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Wrought Tool Steels

Revised by Alan M. Bayer, Teledyne Vasco, and Lee R. Walton, Latrobe Steel Company

Introduction

A TOOL STEEL is any steel used to make tools for cutting, forming, or otherwise shaping a material into a part or component adapted to a definite use. The earliest tool steels were simple, plain carbon steels, but by 1868 and increasingly in the early 20th century, many complex, highly alloyed tool steels were developed. These complex alloy tool steels, which contain, among other elements, relatively large amounts of tungsten, molybdenum, vanadium, manganese, and chromium, make it possible to meet increasingly severe service demands and to provide greater dimensional control and freedom from cracking during heat treatment. Many alloy tool steels are also widely used for machinery components and structural applications in which particularly stringent requirements must be met, for example, high-temperature springs, ultrahigh-strength fasteners, special-purpose valves, and bearings of various types for elevated-temperature service.

In service, most tools are subjected to extremely high loads that are applied rapidly. The tools must withstand these loads a great number of times without breaking and without undergoing excessive wear or deformation. In many applications, tool steels must provide this capability under conditions that develop high temperatures in the tool. 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 optimum combination of properties.

Most tool steels are wrought products, but precision castings can be used to advantage in some applications. The powder metallurgy (P/M) process is also used in making tool steels. It provides, first, a more uniform carbide size and distribution in large sections and, second, special compositions that are difficult or impossible to produce by melting and casting and then mechanically working the cast product.

For typical wrought tool steels, raw materials (including scrap) are carefully selected, not only for alloy content, but also for qualities that ensure cleanliness and homogeneity in the finished product. Tool steels are generally melted in relatively small-tonnage electric arc furnaces and refined in an argon oxygen decarburization (AOD) vessel to achieve composition tolerances at low cost, good cleanliness, and precise control of melting conditions. Special refining and secondary remelting processes have been introduced to satisfy particularly difficult demands regarding tool steel quality and performance. The medium-to-high alloy contents of many tool steels require careful control of forging and rolling, which often results in a large amount of process scrap. Semifinished and finished bars are given rigorous in-process and final inspection. This inspection can be so extensive that both ends of each bar may be inspected for macrostructure (etch quality), cleanliness, hardness, grain size, annealed structure, and hardening ability. Inspection may also require that the entire bar be subjected to magnetic and ultrasonic inspections for surface and internal discontinuities (see the articles "Magnetic Particle Inspection" and "Ultrasonic Inspection" in *Nondestructive Evaluation and Quality Control,* Volume 17 of *ASM Handbook,* formerly 9th Edition *Metals Handbook*). It is important that finished tool steel bars have minimal decarburization within carefully controlled limits, which requires that annealing be done by special procedures under closely controlled conditions.

Such precise production practices and stringent quality controls contribute to the high cost of tool steels, as do the expensive alloying element they contain. Insistence on quality in the manufacture of these specialty steels is justified, however, because tool steel bars generally are made into complicated cutting and forming tools worth many times the cost of the steel itself. Although some standard constructional alloy steels resemble tool steels in composition, they are seldom used for expensive tooling because, in general, they are not manufactured to the same rigorous quality standards as are tool steels.

The performance of a tool in service depends on the proper design of the tool, accuracy with which the tool is made, selection of the proper tool steel, and application of the proper heat treatment. A tool can perform successfully in service only when all four of these requirements have been fulfilled.

With few exceptions, all tool steels must be heat treated to develop specific combinations of wear resistance, resistance to deformation or breaking under high loads, and resistance to softening at elevated temperatures. Some tool steels are available as prehardened bar or other products. A few simple shapes may also be obtained directly from tool steel producers in correctly heat-treated condition. However, most tool steels are first formed or machined to produce the required shape and then heat treated by the tool manufacturer or ultimate user.

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Classification and Characteristics

Table 1 gives composition limits for the tool steels most commonly used in 1989. Each group of tool steels of similar composition and properties is identified by a capital letter; within each group, individual tool steel types are assigned code numbers. Table 2 cross references U.S. tool steel designations with their foreign equivalents. Table 3 identifies tool steel types that have been dropped from active listings because they are no longer commonly used.

Table 1 Composition limits of principal types of tool steels

Designation		Composition[(a)], %								
AISI	**UNS**	**C**	**Mn**	**Si**	**Cr**	**Ni**	**Mo**	**W**	**V**	Co
Molybdenum high-speed steels										
M1	T11301	0.78-0.88	0.15-0.40	0.20-0.50	3.50-4.00	0.30 max	8.20-9.20	1.40-2.10	1.00-1.25	...
M2	T11302	0.78-0.88; 0.95-1.05	0.15-0.40	0.20-0.45	3.75-4.50	0.30 max	4.50-5.50	5.50-6.75	1.75-2.20	...
M3, class 1	T11313	1.00-1.10	0.15-0.40	0.20-0.45	3.75-4.50	0.30 max	4.75-6.50	5.00-6.75	2.25-2.75	...
M3, class 2	T11323	1.15-1.25	0.15-0.40	0.20-0.45	3.75-4.50	0.30 max	4.75-6.50	5.00-6.75	2.75-3.75	...
M4	T11304	1.25-1.40	0.15-0.40	0.20-0.45	3.75-4.75	0.30 max	4.25-5.50	5.25-6.50	3.75-4.50	...
M7	T11307	0.97-1.05	0.15-0.40	0.20-0.55	3.50-4.00	0.30 max	8.20-9.20	1.40-2.10	1.75-2.25	...
M10	T11310	0.84-0.94; 0.95-1.05	0.10-0.40	0.20-0.45	3.75-450	0.30 max	7.75-8.50	. . .	1.80-2.20	...
M30	T11330	0.75-0.85	0.15-0.40	0.20-0.45	3.50-4.25	0.30 max	7.75-9.00	1.30-2.30	1.00-1.40	**4.50-5.50**
M33	T11333	0.85-0.92	0.15-0.40	0.15-0.50	3.50-4.00	0.30 max	9.00-10.00	1.30-2.10	1.00-1.35	**7.75-8.75**

M34	T11334	0.85-0.92	0.15-0.40	0.20-0.45	3.50-4.00	0.30 max	7.75-9.20	1.40-2.10	1.90-2.30	**7.75-8.75**
M35	T11335	0.82-0.88	0.15-0.40	0.20-0.45	3.75-4.50	0.30 max	4.50-5.50	5.50-6.75	1.75-2.20	**4.50-5.50**
M36	T11336	0.80-0.90	0.15-0.40	0.20-0.45	3.75-4.50	0.30 max	4.50-5.50	5.50-6.50	1.75-2.25	**7.75-8.75**
M41	T11341	1.05-1.15	0.20-0.60	0.15-0.50	3.75-4.50	0.30 max	3.25-4.25	6.25-7.00	1.75-2.25	**4.75-5.75**
M42	T11342	1.05-1.15	0.15-0.40	0.15-0.65	3.50-4.25	0.30 max	9.00-10.00	1.15-1.85	0.95-1.35	**7.75-8.75**
M43	T11343	1.15-1.25	0.20-0.40	0.15-0.65	3.50-4.25	0.30 max	7.50-8.50	2.25-3.00	1.50-1.75	**7.75-8.75**
M44	T11344	1.10-1.20	0.20-0.40	0.30-0.55	4.00-4.75	0.30 max	6.00-7.00	5.00-5.75	1.85-2.20	**11.00-12.25**
M46	T11346	1.22-1.30	0.20-0.40	0.40-0.65	3.70-4.20	0.30 max	8.00-8.50	1.90-2.20	3.00-3.30	**7.80-8.80**
M47	T11347	1.05-1.15	0.15-0.40	0.20-0.45	3.50-4.00	0.30 max	9.25-10.00	1.30-1.80	1.15-1.35	**4.75-5.25**
M48	T11348	1.42-1.52	0.15-0.40	0.15-0.40	3.50-4.00	0.30 max	4.75-5.50	9.50-10.50	2.75-3.25	**8.00-10.00**
M62	T11362	1.25-1.35	0.15-0.40	0.15-0.40	3.50-4.00	0.30 max	10.00-11.00	5.75-6.50	1.80-2.10	**. . .**
Tungsten high-speed steels										
T1	T12001	0.65-0.80	0.10-0.40	0.20-0.40	3.75-4.50	0.30 max	. . .	17.25-18.75	0.90-1.30	**. . .**
T2	T12002	0.80-0.90	0.20-0.40	0.20-0.40	3.75-4.50	0.30 max	1.00 max	17.50-19.00	1.80-2.40	**. . .**
T4	T12004	0.70-0.80	0.10-0.40	0.20-0.40	3.75-4.50	0.30 max	0.40-1.00	17.50-19.00	0.80-1.20	**4.25-5.75**
T5	T12005	0.75-0.85	0.20-0.40	0.20-0.40	3.75-5.00	0.30 max	0.50-1.25	17.50-19.00	1.80-2.40	**7.00-9.50**

T6	T12006	0.75-0.85	0.20-0.40	0.20-0.40	4.00-4.75	0.30 max	0.40-1.00	18.50-21.00	1.50-2.10	**11.00-13.00**
T8	T12008	0.75-0.85	0.20-0.40	0.20-0.40	3.75-4.50	0.30 max	0.40-1.00	13.25-14.75	1.80-2.40	**4.25-5.75**
T15	T12015	1.50-1.60	0.15-0.40	0.15-0.40	3.75-5.00	0.30 max	1.00 max	11.75-13.00	4.50-5.25	**4.75-5.25**
Intermediate high-speed steels										
M50	T11350	0.78-0.88	0.15-0.45	0.20-0.60	3.75-4.50	0.30 max	3.90-4.75	. . .	0.80-1.25	**. . .**
M52	T11352	0.85-0.95	0.15-0.45	0.20-0.60	3.50-4.30	0.30 max	4.00-4.90	0.75-1.50	1.65-2.25	**. . .**
Chromium hot-work steels										
H10	T20810	0.35-0.45	0.25-0.70	0.80-1.20	3.00-3.75	0.30 max	2.00-3.00	. . .	0.25-0.75	**. . .**
H11	T20811	0.33-0.43	0.20-0.50	0.80-1.20	4.75-5.50	0.30 max	1.10-1.60	. . .	0.30-0.60	**. . .**
H12	T20812	0.30-0.40	0.20-0.50	0.80-1.20	4.75-5.50	0.30 max	1.25-1.75	1.00-1.70	0.50 max	**. . .**
H13	T20813	0.32-0.45	0.20-0.50	0.80-1.20	4.75-5.50	0.30 max	1.10-1.75	. . .	0.80-1.20	**. . .**
H14	T20814	0.35-0.45	0.20-0.50	0.80-1.20	4.75-5.50	0.30 max	. . .	4.00-5.25	. . .	**. . .**
H19	T20819	0.32-0.45	0.20-0.50	0.20-0.50	4.00-4.75	0.30 max	0.30-0.55	3.75-4.50	1.75-2.20	**4.00-4.50**
Tungsten hot-work steels										
H21	T20821	0.26-0.36	0.15-0.40	0.15-0.50	3.00-3.75	0.30 max	. . .	8.50-10.00	0.30-0.60	**. . .**
H22	T20822	0.30-0.40	0.15-0.40	0.15-0.40	1.75-3.75	0.30 max	. . .	10.00-11.75	0.25-0.50	**. . .**
H23	T20823	0.25-0.35	0.15-	0.15-	11.00-	0.30	. . .	11.00-	0.75-1.25	**. . .**

			0.40	0.60	12.75	max		12.75		
H24	T20824	0.42-0.53	0.15-0.40	0.15-0.40	2.50-3.50	0.30 max	. . .	14.00-16.00	0.40-0.60	. . .
H25	T20825	0.22-0.32	0.15-0.40	0.15-0.40	3.75-4.50	0.30 max	. . .	14.00-16.00	0.40-0.60	. . .
H26	T20826	0.45-0.55[(b)]	0.15-0.40	0.15-0.40	3.75-4.50	0.30 max	. . .	17.25-19.00	0.75-1.25	. . .
Molybdenum hot-work steels										
H42	T20842	0.55-0.70[(b)]	0.15-0.40	. . .	3.75-4.50	0.30 max	4.50-5.50	5.50-6.75	1.75-2.20	. . .
Air-hardening, medium-alloy, cold-work steels										
A2	T30102	0.95-1.05	1.00 max	0.50 max	4.75-5.50	0.30 max	0.90-1.40	. . .	0.15-0.50	. . .
A3	T30103	1.20-1.30	0.40-0.60	0.50 max	4.75-5.50	0.30 max	0.90-1.40	. . .	0.80-1.40	. . .
A4	T30104	0.95-1.05	1.80-2.20	0.50 max	0.90-2.20	0.30 max	0.90-1.40	. . .	. . .	. . .
A6	T30106	0.65-0.75	1.80-2.50	0.50 max	0.90-1.20	0.30 max	0.90-1.40	. . .	. . .	. . .
A7	T30107	2.00-2.85	0.80 max	0.50 max	5.00-5.75	0.30 max	0.90-1.40	0.50-1.50	3.90-5.15	. . .
A8	T30108	0.50-0.60	0.50 max	0.75-1.10	4.75-5.50	0.30 max	1.15-1.65	1.00-1.50	. . .	. . .
A9	T30109	0.45-0.55	0.50 max	0.95-1.15	4.75-5.50	1.25-1.75	1.30-180	. . .	0.80-1.40	. . .
A10	T30110	1.25-1.50[(c)]	1.60-2.10	1.00-1.50	. . .	1.55-2.05	1.25-1.75		. . .	. . .
High-carbon, high-chromium, cold-work steels										
D2	T30402	1.40-1.60	0.60 max	0.60 max	11.00-13.00	0.30 max	0.70-1.20	. . .	1.10 max	. . .

