensional stability lower than most other engineering types. Also offered in reinforced and filled grades as a moderately priced metal replacement.

Phenylene Oxide-Based (PPO) Resin. This is one of the top choices for electrical applications, housings for computers and appliances, both neat and in structural foam form. It has superior dimensional stability, moisture resistance due to styrene components, which, however, cause some sacrifice of weather and chemical resistance. Used for automobile wheel covers, pool plumbing, consumer electronic external and internal components.

Polycarbonate. Polycarbonate is a tough, transparent plastic that offers resistance to bullets and thrown projectiles in glazing for vehicles, buildings, and security installations. It with- sensitive and has poor solvent resistance in stressed, molded parts and is used in coffeemakers, food blenders, automobile lenses, safety helmets, lenses, and many nonburning electrical applications.

Polyesters, Thermoplastics. Poly(butylene terephthalate) (PBT) is a crystalline polymer and an excellent engineering material. It has marginal chemical resistance but resists moisture, creep, fire, fats, and oils. Molded items are hard, bright colored, and retain impact strength at temperatures as low as −40°F (−40°C). Uses include auto louvres, under-the-hood electricals, and mechanical parts. Poly(ethylene terephthalate) (PET) an amorphous polymer is available in an engineering grade, but is most widely used in beverage bottles.

Polyarylate. Polyarylate is a form of aromatic polyester (amorphous) exhibiting an excellent balance of properties, stiffness, UV resistance, combustion resistance, high heat-distortion temperature, low notch sensitivity, and good electrical insulating values. It is used for solar glazing, safety equipment, electrical hardware, transportation components and in the construction industry.

Polyethylene. This is the leading plastics family in total volume sold. Materials are inexpensive, easy to process and so versatile that they dominate the packaging and disposables fields. Crystalline in structure, they are varied by chain length, or molecular weight into low density (LDPE), linear low density (LLDPE), medium density (MDPE), high density (HDPE) and ultra high density (UHMWPE). Strong and flexible, though not transparent, they are very highly chemical resistant and difficult to cement or paint. They are blow molded into containers and bottles and molded into boxes, buckets, etc, which may be susceptible to stress cracking near the gates if care is not exercised. They are extruded for films, trash bags, and laminated coatings.

Polybutylene. Polybutylene is a polyolefin used for cold and hot water piping. As a blown film it is used for food packaging.

Polyetherimide. This is an engineering-grade amorphous thermoplastic polymer. It has superior strength, heat resistance, flame resistance, UV resistance and is transparent, although of amber brown color. Solvent resistance is especially good against aircraft grade fuels and lubricants, but it is attacked by methylene chloride and trichloroethane. Resistance to creep at lower stress loadings and good retention of strength at sustained high levels of heat are claimed to exceed those of other high performance engineering thermoplastics. Applications include printed circuit boards, heater housings, electrical components, steam sterilizable disposable and reusable parts.

Polyetheretherketone (PEEK). This is a high-temperature, crystalline thermoplastic used for high performance applications such as wire and cable for aerospace applications, military hardware, oil wells and nuclear plants. It holds up well under continuous 450°F (323°C) temperatures with excursions up to 600°F (316°C). Fire resistance rating is UL 94 V-0; it resists abrasion and long-term mechanical loads.

Polyimide. Polyimide is a high-cost heat and fire resistant polymer, capable of withstanding 500°F (260°C) for long periods and up to 900°F (482°C) for limited periods, without oxidation. It is highly creep resistant with good low friction properties. It has a low coefficient of expansion and is difficult to process by conventional means. It is used for critical engineering parts in aerospace, automotive and electronics components subject to high heat, and in corrosive environments. A racing engine with mostly polyimide parts has exceeded 15000 RPM without failure!

Polyphenylene Sulfide (PPS). PPS is able to resist 450°F (232°C), and has good low-temperature strength as well. It has low warpage, good dimensional stability, low mold shrinkage. Used for hair dryers, cooking appliances, and critical under-the-hood automotive and military parts.

Polypropylene. One of the high volume plastics has superior resistance to flexural fatigue stress cracking, with excellent electrical and chemical properties. This versatile polyolefin overcomes poor low temperature performance and other shortcomings through copolymer, filler, and fiber additions. It is widely used in packaging (film and rigid), and in automobile interiors, under-the-hood and underbody applications, dishwashers, pumps, agitators, tubs, filters for laundry appliances and sterilizable medical components.

Polystyrene. One of the high volume plastics, is low in cost, easy to process, has sparkling clarity, and low water absorption. But basic form (crystal PS) is brittle, with low heat and chemical resistance, poor weather resistance. High impact polystyrene is made with butadiene modifiers; provides improvements in impact strength and elongation over crystal polystyrene, accompanied by a loss of transparency and little other property improvement. A styrene–acrylonitrile (SAN) copolymer gains somewhat in strength and chemical and heat resistance. SAN is used for tinted drinking glasses, low-cost blender jars and water pitchers, and other consumer goods with longer life expectancies than ordinary PS.

Styrene Maleic Anhydride (SMA). SMA is a copolymer made with or without rubber modifiers. They are sometimes alloyed with ABS and offer good heat resistance, high impact strength and gloss but with little appreciable improvement in weatherability or chemical resistance over other styrene based plastics.

Expandable Polystyrene Beads (EPS). This is a modified PS prepared as small beads which, when steamed, expand to form lightweight, cohesive masses for forms used to pack fragile products for shipment. Similar dimensionally stable forms molded from EPS are used as cores for such products as automobile sun visors with surface overlays.

Polysulfone. Polysulfone is a high performance amorphous resin that is tough, highly heat resistant, strong and stiff. Parts are transparent and slightly clouded amber in color. Material exhibits notch sensitivity and is attacked by ketones, esters, and aromatic hydrocarbons. Other similar types in this group include polyethersulfone, polyphenylsulfone, and polyarylsulfone. They are used for medical equipment, solar-heating applications and other performance applications where flame retardance, autoclavability and transparency are needed.

Polyurethane, Thermoplastic (TPU). TPU has excellent properties except for heat resistance (only up to 250°F 121°C). TPU is used in alloys with ABS or PVC for property enhancement. Typical uses are in automobile fascias and exterior body parts, tubing, cord, shoe soles, ski boots and other oil and wear resistant products.

Poly(vinyl chloride) (PVC). PVC is a high-volume plastic that is low in cost, with moderate heat resistance and good chemical, weather and flame resistance. It qualifies for packaging, pipe and outdoor construction products (siding, window profiles, pipe) and a host of low-cost disposable products (including FDA-grade medical uses in blood transfusion and storage). PVC comes in a variety of grades, flexible to rigid. They are tough, can be transparent (as in blow-molded bottles and jugs), and are also a good alloying resin to improve properties and reduce costs (ABS/PVC).

106.4 POLYMER MODIFICATION

If plastics material selection required merely the choice of polymer type, blends, alloys and multipolymers, the task of wise selection would be challenging enough, but modifiers must also be considered. Modifiers consist of a broad spectrum of additives, fillers and reinforcers. The combinations that can be specified and the percentage of each addition must be carefully controlled to avoid processing problems and the loss of important physical, chemical or thermal properties. All of the possible combinations result quite literally in a quantum leap in variables.

To give some idea of the complexity designers face, additives can be such things as antioxidants, antistatic agents, biocides, colorants, coupling agents, emulsifiers, flame retardants, foaming agents, fungicides, heat and light stabilizers, lubricants, mold-release agents, organic peroxides, plasticizers, preservatives, processing aids, slip agents smoke suppressants, viscosity depressants, and more.

Fillers include calcium carbonate, talc, kaolinite, alumina trihydrate, feldspar, silica, solid glass microspheres, hollow glass microspheres, agriculture by-products (such as rice hulls, corn starch, sawdust, and corn cobs), mica flake, carbon, metal powders, metal flake and wollastonite (a high aspect ratio mineral particulate). Fiber reinforcers include aramid, carbon, boron, glass (E type, C type, S type), hybrids (aramid/carbon, aramid/glass, carbon/glass), synthetic fibers, and plant fibers.

