CHAPTER 4

TOOL AND DIE STEELS

INTRODUCTION

STEELS USED TO make industrial forming and cutting tools are specially designed to have the unique mechanical properties required for particular applications. The processes used to produce these steels deliver clean, homogeneous material according to precise production requirements for chemical composition and microstructure. Rigid quality control is justified by the high cost of constructing intricate tools, dies and molds, and the cost of downtime associated with premature tool failure. Preserving the unique properties of these steels is a factor that always should be taken into consideration before welding. Such operations should be carefully planned, and proper welding procedures should be used in order to maintain the desired properties and microstructure in the weld deposit and in the heat-affected zone (see Figure 4.1).

Because of the carbon and alloy content in tool steels, and the heat treatment necessary to attain the required mechanical properties, the welding process must be performed by highly skilled technicians using accepted methods and process controls. The welding process greatly affects the workpiece in the heat-affected zone. Therefore, welders must have good working knowledge of heat-treating processes as well as manipulative skills for the actual welding operations.

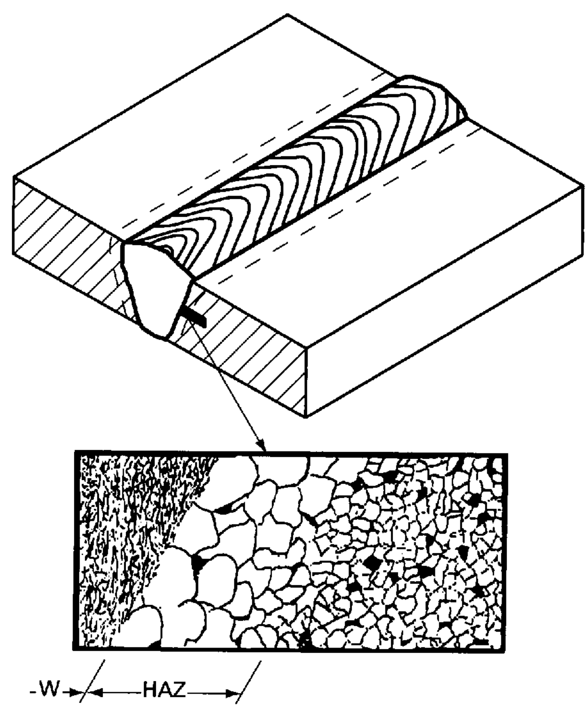


Figure 4.1—Single-Pass Weld in Steel, Showing Weld Metal (W) and Coarse-Grained Heat-Affected Zone (HAZ)

METALLURGY

TOOL STEELS GENERALLY contain carbon in proportions ranging from 0.30 to over 1.00 %, along with other alloying elements. They are characterized by high hardness and wear resistance properties. The high carbon provides martensitic hardness capability of up to 60 HRC, as may be seen in Figure 4.2. Carbides increase the wear resistance of the steel. Some grades of tool steels, designed with less carbon, provide better toughness, and resistance to elevated-temperature softening (called *red hardness*). The hardenability of tool steels follows the same general rules governing other alloy steels—the higher the alloy content, the greater the hardenability.[1]

Tool steels contain significant amounts of other elements in addition to carbon, such as chromium, cobalt, manganese, molybdenum, nickel, silicon, tungsten, and vanadium. These are involved in forming various alloy carbides that increase the hardness, wear resistance, elevated-temperature softening resistance, or some combination of these properties. No single alloy can provide all of these properties, so the selection of a tool steel is based on trade-offs that achieve the optimum combination for a particular application. These properties are primarily a function of the chemical composition of the alloy and the type of heat treatments (including quenching media) applied to them. Table 4.1 shows the effects of various alloying elements on the properties of tool steels.

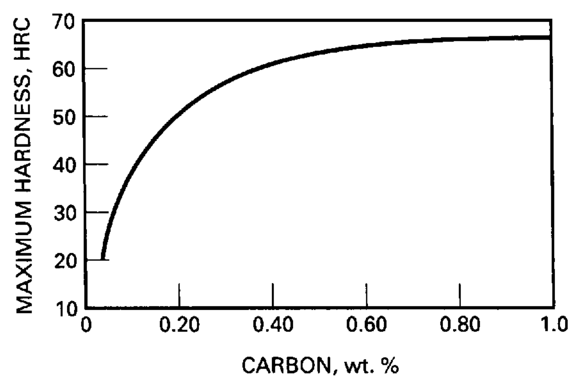


Figure 4.2—Influence of Carbon Content on the Maximum Hardness of As-Quenched Carbon and Alloy Steels