D3	T30403	2.00-2.35	0.60 max	0.60 max	11.00-13.50	0.30 max	. . .	1.00 max	1.00 max	**. . .**
D4	T30404	2.05-2.40	0.60 max	0.60 max	11.00-13.00	0.30 max	0.70-1.20	. . .	1.00 max	**. . .**
D5	T30405	1.40-1.60	0.60 max	0.60 max	11.00-13.00	0.30 max	0.70-1.20	. . .	1.00 max	**2.50-3.50**
D7	T30407	2.15-2.50	0.60 max	0.60 max	11.50-13.50	0.30 max	0.70-1.20	. . .	3.80-4.40	**. . .**
Oil-hardening cold-work steels										
O1	T31501	0.85-1.00	1.00-1.40	0.50 max	0.40-0.60	0.30 max	. . .	0.40-0.60	0.30 max	**. . .**
O2	T31502	0.85-0.95	1.40-1.80	0.50 max	0.50 max	0.30 max	0.30 max	. . .	0.30 max	**. . .**
O6	T31506	1.25-1.55[c]	0.30-1.10	0.55-1.50	0.30 max	0.30 max	0.20-0.30	. . .	. . .	**. . .**
O7	T31507	1.10-1.30	1.00 max	0.60 max	0.35-0.85	0.30 max	0.30 max	1.00-2.00	0.40 max	**. . .**
Shock-resisting steels										
S1	T41901	0.40-0.55	0.10-0.40	0.15-1.20	1.00-1.80	0.30 max	0.50 max	1.50-3.00	0.15-0.30	**. . .**
S2	T41902	0.40-0.55	0.30-0.50	0.90-1.20	. . .	0.30 max	0.30-0.60	. . .	0.50 max	**. . .**
S5	T41905	0.50-0.65	0.60-1.00	1.75-2.25	0.50 max	. . .	0.20-1.35	. . .	0.35 max	**. . .**
S6	T41906	0.40-0.50	1.20-1.50	2.00-2.50	1.20-1.50	. . .	0.30-0.50	. . .	0.20-0.40	**. . .**
S7	T41907	0.45-0.55	0.20-0.90	0.20-1.00	3.00-3.50	. . .	1.30-1.80	. . .	0.20-0.30[d]	**. . .**
Low-Alloy special-purpose tool steels										
L2	T61202	0.45-1.00[b]	0.10-	0.50	0.70-1.20	. . .	0.25 max	. . .	0.10-0.30	**. . .**

			0.90	max						
L6	T61206	0.65-0.75	0.25-0.80	0.50 max	0.60-1.20	1.25-2.00	0.50 max	. . .	0.20-0.30(d)	**. . .**
Low-carbon mold steels										
P2	T51602	0.10 max	0.10-0.40	0.10-0.40	0.75-1.25	0.10-0.50	0.15-0.40	. . .	. . .	**. . .**
P3	T51603	0.10 max	0.20-0.60	0.40 max	0.40-0.75	1.00-1.50	. . .	. . .	. . .	**. . .**
P4	T51604	0.12 max	0.20-0.60	0.10-0.40	4.00-5.25	. . .	0.40-1.00	. . .	. . .	**. . .**
P5	T51605	0.10 max	0.20-0.60	0.40 max	2.00-2.50	0.35 max	. . .	. . .	. . .	**. . .**
P6	T51606	0.05-0.15	0.35-0.70	0.10-0.40	1.25-1.75	3.25-3.75	. . .	. . .	. . .	**. . .**
P20	T51620	0.28-0.40	0.60-1.00	0.20-0.80	1.40-2.00	. . .	0.30-0.55	. . .	. . .	**. . .**
P21	T51621	0.18-0.22	0.20-0.40	0.20-0.40	0.50 max	3.90-4.25	. . .	. . .	0.15-0.25	**1.05-1.25Al**
Water-hardening tool steels										
W1	T72301	0.70-1.50(e)	0.10-0.40	0.10-0.40	0.15 max	0.20 max	0.10 max	0.15 max	0.10 max	**. . .**
W2	T72302	0.85-1.50(e)	0.10-0.40	0.10-0.40	0.15 max	0.20 max	0.10 max	0.15 max	0.15-0.35	**. . .**
W5	**T72305**	**1.05-1.15**	**0.10-0.40**	**0.10-0.40**	**0.40-0.60**	**0.20 max**	**0.10 max**	**0.15 max**	**0.10 max**	**. . .**

(a) All steels except group W contain 0.25 max Cu, 0.03 max P, and 0.03 max S; group W steels contain 0.20 max Cu, 0.025 max P, and 0.025 max S. Where specified, sulfur may be increased to 0.06 to 0.15% to improve machinability of group A, D, H, M, and T steels.

(b) Available in several carbon ranges.

(c) Contains free graphite in the microstructure.

(d) Optional.

(e) Specified carbon ranges are designated by suffix numbers.

Table 2 Cross reference to tool steels. Similar specifications for tool steels established by the United States, West Germany, Japan, Great Britain, France, and Sweden are presented below. Exact chemical compositions for the non-U.S. tool steels can be found in Ref 1 and 2.

United States (AISI)	**West Germany (DIN)**(a)	**Japan (JIS)**(b)	**Great Britain (B.S.)**(c)	**France (AFNOR)**(d)	Sweden (SS_{14})
Molybdenum high-speed steels (ASTM A 600)					
M1	1.3346	. . .	4659 BM1	A35-590 4441 Z85DCWV08-04-02-01	**2715**
M2, reg C	1.3341, 1.3343, 1.3345, 1.3553, 1.3554	G4403 SKH51 (SKH9)	4659 BM2	A35-590 4301 Z85WDCV06-05-04-02	**2722**
M2, high C	1.3340, 1.3342	. . .	. . .	A35-590 4302 Z90WDCV06-05-04-02	**. . .**
M3, class 1	. . .	G4403 SKH52	. . .	. . .	**. . .**
M3, class 2	1.3344	G4403 SKH53	. . .	A35-590 4360 Z120 WDCV06-05-04-03	**(USA M3 class 2)**
M4	. . .	G4403 SKH54	4659 BM4	A35-590 4361 Z130 WDCV06-05-04-04	**. . .**
M7	1.3348	G4403 SKH58	. . .	A35-590 4442 Z100DCWV09-04-02-02	**2782**
M10, reg C	. . .	. . .	. . .	. . .	**. . .**
M10, high C	. . .	. . .	. . .	. . .	**. . .**
M30	1.3249	. . .	4659 BM34	. . .	**. . .**
M33	1.3249	. . .	4659 BM34	. . .	**. . .**

M34	1.3249	. . .	4659 BM34	. . .	**. . .**
M35	1.3243	G4403 SKH55	. . .	A35-590 4371 Z85WDKCV06-05-05-04-02 A35-590 4372 Z9WDKCV06-05-05-04-02	**. . .**
M36	1.3243	G4403 SKH55 G4403 SKH56	. . .	A35-590 4371 Z85WDKCV06-05-05-04	**2723**
M41	1.3245, 1.3246	G4403 SKH55	. . .	A35-590 4374 Z110WKCDV07-05-04-04	**2736**
M42	1.3247	G4403 SKH59	4659 BM42	A35-590 4475 Z110DKCWV09-08-04-02	**. . .**
M43	. . .	. . .	. . .	A35-590 4475 Z110DKCWV09-08-04-02-01	**. . .**
M44	1.3207	G4403 SKH57	4659 (USA M44)	A35-590 4376 Z130KWDCV12-07-06-04-03	**. . .**
M46	1.3247	. . .	. . .	. . .	**. . .**
M47	1.3247	. . .	. . .	. . .	**. . .**
Intermediate high-speed steels					
M50	1.2369, 1.3551	. . .	. . .	A35-590 3551 Y80DCV42.16	**(USA M50)**
M52	. . .	. . .	. . .	. . .	**. . .**
Tungsten high-speed steels (ASTM A 600)					
T1	1.3355, 1.3558	G4403 SKH2	4659 BT1	A35-590 4201 Z80WCV18-04-01	**. . .**
T2	. . .	. . .	4659 BT2 4659 BT20	4203 18-0-2	**. . .**
T4	1.3255	G4403 SKH3	4659 BT4	A35-590 4271 Z80WKCV18-05-04-01	**. . .**

T5	1.3265	G4403 SKH4	4659 BT5	A35-590 4275 Z80WKCV18-10-04-02	**(USA T5)**
T6	1.3257	G4403 SKH4B	4659 BT6	. . .	**. . .**
T8	. . .	. . .	. . .	. . .	**. . .**
T15	1.3202	G4403 SKH10	4659 BT15	A35-590 4171 Z160WKVC12-05-05-04	**(USA T15)**
Chromium hot-work steels (ASTM A 681)					
H10	1.2365, 1.2367	G4404 SKD7	4659 BH10	A35-590 3451 32DCV28	**. . .**
H11	1.2343, 1.7783, 1.7784	G4404 SKD6	4659 BH11	A35-590 3431 FZ38CDV5	**. . .**
H12	1.2606	G4404 SKD62	4659 BH12	A35-590 3432 Z35CWDV5	**. . .**
H13	1.2344	G4404 SKD61	4659 BH13 4659 H13	A35-590 3433 Z40CDV5	**2242**
H14	1.2567	G4404 SKD4	. . .	3541 Z40WCV5	**. . .**
H19	1.2678	G4404 SKD8	4659 BH19	. . .	**. . .**
Tungsten hot-work steels (ASTM A 681)					
H21	1.2581	G4404 SKD5	4659 BH21 4659 H21A	A35-590 3543 Z30WCV9	**2730**
H22	1.2581	G4404 SKD5	. . .	. . .	**. . .**
H23	1.2625	. . .	. . .	. . .	**. . .**
H24	. . .	. . .	. . .	. . .	**. . .**
H25	. . .	. . .	. . .	. . .	**. . .**

H26	. . .	. . .	4659 BH26	. . .	**. . .**
Molybdenum hot-work steels (ASTM A 681)					
H42	. . .	. . .	. . .	3548 Z65WDCV6.05	**. . .**
Air-hardening, medium-alloy, cold-work steels (ASTM A 681)					
A2	1.2363	G4404 SKD12	4659 BA2	A35-590 2231 Z100CDV5	**2260**
A3	. . .	. . .	. . .	. . .	**. . .**
A4	. . .	. . .	. . .	. . .	**. . .**
A5	. . .	. . .	. . .	. . .	**. . .**
A6	. . .	. . .	4659 BA6	. . .	**. . .**
A7	. . .	. . .	. . .	. . .	**. . .**
A8	1.2606	G4404 SKD62	. . .	3432 Z38CDWV5	**. . .**
A9	. . .	. . .	. . .	. . .	**. . .**
A10	. . .	. . .	. . .	. . .	**. . .**
High-carbon, high-chromium, cold-work steels (ASTM A 681)					
D2	1.2201, 1.2379, 1.2601	G4404 SKD11	4659 (USA D2) 4659 BD2 4659 BD2A	A35-590 2235 Z160CDV12	**2310**
D3	1.2080, 1.2436, 1.2884	G4404 SKD1 G4404 SKD2	4659 BD3	A35-590 2233 Z200C12	**. . .**
D4	1.2436, 1.2884	G4404 SKD2	4659 (USA D4)	A35-590 2234 Z200CD12	**2312**