106.5 PROCESS SELECTION

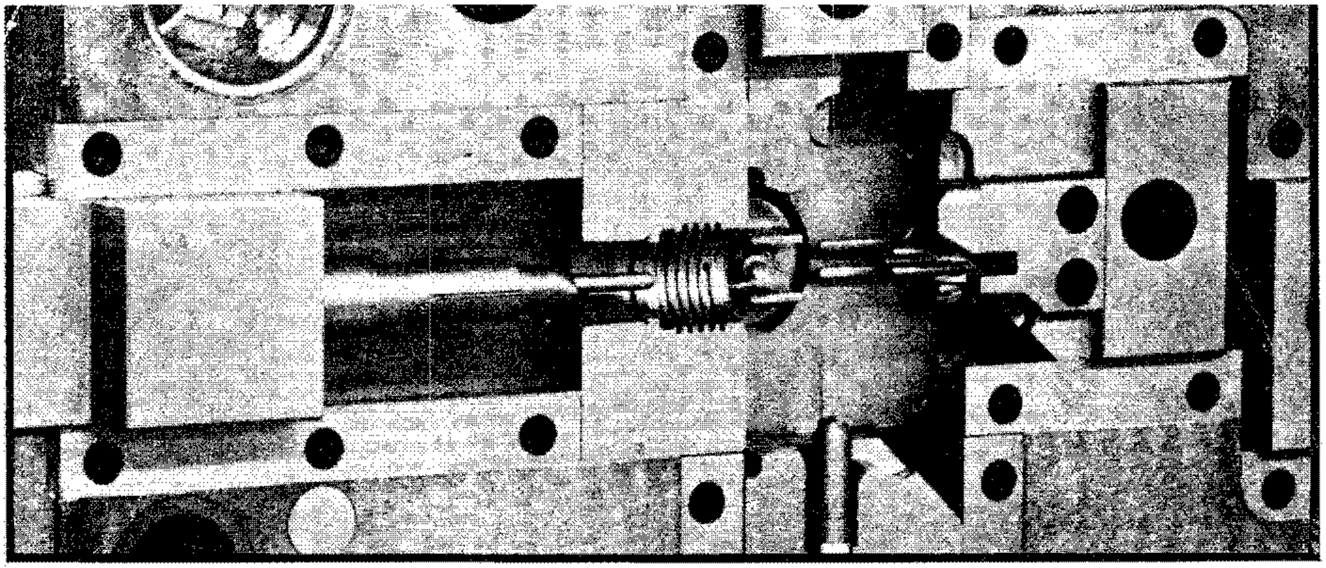
Selection of the processing method should take place in the early stages of the design process, not after the design is nearly complete. Such an obvious axiom may seem superfluous, but unfortunately process selection is frequently an afterthought. It is as though most designs might be produced by nearly any process, which is not so.

The following brief descriptions of the capabilities and limitations the primary plastics processing techniques will be helpful in selecting the optimum manufacturing technique. See the sections in this Handbook on Processing, for more information.

Compression Molding. For thermoset plastics, partially polymerized preforms, pellets or liquids are placed in heated molds usually operated in vertical presses. The application of heat and pressure, as the mating steel molds close, melts and then cures the resin. The volume of the charges must be carefully measured to avoid short shots that will result in voids, or excess thickness with unacceptable flash around the parting line (like carelessly-poured waffles). Some thermoplastics are compression molded; for example, vinyl phonograph records. Transfer molding is a variant of this process. When fibrous glass preforms are inserted prior to application of the resin, the process may be called matched metal die molding.

Extrusion. Thermoplastic pellets are gravity-fed from a hopper into a heated barrel and propelled forward by a rotating screw, where melt occurs. The molten extrudate is forced through a steel die, cooled rapidly and rolled (flexible tubing, film), or cut to lengths and stacked (profiles, pipe, sheet). The process is continuous. If optically specular surfaces are called for, surface striation lines can be press polished with rollers. If textures like woodgrain or prismatic lens patterns are specified, these can be achieved with engraved rolls as the hot extrudate leaves the die. Die costs are relatively low, but long production runs are usually necessary to justify special shapes, colors or materials. Two or more colors or materials can