1. A thorough discussion of welding metallurgy may be found in the *Welding Handbook*, Vol. 1, 8th Ed., 89-124.

Table 4.1
Effects of Various Alloying Elements on Properties of Tool Steels

Alloying Element	Contents, %	Effects on Properties
Carbon	0.30-2.34	Increases hardness and wear resistance
Chromium	0.2-14	Increases depth of hardness (although to a lesser degree than manganese) Increases wear resistance and toughness Increases temperature required for hardening
	12-14	Increases wear resistance and size accuracy Increases (mildly) corrosion resistance in hardened steels
Cobalt	5-12	Increases red hardness (resistance to softening at elevated temperatures) Increases tendency toward decarburization Decreases toughness
Niobium	≤ 0.1	Increases wear resistance Increases maximum allowable hardening temperature Decreases tendency toward decarburization
Manganese	0.15-3	Increases depth of hardness Increases deoxidation of steels in final melt stages (in small quantities) Decreases temperature required for hardening
Molybdenum	0.15-10	Increases depth of hardness (more effectively than tungsten) Increases red hardness Increases wear resistance Causes decarburization in forging and heat treating With silicon, increases toughness
Nickel	0.29-0.3	Increases toughness, wear resistance, and depth of hardness slightly Increases annealing difficulties in high-alloy steels Decreases temperature required for hardening (by small amount)
Sulfur	0.015-0.05	Increases machinability in some air-hardening tool steels (free-machining) Otherwise a harmful impurity
Silicon	0.15-2	Increases likelihood of decarburization With manganese, molybdenum, or chromium, greatly increases strength and toughness
	>0.3	Increases hardenability
Tungsten	0.5-20	With carbon, increases wear resistance
	12-20	With carbon and chromium, increases red hardness
Vanadium	0.15-5	With molybdenum, chromium, and tungsten: Increases toughness Increases red hardness Increases wear resistance (with medium to high vanadium content) Increases maximum allowable hardening temperature Decreases growth of grains in heat-treated steel
Aluminum, Titanium, Zirconium	≤ 0.1	Increases deoxidation of steels in final melt stages Decreases growth of grain size

CLASSIFICATIONS

TOOL STEELS ARE classified into seven major groups by the American Iron and Steel Institute (AISI) and the Society of Automotive Engineers (SAE). The classifications generally are based upon common applications, chemical compositions, or quenching media (water, oil, or air). These tool steel groups and the alloy types that comprise them are shown in Table 4.2.

Tool steels also are produced to several ASTM specifications, including ASTM A600, A681, and A686. Standards such as those from AISI, SAE, and ASTM may be used as the basis for procurement or for detailed specifications that may be required for improved weldability or a particular application. Table 4.3 provides a listing of commonly used tool steels with their compositions and Unified Numbering System (UNS) designations.[2]

2. UNS designations may be found in *Metals and Alloys in the Unified Numbering System*, 6th Ed., Warrendale, Pa.: Society of Automotive Engineers, 1993.

Table 4.2
Major Tool Steel Groups

Group	Letter Symbol*	Type	Properties	Uses
Water-Hardening	W	Plain carbon	Tough core and hard, wear-resistant surface	Cutlery, trim dies, cold header dies, wood chisels, hand punches
Shock-Resisting	S	Medium-carbon, low-alloy	Excellent toughness and high strength	Blank and trim dies, chisels, rivet sets, forming rolls, slitting cutters, and structural applications
Cold-Work	O	Oil-hardening	Wear-resistant to moderate temperatures	Dies and punches where high temperatures are not generated
	A	Medium-alloy, air-hardening	Minimum distortion and cracking on quenching	Dies, punches, and forming rolls
	D	High-carbon, high-chromium	High hardness and excellent wear resistance	Shear blades, long-run stamping dies and brick applications
Hot-Work	H	Chromium (H1-H19) Tungsten (H20-H39) Molybdenum (H40-H59)	Good toughness and resistance to softening at elevated temperatures	High-stressed components and high-temperature extrusion dies (May be water cooled in service without cracking)
High-Speed	T	Tungsten	High hardenability and hardness	Cutting tools and high-temperature structural components, drills, reamers, broaches, milling cutters, punches, and dies
	M	Molybdenum	High hardenability and hardness	Piercing punches, cutting tools, twist drills, planer tools, and insert cutter blades
Mold	P	Low-carbon	Low hardness and low resistance to work hardening	Dies and molds for low-temperature diecasting and for molds for plastics
Special-Purpose	L	Low-alloy	High toughness and good strength	Arbors, cams, chucks, spindles, drift pins, cold-forming rolls, and slitting cutters

* First letter of the specifications of the American Iron and Steel Institute and the Society of Automotive Engineers. These specifications for three water-hardening tool steels, for example, are AISI W-1, W-2, and W-5. Tool steels also are specified by the American Society for Testing and Materials. (Also see ASTM A600, *Standard Specification for High-Speed Tool Steels;* ASTM A681, *Standard Specification for Alloy Tool Steels;* and ASTM A686, *Standard Specification for Carbon Tool Steels.*)