D5	1.2880	. . .	. . .	A35-590 2236 Z160CKDV 12.03	**. . .**
D7	1.2378	. . .	. . .	2237 Z230CVA 12.04	**. . .**
Oil-hardening cold-work steels (ASTM A 681)					
O1	1.2510	G4404 SKS21 G4404 SKS3 G4404 SKS93 G4404 SKS94 G4404 SKS95	4659 BO1	A35-590 2212 90 MWCV5	**2140**
O2	1.2842	. . .	4659 (USA O2) 4659 BO2	A35-590 2211 90MV8	**. . .**
O6	1.2206	. . .	. . .	A35-590 2132 130C3	**. . .**
O7	1.2414, 1.2419, 1.2442, 1.2516, 1.2519	G4404 SKS2	. . .	A35-590 2141 105WC13	**. . .**
Shock-resisting steels (ASTM A 681)					
S1	1.2542, 1.2550	G4404 SKS41	4659 BS1	A35-590 2341 55WC20	**2710**
S2	1.2103	. . .	4659 BS2	A35-590 2324 Y45SCD6	**. . .**
S5	1.2823	. . .	4659 BS5	. . .	**. . .**
S6	. . .	. . .	. . .	. . .	**. . .**
S7	. . .	. . .	. . .	. . .	**. . .**
Low-alloy special-purpose steels (ASTM A 681)					
L2	1.2235, 1.2241, 1.2242,,1.2243	G4404 SKT3 G4410 SKC11	. . .	A35-590 3335 55CNDV4	**. . .**

L6	1.2713, 1.2714	G4404 SKS51 G4404 SKT4	. . .	A35-590 3381 55NCDV7	**. . .**
Low-carbon mold steels (ASTM A 681)					
P2	. . .	. . .	. . .	. . .	**. . .**
P3	1.5713	. . .	. . .	2881 Y10NC6	**. . .**
P4	1.2341	. . .	. . .	. . .	**(USA P4)**
P5	. . .	. . .	. . .	. . .	**. . .**
P6	1.2735, 1.2745	G4410 SKC31	. . .	2882 10NC12	**. . .**
P20	1.2311, 1.2328, 1.2330	. . .	4659 (USA P20)	A35-590 2333 35CMD7	**(USA P20)**
P21	. . .	. . .	. . .	. . .	**. . .**
Water-hardening steels (ASTM A 686)					
W1	1.1525, 1.1545, 1.1625, 1.1654, 1.1663, 1.1673, 1.1744, 1.1750, 1.1820, 1.1830	G4401 SK1 G4401 SK2 G4401 SK3 G4401 SK4 G4401 SK5 G4401 SK6 G4401 SK7 G4410 SKC3	4659 (USA W1) 4659 BW1A 4659 BW1B 4659 BW1C	A35-590 1102 Y(1) 105 A35-590 1103 Y(1) 90 A35-590 1104 Y(1) 80 A35-590 1105 Y(1) 70 A35-590 1200 Y(2) 140 A35-590 1201 Y(2) 120 A35-5906 Y75 A35-596 Y90	**. . .**
W2	1.1645, 1.2206, 1.2833	G4404 SKS43 G4404 SKS44	4659 BW2	A35-590 1161 Y120V A35-590 1162 Y105V A35-590 1163 Y90V A35-590 1164 Y75V A35-590 1230 Y(2) 140C A35-590 2130 Y100C2	**(USA W2A)** **(USA W2B)** **(USA W2C)**
W5	**1.2002, 1.2004, 1.2056**	**. . .**	**. . .**	**A35-590 1232 Y105C**	**. . .**

Source: Ref 1, 2

(a) Deutsche Industries Normen (German Industrial Standards).

(b) Japanese Industrial Standard.

(c) British Standard.

(d) l'Association Francaise de Normalisation (French Standards Association).

Table 3 Compositions of tool steels no longer in common use

Type	Composition, %					
	C	**W**	**Mo**	**Cr**	**V**	Others
High-speed steels						
M6	0.80	4.25	5.00	4.00	1.50	**12.00 Co**
M8	0.80	5.00	5.00	4.00	1.50	**1.25 Nb**
M15	1.50	6.50	3.50	4.00	5.00	**5.00 Co**
M45	1.25	8.00	5.00	4.25	1.60	**5.50 Co**
T3	1.05	18.00	. . .	4.00	3.00	**. . .**
T7	0.75	14.00	. . .	4.00	2.00	**. . .**
T9	1.20	18.00	. . .	4.00	4.00	**. . .**
Hot-work steels						
H15	0.40	. . .	5.00	5.00	. . .	**. . .**
H16	0.55	7.00	. . .	7.00	. . .	**. . .**
H20	0.35	9.00	. . .	2.00	. . .	**. . .**
H41	0.65	1.50	8.00	4.00	1.00	**. . .**

H43	0.55	. . .	8.00	4.00	2.00	**. . .**
Cold-work steels						
D1	1.00	. . .	1.00	12.00	. . .	**. . .**
D6[(a)]						
A5	1.00	. . .	1.00	1.00	. . .	**3.00 Mn**
Shock-resisting steels						
S3	0.50	1.00	. . .	0.74	. . .	**. . .**
S4	0.55	. . .	. . .	. . .	. . .	**2.00 Si, 0.80 Mn**
Mold steel						
P1	0.10	. . .	. . .	. . .	. . .	**. . .**
Special-purpose steels						
L1	1.00	. . .	. . .	1.25	. . .	**. . .**
L3	1.00	. . .	. . .	1.50	0.20	**. . .**
L4	1.00	. . .	. . .	1.50	0.25	**0.60 Mn**
L5	1.00	. . .	0.25	1.00	. . .	**1.00 Mn**
L7	1.00	. . .	0.40	1.40	. . .	**0.35 Mn**
F1	1.00	1.25	. . .	. . .	. . .	**. . .**
F2	1.25	3.50	. . .	. . .	. . .	**. . .**
F3	1.25	3.50	. . .	0.75	. . .	**. . .**
Water-hardening tool steels						
W3	1.00	. . .	. . .	. . .	0.50	**. . .**

W4	0.60/1.40(b)	. . .	. . .	0.25	. . .	. . .
W6	1.00	. . .	. . .	0.25	0.25	. . .
W7	**1.00**	**. . .**	**. . .**	**0.50**	**0.20**	**. . .**

(a) Now included with D3 in Table 1.

(b) Various carbon contents were available.

Tool steels are produced to various standards including several American Society for Testing and Materials (ASTM) specifications. Reference 3 contains much useful information that essentially represents the normal manufacturing practices of most of the tool steel producers. Frequently, more stringent chemical and/or metallurgical standards are invoked by the individual producers or consumers to achieve certain commercial goals. Where appropriate, standard specifications for tool steels--ASTM A 600, A 681, and A 686--may be used as a basis for procurement. ASTM A 600 sets forth standard requirements for both tungsten and molybdenum high-speed steels; A 681 is applicable to hot-work, cold-work, shock-resisting, special-purpose, and mold steels; A 686 covers water-hardening tool steels. In many instances, however, tool steels are purchased by trade name because the user has found that a particular tool steel from a certain producer gives better performance in a specific application than does a tool steel of the same AISI type classification purchased from another source. Table 4 categorizes tool steels on the basis of specific machining applications.

Table 4 Reference guide for tool steel selection

Application areas	Tool steel groups, AISI letter symbols, and typical applications						
	High-speed tool steels, M and T	**Hot-work tool steels, H**	**Cold-work tool steels, D, A, and O**	**Shock-resisting tool steels, S**	**Mold steels, P**	**Special-purpose tool steels, L**	Water-hardening tool steels, W
Cutting tools Single-point types (lathe, planer, boring) Milling cutters Drills Reamers Taps Threading dies Form cutters	General-purpose production tools: M2, T1 For increased abrasion resistance: M3, M4, M10 Heavy-duty work calling for high hot hardness: T5, T15 Heavy-duty work calling for high abrasion resistance: M42, M44	. . .	Tools with sharp edges (knives, razors) Tools for operations in which no high speed is involved, yet stability in heat treatment and substantial abrasion resistance are needed	Pipe cutter wheels	. . .	. . .	**Uses that do not require hot hardness or high abrasion resistance** **Examples with carbon content of applicable group:** **Taps (1.05-1.10% C)** **Reamers (1.10-1.15% C)** **Twist drills (1.20-1.25% C)** **Files (1.35-40% C)**
Hot-forging tools and dies Dies and	For combining hot hardness with high	Dies for presses and hammers: H20,	Hot trimming dies: D2	Hot-trimming dies Blacksmith	. . .	. . .	**Smith tools (0.65-0.70% C)**

inserts Forging machine plungers and piercers	abrasion resistance: M2, T1	H21 For severe conditions over extended service periods: H22-H26		tools Hot-swaging dies			**Hot chisels (0.70-0.75% C)** **Drop forging dies (0.90-1.00% C)** **Applications limited to short-run production**
Hot extrusion tools and dies Extrusion dies and mandrels Dummy blocks Valve extrusion tools	Brass extrusion dies: T1	Extrusion dies and dummy blocks: H21-H26 For tools that are exposed to less heat: H10-H14, H19	. . .	Compression molding: S1	. . .	. . .	**. . .**
Cold-forming dies Bending, forming, drawing, and deep-drawing dies and punches	Burnishing tools: M1, T1	Cold-heading die castings: H13	Drawing dies: O1 Coining tools:O1, D2 Forming and bending dies: A2 Thread rolling dies: D2	Hobbing and short-run applications: S1, S7 Rivet sets and rivet busters	. . .	Blanking, forming, and trimmer dies when toughness has precedence over abrasion resistance: L6	**Cold-heading dies: W1 or W2 (C ~1.00%)** **Bending dies: W1(C ~1.00%)**
Shearing tools Dies for piercing, punching, and trimming Shear blades	Special dies for cold and hot work: T1 For work requiring high abrasion resistance: M2, M3	For shearing knives: H11, H12 For severe hot-shearing applications: H21, H25	Dies for medium runs: A2, A6, O1 Dies for long runs: D2, D3 Trimming dies (also for hot trimming): A2	Cold and hot shear blades Hot punching and piercing tools Boilermaker tools	. . .	Knives for work requiring high toughness: L6	**Trimming dies (0.90-0.95% C)** **Cold-blanking and punching dies (1.00% C)**
Die casting and molding dies	. . .	For aluminum and lead: H11, H13 For brass: H21	A2, A6, O1	. . .	Plastic molds: P2-P4, P20	. . .	**. . .**
Structural parts for severe service conditions	Roller bearings for high-temperature environment: T1 Lath centers: M2, T1	For aircraft components (landing gears, arrester hooks, rocket cases): H11	Lathe centers: D2, D3 Arbors: O1 Bushings A4 Gages: D2	Pawls Clutch parts	. . .	Spindles and clutch parts (if high toughness is needed): L6	**Spring steel (1.10-1.15% C)**
Battering tools, hand and power	. . .	. . .	. . .	**Pneumatic chisels for cold work: S5** **For higher performance: S7**	. . .	. . .	**For intermittent use: W1 (0.80% C)**

Source: Ref 4

High-Speed Steels

High-speed steels are tool materials developed largely for use in high-speed cutting tool applications. A chronology of some of the significant breakthroughs in high-speed tool steel technology is given in Table 5. There are two classifications of high-speed steel: molybdenum high-speed steels, or group M, and tungsten high-speed steels, or group T. Group M steels constitute greater than 95% of all high-speed steel produced in the United States. There is also a subgroup consisting of intermediate high-speed steels in the M group.

Table 5 Significant dates in the development of high-speed tool steels

Date	Development
1903	**0.70% C, 14% W, 4% Cr prototype of modern high-speed tool steels**
1904	**0.30% V addition**
1906	**Introduction of electric furnace melting**
1910	**Introduction of first 18-4-1 composition (AISI T1)**
1912	**3-5% Co addition for improved hot hardness**
1923	**12% Co addition for increased cutting speeds**
1939	**Introduction of high-carbon, high-vanadium, super high speed tool steels (M4 and T15)**
1940-1952	**Increasing substitution of molybdenum for tungsten**
1953	**Introduction of sulfurized free-machining high-speed tool steel**
1961	**Introduction of high-carbon, high-cobalt, superhard high speed tool steels (M40 series)**
1970	**Introduction of powdered metal high-speed tool steels**
1973	**Addition of higher silicon/nitrogen content to M7 to increase hardness**
1980	**Development of cobalt-free super high speed tool steels**
1982	**Introduction of aluminum-modified high-speed tool steels for cutting tools**

Group M and group T high-speed steels are equivalent in performance; the main advantage of the group M steels is lower initial cost (approximately 40% lower than that of similar group T steels). This difference in cost results from the lower atomic weight of molybdenum, about one-half that of tungsten. Based on weight percent, only about one-half as much molybdenum as tungsten is required to provide the same atom ratio.

Molybdenum high-speed steels and tungsten high-speed steels are similar in many other respects, including hardening ability. Typical applications for both categories include cutting tools of all sorts, such as drills, reamers, end mills, milling cutters, taps, and hobs (see the Section "Traditional Machining Processes" in *Machining,* Volume 16 of *ASM Handbook,* formerly 9th Edition *Metals Handbook*). Some grades are satisfactory for cold-work applications, such as cold-header die inserts, thread-rolling dies, punches, and blanking dies. Steels of the M40 series are used to make cutting tools for machining modern, very tough, high-strength steels.