ASSAB	STAVAX S136	420,電渣重溶	退火至約HB 215	0.38	0.8	13.6	-	0.5	-	0.3	-	高純度、高鏡面度，拋光性能好，抗銹防酸能力極佳，熱處理變形少	1025	油、氣冷	54	53	-
	STAVAX S136H		預硬至HB 290-330										預加硬，毋須淬火				
	OPTIMAX	420(光學級鏡面鋼)	退火至約HB 215	0.38	0.8	13.6	-	0.5	-	0.3	-	極高純潔度及鏡面度，抗銹防酸能力極佳，熱處理變形少	1025	油、氣冷	54	53	-
	CORRAX S336	特殊時效不銹鋼	固溶處理至約32HRC	0.03	0.3	12.0	9.2	0.3	1.4	-	-	抗腐蝕性極佳，通過簡單的時效處理，硬度可提升至50HRC而尺寸穩定，焊接性能良好	在攝氏425、600度的範圍內進行時效處理，可硬化至32、50HRC				
	ORVAR 8407	H13,電渣重溶改良型	退火至約HB 185	0.38	1.0	5.3	-	0.4	1.3	0.9	-	熱模鋼，高韌性及耐熱性能良好	1020	油、氣冷	-	52	52
	ARNE DF2	O1	退火至約HB 190	0.95	-	0.6	-	1.1	-	0.1	0.6	微變形油鋼，耐磨	820	油冷	61	60	57
	XW 42	D2	退火至約HB 210	1.42	0.3	11.2	-	0.4	0.8	0.2	-	韌性高鉻鋼，耐磨性佳，高抗壓強度	1020	油、氣冷	63	62	60
	VANADIS 10	特殊成份粉末鋼	退火至約HB 280-310	2.9	1.0	8.0	-	0.5	1.5	9.8	-	極高的耐磨性，淬火後保持高的表面硬度，抗壓強度及尺寸穩定	1020	氣冷	-	62	62
	CALMAX 635	高耐磨多功能模具	退火至約HB 200	0.6	0.35	4.5	-	0.8	0.5	0.2	-	極佳的韌性及耐磨性，淬透及焊接性好，可火焰硬化至HRC56-60，淬硬層達5mm厚	960	氣冷	60	58	55
DAIDO	**日本大同特殊鋼**																
	PX88	P20,改良型	預硬至HB 290-330	專利合金成份待公佈								以焊接裂開敏感性低的合金成份設計，大幅度改善焊接性能	預加硬，毋須淬火				
	NAK55	P21加硫,電渣重溶改良型	預硬至HB 370-400	0.15	0.3	-	3.0	1.5	0.3	-	-	高硬度，易切削，加厚焊接性良好					
	NAK80	P21,電渣重溶改良型	預硬至HB 370-400	為NAK55的鏡面性改善材料								高硬度，鏡面效果特佳，放電加工良好，焊接性能極佳					
	PAK90 (S-Star)	SUS420J2,電渣重溶改良型	預硬至HB 300-330	0.38	0.9	13.5	-	0.1	0.3	-	-	極佳的耐蝕、耐磨及高鏡面特性					
	GOA	SKS3改良型	退火至約HB 217	0.86	0.3	0.5	0.25	1.2	0.13	-	0.5	淬透性和耐磨性均良好的合金工具鋼	830	油冷	62	60	58
	DC11	SKD11	退火至約HB 255	1.6	0.4	13.0	0.5	0.6	1.2	0.5	-	優秀的耐磨高鉻工具鋼	1025	氣冷	62	60	58
LKM SPECIAL STEEL	**龍記優質進口特殊鋼材**																
	LKM 738	P20 加鎳	預硬至HB 290-330	0.37	-	2.0	1.0	1.1	0.4	-	-	優質預硬，硬度均勻易切削加工	預加硬，毋須淬火				
	LKM 738H		預硬至HB 330-370														
	LKM 2311	P20	預硬至HB 280-325	0.37	-	1.9	-	1.45	0.2	-	-	預硬塑膠模具鋼					
	LKM 2312	P20, 加硫	預硬至HB 280-325	0.37	-	1.9	-	1.45	0.2	-	-	極易切削，適宜大批量快速加工					
	LKM 638	P20	預硬至HB 270-300	專利合金成份待公佈								加工性能良好					
	LKM 2711	P20, 特級版	預硬至HB 315-360	0.55	-	0.7	1.7	0.8	0.25	-	-	高硬度及高韌性					
	LKM 2083	420	退火至HB 215-240	0.43	-	13.0	-	0.3	適量	-	-	可加硬至約 HRC52，防酸及拋光性能良好	1020	油、氣冷	56	56	55
	LKM 2083H		預硬至HB 280-310									預加硬，防酸及拋光性能良好	預加硬，毋須淬火				
	LKM 2316A	SUS 420 J2	退火至HB 230(最高)	0.4	-	16.0	適量	0.5	1.0	-	-	可加硬至約 HRC47，抗腐蝕性效果特佳	1010	油、氣冷	47	46	45
	LKM 2316		預硬至HB 265-310									預加硬，抗腐蝕性效果特佳	預加硬，毋須淬火				
	LKM 2316 ESR	SUS 420 J2, 電渣重溶	預硬至HB 265-310	0.4	-	16.0	適量	0.6	1.2	-	-	鋼質精純，適合於高光潔度的模具，抗腐蝕性效果特佳					
	LKM 2344	H13	退火至HB 180-210	0.38	1.0	5.0	-	0.4	1.3	1.0	-	耐熱特佳，用於壓鑄模具鋼	1030	油、氣冷	-	51	51
	LKM 2344 Super	H13, 電渣重溶(改良型)	退火至HB 180-220									高韌性熱模鋼，抗衝擊強度優於300J	1030	油、氣冷	-	51	51
	LKM 2510	O1	退火至約HB 230	0.93	-	0.6	-	1.1	-	0.1	0.6	淬透性和耐磨性良好	820	油冷	62	60	56
	LKM 2379	D2	退火至約HB 255	1.55	-	12.0	-	-	0.7	1.0	-	高韌性鉻鋼	1020	油、氣冷	62	61	59
	LKM 2767	6F7(高韌性多功能鋼)	退火至HB 262(最高)	0.45	-	1.4	4.1	-	0.3	-	-	極佳的韌性及沖壓能力，可淬硬至約HRC50-54	840	油、氣冷	57	56	54
	日本三菱優質模具用鋼																
	MUP	P20	預硬至HB 270-320	0.34	0.8	1.8	0.5	0.5	0.4	-	-	硬度良好，耐磨性高，加工性能良好，適合電蝕加工	預加硬，毋須淬火				
Sambo	**日本三寶EDM電蝕純紅銅**																
	C1100P	JIS H3100		Cu 銅 99.95								高純度，導電性能特佳，容易加工，變形度低	-	-	-	-	-
SINO	**日本新東透氣鋼**																
	Porcerax II PM-35	特殊燒結粉末鋼	預硬至HV 350-400 (預硬至HRC 35-40)	0.012	0.07	16.5	1.2	0.17	1.9	-	-	優質預硬，具透氣功能，抗銹防酸能力極佳，易切削，放電加工性能良好	預加硬，毋須淬火				
BRUSH	**美國 BRUSH WELLMAN 模具合金鈹銅**																
	Moldmax 30 Moldmax 40	-	預硬至HRC 26-32 預硬至HRC 36-42	Be 鈹 1.9			Co 鈷 + Ni 鎳 0.25			Cu 銅 97.85		高強度合金鈹銅，優良導熱性，減少注塑的週期時間及散熱效果好	-	-	-	-	-
ALCOA	**美國 ALCOA 合金鋁**																
	6061-T6/651/6511	-	時效處理至HB 95	詳細化學成份分析可參考有關技術資料								高抗腐蝕鋁合金，優良的接合特點及電鍍性	-	-	-	-	-
ALUSUISSE	**瑞士 ALUSUISSE 高硬度鋁合金**																
	CERTAL 7022-T651	AlZnMgCu0.5	預硬至HB 145-170	詳細化學成份分析可參考有關技術資料								高強度、高硬度鋁合金，優良的加工性能	-	-	-	-	-
	精選特級黃牌鋼材																



This ejector half of a nylon valve mold utilizes at least five different materials of construction, each chosen for a specific purpose. Cavity, cores and slides are of H13 steel, a good all-around mold material. The cores, however, are nitrided to 70 RC hardness to prevent galling and wear against other metal parts. Core pins are of M2 high-speed steel, offering rigidity and high strength. Cavity and blade inserts are of 250 maraging steel, chosen for toughness and resistance to injection pressures. Slide heel blocks are of case-hardened carburized steel, which offers both a hard surface and easy machinability prior to hardening. In addition, a core insert is made of beryllium copper to provide a heat sink for extra cooling capacity.

What You Should Know About Mold Steels

In an age that demands high productivity in manufacturing, there is no substitute for high-quality molds in your injection or other molding process. Yet few mold buyers are as knowledgeable as they should be about the materials of which their molds are constructed. Given the wide variety of mold steels available today, proper selection must take into account more factors than just price or traditional practice. Here, then, is what one moldmaker thinks the mold buyer should know about today's mold steels, where they're used, and why. Following this general update on the subject, we've appended some comments from a tool steel supplier on how usage of mold steels is changing.

By Manfred Hoffmann, V.P. Manufacturing & Engineering, Caco-Pacific Div., Amerace Corp., Covina, Calif.

In a time of increasing competitiveness in the marketplace, and of increasing investment in high-production, automated molding systems, the importance of a knowledgeable mold buyer becomes greater than ever. In order to maximize the life expectancy and minimize operating expenses in the form of mold downtime and mold-repair costs, extreme care must be taken in the selection and proper combination of mold steels or special materials.

It is important that not only the moldmaker, but especially the mold buyer, understand what types are required to meet the needs of specific applications. Both parties must understand the influence of such factors as the plastic material to be processed, the number of parts expected from the tool, part surface finish requirements, and the mold design itself. A certain amount of extra up-front expense in selecting the right mold material can minimize the much greater potential cost of mold operating expenses. Those often unnecessary expenses cost American industries millions of dollars in molded parts production losses, and have a serious impact on productivity as well as world market competition.

Most mold buyers devote their attention to the number of cavities that are needed to meet the production requirements and to the total price and delivery time of a finished mold. Mold buyers are often far less concerned with superior mold-design features or with the best possible steel and material selections, both of which will increase the purchase price but will also dramatically decrease operating expenses over the life of a high-production mold.

Most reputable moldmakers will try to design and build the best possible mold at a competitive price. It is often hard to explain to a less knowledgeable mold buyer what a competitive price is, and under what conditions and why such "minor" details as proper steel selection can make a difference in the price and performance of the mold.

It may be even more difficult for the mold buyer to explain to his nontechnical supervisor how he can justify the higher price of a mold, unless the purchasing process includes very serious consideration of the life and performance of the mold as a long-term investment—which it is.

The knowledgeable mold buyer can easily correct this problem by educating himself or by consulting other experts in his organization or a reputable mold builder. The molder who has to live with a mold for sometimes 10 or 15 years, and who is responsible for the molded parts production, should most certainly have some input in establishing the needs and requirements for a new mold project.