Table 4.3
Compositions of Typical Tool Steels

Type	UNS Number	Composition, %[a] C	Mn	Si	Cr	Ni	V	W	Mo	Co
					Water-Hardening					
W1	T72301	0.70-1.50	0.10-0.40	0.10-0.40	0.15 max.	0.20 max.	0.10 max.	0.15 max.	0.10 max.	—
W2	T72302	0.85-1.50	0.10-0.40	0.10-0.40	0.15 max.	0.20 max.	0.15-0.35	0.15 max.	0.10 max.	—
W5	T72305	1.05-1.15	0.10-0.40	0.10-0.40	0.40-0.60	0.20 max.	0.10 max.	0.15 max.	0.10 max.	—
					Shock-Resisting					
S1	T41901	0.40-0.55	0.10-0.40	0.15-1.20	1.00-1.80	0.30 max.	0.15-0.30	1.50-3.00	0.50 max.	—
S2	T41902	0.40-0.55	0.30-0.50	0.90-1.20	—	0.30 max.	0.50 max.	—	0.30-0.60	—
S5	T41905	0.50-0.65	0.60.1.00	1.75-2.25	0.35 max.	—	0.35 max.	—	0.20-1.35	—
S6	T41906	0.40-0.50	1.20-1.50	2.00-2.50	1.20-1.50	—	0.20-0.40	—	0.30-0.50	—
S7	T41907	0.45-0.55	0.20.0.80	0.20-1.00	3.00-3.50	—	0.20-0.30[c]	—	1.30-1.80	—
					Cold-Work: Oil-Hardening					
O1	T31501	0.85-1.00	1.00-1.40	0.50 max.	0.40-0.60	0.30 max.	0.30 max.	0.40-0.60	—	—
O2	T31502	0.85-0.95	1.40-1.80	0.50 max.	0.35 max.	0.30 max.	0.30 max.	—	0.30 max.	—
O6[b]	T31506	1.25-1.55	0.30-1.10	0.55-1.50	0.30 max.	0.30 max.	—	—	0.20-0.30	—
O7	T31507	1.10-1.30	1.00 max.	0.60 max.	0.35-0.85	0.30 max.	0.40 max.	1.00-2.00	0.30 max.	—
					Cold-Work: Medium-Alloy, Air-Hardening					
A2	T30102	0.95-1.05	1.00 max.	0.50 max.	4.75-5.50	0.30 max.	0.15-0.50	—	0.90-1.40	—
A3	T30103	1.20-1.30	0.40-0.60	0.50 max.	4.75-5.50	0.30 max.	0.80-1.40	—	0.90-1.40	—
A4	T30104	0.95-1.05	1.80-2.20	0.50 max.	0.90-2.20	0.30 max.	—	—	0.90-1.40	—
A6	T30106	0.65-0.75	1.80-2.50	0.50 max.	0.90-1.20	0.30 max.	—	—	0.90-1.40	—
A7	T30107	2.00-2.85	0.80 max.	0.50 max.	5.00-5.75	0.30 max.	3.90-5.15	0.50-1.50	0.90-1.40	—
A8	T30108	0.50-0.60	0.50 max.	0.75-1.10	4.75-5.50	0.30 max.	—	1.00-1.50	1.15-1.65	—
A9	T30109	0.45-0.55	0.50 max.	0.95-1.15	4.75-5.50	1.25-1.75	0.80-1.40	—	1.30-1.80	—
A10[b]	T30110	1.25-1.50	1.60-2.10	1.00-1.50	—	1.55-2.05	—	—	1.25-1.75	—
					Cold-Work: High-Carbon, High-Chromium					
D2	T30402	1.40-1.60	0.60 max.	0.60 max.	11.00-13.00	0.30 max.	1.10 max.	—	0.70-1.20	1.00 max.
D3	T30403	2.00-2.35	0.60 max.	0.60 max.	11.00-13.50	0.30 max.	1.00 max.	1.00 max.	—	—
D4	T30404	2.05-2.40	0.60 max.	0.60 max.	11.00-13.00	0.30 max.	1.00 max.	—	0.70-1.20	—
D5	T30405	1.40-1.60	0.60 max.	0.60 max.	11.00-13.00	0.30 max.	1.00 max.	—	0.70-1.20	2.50-3.50
D7	T30407	2.15-2.50	0.60 max.	0.60 max.	11.50-13.50	0.30 max.	3.80-4.40	—	0.70-1.20	—
					Hot-Work: Chromium					
H10	T20810	0.35-0.45	0.25-0.70	0.80-1.20	3.00-3.75	0.30 max.	0.25-0.75	—	2.00-3.00	—
H11	T20811	0.33-0.43	0.20-0.50	0.80-1.20	4.75-5.50	0.30 max.	0.30-0.60	—	1.10-1.60	—
H12	T20812	0.30-0.40	0.20-0.50	0.80-1.20	4.75-5.50	0.30 max.	0.50 max.	1.00-1.70	1.25-1.75	—
H13	T20813	0.32-0.45	0.20-0.50	0.80-1.20	4.75-5.50	0.30 max.	0.80-1.20	—	1.10-1.75	—
H14	T20814	0.35-0.45	0.20-0.50	0.80-1.20	4.75-5.50	0.30 max.	—	4.00-5.25	—	—
H19	T20819	0.32-0.45	0.20-0.50	0.20-0.50	4.00-4.75	0.30 max.	1.75-2.20	3.75-4.50	0.30-0.55	4.00-4.50
					Hot-Work: Tungsten					
H21	T20821	0.26-0.36	0.15-0.40	0.15-0.50	3.00-3.75	0.30 max.	0.30-0.60	8.50-10.00	—	—
H22	T20822	0.30-0.40	0.15-0.40	0.15-0.40	1.75-3.75	0.30 max.	0.25-0.50	10.00-11.75	—	—
H23	T20823	0.25-0.35	0.15-0.40	0.15-0.60	11.00-12.75	0.30 max.	0.75-1.25	11.00-12.75	—	—
H24	T20824	0.42-0.53	0.15-0.40	0.15-0.40	2.50-3.50	0.30 max.	0.40-0.60	14.00-16.00	—	—
H25	T20825	0.22-0.32	0.15-0.40	0.15-0.40	3.75-4.50	0.30 max.	0.40-0.60	14.00-16.00	—	—
H26	T20826	0.45-0.55	0.15-0.40	0.15-0.40	3.75-4.50	0.30 max.	0.75-1.25	17.25-19.00	—	—