For die inserts and punches, high-speed steels frequently are under hardened, that is, quenched from austenitizing temperatures lower than those recommended for cutting tool applications, as a means of increasing toughness.

Molybdenum high-speed steels contain molybdenum, tungsten, chromium, vanadium, cobalt, and carbon as principal alloying elements. Group M steels have slightly greater toughness than group T steels at the same hardness. Otherwise, mechanical properties of the two groups are similar.

Increasing the carbon and vanadium contents of group M steels increases wear resistance; increasing the cobalt content improves red hardness (that is, the capability of certain steels to resist softening at temperatures high enough to cause the steel to emit radiation in the red part of the visible spectrum) but simultaneously lowers toughness. Type M2 and other grades in the M group have unusually high resistance to softening at elevated temperatures as a result of high alloy content (Fig. 1).

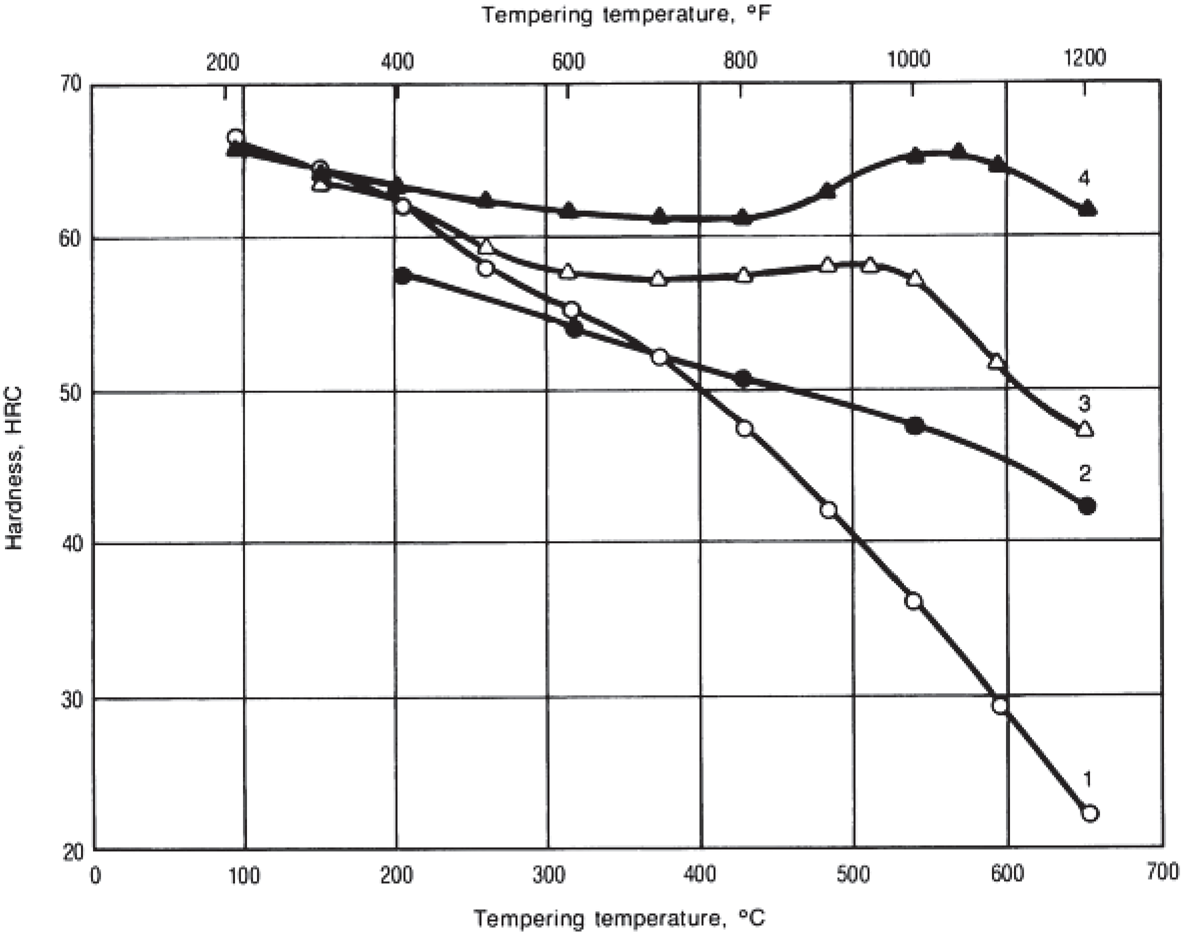

Fig. 1 Variation of hardness with tempering temperature for four typical tool steels. Curves are for 1 h at temperature. Curve 1 illustrates low resistance to softening as tempering temperatures increase, such as is exhibited by group W and group O tool steels. Curve 2 illustrates medium resistance to softening, such as is exhibited by type S1 tool steel. Curves 3 and 4 illustrate high and very high resistance to softening, respectively, such as are exhibited by the secondary hardening tool steels A2 and M2.

Because group M steels readily decarburize and can be damaged from overheating under adverse austenitizing environments, they are more sensitive than group T steels to hardening conditions, particularly austenitizing temperature and atmosphere. This is especially true of high-molybdenum, low-tungsten compositions.

Group M high-speed steels are deep hardening. They must be austenitized at temperatures lower than those for hardening group T steels to avoid incipient melting. Group M high-speed steels can develop full hardness when quenched from temperatures of 1175 to 1230 °C (2150 to 2250 °F).

The maximum hardness that can be obtained in group M high-speed steels varies with composition. For those with lower carbon contents, that is, types M1, M2, M10 (low-carbon composition), M30, M33, M34, and M36, maximum hardness is usually 65 HRC. For higher carbon contents, including types M3, M4, and M7, maximum hardness is about 66 HRC. Maximum hardness of the higher-carbon cobalt-containing steels, that is, types M41, M42, M43, M44, and M46, is 69 to 70 HRC. However, few industrial applications exist for steels of the M40 series at this maximum hardness. Usually, the heat treatment is adjusted to provide a hardness of 66 to 68 HRC.

Tungsten high-speed steels contain tungsten, chromium, vanadium, cobalt, and carbon as the principal alloying elements. Type T1 was developed partly as a result of the work of Taylor and White, who in the early 1900s, found that certain steels with more than 14% W, about 4% Cr, and about 0.3% V exhibited red hardness. In its earliest form, type T1 contained about 0.68% C, 18% W, 4% Cr, and 0.3% V. By 1920, the vanadium content had been increased to about 1.0%. Over a 30-year period, the carbon content was gradually increased to its present level of 0.75%.

Group T high-speed steels are characterized by high red hardness and wear resistance. They are so deep hardening that sections up to 76 mm (3 in.) in thickness or diameter can be hardened to 65 HRC or more by quenching in oil or molten salt. The high alloy and high carbon contents produce a large number of hard, wear-resistant carbides in the microstructure, particularly in those types containing more than 1.5% V and more than 1.0% C. Type T15 is the most wear-resistant steel of this group.

The combination of good wear resistance and high red hardness makes group T high-speed steels suitable for many high-performance cutting tool applications; their toughness allows them to outperform cemented carbides in delicate tools and interrupted-cut applications. Group T high-speed steels are primarily used for cutting tools such as bits, drills, reamers, taps broaches, milling cutters, and hobs. These steels are also used for making dies, punches, and high-load high-temperature structural components such as aircraft bearings and pump parts.

Group T high-speed steels are all deep hardening when quenched from their recommended hardening temperatures of 1205 to 1300 °C (2200 to 2375 °F). They are seldom used to make hardened tools with section sizes greater than 76 mm (3 in.). Even very large cutting tools, such as drills 76 and 102 mm (3 and 4 in.) in diameter, have relatively small effective sections for hardening because metal has been removed to form the flutes. Some large-diameter solid tools are made from group T high-speed steels; these include broaches and cold extrusion punches as large as 102 to 127 mm (4 to 5 in.) in diameter.

As shown in Fig. 2, the difference between surface hardness and center hardness varies with bar size. The data in Fig. 2 are given to indicate the general trend of hardness variation rather than to provide specific values. The section size and total mass of a given tool often have an effect on its response to a given hardening treatment that is equal to or greater than the effect of the grade of tool steel selected. For tools of extremely large diameter or heavy section, it is relatively common practice to use an accelerated oil quench to provide full hardness. This practice may yield values of Rockwell C hardness only one or two points higher than those obtainable through hot-salt quenching or air cooling, which ordinarily produce full hardness in tools smaller than about 76 mm (3 in.) in diameter, but at such high hardnesses that a one- or two-point increase in Rockwell hardness may prove quite significant.

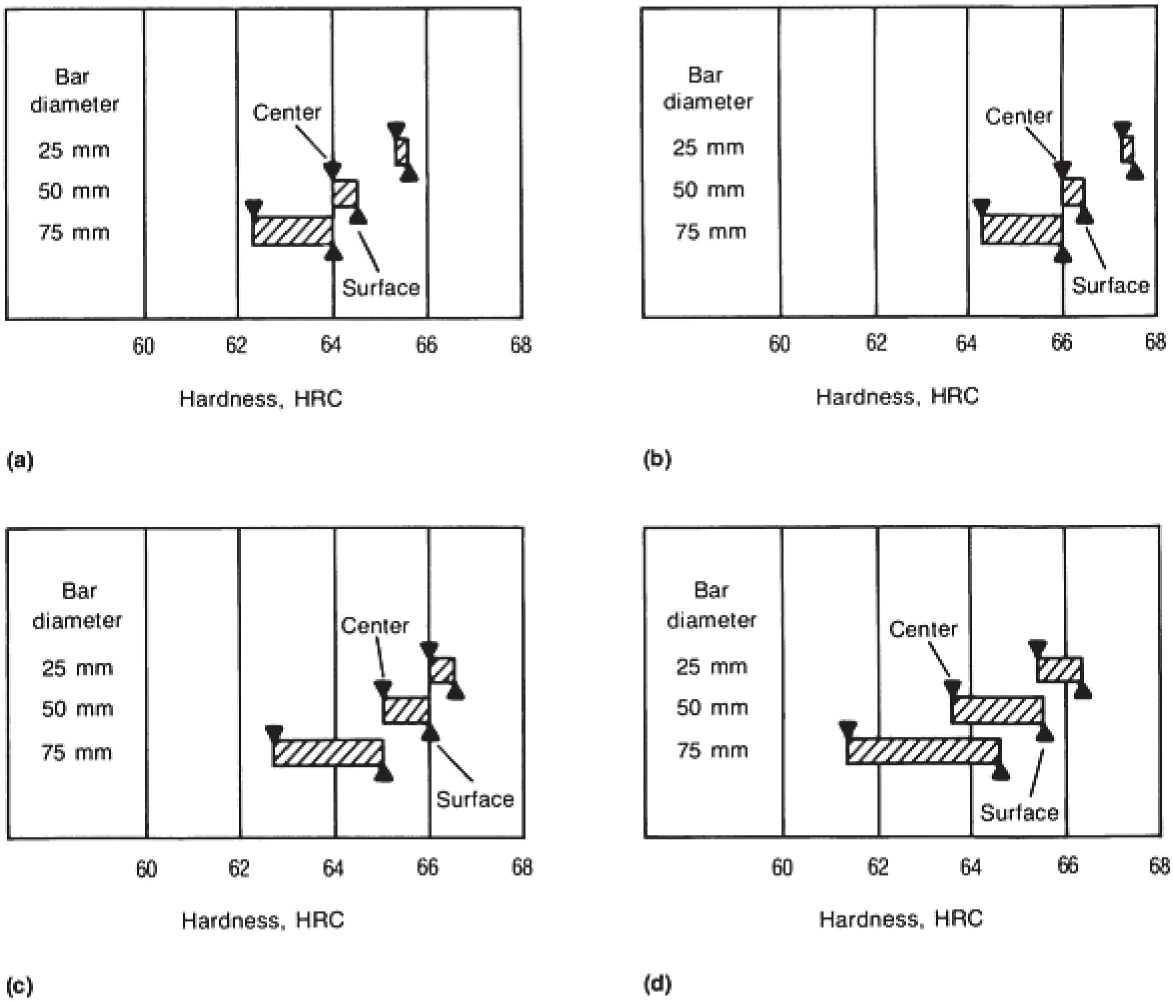

Fig. 2 Variation of surface and center hardness with bar diameter for four high-speed steels. (a) M2. (b) M3. (c) T1. (d) T2. Steels M2 and M3 were oil quenched from 1205 °C (2200 °F) and 1230 °C (2250 °F), respectively. Steels T1 and T2 were oil quenched from 1290 °C (2350 °F).