The most important part of the mold purchasing process, however, is to develop and apply professional forms that call out special mold-design features as well as steel type, heat treatment and surface finish requirements. Sample forms of this type have been developed by the Moldmakers Div. of SPI, for example. The value of such forms is to provide a fair basis for quoting, thus preventing comparisons of apples and oranges, and generally guaranteeing a better quality mold.

While steel costs are generally considered to be a relatively small percentage of mold building expenses, the best possible selection of mold steels requires greater inventory, purchasing and heat-treating expenses on the part of the toolmaker, as well as increased cutting-tool and grinding costs. But over the lifetime of a high-pro-

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Comparison Chart for 12 Major Tool Steels and Beryllium Copper

			Point Ratings, 1 to 10 (10 Is Highest)[a]								
Type	AISI Designation	Recommended Hardness, Rockwell C[b]	Wear Resistance	Toughness	Compressive Str.	Hot Hardness	Corrosion Resistance	Thermal Conductivity	Hobbability	Machineability
Prehardened	4130/4140	30-36	2	8	4	3	1	5	1	5
	P-20	30-36	2	9	4	3	2	5	1	5
Prehardened Stainless	414 SS	30-35	3	9	4	3	7	2	1	4
	420 SS	30-35	3	9	4	3	6	2	1	4
Carburizing	P-5	59-61	8	6	6	5	2	3	9	10
	P-6	58-60	8	7	6	5	3	3	8	10
Oil Hardening	01	58-62	8	3	9	5	1	5	5	8
	06	58-60	8	4	8	5	1	5	7	10
Air Hardening	H-13	50-52	6	7	7	8	3	4	6	9
	S7	54-56	7	5	8	8	3	4	6	9
	A2	56-60	9	3	9	7	3	4	4	8
	A6	56-60	8	4	8	7	2	5	5	10
	A10	58-60	9	5	9	7	2	5	5	8
	D2	56-58	10	3	8	8	4	2	4	4
Stainless	420 SS	50-52	6	6	6	8	7	2	4	7
	440C SS	56-58	8	3	8	7	8	2	3	6
Maraging	250	50-52	5	10	6	7	4	3	4	4
	350	52-54	6	10	7	7	4	3	4	4
Maraging Stainless	455M	46-48	5	10	5	7	10	2	3	4
High-Speed	M2	60-62	10	2	10	10	3	3	2	4
	ASP 30[c]	64-66	10	4	10	10	4	3	1	4
Beryllium Copper	Be Cu	28-32	1-2	1	2	4	6	10	10	10

[a] The above points have been carefully awarded by manipulation and cross-reference of available technical data from various steel manufacturers, professional experience, and applicable formulas out of the Uddeholm Steel Grading Pamphlet. This chart is a general guide only, since steel manufacturing tolerances, machining procedures and heat-treating methods can have a detrimental effect on most steel properties. Most of the point ratings can vary substantially with changing Rockwell C hardness. [b] The recommended hardness is typically at least 2-4 RC points below maximum hardness, in order to increase toughness and minimize risk of cracking. [c] Trade name of Uddeholm Corp., Totowa, N.J. [d] NA = not applicable.

duction mold, the additional 5% or 10% in overall cost may prove to be the best investment of all. This becomes even more crucial in fully automatic molding operations when robots, pick-off devices, conveyors, and assembly machines are depending on a constant and uninterrupted flow of molded parts.

What are the demands on mold steels? In order to make the proper selection, one must understand the multiple demands that are placed upon mold steels, depending on the specific application. There are two major categories of demands on plastics tool steels, which together add up to 12 desirable qualities:

A. Molders' demands
  1) Wear resistance
  2) Toughness (impact strength)
  3) Compressive strength
  4) Hot hardness
  5) Corrosion resistance
  6) Thermal conductivity
B. Moldmakers' demands
  7) Hobbability
  8) Machinability
  9) Polishability
  10) Heat-treating dimensional stability
  11) Weldability
  12) Nitriding ability

Taking each of these requirements in turn, *wear resistance* is important to consider for cavity components if the plastic material is abrasive—filled with glass or minerals—or if metal-to-metal contact is unavoidable due to mold-design requirements.

Toughness, or impact strength, can be an important factor in repair or component replacement cost, especially where small, thin or unsupported inserts or cross-sections are necessary.

Compressive strength is needed to withstand mold clamping forces so as to minimize "parting-line hobbing" or "mushrooming" of shut-off surfaces.

Hot hardness is needed when molds must operate at high temperatures, in order to prevent annealing or decarburizing.

Corrosion resistance is very important in two major aspects—first, when corrosive plastics or additives are used; and second, when molds operate in high-humidity areas or in regions where the water supply is particularly corrosive. (This accounts for increasing use of stainless steels, especially in some parts of the country.)

Thermal conductivity can have an impact on the cycle time of high-production molds, and although it's not often a major factor in selecting among mold steels, it *is* a reason for choosing beryllium copper instead of steel in some cases.

Hobbability has long been a major desire of moldmakers in order to permit production of numbers of intricate mold cavities fairly economically. With greater availability and refinement of the EDM machining process, hobbability is becoming less important, since the sacrifice of other important qualities in hobbing steels is often disadvantageous for mold-life expectancy.

Machinability is of great economic importance for the moldmaker. An estimated 30% of the total mold cost is for chip-forming machining operations.

Polishability of a steel depends on homogeneity and "cleanliness" of the micro-

Polish-ability	Heat Treat-ability	Weld-ability	Nitriding Ability
5	10	4	4
8	10	4	5
9	10	4	6
9	10	4	7
7	6	9	8
7	6	8	8
8	7	2	3
5	6	2	3
8	8	5	10
8	8	3	8
7	9	2	8
7	7	4	7
6	7	2	NA[d]
6	9	1	10
10	8	6	8
9	7	4	NA[d]
7	9	5	9
7	9	5	9
8	9	5	NA[d]
6	8	2	10
7	8	2	NA[d]
8-9	7	7	NA[d]

structure. Cavities that require a mirror-like or optical-quality finish must be made of special mold steels that have been vacuum degassed or electroslag remelted.

Heat treating is of key importance to the moldmaker. In order to minimize the re-machining or finish machining costs after heat treatment, a steel with good dimensional stability must be selected. It should also be pointed out that very large cavities or cores, especially with varying cross-section, cannot be heat treated without risk of cracking, and therefore such treatment should be avoided. Special prehardened steels have been developed for this purpose.

Weldability of a mold steel should be considered because part design and engineering changes as well as repairs are often necessary. Case-hardening steels should be welded only in the annealed condition, because after carburizing the risk of cracking is extremely high. As a general rule, very few steels can be welded after heat treatment with a low risk of cracking, and then only when careful consideration has been given to weld location and welding procedure.

Nitriding ability should be considered in certain applications or special components. Nitriding gives a very hard surface layer to the steel and very good resistance to abrasion or erosion. It also increases compressive strength somewhat. However, the hard nitrided layer (2 to 10 mils thick) is very brittle and easily cracks or flakes off if the mold component is subjected to impact blows, rapid temperature changes, or uneven pressures. Nitriding of sharp edges with angles less than 90° should therefore be avoided.

What improves or determines these qualities in steels? In order to specifically enhance certain qualities of mold steels, special alloying elements are added during steel manufacture. These alloying additives in plastic mold steels can range in composition from the relatively low-alloy oil-hardening types, containing less than 3% of total alloying elements, through the medium-alloy air-hardening types, up to the most highly alloyed steels of the maraging type, which contain over 30% of alloying elements by weight (see Table, p.70 for alloy composition of common mold steels).

While it is true that certain alloying elements contribute certain properties in mold steels, it is closer to the truth to say that alloying elements, either alone or in combination, enable heat treatments to be carried out that change the microstructure, which in turn provides the desirable properties or characteristics of the finished mold.