a. All steels except Type W have content maximums of 0.25 Cu, 0.03 P, and 0.03 S. Sulfur, where specified, may be increased to 0.06 to 0.15% to improve the machinability of Type H, T, and M steels.

b. Contains free graphite in the microstructure to improve machinability.

c. Optional.

Table 4.3 (continued)
Compositions of Typical Tool Steels

Type	UNS Number	Composition, %[a]								
		C	Mn	Si	Cr	Ni	V	W	Mo	Co
					Hot-Work: Molybdenum					
H42	T20842	0.55-0.70	0.15-0.40	—	3.75-4.50	0.30 max.	1.75-2.20	5.50-6.75	4.50-5.50	—
					High-Speed: Tungsten					
T1	T12001	0.65-0.80	0.10-0.40	0.20-0.40	3.75-4.00	0.30 max.	0.90-1.30	17.25-18.75	—	—
T2	T12002	0.80-0.90	0.20-0.40	0.20-0.40	3.75-4.50	0.30 max.	1.80-2.40	17.50-19.00	1.00 max.	—
T4	T12004	0.70-0.80	0.10-0.40	0.20-0.40	3.75-4.50	0.30 max.	0.80-1.20	17.50-19.00	0.40-1.00	4.75-5.75
T5	T12005	0.75-0.85	0.20-0.40	0.20-0.40	3.75-5.00	0.30 max.	1.80-2.40	17.50-19.00	0.50-1.25	7.00-9.50
T6	T12006	0.75-0.85	0.20-0.40	0.20-0.40	4.00-4.75	0.30 max.	1.50-2.10	18.50-21.00	0.40-1.00	11.00-13.00
T8	T12008	0.75-0.85	0.20-0.40	0.20-0.40	3.75-4.50	0.30 max.	1.80-2.40	13.25-14.75	0.40-1.00	4.25-5.75
T15	T12015	1.50-1.60	0.15-0.40	0.15-0.40	3.75-5.00	0.30 max.	4.50-5.25	11.75-13.00	1.00 max.	4.75-5.25
					High-Speed: Molybdenum					
M1	T11301	0.78-0.88	0.15-0.40	0.20-0.50	3.50-4.00	0.30 max.	1.00-1.35	1.40-2.10	8.20-9.20	—
M2	T11302	0.78-0.88; 0.95-1.05	0.15-0.40	0.20-0.45	3.75-4.50	0.30 max.	1.75-2.20	5.50-6.75	4.50-5.50	—
M3, class 1	T11313	1.00-1.10	0.15-0.40	0.20-0.45	3.75-4.50	0.30 max.	2.25-2.75	5.00-6.75	4.75-6.50	—
M3, class 2	T11323	1.15-1.25	0.15-0.40	0.20-0.45	3.75-4.50	0.30 max.	2.75-3.75	5.00-6.75	4.75-6.50	—
M4	T11304	1.25-1.40	0.15-0.40	0.20-0.45	3.75-4.75	0.30 max.	3.75-4.50	5.25-6.50	4.25-5.50	—
M6	T11306	0.75-0.85	0.15-0.40	0.20-0.45	3.75-4.50	0.30 max.	1.30-1.70	3.75-4.75	4.50-5.50	11.00-13.00
M7	T11307	0.97-1.05	0.15-0.40	0.20-0.55	3.50-4.00	0.30 max.	1.75-2.25	1.40-2.10	8.20-9.20	—
M10	T11310	0.84-0.94; 0.95-1.05	0.10-0.40	0.20-0.45	3.75-4.50	0.30 max.	1.80-2.20	—	7.75-8.50	—
M30	T11330	0.75-0.85	0.15-0.40	0.20-0.45	3.50-4.25	0.30 max.	1.00-1.40	1.30-2.30	7.75-9.00	4.50-5.50
M33	T11333	0.85-0.92	0.15-0.40	0.15-0.50	3.50-4.00	0.30 max.	1.00-1.35	1.30-2.10	9.00-10.00	7.75-8.75
M34	T11334	0.85-0.92	0.15-0.40	0.20-0.45	3.50-4.00	0.30 max.	1.90-2.30	1.40-2.10	7.75-9.20	7.75-8.75
M36	T11336	0.80-0.90	0.15-0.40	0.20-0.45	3.75-4.50	0.30 max.	1.75-2.25	5.50-6.50	4.50-5.50	7.75-8.75
M41	T11341	1.05-1.15	0.20-0.60	0.15-0.50	3.75-4.50	0.30 max.	1.75-2.25	6.25-7.00	3.25-4.25	4.75-5.75
M42	T11342	1.05-1.15	0.15-0.40	0.15-0.65	3.50-4.25	0.30 max.	0.95-1.35	1.15-1.85	9.00-10.00	7.75-8.75
M43	T11343	1.15-1.25	0.20-0.40	0.15-0.65	3.50-4.25	0.30 max.	1.50-1.75	2.25-3.00	7.50-8.50	7.75-8.75
M44	T11344	1.10-1.20	0.20-0.40	0.30-0.55	4.00-4.75	0.30 max.	1.85-2.20	5.00-5.75	6.00-7.00	11.00-12.00
M46	T11346	1.22-1.30	0.20-0.40	0.40-0.65	3.70-4.20	0.30 max.	3.00-3.30	1.90-2.20	8.00-8.50	7.80-8.80
M47	T11347	1.05-1.15	0.15-0.40	0.20-0.45	3.50-4.00	0.30 max.	1.15-1.35	1.30-1.80	9.25-10.00	4.75-5.25
					Mold					
P2	T51602	0.10 max.	0.10-0.40	0.10-0.40	0.75-1.25	0.10.0.50	—	—	0.15-0.40	—
P3	T51603	0.10 max.	0.20-0.60	0.40 max.	0.40-0.75	1.00-1.50	—	—	—	—
P4	T51604	0.12 max.	0.20-0.60	0.10-0.40	4.00-5.25	—	—	—	0.40-1.00	—
P5	T51605	0.10 max.	0.20-0.60	0.40 max.	2.00-2.50	0.35 max.	—	—	—	—
P6	T51606	0.05-0.15	0.35-0.70	0.10-0.40	1.25-1.75	3.25-3.75	—	—	—	—
P20	T51620	0.28-0.40	0.20-0.60	0.20-0.80	1.40-2.00	—	—	—	0.30-0.55	—
P21[d]	T51621	0.18-0.22	0.20-0.60	0.20-0.40	0.20-0.30	3.90-4.25	0.15-0.25	—	— Note d	—
					Special-Purpose					
L2	T61202	0.45-1.00	0.10-0.90	0.50 max.	0.70-1.20	—	0.10-0.30	—	0.25 max.	—
L6	T61206	0.65-0.75	0.25-0.80	0.50 max.	0.60-1.20	1.25-2.00	0.20-0.30[c]	—	0.50 max.	—