The maximum hardness of tungsten high-speed steels varies with carbon content and, to a lesser degree, with alloy content. A hardness of a least 64.5 HRC can be developed in any high-speed steel. Those types that have high carbon contents and hard carbides, such as T15, may be hardened to 67 HRC.

Hot-Work Steels

Many manufacturing operations involve punching, shearing, or forming of metals at high temperatures. Hot-work steels (group H) have been developed to withstand the combinations of heat, pressure, and abrasion associated with such operations. Table 6 gives data on resistance to softening after 100 h at temperatures from 48 to 760 °C (900 to 1400 °F) for four of these steels.

Table 6 Resistance of four hot-work steels to softening at elevated temperatures

Type	**Original hardness, HRC**	Hardness[a], HRC, after 100 h at					
		480 °C (900 °F)	**540 °C (1000 °F)**	**595 °C (1100 °F)**	**650 °C (1200 °F)**	**705 °C (1300 °F)**	760 °C (1400 °F)

H13	50.2	48.7	45.3	29.0	22.7	20.1	**13.9**
	41.7	38.6	39.3	27.7	23.7	20.2	**13.2**
H21	49.2	48.7	47.6	37.2	27.4	19.8	**15.2**
	36.7	34.8	34.9	32.6	27.1	19.8	**14.9**
H23	40.8	40.0	40.6	40.8	38.6	33.2	**25.8**
	38.9	38.9	38.0	38.0	37.1	32.5	**25.6**
H26	51.0	50.6	50.3	47.1	38.4	26.9	**21.3**
	42.9	**42.4**	**42.3**	**41.3**	**34.9**	**26.4**	**21.1**

(a) At room temperature

Group H tool steels usually have medium carbon contents (0.35 to 0.45%) and chromium, tungsten, molybdenum, and vanadium contents of 6 to 25%. H steels are divided into three subgroups: chromium hot-work steels (types H10 to H19), tungsten hot-work steels (types H21 to H26), and molybdenum hot-work steels (types H42 and H43).

Chromium hot-work steels (types H10 to H19) have good resistance to heat softening because of their medium chromium content and the addition of carbide-forming elements such as molybdenum, tungsten, and vanadium. The low carbon and low total alloy contents promote toughness at the normal working hardnesses of 40 to 55 HRC. Higher tungsten and molybdenum contents increase hot strength but slightly reduce toughness. Vanadium is added to increase resistance to washing (erosive wear) at high temperatures. An increase in silicon content improves oxidation resistance at temperatures up to 800 °C (1475 °F). The most widely used types in this group are H11, H12, H13, and, to a lesser extent, H19.

All of the chromium hot-work steels are deep hardening. The H11, H12, and H13 steels may be air hardened to full working hardness in section sizes up to 152 mm (6 in.); other group H steels may be air hardened in section sizes up to 305 mm (12 in.). The air-hardening qualities and balanced alloy contents of these steels result in low distortion during hardening. Chromium hot-work steels are especially well adapted to hot die work of all kinds, particularly dies for the extrusion of aluminum and magnesium, as well as die casting dies, forging dies, mandrels, and hot shears. Most of these steels have alloy and carbon contents low enough that tools made from them can be water cooled in service without cracking.

Tool steel H11 is used to make certain highly stressed structural parts, particularly in aerospace technology. Material for such demanding applications is produced by vacuum arc remelting of air-melted electrodes, which provides extremely low residual-gas content, excellent microcleanliness, and a high degree of structural homogeneity.

The chief advantage of H11 over conventional high-strength steels is its ability to resist softening during continued exposure to temperatures up to 540 °C (1000 °F) and at the same time provide moderate toughness and ductility at room-temperature tensile strengths of 1720 to 2070 MPa (250 to 300 ksi). In addition, because of its secondary hardening characteristic, H11 can be tempered at high temperatures, resulting in nearly complete relief of residual hardening stresses, which is necessary for maximum toughness at high strength levels. Other important advantages of H11, H12, and H13 steels for structural and hot-work applications include ease of forming and working, good weldability, relatively low coefficient of thermal expansion, acceptable thermal conductivity, and above-average resistance to oxidation and corrosion.

Tungsten Hot-Work Steels. The principal alloying elements of tungsten hot-work steels (types H21 to H26) are carbon, tungsten, chromium, and vanadium. The higher alloy contents of these steels make them more resistant of high-temperature softening and washing than H11 and H13 hot-work steels. However, high alloy content also makes them more prone to brittleness at normal working hardnesses (45 to 55 HRC) and makes it difficult for them to be safely water cooled in service.

Although tungsten hot-work steels can be air hardened, they are usually quenched in oil or hot salt to minimize scaling. When air hardened, they exhibit low distortion. Tungsten hot-work steels require higher hardening temperatures than do chromium hot-work steels, making the former more likely to scale when heated in an oxidizing atmosphere.

Although these steels have much greater toughness, in many characteristics they are similar to high-speed steels; in fact, type H26 is a low-carbon version of T1 high-speed steel. If tungsten hot-work steels are preheated to operating temperature before use, breakage can be minimized. These steels have been used to make mandrels and extrusion dies for high-temperature applications, such as the extrusion of brass, nickel alloys, and steel, and are also suitable for use in hot-forging dies of rugged design.

Molybdenum Hot-Work Steel. There are only two active molybdenum hot-work steels: type H42 and type H43. These alloys contain molybdenum, chromium, vanadium, carbon, and varying amounts of tungsten. They are similar to tungsten hot-work steels, having almost identical characteristics and uses. Although their compositions resemble those of various molybdenum high-speed steels, they have a low carbon content and greater toughness. The principal advantage of types H42 and H43 over tungsten hot-work steels is their lower initial cost. They are more resistant to heat checking than are tungsten hot-work steels but, in common with all high-molybdenum steels, require greater care in heat treatment, particularly with regard to decarburization and control of austenitizing temperature.

Cold-Work Steels

Cold-work tool steels, because they do not have the alloy content necessary to make them resistant to softening at elevated temperature, are restricted in application to those uses that do not involve prolonged or repeated heating above 205 to 260 °C (400 to 500 °F). There are three categories of cold-work steels: air-hardening steels, or group A; high-carbon, high-chromium steels, or group D; and oil-hardening steels, or group O.

Air-hardening, medium-alloy, cold-work steels (group A) contain enough alloying elements to enable them to achieve full hardness in sections up to about 102 mm (4 in.) in diameter upon air cooling from the austenitizing temperature. (Type A6 through hardens in sections as large as a cube 178 mm, or 7 in., on a side.) Because they are air hardening, group A tool steels exhibit minimum distortion and the highest safety (least tendency to crack) in hardening. Manganese, chromium, and molybdenum are the principal alloying elements used to provide this deep hardening. Types A2, A3, A7, A8, and A9 contain a high percentage of chromium (5%), which provides moderate resistance to softening at elevated temperatures (see curve 3 in Fig. 1 for a plot of hardness versus tempering temperature for type A2).

Types A4, A6, and A10 are lower in chromium content (1%) and higher in manganese content (2%). They can be hardened from temperatures about 110 °C (200 °F) lower than those required for the high-chromium types, further reducing distortion and undesirable surface reactions during heat treatment.

To improve toughness, silicon is added to type A8, and both silicon and nickel are added to types A9 and A10. Because of the high carbon and silicon contents of type A10, graphite is formed in the microstructure; as a result, A10 has much better machinability when in the annealed condition, and somewhat better resistance to galling and seizing when in the fully hardened condition, than other group A tool steels.

Typical applications for group A tool steels include shear knives, punches, blanking and trimming dies, forming dies, and coining dies. The inherent dimensional stability of these steels makes them suitable for gages and precision measuring tools. In addition, the extreme abrasion resistance of type A7 makes it suitable for brick molds, ceramic molds, and other highly abrasive applications.

The complex chromium or chromium-vanadium carbides in group A tool steels enhance the wear resistance provided by the martensitic matrix. Therefore, these steels perform well under abrasive conditions at less than full hardness. Although cooling in still air is adequate for producing full hardness in most tools, massive sections should be hardened by cooling in an air blast or by interrupted quenching in hot oil.

High-carbon, high-chromium, cold-work steels (group D) contain 1.50 to 2.35% C and 12% Cr; with the exception of type D3, they also contain 1% Mo. All group D tool steels except type D3 are air hardening and attain full hardness when cooled in still air. Type D3 is almost always quenched in oil (small parts can be austenitized in vacuum and then gas quenched); therefore, tools made of D3 are more susceptible to distortion and are more likely to crack during hardening.

Group D steels have high resistance to softening at elevated temperatures. These steels also exhibit excellent resistance to wear, especially type D7, which has the highest carbon and vanadium contents. All group D steels, particularly the higher-carbon types D3, D4, and D7, contain massive amounts of carbides, which make them susceptible to edge brittleness.

Typical applications of group D steels include long-run dies for blanking, forming, thread rolling, and deep drawing; dies for cutting laminations; brick molds; gages; burnishing tools; rolls; and shear and slitter knives.

Oil-hardening cold-work steels (group O) have high carbon contents, plus enough other alloying elements that small-to-moderate sections can attain full hardness when quenched in oil from the austenitizing temperature. Group O tool steels vary in type of alloy, as well as in alloy content, even though they are similar in general characteristics and are used for similar applications. Type O1 contains manganese, chromium, and tungsten. Type O2 is alloyed primarily with manganese. Type O6 contains silicon, manganese, and molybdenum; it has a high total carbon content that includes free carbon, as well as sufficient combined carbon to enable the steel to achieve maximum as-quenched hardness. Type O7 contains manganese and chromium and has a tungsten content higher than that of type O1.

The most important service-related property of group O steels is high resistance to wear at normal temperatures, a result of high carbon content. On the other hand, group O steels have a low resistance to softening at elevated temperatures.

The ability of group O steels to harden fully upon relatively slow quenching yields lower distortion and greater safety (less tendency to crack) in hardening than is characteristic of the water-hardening tool steels. Tools made from these steels can be successfully repaired or renovated by welding if proper procedures are followed. In addition, graphite in the microstructure of type O6 greatly improves the machinability of annealed stock and helps reduce galling and seizing of fully hardened steel.

Group O steels are used extensively in dies and punches for blanking, trimming, drawing, flanging, and forming. Surface hardnesses of 56 of 62 HRC, obtained through oil quenching followed by tempering at 175 to 315 °C (350 to 600 °F), provide a suitable combination of mechanical properties for most dies made from type O1, 02, or O6. Type O7, which has lower hardenability but better general wear resistance than any other group O tool steel, is more often used for tools requiring keen cutting edges. Oil-hardening tool steels are also used for machinery components (such as cams, bushings, and guides) and for gages (where good dimensional stability and wear resistance properties are needed).

The hardenability of group O steels can be measured effectively by the Jominy endquench test. Hardenability bands for group O steels are shown in Fig. 3. Variation of hardness with diameter is shown in Fig. 4 for center, surface, and $\frac{3}{4}$ radius locations in oil-quenched bars of group O steels.

