Tool steels are iron-based alloys that are melted and processed to develop characteristics useful in the working and shaping of other metals. Many tool steels are also suitable for machinery components and structural applications in which particularly stringent requirements must be met. Such parts include high-temperature springs, ultrahigh-strength fasteners, special-purpose valves, and bearings of various types for elevated-temperature service.

Tools are typically subjected to extremely high loads that are applied rapidly. The tools must withstand these loads without breaking and without undergoing excessive wear or deformation. No single tool material combines maximum wear resistance, toughness, and resistance to softening at elevated temperatures. Consequently, the selection of the proper tool material for a given application often requires a trade-off to achieve the optimal combination of properties.

Most tool steels are wrought, but some are cast and some are made via powder metallurgy. This article describes the effects of alloying elements, discusses the categories of tool steels, and describes advanced powder metallurgy tool steels and nickel-base tool alloys.

**Effects of alloying elements**

Metals producers customarily melt tool steel alloys in an electric arc furnace. The alloys are refined to produce final chemistries and eliminate deleterious elements, and then poured into molds to solidify into ingots. The ingots are often electroslag remelted (ESR) to improve the microstructure prior to hot rolling or forging into mill forms such as bar, plate, and sheet. Producers then cut the forms to length for fabrication into tools for turning, milling, boring, and drilling.

Conventional cast/wrought steels are preferred for tools and dies in general-purpose machining and forming. These grades are alloyed with carbon, chromium, and small amounts of other elements.

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* Member of ASM International
steel must exhibit certain properties. Many tool producers develop these alloys for specific applications. To better understand and evaluate the many available tool steels, it is helpful to group them into categories based on how they are used and how they are heat treated. Common categories include cold-work tool steels, high-speed tool steels, and hot-work tool steels.

Because tool steels have numerous applications, each with its own requirements, a large variety of alloys have been developed over the years. In 1937, the Carpenter Steel Company helped take the mystery out of tool steel selection with the introduction of the Matched Set method. This simple technique utilizes a matrix in which common tool steels are positioned by their relative properties such as toughness, wear resistance, and hardness. With an alloy of known performance as a starting point, the toolmaker simply moves in the appropriate direction on the diagram to find the best alloy, as shown in the chart above.

This method later evolved into “Advanced Tooling Materials – plus Carpenter Matched Tool and Die Steels,” a detailed manual on tool and die steels and advanced tooling materials.

**Cold-work tool steels**

Cold-work tool steels do not have the alloy content necessary to make them resistant to softening at elevated temperatures. Therefore, they are restricted to applications that do not involve prolonged or repeated heating above 205 to 260°C (400 to 500°F). For cold-work applications, they may be air- or oil-quenched during hardening. Because they do not require a severe water quench, such alloys have less heat treat distortion and cracking than do the water-hardening alloys.

Cold-work tool steels share similar characteristics, such as chemistry. Common cold-work alloys include the oil-hardening types, such as O2; the air-hardening grades such as A2 and A6; and the high-chromium, high-carbon, air- or oil-hardened alloys, such as D2. This group includes carbon steels, shock-resisting grades, and air-hardening and oil-hardening grades.

- **Carbon-steel tool alloys (group W)** contain carbon as the principal alloying element in amounts ranging from 0.60 to 1.4%. They have very little alloy content and must be water quenched to achieve proper hardenability and toughness. Also known as water-hardening grades, they have a low hard surface or case, and a softer core. They are suitable for cold heading, striking, coining, taps, reamers, and similar parts. Group W alloys are not as popular today as in the past.

- **Shock-resisting grades (group S)** have high toughness for applications such as chisels and punches. Carbon content is about 0.5% for all group S steels, and this results in a combination of high strength, high toughness, and low to medium wear resistance. Group S steels vary in hardenability from shallow hardening (S2) to deep hardening (S7). Type S2 is normally water quenched, types S1, S5, and S6 are oil quenched. Type S7 can be air hardened, but atmosphere control is important, as S7 is susceptible to decarburization.