a. All steels except Type W have content maximums of 0.25% copper, 0.03% phosphorus, and 0.03% sulfur. Sulfur, where specified, may be increased to 0.06 to 0.15% to improve the machinability of Type H, T, and M steels.

b. Contains free graphite in the microstructure to improve machinability.

c. Optional.

d. Also contains 1.05-1.25 Al.

WATER-HARDENING TOOL STEELS

TOOL STEELS IN the water-hardening group (AISI W series) are essentially plain carbon steels, although some of the high-carbon types have small amounts of chromium and vanadium added to improve toughness and wear resistance. The carbon content varies between 0.60 and 1.40 percent. In general, plain carbon tool steels are less expensive than alloy tool steels. With proper heat treatment, these steels will have a hard martensitic surface with a tough core. They must be water-quenched for high hardness and therefore are subject to considerable distortion. Steels in the water-hardening group have the best machinability ratings of all tool steels, and they are the best with respect to loss of carbon during heat treatment. However, their resistance to wear and elevated temperatures is poor compared to higher alloy tool steels. They also are hardened at lower temperatures.

SHOCK-RESISTING TOOL STEELS

TOOL STEELS IN the shock-resisting group (AISI S series) are used for applications where toughness and the ability to withstand repeated shock are paramount. They are comparatively low in carbon content, varying between 0.40 and 0.65 percent. The principal alloying elements in these steels are silicon, chromium, tungsten, and sometimes molybdenum. Silicon strengthens the ferrite, while chromium increases hardenability and contributes slightly to wear resistance. Tungsten imparts some red hardness (i.e., resistance to softening at elevated temperature), while molybdenum aids in increasing hardenability. These steels are mostly air-hardening or oil-hardening.

The high silicon content in shock-resisting tool steels tends to accelerate decarburization, and suitable precautions should be taken during heat treatment to minimize this. These steels are considered fair in wear resistance, and machinability. Hardness usually is kept below 60 HRC.

Shock-resisting tool steels are used in the manufacture of forming tools, punches, chisels, pneumatic tools, shear blades and other applications where both high resistance to impact loading and moderate wear resistance are needed.

COLD-WORK TOOL STEELS

THIS GROUP OF tool steels (AISI O, A, and D series) are used for a variety of shearing and forming processes where the operation is performed cold. Cold-work tool steels are especially important because the majority of tool applications can be served by one or more of these steels.

Oil-Hardening Type Steels

THE OIL-HARDENING, LOW-ALLOY types (AISI O series) contain manganese and smaller amounts of chromium and tungsten. These steels have very good deformation resistance, and they are less likely to distort or crack during heat treatment than are the water-hardening steels. They are relatively inexpensive, and their high carbon content produces adequate wear resistance for short-run applications at or near room temperature. They also have good machinability, toughness, and resistance to decarburization. Typical applications are thread taps, solid threading dies, and forming tools.