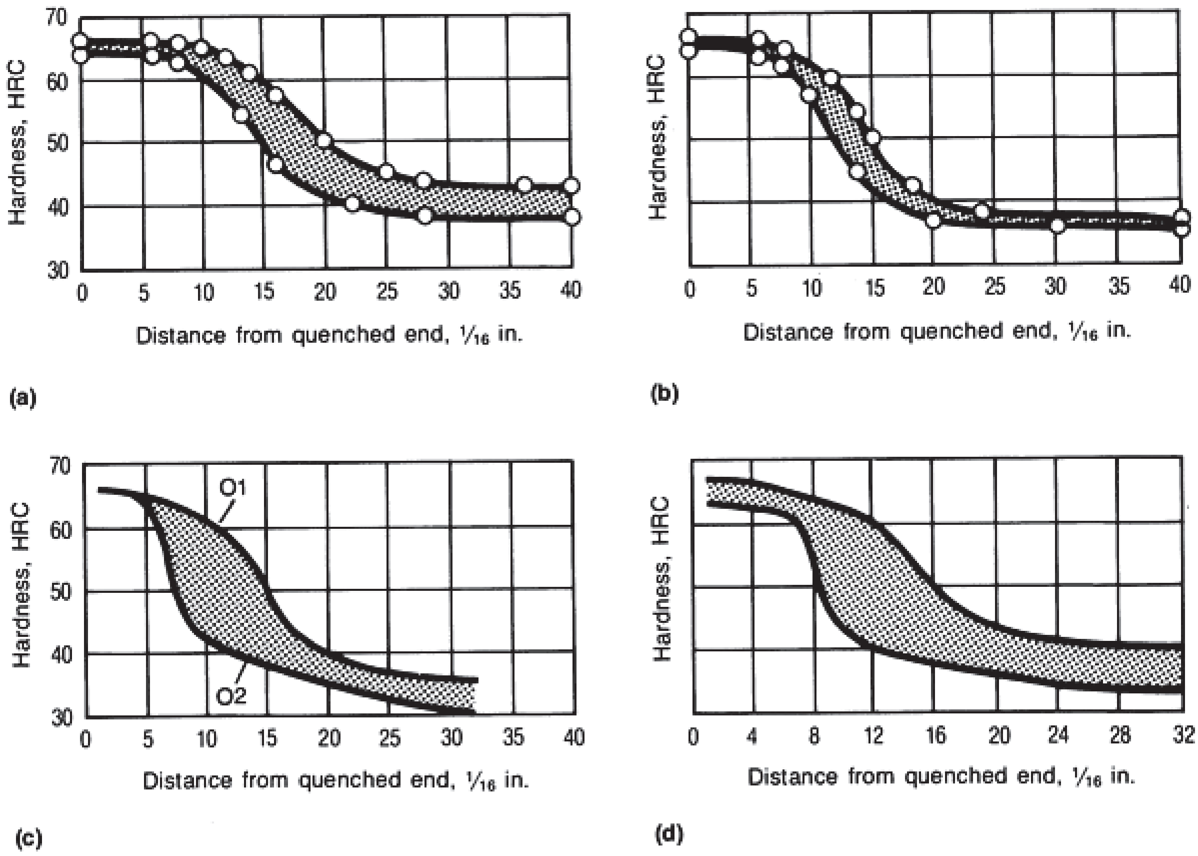

Fig. 3 End-quench hardenability bands for group O tool steels. (a) O1, source A. (b) O2, source A. (c) O1 and O2, source B. (d) O6. Hardenability bands from source B represent the data from five heats each for O1 and O2 tool steels. Data from source A were determined only on the basis of average hardness, not as hardenability bands. Data for O6 is for a spheroidized prior structure. Steels O1 and O6 were quenched from 815 °C (1500 °F); 02, from 790 °C (1450 °F).

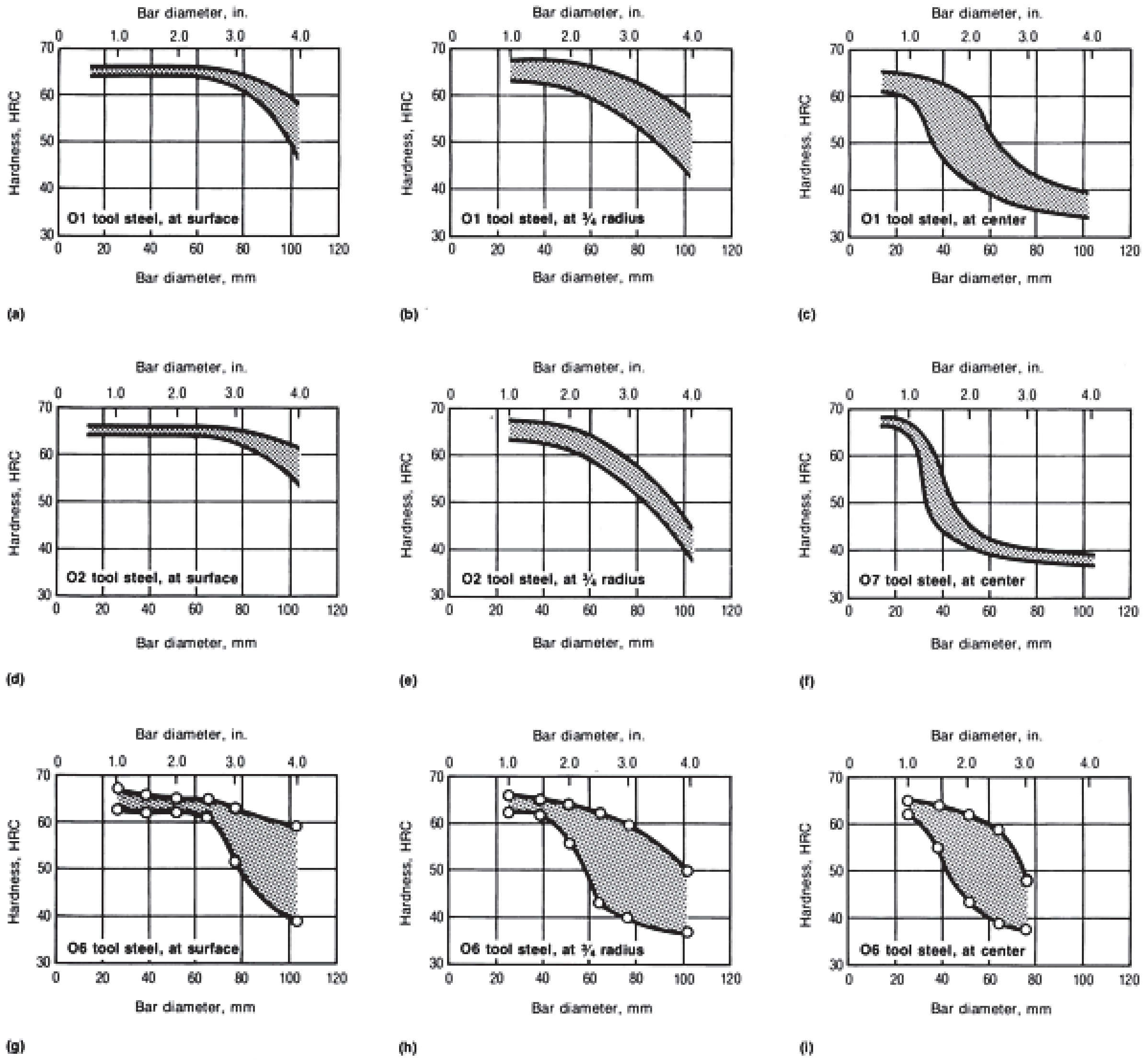

Fig. 4 Variation of as-quenched hardness with bar diameter for four oil-hardening tool steels. Data for (a), (b), (d), and (e) are from tests on 5 heats of each steel from source A. Data for (c) are from tests on 23 heats of O1 from source B. Data for (f) are from tests on 8 heats (source unknown). Information on the number of heats and source of data not available for (g), (h), and (i). Center hardness data not available for type O2; surface and $\frac{3}{4}$-radius data not available for type O7. Type O1 austenitized at 815 °C (1500 °F) in source A and at 775 °C (1425 °F) in source B. Type O2 austenitized at 790 °C (1450 °F). Austenitizing temperatures for types O6 and O7 not available

At normal hardening temperatures, group O steels retain greater amounts of undissolved carbides and thus do not harden as deeply as do steels that are lower in carbon but similar in alloy content. On the other hand, group O steels attain higher surface hardness. Raising the hardening temperature increases grain size; increases solution of alloying elements; and dissolves more of the excess carbide, thereby increasing hardenability. However, raising the hardening temperature can have an adverse effect on certain mechanical properties, most notably ductility toughness, and also can increase the likelihood of cracking during hardening.

Shock-Resisting Steels

The principal alloying elements in shock-resisting, or group S, steels are manganese, silicon, chromium, tungsten, and molybdenum, in various combinations. Carbon content is about 0.50% for all group S steels, which produces a combination of high strength, high toughness, and low-to-medium wear resistance. Group S steels are used primarily for chisels, rivet sets, punches, driver bits, and other applications requiring high toughness and resistance to shock loading. Types S1 and S7 are also used for hot punching and shearing, which require some heat resistance.

Group S steels vary in hardenability from shallow hardening (S2) to deep hardening (S7). In these steels of intermediate alloy content, hardenability is controlled to a greater extent by composition than by the incidental effects of grain size and melting practice, which are so important for group W steels. Group S steels require relatively high austenitizing temperatures to achieve optimum hardness; consequently, undissolved carbides are not a factor in the control of hardenability. Type S2 is normally water quenched; types S1, S5, and S6 are oil quenched; and type S7 is normally cooled in air, except for large sections, which are oil quenched.

Because group S steels exhibit excellent toughness at high strength levels, they are often considered for nontooling or structural applications. The nominal mechanical properties of S1, S5, and S7, in both annealed and hardened and tempered conditions, are presented in Table 7.

Table 7 Nominal room-temperature mechanical properties of group L and group S tool steels

Type	**Condition**	**Tensile strength**		**0.2% yield strength**		**Elongation(a), %**	**Reduction in area, %**	**Hardness, HRC**	Impact energy	
		MPa	**ksi**	**MPa**	**ksi**				**J**	ft · lbf
L2	Annealed	710	103	510	74	25	50	96 HRB	. . .	**. . .**
	Oil quenched from 855 °C (1575 °F) and single tempered at:									
	205 °C (400 °F)	2000	290	1790	260	5	15	54	28(b)	**21(b)**
	315 °C (600 °F)	1790	260	1655	240	10	30	52	19(b)	**14(b)**
	425 °C (800 °F)	1550	225	1380	200	12	35	47	26(b)	**19(b)**
	540 °C (1000 °F)	1275	185	1170	170	15	45	41	39(b)	**29(b)**
	650 °C (1200 °F)	930	135	760	110	25	55	30	125(b)	**92(b)**
L6	Annealed	655	95	380	55	25	55	93 HRB	. . .	**. . .**
	Oil quenched from 845 °C (1550 °F) and single tempered at:									
	315 °C (600 °F)	2000	290	1790	260	4	9	54	12(b)	**9(b)**
	425 °C (800 °F)	1585	230	1380	200	8	20	46	18(b)	**13(b)**
	540 °C (1000 °F)	1345	195	1100	160	12	30	42	23(b)	**17(b)**

	650 °C (1200 °F)	965	140	830	120	20	48	32	81(b)	**60(b)**
S1	Annealed	690	100	415	60	24	52	96 HRB	. . .	**. . .**
	Oil quenched from 925 °C (1700 °F) and single tempered at:									
	205 °C (400 °F)	2070	300	1895	275	. . .	. . .	57.5	249(c)	**184(c)**
	315 °C (600 °F)	2025	294	1860	270	4	12	54	233(c)	**172(c)**
	425 °C (800 °F)	1790	260	1690	245	5	17	50.5	203(c)	**150(c)**
	540 °C (1000 °F)	1680	244	1525	221	9	23	47.5	230(c)	**170(c)**
	650 °C (1200 °F)	1345	195	1240	180	12	37	42	. . .	**. . .**
S5	Annealed	725	105	440	64	25	50	96 HRB	. . .	**. . .**
	Oil quenched from 870 °C (1600 °F) and single tempered at:									
	205 °C (400 °F)	2345	340	1930	280	5	20	59	206(c)	**152(c)**
	315 °C (600 °F)	2240	325	1860	270	7	24	58	232(c)	**171(c)**
	425 °C (800 °F)	1895	275	1690	245	9	28	52	243(c)	**179(c)**
	540 °C (1000 °F)	1515	220	1380	200	10	30	48	188(c)	**139(c)**
	650 °C (1200 °F)	1035	150	1170	170	15	40	37	. . .	**. . .**
S7	Annealed	640	93	380	55	25	55	95 HRB	. . .	**. . .**
	Fan cooled from 940 °C (1725 °F) and single tempered at:									
	205 °C (400 °F)	2170	315	1450	210	7	20	58	244(c)	**180(c)**
	315 °C (600 °F)	1965	285	1585	230	9	25	55	309(c)	**228(c)**

	425 °C (800 °F)	1895	275	1410	205	10	29	53	243(c)	**179(c)**
	540 °C (1000 °F)	1820	264	1380	200	10	33	51	324(c)	**239(c)**
	650 °C (1200 °F)	**1240**	**180**	**1035**	**150**	**14**	**45**	**39**	**358(c)**	**264(c)**

(a) In 50 mm, or 2 in.

(b) Charpy V-notch.

(c) Charpy unnotched

Low-Alloy Special-Purpose Steels

The low-alloy special-purpose, or group L, tool steels contain small amounts of chromium, vanadium, nickel, and molybdenum. At one time, seven steels were listed in this group, but because of falling demand, only types L2 and L6 remain. Type L2 is available in several carbon contents from 0.50 to 1.10%; its principal alloying elements are chromium and vanadium, which make it an oil-hardening steel of fine grain size. Type L6 contains small amounts of chromium and molybdenum, as well as 1.50% Ni for increased toughness.

Although both L2 and L6 are considered oil-hardening steels, large sections of L2 are often quenched in water. A type L2 steel containing 0.50% C is capable of attaining about 57 HRC as oil quenched, but it will not through harden in sections of more than about 12.7 mm (0.5 in.) thickness. Type L6, which contains 0.70% C, has an as-quenched hardness of about 64 HRC; it can maintain a hardness above 60 HRC through sections of 76 mm (3 in.) thickness.