A list of common alloying elements and the properties they contribute appears in the box below.

A steel grading system can help With the great number of tool steels available today, the correct choice and application can become a challenging task. Since it's practically impossible to obtain the highest level of every desirable quality in any one steel, the selection process must be based on a priority system determined by the specific application.

There are three major categories of applications in molds, which make somewhat different or specific demands on the steel to be selected. These categories are:

1) Mold cavity and core unit components
2) Mold base plates
3) Mold base special function compo-

Effects of Alloying Elements

Aluminum (Al)—Combines with nickel and titanium to form an intermetallic compound, which precipitates on aging and provides strength and hardness. Also used as a deoxidizer and to produce fine grain size.

Carbon (C)—Very influential in controlling hardness, depth of hardness, and strength.

Chromium (Cr)—A carbide-forming element that contributes strongly to hardenability and abrasion and wear resistance. Additional amounts of chromium, greater than are needed for carbide formation, remain in solution and enhance corrosion resistance.

Cobalt (Co)—An element added to the maraging steels to improve strength.

Manganese (Mn)—Combines with free sulfur to form discrete sulfide inclusions and improve hot workability. It is also a deoxidizing agent. In larger quantities, it increases hardenability by decreasing the required quenching rate. It is the principal element used to obtain quenching by air cooling, which minimizes distortion.

Molybdenum (Mo)—Promotes hardenability in mold steels. The elevated tempering requirement increases the steel's strength at higher operating temperatures and provides more complete relief of residual stresses for greater dimensional stability.

Nickel (Ni)—Usually added to improve hardenability of low-alloy steels. In maraging steels, nickel combines with aluminum and titanium to form an intermetallic compound that increases hardness and strength on aging. Larger amounts of nickel also assist in corrosion resistance.

Silicon (Si)—Principal function is as a deoxidizing agent during melting. In higher quantities, it retards tempering, thus allowing higher tempering and operating temperatures (hot hardness).

Titanium (Ti)—Found in maraging steels, where it acts as a potent strengthener by combining with nickel and/or aluminum to form an intermetallic compound, which precipitates on aging.

Tungsten (W)—Increases hardness, strength and toughness.

Vanadium (V)—A strong carbide-forming element, which is usually added to control grain size and to increase wear resistance.

Chemical Composition of Typical Mold Steels

Steel Type	AISI Designation	Alloy Percent By Weight C	Mn	Si	Cr	Ni	Mo	V	W	Co	Ti	Al
Prehardened	4130/4140	0.40	0.90	0.30	0.95		0.20					
	P20	0.35	0.90	0.50	1.70		0.40					
	414 SS	0.03	1.00	1.00	12.5	1.90						
	420 SS	0.38	0.80	0.80	13.5							
Carburizing	P-5	0.10	0.30	0.20	2.30							
	P-6	0.10	0.50	0.25	1.50	3.50						
Oil Hardening	01	0.90	1.00		0.50				0.50			
	06	1.45[a]	1.00	1.25			0.25					
Air Hardening	H-13	0.35	0.40	1.10	5.30		1.40	1.0				
	S-7	0.50	0.70	0.25	3.25		1.40					
	A-2	1.00	0.70	0.30	5.00		1.00					
	A-6	0.70	2.00	0.30	1.00		1.25					
	A-10	1.35[a]	1.80	1.20		1.85	1.50					
	D-2	1.50	0.30	0.30	12.0		1.00	1.00				
Stainless	420 SS	0.38	0.80	0.80	13.5							
	440C SS	1.00	1.00	1.00	17.0		0.75					
Maraging	250	0.03	0.10	0.10		18.5	4.80			7.50	0.40	0.10
	350	0.03	0.10	0.10		18.5	4.80			12.0	1.40	0.10
Maraging Stainless	455M	0.05	0.10	0.10	12.5	8.00	2.20					1.00
High-Speed	M2	0.85			4.00		5.00	2.00	6.00			
	ASP 30[b]	1.27			4.20		5.00	3.10	6.40	8.50		

[a] Contains free graphite in microstructure to improve machinability and enhance wear resistance. [b] Trade name of Uddeholm Corp., Totowa, N.J.

nents.

Of these three categories, the first one (mold cavity and core unit components) is the most demanding category by far, because optimum steel selection for it is further influenced by the following factors:

a) Type of plastic to be molded—glass-filled, corrosive, etc.;
b) Molding process—temperature and pressure requirements;
c) Number of parts to be molded;
d) Surface finish of molded parts;
e) Cavity design requirements—metal-to-metal contact, etc.;
f) Method of cavity forming—machining requirements;
g) Method of heat treating—related to size of component and other factors.

In order to balance all these sometimes conflicting requirements, it is handy to have a grading system for the many tool steels available. Of all the grading systems I have seen, the one developed by Uddeholm Corp., Totowa, N.J., provides a comparison chart that is easy to understand even by the nonspecialist, yet conclusive enough to assist in making a proper choice. Our own grading system, based in part on the Uddeholm chart, appears in the table on p.68. It awards points from one to 10, where 10 is best, to each steel for each of several characteristics. These point ratings were carefully awarded by manipulation and cross-referencing of available technical data from various steel manufacturers, professional experience, and applicable formulas out of the *Uddeholm Steel Grading Pamphlet*. Most of the points were awarded on the basis of well known test methods, although in some cases no such objective method existed and we had to rely on subjective evaluation based on experience. The point chart is intended as a general guide only, since steel manufacturing tolerances, machining procedures, and heat-treating methods can have a detrimental effect on most steel properties. Also, most of the assigned point ratings can vary substantially with changing Rockwell hardness.

Where typical steels are used The following is an indication of where most common mold steels and beryllium copper find application in injection molds, along with comments on each material's particular strengths or weaknesses. This information is summarized in the table at right.

- **Types 4130, 4140:** Most commonly used in a prehardened state at a hardness of 30-36 RC for load- or pressure-bearing mold base plates, such as cavity and core retainer plates, or extra-large cavities and cores which have no special surface-quality requirements.
- **Type P20:** Same as 4130/4140; however, its cleaner manufacturing requirement results in a more homogeneous microstructure and thus good polishability. It's used for large cavities and cores requiring good polish, and for hot-runner manifolds.
- **Types 414 SS/420 SS prehardened:** Most commonly used at 30-35 RC hardness; excellent for large cavities and cores that require good polished finish and corrosion resistance. They're also very good for cavity and core retainer mold base plates, providing toughness and corrosion resistance without need for plating.
- **P-5 and P-6:** Carburizing steels available in annealed condition. They're easy to hob and/or machine for making cavities, and can be carburized to a depth of 60 mils and a case hardness of 58-61 RC. The relatively soft core hardness (15-30 RC) lowers the overall compressive strength, which is a key quality in modern mold-steel requirements. In the long run, it is often more economical to pay for the higher mold manufacturing cost of EDM'd tool steel cavities of the through-hardened type, rather than using the hobbing process, because of the much longer life expectancy.
- **01 oil hardening:** Available in annealed condition; is capable of attaining a maximum of 62 RC hardness. It's excellent for gibs, slides, wear plates, and the like, but not recommended for cavity or core components or mold base plates.
- **06 oil-hardening:** Same applications as 01, but provides better machinability and especially good wear characteristics in applications with metal-to-metal contact, be-

cause of the presence of free graphite in its microstructure.