Medium-Alloy, Air-Hardening Type Steels

THE AIR-HARDENING, MEDIUM-ALLOY types (AISI A series) with about 1% carbon contain up to 2% manganese, up to 5% chromium, and 1% molybdenum. The increased content of alloys, particularly manganese and molybdenum, provides greater hardenability and gives this alloy series its characteristic air-hardening properties. These alloys also have excellent deformation resistance and good wear resistance. They possess fair red hardness (maintaining hardness at elevated temperatures) and resistance to decarburization. These steels are used for blanking, forming, trimming, and thread-rolling dies.

High-Carbon, High-Chromium Type Steels

THE HIGH-CARBON, HIGH-CHROMIUM types (AISI D series) contain up to 2.25% carbon and 12.0% chromium. They also may contain molybdenum, vanadium, and cobalt. The combination of high carbon and high chromium gives these steels excellent resistance to wear and deformation. They also have good abrasion resistance. The low dimensional change in hardening makes these steels popular for blanking and piercing dies; drawing dies for wire, bars, and tubes; thread-rolling dies; and master gauges.

HOT-WORK TOOL STEELS

TOOL STEELS IN the hot-work group (AISI H series) have good resistance to softening at elevated temperatures, a property introduced earlier as *red hardness*. In many applications, a tool is exposed to high service temperatures because it is being used to hot-work some other material, as in the case of hot forging and extruding, die casting, or plastic molding. Hot-work tool steels have been developed for these applications.

The alloying elements that promote red hardness are chromium, tungsten, and molybdenum. This group of tool steels is divided into three types depending upon the primary alloying element. The amounts of chromium, tungsten, and molybdenum must total at least 5 percent in order for red hardness to be adequate.

Chromium Type Steels

THESE CHROMIUM STEELS (H10 to H19) contain at least 3.25 percent chromium and smaller amounts of vanadium, tungsten, and molybdenum. They have good red hardness because of their moderate chromium content, together with the three other strong carbide-forming elements. The low carbon and relatively low total alloy content promote toughness at hardnesses of 40 to 50 HRC. Higher tungsten and molybdenum contents will increase red hardness, but will reduce the toughness slightly.

These steels are extremely deep hardening, with the capacity to be air-hardened to full hardness in sections up to 12 in. (305 mm) thick. Their air-hardening qualities and balanced alloy content are responsible for low distortion during hardening. These steels are especially adapted to hot die work of all kinds, particularly extrusion dies, diecasting dies, forging dies, mandrels, and hot shears.

Tungsten Type Steels

THESE TUNGSTEN STEELS (H21 to H26) contain 9 to 18% tungsten and 2 to 12% chromium. Their higher alloy content relative to the chromium-type steels increases their resistance to softening at high temperatures. However, it also makes them more susceptible to brittleness at hardnesses of 45 to 55 HRC. They can be air hardened to reduce distortion, or quenched in oil or hot salt to minimize scaling. These steels have many of the characteristics of the high-speed tool steels but have better toughness. They can be used for high-temperature applications such as mandrels and extrusion dies for brass, nickel alloys, and steel.

Molybdenum Type Steel

THIS MOLYBDENUM TYPE (H42) hot-work steel is similar to the tungsten hot-work steels in characteristics and uses. It resembles in composition the various types of molybdenum high-speed tool steels, but it has lower carbon content and greater toughness. Its principal advantages over tungsten hot-work steels are lower initial cost and greater resistance to heat cracking or checking. As with all high-molybdenum steels, H42 steel requires care during heat treatment to avoid decarburization.

HIGH-SPEED TOOL STEELS

HIGH-SPEED TOOL STEELS are divided into two groups: molybdenum type (AISI M series) and tungsten type (AISI T series). The important mechanical properties are about the same. These steels are highly alloyed and normally contain large amounts of molybdenum or tungsten along with chromium, vanadium, and sometimes cobalt for additional red hardness. The carbon content ranges between 0.75 and 1.5%.

The major application for high-speed steels is for cutting tools, but they also are employed in the making of extrusion dies, burnishing tools, and blanking and piercing punches and dies.

Molybdenum Type Steels

MOLYBDENUM HIGH-SPEED TOOL steels classified as AISI M series contain from 3.5 to 9.5% molybdenum. All contain some chromium, and many have up to 12.0% cobalt. These steels are rated as deep hardening, have good wear resistance, fair machinability, and fair to poor resistance to decarburization.

Tungsten Type Steels

TUNGSTEN TOOL STEELS classified as AISI T series contain from 0.75 to 1.5% carbon and from 12.0 to 18.0% tungsten. These steels have all of the characteristics of molybdenum type, but they are not recommended for welding due to high tungsten and carbon content.

MOLD STEELS

MOLD STEELS (AISI P series) are relatively low in carbon, but their alloy content can be as high as 5.0%. These steels are used throughout the plastic molding industry to make injection molds, blow molds, and compression molds. A large portion of the mold steel produced is used in the as-tempered condition, with hardnesses in the range of 28-32 HRC. These steels can be carburized as well as nitrided, using the standard heat-treating practices applied to low-carbon steels.