Group L steels are generally used for machine parts such as arbors, cams, chucks, and collets, and for other special applications requiring good strength and toughness. Nominal mechanical properties of annealed and hardened-and-tempered L2 and L6 steels are given in Table 7.

Mold Steels

Mold steels, or group P, contain chromium and nickel as principal alloying elements. Types P2 and P6 are carburizing steels produced to tool steel quality standards. They have very low hardness and low resistance to work hardening in the annealed condition. These factors make it possible to produce a mold impression by cold hubbing. After the impression is formed, the mold is carburized, hardened, and tempered to a surface hardness of about 58 HRC. Types P4 and P6 are deep hardening; with type P4, full hardness in the carburized case can be achieved by cooling in air.

Types P20 and P21 normally are supplied heat treated to 30 to 36 HRC, a condition in which they can be machined readily into large, intricate dies and molds. Because these steels are prehardened, no subsequent high-temperature heat treatment is required, and distortion and size changes are avoided. However, when used for plastic molds, type P20 is sometimes carburized and hardened after the impression has been machined. Type P21 is an aluminum-containing precipitation-hardening steel that is supplied prehardened to 32 to 36 HRC. This steel is preferred for critical-finish molds because of its excellent polishability.

All group P steels have low resistance to softening at elevated temperatures, with the exception of P4 and P21, which have medium resistance. Group P steels are used almost exclusively in low-temperature die casting dies and in molds for the injection or compression molding of plastics. Plastic molds often require massive steel blocks up to 762 mm (30 in.) thick and weighing as much as 9 Mg (10 tons). Because these large die blocks must meet stringent requirements for soundness, cleanliness, and hardenability, electric furnace melting, vacuum degassing, and special deoxidation treatments have become standard practice in the production of group P tool steels. In addition, ingot casting and forging practices have been refined so that a high degree of homogeneity can be achieved.

Water-Hardening Steels

Water-hardening, or group W, tool steels contain carbon as the principal alloying element. Small amounts of chromium and vanadium are added to most of the group W steels--chromium to increase hardenability and wear resistance, and vanadium to maintain fine grain size and thus enhance toughness. Group W tool steels are made with various nominal carbon contents (~0.60 to 1.40%); the most popular grades contain approximately 1.00% C.

Group W tool steels are very shallow hardening and consequently develop a fully hardened zone that is relatively thin, even when quenched drastically. Sections more than about 13 mm ($\frac{1}{2}$ in.) thick generally have a hard case over a strong, tough, and resilient core.

Group W steels have low resistance to softening at elevated temperatures. They are suitable for cold heading, striking, coining, and embossing tools; woodworking tools; hard metal-cutting tools, such as taps and reamers; wear-resistant machine tool components; and cutlery.

This group of steels is made in as many as four different grades or quality levels for the same nominal composition. These quality levels, which have been given various names by different manufacturers, range from a clean carbon tool steel with precisely controlled hardenability, grain size, microstructure, and annealed hardness to a grade less carefully controlled but satisfactory for noncritical low-production applications.

The Society of Automotive Engineers (SAE) defines four grades of plain carbon tool steels as follows:

- *Special (grade 1):* The highest-quality water-hardening tool steel. Hardenability is controlled, and composition is held to close limits. Bars are subjected to rigorous testing to ensure maximum uniformity in performance
- *Extra (grade 2):* A high-quality water-hardening tool steel that is controlled for hardenability and is subjected to tests that ensure good performance in general applications
- *Standard (grade 3):* A good-quality water-hardening tool steel that is not controlled for hardenability and that is recommended for applications in which some latitude in uniformity can be tolerated
- *Commercial (grade 4)*: A commercial-quality water-hardening tool steel that is neither controlled for hardenability nor subjected to special tests

Limits on manganese, silicon, and chromium generally are not required for special and extra grades. Instead, the Shepherd hardenability limits are prescribed:

Hardenability classification	**Radial depth of hardening (*P*), $\frac{1}{64}$ in.**	Minimum fracture grain size, *F*
Carbon content, 0.70-0.95%		
Shallow	10 max	**8**
Regular	9-13	**8**

Deep	12 min	**8**
Carbon content, 0.95-1.30%		
Shallow	8 max	**9**
Regular	7-11	**9**
Deep	**10-16**	**8**

See the section "Testing of Tool Steels" in this article for more information on Shepherd hardenability.

The combined manganese, silicon, and chromium contents of SAE standard and commercial grades should not exceed 0.75%. Generally, both manganese and silicon are limited to 0.35% maximum in all standard and commercial grades; chromium is limited to 0.15% maximum in standard grades and to 0.20% maximum in commercial grades.

The ability of a group W tool steel to perform satisfactorily in many applications depends on the depth of the hardened zone. Depth of hardening in these steels is primarily controlled by the austenitic grain size, melting practice, alloy content, amount of excess carbide present at the quenching temperature and, to a lesser extent, initial structure of the steel prior to austenitizing for hardening.

Typical results in the Shepherd penetration-fracture (PF) test indicate an increase in *P* value of 0.8 mm ($\frac{1}{64}$ in.) for every increase in austenitic grain size of one ASTM number for the same grade. Increased amounts of undissolved carbides at the hardening temperature will reduce hardenability. This is doubly important in hypereutectoid grades, which are deliberately quenched to retain carbides undissolved at the austenitizing temperature in order to increase wear resistance. A fine lamellar microstructure prior to hardening, such as that obtained by normalizing, will result in fewer undissolved carbides at the normal austenitizing temperature than will a previously spheroidized microstructure. The presence of fewer carbides at the austenitizing temperature promotes deeper hardening because more carbon is dissolved in the austenite and there are fewer carbides to act as nucleation sites for nonmartensitic transformation products. Thus, normalized bars have deeper hardenability than do spheroidized bars of the same grade.

The addition of vanadium frequently decreases hardenability under normal hardening conditions because of the formation of many fine carbides that not only act as nucleation sites for nonmartensitic transformation products, but also refine the austenitic grain size. Austenitizing at higher-than-normal temperatures dissolves these excess carbides and thus increases the hardenability.

Group W steels with carbon contents lower than that of the eutectoid composition often have greater hardenability than do hypereutectoid grades. Grain coarsening resulting from the higher austenitizing temperatures used for hypoeutectoid grades is one cause of this, but the main cause is the absence of excess carbides at the austenitizing temperature.

Figure 5 shows a typical relationship between bar diameter and case depth (60 HRC or above) for three W1 tool steels that have the same carbon content (1% C) but different hardenabilities. Hardenability is varied by adjusting the manganese and silicon contents and altering the deoxidation procedure. This relationship illustrates the need for precise specification of hardenability in the selection of these grades: Group W tool steels purchased without hardenability requirements could vary widely enough in this property to cause severe processing difficulties or actual tool failures.

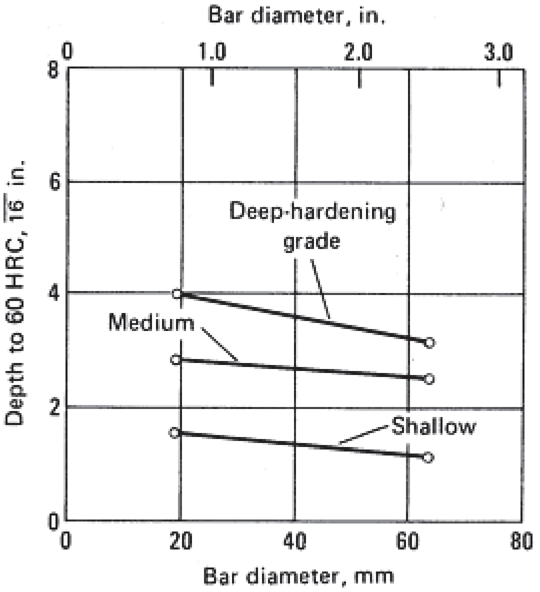

Fig. 5 Relationship of bar diameter and depth of hardened zone for shallow-, medium-, and deep-hardening grades of W1 tool steel containing 1% C

With the very fast cooling rate required for the hardening of the W grades, there is a greater chance that a tool will crack during hardening. Consequently, most manufacturers prefer to use tool steels that can be satisfactorily hardened by quenching in oil or cooling in air to attempt to avoid the expense involved when a tool cracks during heat treatment.

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Wrought Tool Steels

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Typical Heat Treatments and Properties

Condensed information on heat-treating specifications and on the processing and service characteristics of tool steels is presented in Tables 8, 9, and 10. This information clarifies the problems involved in the selection, processing, and application of tool steels.

Table 8 Normalizing and annealing temperatures of tool steels

Type	**Normalizing**[(a)]	Annealing[(b)]

			Temperature		**Rate of cooling, maximum**		Hardness, HB
	°C	**°F**	**°C**	**°F**	**°C/h**	**°F/h**	
Molybdenum high-speed steels							
M1, M10	Do not normalize		815-870	1500-1600	22	40	**207-235**
M2	Do not normalize		870-900	1600-1650	22	40	**212-241**
M3, M4	Do not normalize		870-900	1600-1650	22	40	**223-255**
M7	Do not normalize		815-870	1500-1600	22	40	**217-255**
M30, M33, M34, M35, M36, M41, M42, M46, M47	Do not normalize		870-900	1600-1650	22	40	**235-269**
M43	Do not normalize		870-900	1600-1650	22	40	**248-269**
M44	Do not normalize		870-900	1600-1650	22	40	**248-293**
M48	Do not normalize		870-900	1600-1650	22	40	**285-311**
M62	Do not normalize		870-900	1600-1650	22	40	**262-285**
Tungsten high-speed steels							
T1	Do not normalize		870-900	1600-1650	22	40	**217-255**
T2	Do not normalize		870-900	1600-1650	22	40	**223-255**
T4	Do not normalize		870-900	1600-1650	22	40	**229-269**
T5	Do not normalize		870-900	1600-1650	22	40	**235-277**
T6	Do not normalize		870-900	1600-1650	22	40	**248-293**
T8	Do not normalize		870-900	1600-1650	22	40	**229-255**
T15	Do not normalize		870-900	1600-1650	22	40	**241-277**

Intermediate high-speed steels						
M50	Do not normalize	830-845	1525-1550	22	40	**197-235**
M52	Do not normalize	830-845	1525-1550	22	40	**197-235**
Chromium hot-work steels						
H10, H11, H12, H13	Do not normalize	845-900	1550-1650	22	40	**192-229**
H14	Do not normalize	870-900	1600-1650	22	40	**207-235**
H19	Do not normalize	870-900	1600-1650	22	40	**207-241**
Tungsten hot-work steels						
H21, H22, H25	Do not normalize	870-900	1600-1650	22	40	**207-235**
H23	Do not normalize	870-900	1600-1650	22	40	**212-255**
H24, H26	Do not normalize	870-900	1600-1650	22	40	**217-241**
Molybdenum hot-works steels						
H41, H43	Do not normalize	815-870	1500-1600	22	40	**207-235**
H42	Do not normalize	845-900	1550-1650	22	40	**207-235**
High-carbon, high-chromium, cold-work steels						
D2, D3, D4	Do not normalize	870-900	1600-1650	22	40	**217-255**
D5	Do not normalize	870-900	1600-1650	22	40	**223-255**
D7	Do not normalize	870-900	1600-1650	22	40	**235-262**
Medium-alloy, air-hardening, cold-work steels						
A2	Do not normalize	845-870	1550-1600	22	40	**201-229**
A3	Do not normalize	845-870	1550-1600	22	40	**207-229**

A4	Do not normalize		740-760	1360-1400	14	25	**200-241**
A6	Do not normalize		730-745	1350-1375	14	25	**217-248**
A7	Do not normalize		870-900	1600-1650	14	25	**235-262**
A8	Do not normalize		845-870	1550-1600	22	40	**192-223**
A9	Do not normalize		845-870	1550-1600	14	25	**212-248**
A10	790	1450	765-795	1410-1460	8	15	**235-269**
Oil-hardening cold-work steels							
O1	870	1600	760-790	1400-1450	22	40	**183-212**
O2	845	1550	845-770	1375-1425	22	40	**183-212**
O6	870	1600	765-790	1410-1450	11	20	**183-217**
O7	900	1650	790-815	1450-1500	22	40	**192-217**
Shock-resisting steels							
S1	Do not normalize		790-815	1450-1500	22	40	**183-229**(c)
S2	Do not normalize		760-790	1400-1450	22	40	**192-217**
S5	Do not normalize		775-800	1425-1475	14	25	**192-229**
S7	Do not normalize		815-845	1500-1550	14	25	**187-223**
Mold steels							
P2	Not required		730-815	1350-1500	22	40	**103-123**
P3	Not required		730-815	1350-1500	22	40	**109-137**
P4	Do not normalize		870-900	1600-1650	14	25	**116-128**

P5	Not required		845-870	1550-1600	22	40	**105-116**
P6	Not required		845	1550	8	15	**183-217**
P20	900	1650	760-790	1400-1450	22	40	**149-179**
P21	900	1650	Do not anneal	Do not anneal			
Low-alloy special-purpose steels							
L2	871-900	1600-1650	760-790	1400-1450	22	40	**163-197**
L3	900	1650	790-815	1450-1500	22	40	**174-201**
L6	870	1600	760-790	1400-1450	22	40	**183-212**
Carbon-tungsten special-purpose steels							
F1	900	1650	760-800	1400-1475	22	40	**183-207**
F2	900	1650	790-815	1450-1500	22	40	**207-235**
Water-hardening steels							
W1, W2	790-925(d)	1450-1700(d)	740-790(e)	1360-1450(e)	22	40	**156-201**
W5	**870-925**	**1600-1700**	**760-790**	**1400-1450**	**22**	**40**	**163-201**

(a) Time held at temperature varies from 15 min for small sections to 1 h for large sizes. Cooling is done in still air. Normalizing should not be confused with low-temperature annealing.