- **Air-hardening, medium-alloy grades (group A)** contain enough alloying elements to achieve full hardness in sections up to about 100 mm (4 in.) diameter when air cooled. Because they are air-hardening alloys, Group A tool steels exhibit minimum distortion and the lowest tendency to crack during hardening. Manganese, chromium, and molybdenum are the principal alloying elements. Types A2, A3, and A7, A8, and A9 contain 5% chromium. Typical applications include shear knives, punches, forming dies, and coining dies.

- **High-carbon, high-chromium grades (group D)** contain 1.5 to 2.35% carbon and 12% chromium. All group D tool steels (except D3) are air-hardening and reach full hardness when cooled in still air. Type D3 is usually quenched in oil, making it more susceptible to cracking. Group D steels have high resistance to softening and excellent resistance to wear. Typical applications include forming dies, rolls, burningishing tools, and slitter knives.

- **Molybdenum high-speed (group M)** steels contain molybdenum, tungsten, chromium, vanadium, cobalt, and carbon as principal alloying elements. Type M2 contains 4.5 to 5.5% molybdenum, and 5.5 to 6.75% tungsten. Type M7 contains 8.2 to 9.2% molybdenum, and only 1.4 to 2.1% tungsten. Group

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This chart shows the wear resistance versus toughness comparison for various Carpenter tooling alloys. *Equivalent in hardness, heat treating response, toughness, and wear resistance to CPM 76 from Crucible Materials Corp. **Equivalent in hardness, heat treating response, and wear resistance to CPM 10V from Crucible Materials Corp. ***Equivalent in hardness, heat treating response, and toughness, wear resistance to CPM Rex low-alloy steels. **"Advanced Tooling Materials – plus Carpenter Matched Tool and Die Steels," a detailed manual on tool and die steels and advanced tooling materials.
M steels were primarily developed for the manufacture of cutting tools. Their most important property is the ability to retain high hardness at elevated temperatures. These materials are heavily alloyed, and their composition provides high strength as well as excellent wear resistance. For this reason, they are often chosen for cold-work applications such as punches and dies.

- Tungsten high-speed steels (group T) also contain molybdenum, tungsten, chromium, vanadium, cobalt, and carbon as principal alloying elements. However, T2 contains only 1% max of molybdenum, and 17.5 to 19% tungsten. T8 contains 0.4 to 1% molybdenum and 13.25 to 14.75% tungsten. Group T steels are characterized by high red hardness and wear resistance, as well as deep hardening. They are primarily chosen for cutting tools such as bits, drills, reamers, taps, broaches, and high-temperature structural parts.

Because a combination of factors can contribute to cold-work tooling failure, alloy selection can be challenging. The best choices for cold-work tooling applications typically result from the right compromise between wear resistance and toughness. In selecting cold-work tool steels, the user must first accurately predict the service conditions. For example, breaks or chips in the tool indicate insufficient toughness, suggesting replacement by a shock-resistant tool steel such as S7. Excessive abrasion or galling indicates a need for a wear-resistant alloy such as D2 or M2.

**Hot-work tooling alloys**

Hot-work steels (group H) were developed to withstand the combination of heat, pressure, and abrasion associated with punching, shearing, or forming at high temperatures. Group H steels have carbon contents ranging from 0.35 to 0.45%. Contents of chromium, tungsten, molybdenum, and vanadium range from 6 to 25%. Common hot-work alloys include H11, H13, and H19. These alloys have good resistance to heat softening because of their chromium contents of 3 to 5.5%.

Important characteristics of hot-work alloys include hardness at the tool’s elevated working temperature, temper resistance, and impact toughness.

The hot hardness of a low-alloy steel diminishes rapidly upon heating to 230°C (450°F). However, chromium die steels such as H13 or H19 are relatively unaffected until heated to over 425°C (800°F).

Temper resistance reflects an alloy’s ability to retain its hardness after lengthy exposure to elevated temperature. When subjected to thermal fatigue, it is critical that these hot-work tooling alloys exhibit resistance to heat checking. High toughness and high hardness have been found to prevent these surface cracks.

**ADVANCED TOOLING ALLOYS**

In addition to the conventional tool steels described above, a number of advanced tooling materials are available today. By working closely with the users of tool steels, suppliers have been able to develop products that provide significantly longer service life.