SPECIAL-PURPOSE STEELS

THIS GROUP OF special-purpose steels (AISI L series) are not categorized in the usual groups because they were developed to handle the unique requirements of certain applications.

These special-purpose steels contain chromium as the principal alloying element in combination with molybdenum, nickel, and vanadium. The high chromium content not only increases hardenability; it also promotes wear resistance by the formation of hard complex iron-chromium carbides. Molybdenum also increases hardenability, while nickel increases toughness. Vanadium serves simply to refine the grain size.

These steels are oil-hardening; thus, they are only fair in resisting dimensional change. Typical applications include various machine tools that require both high wear resistance and good toughness such as bearings, rollers, clutch plates, cams, collets, and wrenches. The high-carbon types are used for arbors, dies, drills, taps, knurls, and gauges.

WELDABILITY

INCREASED ALLOY CONTENT of tool steels generally is related to increased wear resistance, maximum hardness, depth of hardening, and dimensional stability. For example, the air-hardening steels, which are higher in alloy additions than the water-hardening steels, also possess better mechanical properties and usually have superior performance as tools or dies. However, increased alloy content also diminishes weldability, which is the reason air-hardening steels require the greatest care during welding. Generally, in the AISI classification of tool steels, there is an inverse relationship between the alloy content of the steels and the weldability. The principal element influencing weldability is carbon; as the carbon content increases, the welding becomes more difficult. Thus, a steel's carbon equivalent is a good indicator of its ease of welding.[3]

3. One carbon equivalent frequently applied to this type of steel is the International Institute of Welding expression:

$$CE = \%C + \%Mn/6 + \%(Cr + Mo + V)/5 + \%(Ni + Cu)/15$$

HEAT TREATMENT

TOOL STEELS USUALLY are received from the supplier in the annealed condition. If practical, tools and dies should be welded in this condition because the steel will have the best ductility. Previously hardened tools should be annealed prior to welding if feasible. The welded tool should then be heat treated to provide the desired properties. Suggested annealing and hardening heat treatments for several tool steels are given in Table 4.4. However, the appropriate heat treatment for a specific tool steel should be obtained from the manufacturer. When a hardening heat treatment is required after welding, the weld metal also must respond favorably to the treatment. This must be considered when selecting a proper filler metal for the job.

Where hardened tools must be welded, appropriate procedures must be followed to minimize cracking. Almost all repair welding of tools falls into this category. Suitable preheat and postweld heat treatments may include stress relieving or tempering.[4] In general, the temperature of the part should not exceed the original tempering temperature.

4. Information on heat treating tool steels is given in the *Metals Handbook*, Vol. 4, 9th Ed., Metals Park, Ohio: American Society for Metals, 559-613, 1981.

FULL ANNEALING

ANNEALING OF TOOL steel is performed to soften the material prior to welding. It typically involves the following steps:

(1) Slow, gradual heating to a temperature that is slightly above the steel's transformation range

(2) Holding at temperature long enough to allow the entire piece to reach temperature, and completely transform to austenite

(3) Cooling at a slow rate to prevent martensitic transformation, yielding a soft microstructure

Figure 4.3 illustrates the use of a transformation diagram to plan a cooling cycle so that transformation from austenite to martensite is avoided. A maximum cooling rate for a typical tool steel is approximately 25 °F to 50 °F (14 °C to 28 °C) per hour depending on the specific alloy involved, down to about 1000 °F (538 °C). Further cooling usually can be performed in still air at a faster rate. The cooling rate also must be adjusted to suit the tool size so that thermal stresses are

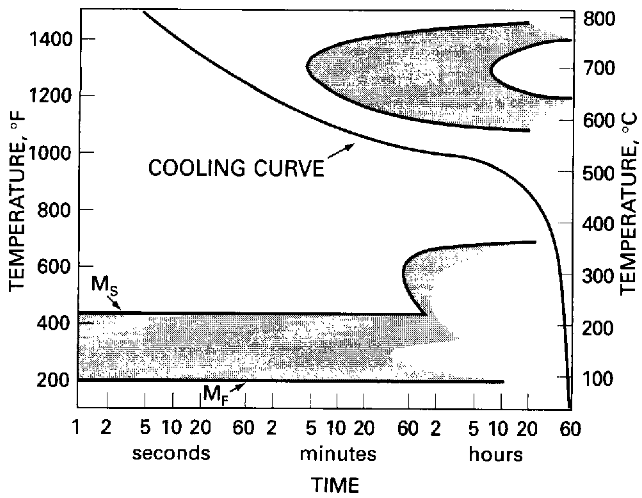
Table 4.4
Typical Heat-Treating Procedures for Representative Tool Steels