- **H-13 air-hardening:** One of the most useful steels for moldmaking, providing good all-around steel qualities for cavities and cores, as well as inserts.
- **S-7 air-hardening:** Same as H-13 but providing the often required higher hardness of 54-56 RC. Extreme care is required in the heat-treating process; and, to prevent cracking in the quench, a double draw is highly recommended. It is very important also that hardness of 55 RC is achieved accurately, because of this steel's very sharp break-off point in impact strength or toughness (highest at 55 RC, lowest at 57-58 RC).
- **Types A2, A6, A10 air-hardening:** Medium-alloy tool steels available in annealed condition. A2 is the most abrasion-resistant steel of this group under molding conditions, because of its higher chrome content. A10 has remarkable wear and non-seizing qualities in metal-to-metal contact applications, because of its free graphite content. All three are easy to machine and very high in compressive strength. Welding, however, can create cracking problems.
- **D2 air-hardening:** In a class by itself with respect to excellent abrasion resistance, and is recommended for severe molding conditions, such as when glass or mineral fillers are used. It's not recommended for welding and is somewhat sensitive to cracking, owing to its low toughness.
- **Types 420 and 440C stainless:** Good choices for corrosion resistance where corrosive plastics are used or where moisture or humidity could affect cavity surface finish or cooling-channel corrosion. Type 440C is somewhat better in wear resistance and compressive strength, due to its higher hardness, while 420 SS represents the true mold cavity steel with good to very good all-around qualities and exceptionally high and consistent polishability, provided that it is manufactured by vacuum degassing and/or electroslag remelting. Relatively low thermal conductivity compared with other mold steels is only a minor factor in the first few days or weeks of processing a new mold. As soon as corrosion inside cooling channels takes hold, thermal conductivity of other mold steels, with respect to cooling-channel effectiveness, will be worse than that of stainless steels!
- **Maraging types 250, 350, 440M:** Excellent mold cavity and insert steels. They are by far the best performers when toughness is the number-one priority. This could be a very important factor in cases of very thin cross-sections or small, fragile and unsupported cavity or core inserts. Their resistance to cracking could, in the long life of the mold, be a crucial factor in mold-repair expenses, offsetting the much higher initial price of these steels (5-10 times that of other tool steels). Dimensional stability and simplicity of heat treating these steels are valuable considerations for the moldmaker.
- **M2 and ASP 30 high-speed steels:** Probably the most useful of all the many high-speed steels for moldmaking. M2 is by far the most useful steel for good-quality, long-lasting round core pins or blade ejectors, and is also readily available. ASP 30 is an advanced-generation steel manufactured by Uddeholm, using a new powder-metallurgy process. Its extremely high density gives it remarkable rigidity, which can be very important in resisting deflection of tall, unsupported cores.
- **Beryllium copper:** When heat treated, the strongest of all copper-based alloys. It's not usually recommended for high-production molds, because of its relatively low wear resistance, toughness and compressive strength, compared with tool steel. It does, however, have a special place in moldmaking when economy in cavity manufacturing and injection molding cycle time (the latter minimized by Be/Cu's high thermal conductivity) are of the utmost importance. But one must take into consideration that, over the lifetime of a mold, periodic cavity replacement costs can become a great disadvantage.

Where Typical Mold Steels Are Used

Type of Steel	Typical Uses in Injection Molds
4130/4140	General mold base plates
P-20	High-grade mold base plates, hot-runner manifolds, large cavities and cores, gibs, slides, interlocks
414 SS, 420 SS (prehardened)	Best grade mold base plates (no plating required), large cores, cavities and inserts
P5, P6	Hobbed cavities
01	Gibs, slides, wear plates
06	Gibs, slides, wear plates, stripper rings
H-13	Cavities, cores, inserts, ejector pins and sleeves (nitrided)
S7	Cavities, cores, inserts, stripper rings
A2	Small inserts in high-wear areas
A6	Cavities, cores, inserts for high-wear areas
A10	Excellent for high-wear areas, gibs, interlocks, wedges
D2	Cavities, cores, runner and gate inserts for abrasive plastics
420 SS	Best all-around cavity, core and insert steel; best polishability
440C SS	Small to medium-size cavities, cores, inserts, stripper rings
250, 350	Highest toughness for cavities, cores, small unsupported inserts
455M SS	High toughness for cavities, cores, inserts
M2	Small core pins, ejector pins, ejector blades (up to ⅝ in. diam)
ASP 30[a]	Best high-strength steel for tall, unsupported cores and core pins

[a] Trade mark of Uddeholm Corp.

Component size limits steel choice As a general rule, the larger the physical size of a piece of tool steel, and the greater the cross-section variations in the machined details, the more risk there is of developing cracks either during heat treatment or after a relatively short time of mold operation. Even with careful mold design and manufacturing methods, such cracks are to a large ex-

nents, the choice of steel can be made from the total spectrum of available materials, since distortion or cracking in heat treatment becomes insignificant.

Special plating and surface treatments There are a great number of special surface treatments and plating procedures available today for improving certain qualities in a

For More Information on Mold Steels

The following references were used in this article:

Metal Progress Data Book, American

Component size limits steel choice As a general rule, the larger the physical size of a piece of tool steel, and the greater the cross-section variations in the machined details, the more risk there is of developing cracks either during heat treatment or after a relatively short time of mold operation. Even with careful mold design and manufacturing methods, such cracks are to a large extent unpredictable, and almost always result in the total loss of the cavity component or mold base plate, since welding of such cracks usually results in repeated or further failure.

It is therefore advisable to limit the material choices for large mold components or mold base plates to the following prehardened steels:

- 4130/4140 prehardened to 30-36 Rockwell C;
- P-20 prehardened to 30-36 RC (for good polishability);
- 414 or 420 stainless prehardened to 30-36 RC (for good polishability and corrosion resistance).

If necessary, these large components can be inserted with high-grade, heat-treated tool steel in strategically located wear or shutoff areas, in order to extend mold life and provide replaceability.

Conversely, on very small mold components, the choice of steel can be made from the total spectrum of available materials, since distortion or cracking in heat treatment becomes insignificant.

Special plating and surface treatments There are a great number of special surface treatments and plating procedures available today for improving certain qualities in a mold steel. Of the 50 or more special treatments that are obtainable under many different proprietary names, a very small percentage has a life-prolonging effect on the mold cavity, and then only when the process is performed under extremely careful and conscientious methods.

More often than not, plating procedures can be, and are, over-used—typically as an afterthought to make up for improper mold steel selection in the first place. Also, in many such cases, the improper application of these plating procedures or treatments has only a very short protective effect; and when they start cracking and/or peeling, they drastically shorten the life of the mold and actually increase the degree of damage in metal-to-metal contact areas.

It is therefore advisable to be extremely selective and apply plating or surface treatments only in very special cases and with exact quality controls. ☐☐

For More Information on Mold Steels

The following references were used in this article:

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Trends in Mold Steels — A Steel Maker's View

By John Worbye, Technical Service Manager, Uddeholm Corp., Totowa, N.J.

In the last eight to 10 years, steel makers began devoting attention specifically toward R&D on plastic mold steels. The changes that have resulted have been more in the way of evolutionary improvements rather than dramatic innovations. Some changes in the pattern of use of tool steels have come in consequence of changing needs in the marketplace, as well as new developments in moldmaking technology.

One area of advance in the steel-making process is improved "cleanliness" through techniques such as vacuum degassing and electroslag remelting. By reducing the incidence of particles of nonmetallic inclusions, and making what inclusions do remain softer and more easily machinable, today's steels lend themselves more readily to polishing and texturing. Cleanliness also lessens the chances that a moldmaker might spend hundreds of hours of time machining a component, only to strike an unyielding inclusion, resulting in scrappage of the workpiece.

Another area of steel-making advances has been in uniformity of the metal's microstructure, resulting in greater uniformity and predictability of heat-treating behavior and also in more consistent, isotropic properties in three dimensions. Some new developments in this area have been achieved very recently in H13-type steel (see *PT, Feb. '82 p. 14*).

Other newer developments have followed changes in needs and preferences in the marketplace. For example, the need for longer tool life in high-production applications has led to increasing dominance of through-hardened steels, which offer higher hardness than prehardened types. A relatively recent addition to the repertoire of through-hardening tool steels is the S7 type, which offers extra-high hardness for special applications.