Many indicators point to the need for upgrading tool materials. Chief among them are frequent production line stoppages and competitive price disadvantage. Improving the quality of the tool material can dramatically reduce downtime and improve run times, thereby reducing production costs.

When considering an upgrade to an advanced tooling material, for which the initial cost may be higher, it is important to consider the total cost over the life of the tool. The cost of the steel is usually a small fraction of the total tool cost.

**Powder metallurgy tool alloys**

Powder metallurgy cold-work tool steels offer superior wear resistance compared with conventional tool steel grades, and have good strength and toughness characteristics. Upgrading to powder cold-work steels should be considered for applications such as cold extrusion, cold extrusion barrels, cold extrusion liners, cold heading, compacting tools, dies for blanking, forming rolls and dies, nozzles, pelletizer blades, piercing dies, plastic injection molds, punches, shears, slitter knives, steel mill rolls, and woodworking tools.

To make powder metal alloys, molten metals containing the required alloying elements are nitrogen-gas-atomized to produce powder particles.
The high quench rate of the gas-atomized metal powder particles allows for finer grain size; smaller, more uniformly distributed carbide particles; and reduced or eliminated segregation. These powders are blended and poured into a canister, then hot isostatically pressed to produce 100% dense billets. The billets are further processed by state-of-the-art specialty steelmaking methods. The more refined and homogeneous microstructure of wrought powder mill forms such as bar, wire, flats, and plate offer significant benefits over conventional cast/wrought stock (Fig. 7). These include:

- More dependable and productive tools that provide longer service life.
- Refined microstructure, improved product uniformity, and consistent performance.
- Improved machinability in the annealed condition.
- Easier grinding and sharpening in the hardened and tempered condition, with no loss in the finished tool’s abrasion resistance.
- Superior toughness in the finished tool.
- Better dimensional stability when making the tool, and less out-of-round distortion after heat treatment.
- Availability of higher alloy-content steels that can improve speed and reduce production costs through superior wear resistance and improved cutting performance.

Typical powder-metal high-speed steel tooling applications include forming tools, milling cutters, and screw machine tools. They also are work well in broaches and hobs, which carry out multiple operations with a single stroke. Among the available grades of Micro-Melt powder high-speed steels are M3 Type 2, M4, T15, M48, M62, HS30, and Maxamet.

Ultra-high strength alloys
Upgrading to ultra-high-strength steels should be considered for tools requiring high strength, hardness, and exceptional fracture toughness and ductility, particularly in applications where tool failure would be costly, if not catastrophic. Carpenter’s AerMet-for-Tooling is an ultra-high-strength steel that also has very high toughness. This was originally introduced for aerospace applications, but was later made available for tools that could benefit from high strength and hardness along with high fracture toughness and ductility. It is serving successfully in applications such as punches, dies, shrink rings and retaining rings, shafts, and mandrels.

Toolmakers should upgrade to ultra-high-strength steels to prevent the premature cracking or breaking of tools under heavy loads or impact. Ultra-high-strength steels have great compressive strength, and are specified for auxiliary tooling, such as stems and rams on extrusion presses. AerMet-for-Tooling also has been used for shrink ring-type tool holders subject to millions of pounds of pressure per square inch, as encountered in the manufacture of artificial gemstones. Other applications include heavy-duty punches and dies for blanking, crimping, and embossing.

Nickel-base tool alloys
Hot-work steels are suitable for tooling exposed to high-temperature environments ranging from 540 to 650°C (1000 to 1200°F). However, when temperatures exceed these levels, nickel-base, high-temperature alloys should be considered.

Carpenter offers its line of high temperature Pyrotool Alloys, such as Pyrotool Alloy 7, and Pyrotool Alloy A. These grades were originally developed as superalloys for application in jet engines. As tooling alloys, they are suitable for temperatures above 620°C (1150°F), where the standard hot work tool steels begin to soften. These alloys are designed for hot extrusion tooling such as liners, dummy blocks, mandrels, and dies.

For more information: Robert E. Carnes, Carpenter Powder Products Inc., a subsidiary of Carpenter Technology Corporation, Reading, PA 19612; tel: 610/208-2579; e-mail: rcarnes@cartech.com. Gary Maddock, tel: 815/979-2610; e-mail: gmaddock@cartech.com.