Type	Group	Annealing Temperature, °F (°C)	Austenitizing Temperature, °F (°C)	Quenching Media[a]	Tempering Temperature, °F (°C)	Hardness, HRC[b]
W1, W2	Water-hardening	1360-1450 (738-788)	1400-1550 (760-843)	B, W	350-650 (177-343)	54-64
S1	Shock-resisting	1450-1500 (788-816)	1650-1750 (899-954)	O	400-1200 (204-649)	40-58
S5	Shock-resisting	1425-1475 (773-801)	1600-1700 (871-927)	O	350-800 (177-426)	50-60
S7	Shock-resisting	1500-1550 (816-843)	1700-1750 (927-954)	A, O	400-1100[c] (204-621)	47-58
O1	Oil-hardening	1400-1450 (760-788)	1450-1500 (788-816)	O	350-500 (177-260)	57-62
O6	Oil-hardening	1400-1450 (766-788)	1450-1500 (788-816)	O	350-600 (177-316)	58-63
A2	Air-hardening	1550-1600 (843-871)	1700-1800 (927-982)	A	350-1000[c] (177-538)	57-62
A4	Air-hardening	1360-1400 (738-760)	1500-1600 (816-871)	A	350-800[c] (177-426)	54-62
D2	Air-hardening	1600-1650 (871-899)	1800-1875 (982-1023)	A	400-1000[c] (204-538)	54-61
H12, H13, H19	Hot-work	1550-1600 (843-871)	1825-1900 (996-1037)	A	1000-1200[c] (538-649)	38-56
M1	High-speed	1500-1600 (816-871)	2150-2225 (1177-1218)	A, O, S	1000-1100[c] (538-593)	60-65
M2	High-speed	1600-1650 (871-899)	2175-2250 (1190-1232)	A, O, S	1000-1100[c] (538-593)	60-65
M10	High-speed	1500-1600 (816-871)	2150-2225 (1177-1218)	A, O, S	1000-1100[c] (538-593)	60-65
T1, T2, T4	High-speed	1600-1650 (871-899)	2300-2375 (1260-1301)	A, O, S	1000-1100[c] (538-593)	60-66
P20	Mold steel	1400-1450 (760-788)	1500-1600 (816-871)	O	900-1100 (482-593)	28-42

a. A – air cool, B – brine quench, O – oil quench, S – salt-bath quench, W – water quench

b. Hardness after tempering

c. Double temper



Note: M_S (martensite start) is where martensite transformation begins. M_F (martensite finish) represents 100% martensite.

Figure 4.3—Cooling Curve Avoiding Martensitic Transformation Plotted Over Isothermal Transformation Diagram

minimized. Small tools can be cooled at faster rates than large tools. If the cooling cycle will be planned using an isothermal transformation diagram, rather than a continuous cooling transformation diagram, one must compensate for the fact that the continuous cooling transformation diagram is slightly shifted to longer times and lower temperatures compared to the isothermal transformation diagram.

The annealing equipment must provide the means to prevent carburization or decarburization. Atmosphere furnaces or salt baths may be used for heating. Pack annealing also may be used in some cases.

STRESS RELIEVING

STRESS RELIEVING IS used to reduce internal stresses caused by welding or machining. It is done by heating the tool at a temperature below the steel's transformation range, the temperatures at which a change in phase occurs.

For materials that have not been hardened, a stress relieving temperature of approximately 950-1100 °F (510-590 °C) is normally used. When the tool is in the hardened condition, it may be stress relieved by tempering. Stress relief of a tool that was welded in the hardened condition should not be done above the tempering temperature of the steel. Such a treatment would alter the hardness and toughness of the entire tool, whereas the welding only softens the heat-affected zone. Heating and cooling rates for stress relieving should be similar to those used for annealing.

NORMALIZING

NORMALIZING IS THE process of heating to a suitable temperature above the steel's transformation range, followed by cooling in air to a temperature substantially below the transformation range, at a rate sufficient to form a microstructure suitable for subsequent hardening. This process is sometimes combined with stress relieving. Most tool steels that have been annealed do not require normalizing.

AUSTENITIZING

THIS OPERATION IS accomplished by slowly heating the steel to a temperature above its transformation range and holding at that temperature long enough for the resolutioning of the carbides. Small tools may be heated more quickly than large ones. High-alloy steels are normally heated very slowly to a temperature just below the transformation range of the steel. They are then heated quickly into the austenitizing temperature range, which may be several hundred degrees higher.

Several precautions are necessary when austenitizing tool steels. First, tools and dies should be heated in a suitable protective atmosphere or vacuum to avoid scaling and decarburization. Steels will scale heavily in an oxidizing atmosphere, depending upon the temperature and time. Decarburization also will occur, especially in the austenitizing temperature range. As a precaution against grain growth, excessive soaking time should be avoided. Finally, the tool should be properly supported during austenitizing to prevent sagging and distortion.

QUENCHING

QUENCHING IS PERFORMED to provide the cooling required for transformation from austenite to martensite. Tool steels are quenched in water, brine, oil, polymers, salt, or air depending on alloy composition and section thickness. The quenching medium must cool the workpiece at a sufficient rate to obtain full hardness. However, an excessive cooling rate should be avoided because of the danger of cracking the tool.

Air-hardening tool steels may be quenched to between 1000 and 1200 °F (538 and 649 °C). The workpiece should be removed from the quenching medium as soon as the tool temperature has stabilized. If the holding time is too long, austenite will start to transform. After hot quenching, the tool can be air cooled or oil quenched to about 150 °F (66 °C) before tempering.

Water-hardening steels tend to distort and change size during quenching. Internal stresses developed during