Ever-increasing usage of abrasive fillers and reinforcements is also spurring demand for higher hardness and is one factor in the increasing popularity of so-called high-speed steels for inserts and small components subject to wear. A recent advance in this area is the development of an advanced-generation high-speed steel based on powder metallurgy, which has even higher working hardness than previous high-speed steels.

Still another trend has been to greater and greater usage of stainless steels, both because of more frequent processing of corrosive resins and additives, and also because of greater interest in protecting molds from corrosion and rusting during use and/or storage. In Los Angeles, for instance, use of stainless is a popular means of protecting one's mold investment from smoggy air; the same is true in Florida, where the enemy is chronic high humidity. In these and many other locations, processors have learned that stainless is not really more expensive, when one considers the longer life expectancy and the elimination of chrome plating. What's more, the somewhat lower thermal conductivity of stainless (about 85% as great as a P20 steel and 95% of an H13) is insignificant, considering its greater resistance to formation of rust inside cooling channels, which greatly reduces heat transfer. The result is that stainless-steel molds can go five to six times longer without downtime for cleaning out the cooling channels.

Improvements in steel "cleanliness" in recent years have been particularly important to stainless varieties, because of the more stringent demands placed upon them. These improvements have led to development of new grades with even better polishability than in the past.

Climbing that learning curve Perhaps not surprisingly, the arrival of new steels and changing patterns of usage of old steels have

certain cold-work and powder-metallurgy steels. Case-hardening hobbing steels are relatively little used today; because the hardening is only "skin deep" over a still soft core, these steels have low overall compressive strength and do not meet the long-life requirements imposed by the economics of molding today.

Originally, prehardened steels had the signal advantage of not requiring heat treatment after machining, and therefore were not subject to the risk of distortion from the multiple stresses induced by heating, transformation of the microstructure and subsequent cooling. This made up for the lower final hardness of prehardened steels—typically around 32 Rockwell C, vs. 48-56 RC for heat-treated molds.

The rapid penetration of EDM machining techniques in the last 5-10 years has greatly reduced this advantage of prehardened steels, since the EDM work is now done after heat-treating a block of steel. Thus, not only is there no further risk of losing tight tolerances from distortion during heat treatment, but through-hardened molds actually retain their tolerances better in use because of their greater hardness and wear resistance. Besides lower wear resistance, prehardened steels also lack the compressive strength of heat-treated types, making them subject to impressions caused by bits of flash, and other damage. Prehardened steels also don't measure up in fatigue strength—i.e., ability to resist the cyclic stresses of molding.

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Climbing that learning curve Perhaps not surprisingly, the arrival of new steels and changing patterns of usage of old steels have created a need for greater familiarity with some of these materials on the part of moldmakers and heat treaters. For example, relatively few heat treaters are yet knowledgeable in handling H13 or stainless steels (420 in particular), which require special care in heat treating. Likewise, although stainless steels are actually easier to polish than other materials, many moldmakers do not realize that different polishing techniques must be used with stainless grades, particularly the newest, easiest to polish ones. And some heat treaters have yet to learn that optimum toughness and corrosion resistance in stainless steels requires tempering at no higher than 400-500 F. This is even a problem with H13 steel—most heat treaters are still tempering it at temperatures over 1000 F, which are fine for die casting molds, but provide lower mechanical properties than tempering at 400-500 F.

And besides the growing variety of steels, proliferation of special surface treatments and coatings adds further complexities to the industry's learning curve. To cite just one example of a potentially promising approach that's still too new to be well known in plastics molds, chemical vapor deposition (CVD) of titanium carbides and nitrides is a process that can be combined with heat treatment to provide extreme wear resistance to certain steels, such as H13 and high-speed types (but not low-alloy steels.)

And besides the many new processes not yet fully evaluated, there's much to be learned about established methods. Hard chrome plating, for example, is well known, yet most commonly is not used to full advantage. The reason is that the chrome is typically applied directly to the tool steel, whereas it should be underlaid with nickel plating for maximum corrosion resistance.

Heat treatment becoming the norm As was indicated above, probably the single most important and widespread trend in selection of mold steels has been the shifting of emphasis away from prehardened and toward through-hardening steels. In the early days of plastics moldmaking, case-hardened steels such as P4, P5 and P6, and prehardened steels like P20 and 4140 were dominant; today, the greater number of molds being built (though probably not the greatest tonnage of mold steel) consists of through-hardening steels, primarily air-hardening types like H13, 420, S7 and certain cold-work and powder-metallurgy steels. Case-hardening hobbing steels are relatively little used today; because the hardening is only "skin deep" over a still soft core, these steels have low overall compressive strength and do not meet the long-life requirements imposed by the economics of molding today.

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In today's competitive environment, molders simply cannot tolerate the economic penalty imposed by unnecessary downtime for mold maintenance. Hence, they have been turning more and more to through-hardened steels, especially H13 and 420, for greater mold life expectancy in high-production jobs. The higher hardness of these steels has the added advantage of improved polishability and better release of parts from the mold. These benefits have more than made up for the slightly greater initial expense and lead time required for the added step of heat treatment.

However, prehardened steels definitely still have a place—most notably in very large automotive and other molds that would be prohibitively expensive or impossible to heat treat because of their size. Prehardened steels may also make sense for short-run jobs and in cases where sharp corners or other elements of mold design recommend these steel's higher toughness and resistance to cracking.

As the predominance of heat-treated molds should only increase in the future, it is essential that moldmakers, heat treaters and molders understand fully how to obtain best performance from through-hardened steels. For one thing, time pressures should not be an excuse for attempting to rush the heat-treating process. That can only result in poorer dimensional stability and premature cracking of mold components.

Also, for the sake of dimensional stability, mold components should definitely be stress relieved after rough machining. (Typically, this requires heating for 1-2 hr at around 1200 F.) Although most moldmakers know this to be good practice, many neglect it because it's an extra step that usually requires the mold component to be sent out to a heat-treating facility. Although it's also important to relieve the stresses of machining with prehardened steels, this is even more essential with through-hardening steels, as those stresses, if not relieved, will be compounded by the stresses of heat treating. Moldmakers should get into the habit of stress relieving and should incorporate the cost of this step in the original quote.

Finally, molders and tool makers should anticipate greater difficulty in welding heat-treated molds if repairs become necessary. The higher hardness of these molds means greater risk of cracking, but this risk can be overcome by careful preheating and stress tempering afterward. □□

EDM: A Metallurgical Perspective

By Ed Severson

Electrical Discharge Machining (EDM) technology has become a basic means of making parts in virtually all forms of toolmaking. The process itself has many advantages to toolmakers and its popularity has grown because of this. Even though the EDM process has many advantages, one must consider the metallurgical aspect. EDM has a dramatic effect on the surface of the material being machined. This effect may contribute or be the sole cause of tool failure, if not understood and addressed properly.

This article is going to show the EDM process and the metallurgical effects this process has on tooling materials. The article will also offer recommendations on ways to minimize potential problems associated with EDM.

A Review of the EDM Process

EDM is frequently used to produce components for molds and dies. The process is typically used for two reasons:

1. Parts can be machined after heat treatment. This reduces the risk of distortion caused by heat treatment and essentially allows a finished part to be produced in one step.
2. Complex geometries that would be very difficult or impossible to produce using conventional machining technology are possible using EDM.

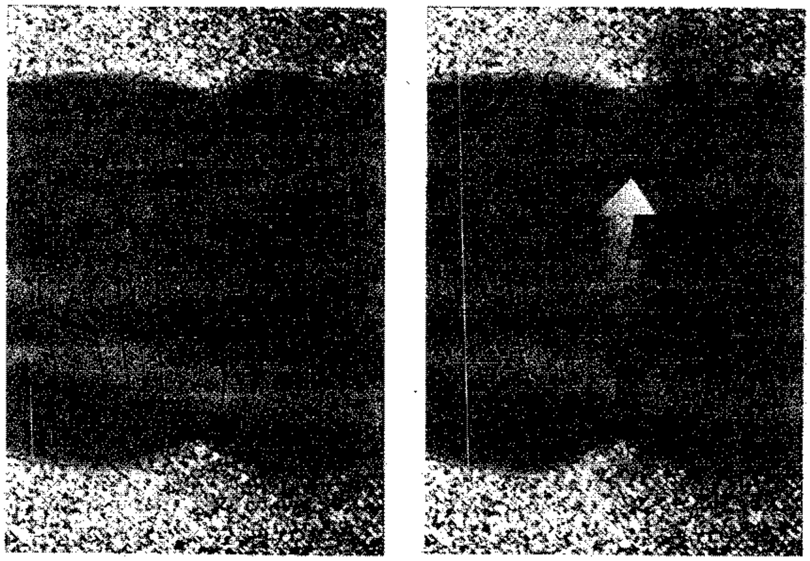
There are two basic types of electrical discharge machining—wire EDM and ram or plunge EDM. Wire EDM uses a thin metal wire as an electrode to "cut" through materials. Ram EDM uses a three dimensional electrode of either graphite or metal to "cut" all surfaces of a complex shape.

The EDM process itself is relatively simple. The material to be cut and the electrode are immersed in a dielectric fluid. An electrical field is established between the electrode and the workpiece. This electric field causes an electric arc or spark in the gap between the material and the electrode. The heat generated by the arc melts the workpiece material—causing some of material to be removed into the dielectric fluid. The material solidifies in the fluid and is flushed away from the part surface. This series of events is repeated over and over until the material is cut through or the desired three-dimensional contour is achieved (see **Figure 1**).

Surface Effects of EDM

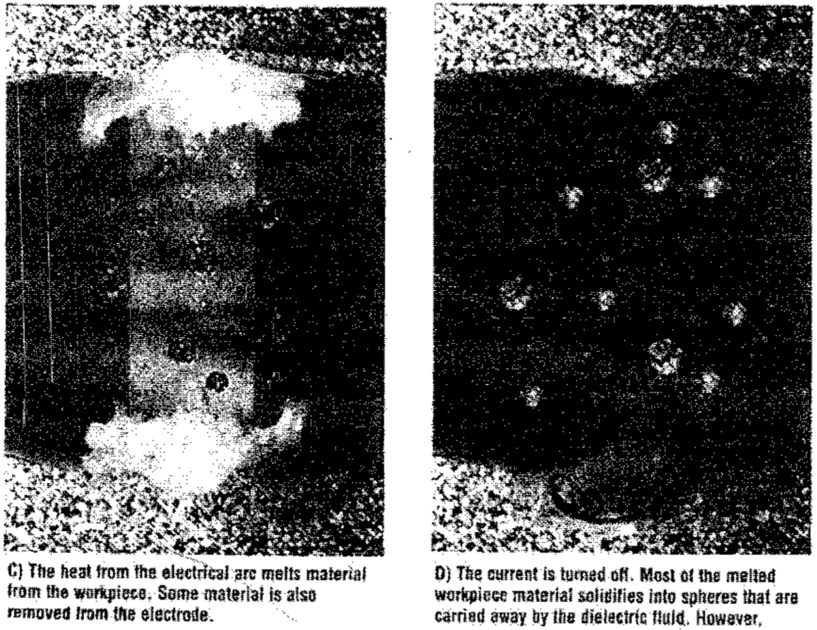
While most of the molten material is flushed away during the EDM process, some of the molten material solidifies on the surface of the tool material. This re-solidified layer on the workpiece is called the "white layer"

Figure 1
Schematic of the EDM Process



A) An electrical field is created in the dielectric fluid between the workpiece and the electrode.

B) An electrical spark jumps between the workpiece and the electrode.



C) The heat from the electrical arc melts material from the workpiece. Some material is also removed from the electrode.

D) The current is turned off. Most of the melted workpiece material solidifies into spheres that are carried away by the dielectric fluid. However, some of the molten material solidifies on the surface of the workpiece.

because it normally does not etch when microscopic inspections are done on the material surface. **Figure 2** shows a typical etched cross-section of an EDM white layer on H-13 tool steel. **Figure 3** shows the white layer on a cracked section of CPM 3V tool steel. It is important to note the materials were properly heat-treated and showed no material defects other than the white layer effect.

To understand why the EDM layer can be detrimental, one must understand the metallurgical effect of this process. EDM creates three distinct layers that have an effect on the performance of the tool material.

The first layer is one mentioned earlier, the "white layer". This layer is the molten material that solidifies on the surface of the work material. This layer is typically one-half to one-thousandth of an inch thick. The problem with this layer is the structure is composed of re-cast and liquid-quenched tool material. This re-cast layer is under a considerable amount of stress due to the solidification and structure changes during EDM.

The second layer will be two- to five-thousandths of an inch thick and will be located directly behind the re-cast layer. This layer will be composed of material that has reached a high enough temperature to re-heat treat. This re-hardened layer will have considerable stress from the heat treatment effect.

The last area of concern is located directly behind the re-hardened layer. This layer will be composed of material that has seen temperatures not high enough to re-harden, but higher than the base materials' tempering temperature. The re-tempered zone will have a hardness lower than the base material. The lower hardness results in lower tensile and yields strengths in this zone. This re-tempered zone is typically one- to five-thousandths of an inch thick. **Figure 4 (see page 25)** shows a schematic of these EDM layers.

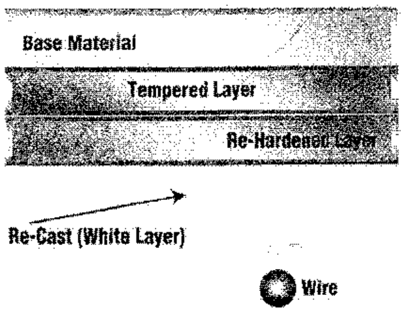
The first two layers are under an extreme amount of stress, due to the fact they are not stress relieved (tempered). The layers may be only a few thousandths of an inch thick, but cover a large surface area. The stresses involved may be enough to crack a part by itself, but usually need a small amount of stress as a push over edge. This typically happens during the initial use of the tool. Analysis of failed tooling over the last three to four years has shown that tool failures due to breakage can be directly related to EDM nearly one out of three times. Tool materials themselves have somewhat limited cracking resistance. Combine corner areas, which was one of the main reasons for using the EDM process, and the potential for cracking is very high.

Figure 3

White layer on a cross section of CPM 3V tool steel. (500x magnification)

Figure 4

EDM Diagram



Addressing the EDM Layer

There are two basic ways to address the EDM layer effect. The first is to remove the few thousandths of an inch of affected material, thus eliminating the condition. This solution may not always be practical due to intricate geometries and dimensional considerations.

The second and most efficient way to address the EDM layer effect is to give the entire tool a stress relief (temper) operation. The recommended process for doing this temper is to use a temperature that is 25°F below that used for the original heat treatment. This will eliminate the stress caused by the localized heat generated by the EDM process and greatly diminish the risk of cracking. The as-solidified structure of the white layer will not be changed, but with no stresses in the layer the potential for cracking becomes a minor issue. Tool material that has not been heat-treated, but has been EDM'ed will be stress relieved during the heat treatment process itself.

Summary

The above comments are not designed to discourage anyone from using the EDM process. The intention is to make those using EDM aware that a condition exists from the EDM operation that may cause tool failures if not addressed. The EDM manufacturers over the last few years also have been attempting to minimize the depth of the layers using better EDM parameters and equipment. Their efforts combined with tempering of the EDM layers can greatly reduce any potential cracking problems associated with the process.

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Ed Severson *is a metallurgical engineer with Crucible Service Centers (Camillus, NY). For more information call (800) 365-1185.*