(b) The upper limit of ranges should be used for large sections, and the lower limit for smaller sections. Time held at temperature varies from 1 h for light sections to 4 h for heavy sections and large furnace charges of high-alloy steel.

(c) For 0.25 Si type, 183 to 207 HB; for 1.00 Si type, 207 to 229 HB.

(d) Temperature varies with carbon content: 0.60 to 0.75 C, 815 °C (1500 °F); 0.75 to 0.90 C, 790 °C (1450 °F); 0.90 to 1.10 C, 870 °C (1600 °F); 1.10 to 1.40 C, 870 to 925 °C (1600 to 1700 °F).

(e) Temperature varies with carbon content: 0.60 t 0.90 C, 740 to 790 °C (1360 to 1450 °F); 0.90 to 1.40 C, 760 to 790 °C (1400 to 1450 °F).

Table 9 Hardening and tempering of tool steels

Type	**Rate of heating**	**Hardening**					**Quenching medium(a)**	Tempering temperature	
		Preheat temperature		**Hardening temperature**		**Time at temperature, min**			
		°C	**°F**	**°C**	**°F**			**°C**	°F
Molybdenum high-speed steels									
M1, M7, M10	Rapidly from preheat	730-845	1350-1550	1175-1220	2150-2225(b)	2-5	O, A, or S	540-595(c)	**1000-1100(c)**
M2	Rapidly from preheat	730-845	1350-1550	1190-1230	2175-2250(b)	2-5	O, A, or S	540-595(c)	**1000-1100(c)**
M3, M4, M30, M33, M34, M35	Rapidly from preheat	730-845	1350-1550	1205-1230(b)	2200-2250(b)	2-5	O, A, or S	540-595(c)	**1000-1100(c)**
M36	Rapidly from preheat	730-845	1350-1550	1220-1245(b)	2225-2275(b)	2-5	O, A, or S	540-595(c)	**1000-1100(c)**
M41	Rapidly from preheat	730-845	1350-1550	1190-1215(b)	2175-2220(b)	2-5	O, A, or S	540-595(d)	**1000-1100(d)**
M42	Rapidly from preheat	730-845	1350-1550	1190-1210(b)	2175-2210(b)	2-5	O, A, or S	510-595(d)	**950-1100(d)**
M43	Rapidly from preheat	730-845	1350-1550	1190-1215(b)	2175-2220(b)	2-5	O, A, or S	510-595(d)	**950-1100(d)**
M44	Rapidly from preheat	730-845	1350-1550	1200-1225(b)	2190-2240(b)	2-5	O, A, or S	540-625(d)	**1000-1160(d)**
M46	Rapidly from preheat	730-845	1350-1550	1190-1220(b)	2175-2225(b)	2-5	O, A, or S	525-565(d)	**975-1050(d)**
M47	Rapidly from preheat	730-845	1350-1550	1175-1200(b)	2150-2200(b)	2-5	O, A, or S	525-595(d)	**975-1100(d)**
M48	Rapidly from preheat	730-845	1350-1550	1175-1200(b)	2150-2200(b)	2-5	O, A, or S	540-595(d)	**1000-1100(d)**
M62	Rapidly from preheat	730-845	1350-1550	1175-1200(b)	2150-2200(b)	2-5	O, A, or S	540-595(d)	**1000-1100(d)**

Tungsten high-speed steels									
T1, T2, T4, T8	Rapidly from preheat	815-870	1500-1600	1260-1300(b)	2300-2375(b)	2-5	O, A, or S	540-595(c)	**1000-1100(c)**
T5, T6	Rapidly from preheat	815-870	1500-1600	1275-1300(b)	2325-2375(b)	2-5	O, A, or S	540-595(c)	**1000-1100(c)**
T15	Rapidly from preheat	815-870	1500-1600	1205-1260(b)	2200-2300(b)	2-5	O, A, or S	540-650(d)	**1000-1200(d)**
Intermediate high-speed steels									
M50	Rapidly from preheat	730-845	1350-1550	1095-1120	2000-2050	2-5	O, A, or S	525-595	**975-1100**
M52	Rapidly from preheat	730-845	1350-1550	1120-1175	2050-2150	2-5	O, A, or S	525-595	**975-1100**
Chromium hot-work steels									
H10	Moderately from preheat	815	1500	1010-1040	1850-1900	15-40(e)	A	540-650	**1000-1200**
H11, H12	Moderately from preheat	815	1500	995-1025	1825-1875	15-40(e)	A	540-650	**1000-1200**
H13	Moderately from preheat	815	1500	995-1040	1825-1900	15-40(e)	A	540-650	**1000-1200**
H14	Moderately from preheat	815	1500	1010-1065	1850-1950	15-40(e)	A	540-650	**1000-1200**
H19	Moderately from preheat	815	1500	1095-1205	2000-2200	2-5	A or O	540-705	**1000-1300**
Tungsten hot-work steels									
H21, H22	Rapidly from preheat	815	1500	1095-1205	2000-2200	2-5	A or O	595-675	**1100-1250**
H23	Rapidly from preheat	845	1550	1205-1260	2200-2300	2-5	O	650-815	**1200-1500**
H24	Rapidly from preheat	815	1500	1095-1230	2000-2250	2-5	O	565-650	**1050-1200**

H25	Rapidly from preheat	815	1500	1150-1260	2100-2300	2-5	A or O	565-675	**1050-1250**
H26	Rapidly from preheat	870	1600	1175-1260	2150-2300	2-5	O, A or S	565-675	**1050-1250**
Molybdenum hot-work steels									
H41, H43	Rapidly from preheat	730-845	1350-1550	1095-1190	2000-2175	2-5	O, A or S	565-650	**1050-1200**
H42	Rapidly from preheat	730-845	1350-1550	1120-1220	2050-2225	2-5	O, A or S	565-650	**1050-1200**
High-carbon, high-chromium, cold-work steels									
D1, D5	Very slowly	815	1500	980-1025	1800-1875	15-45	A	205-540	**400-1000**
D3	Very slowly	815	1500	925-980	1700-1800	15-45	O	205-540	**400-1000**
D4	Very slowly	815	1500	970-1010	1775-1850	15-45	A	205-540	**400-1000**
D7	Very slowly	815	1500	1010-1065	1850-1950	30-60	A	150-540	**300-1000**
Medium-alloy, air-hardening, cold-work steels									
A2	Slowly	790	1450	925-980	1700-1800	20-45	A	175-540	**350-1000**
A3	Slowly	790	1450	955-980	1750-1800	25-60	A	175-540	**350-1000**
A4	Slowly	675	1250	815-870	1500-1600	20-45	A	175-425	**350-800**
A6	Slowly	650	1200	830-870	1525n-;1600	20-45	A	150-425	**300-800**
A7	Very slowly	815	1500	955-980	1750-1800	30-60	A	150-540	**300-1000**
A8	Slowly	790	1450	980-	1800-	20-45	A	175-	**350-**

				1010	1850			595	**1100**
A9	Slowly	790	1450	980-1025	1800-1875	20-45	A	510-620	**950-1150**
A10	Slowly	650	1200	790-815	1450-1500	30-60	A	175-425	**350-800**
Oil-hardening cold-work steels									
O1	Slowly	650	1200	790-815	1450-1500	10-30	O	175-260	**350-500**
O2	Slowly	650	1200	760-800	1400-1475	5-20	O	175-260	**350-500**
O6	Slowly	. . .	. . .	790-815	1450-1500	10-30	O	175-315	**350-600**
O7	Slowly	650	1200	790-830 845-885	W: 1450-1525 O: 1550-1625	10-30	O or W	175-290	**350-550**
Shock-resisting steels									
S1	Slowly	. . .	. . .	900-955	1650-1750	15-45	O	205-650	**400-1200**
S2	Slowly	650(f)	1200(f)	845-900	1550-1650	5-20	B or W	175-425	**350-800**
S5	Slowly	760	1400	870-925	1600-1700	5-20	O	175-425	**350-800**
S7	Slowly	650-705	1200-1300	925-955	1700-1750	15-45	A or O	205-260	**400-1150**
Mold steels									
P2	. . .	900-925(g)	1650-1750(g)	830-845(h)	1525-1550(h)	15	O	175-260	**350-500**
P3	. . .	900-925(g)	1650-1700(g)	800-830(h)	1475-1525(h)	15	O	175-260	**350-500**
P4	. . .	970-	1775-	970-	1775-	15	A	175-	**350-900**

		995(g)	1825(g)	995(h)	1825(h)			480	
P5	. . .	900-925(g)	1650-1700(g)	845-870(h)	1550-1600(h)	15	O or W	175-260	**350-500**
P6	. . .	900-925(g)	1650-1700(g)	790-815(h)	1450-1500(h)	15	A or O	175-230	**350-450**
P20	. . .	870-900(h)	1600-1650(h)	815-870	1500-1600	15	O	480-595(i)	**900-1100(i)**
P21(j)	Slowly	Do not preheat		705-730	1300-1350	60-180	A or O	510-550	**950-1025**
Low-alloy special-purpose steels									
L2	Slowly	. . .	. . .	W: 790-845 O: 845-925	W: 1450-1550 O: 1550-1700	10-30	O or W	175-540	**350-1000**
L3	Slowly	. . .	. . .	W: 775-815 O: 815-870	W: 1425-1500 1500-1600	10-30	O or W	175-315	**350-600**
L6	Slowly	. . .	. . .	790-845	1450-1550	10-30	O	175-540	**350-1000**
Carbon-tungsten special-purpose steels									
F1, F2	Slowly	650	1200	790-870	1450-1600	15	W or B	175-260	**350-500**
Water-hardening steels									
W1, W2, W3	**Slowly**	**565-650(k)**	**1050-1200(k)**	**760-845**	**1400-1550**	**10-30**	**B or W**	**175-345**	350-650

(a) O, oil quench; A, air cool; S, salt bath quench; W, water quench; B, brine quench.

(b) When the high-temperature heating is carried out in a salt bath, the range of temperatures should be about 14 °C (25 °F) lower than given here.

(c) Double tempering recommended for not less than 1 h at temperature each time.

(d) Triple tempering recommended for not less than 1 h at temperature each time.

(e) Times apply to open furnace heat treatment. For pack hardening, a common rule is to heat 1.2 min per mm (30 min per in.) of cross section of the pack.

(f) Preferable for large tools to minimize decarburization.

(g) Carburizing temperature.

(h) After carburizing.

(i) Carburized per case hardness.

(j) P21 is a precipitation-hardening steel having a thermal treatment that involves solution treating and aging rather than hardening and tempering.

(k) Recommended for large tools and tools with intricate sections

Table 10 Processing and service characteristics of tool steels

AISI designation	**Resistance to decarburization**	**Hardening and tempering**				Fabrication and service			
		Hardening response	**Amount of distortion**[(a)]	**Resistance to cracking**	**Approximate hardness**[(b)]**, HRC**	**Machinability**	**Toughness**	**Resistance to softening**	Resistance to wear
Molybdenum high-speed steels									
M1	Low	Deep	A or S, low; O, medium	Medium	60-65	Medium	Low	Very high	**Very high**
M2	Medium	Deep	A or S, low; O, medium	Medium	60-65	Medium	Low	Very high	**Very high**
M3 (class 1 and class 2)	Medium	Deep	A or S, low; O, medium	Medium	61-66	Medium	Low	Very high	**Very high**
M4	Medium	Deep	A or S, low; O, medium	Medium	61-66	Low to medium	Low	Very high	**Highest**
M7	Low	Deep	A or S, low; O, medium	Medium	61-66	Medium	Low	Very high	**Very high**
M10	Low	Deep	A or S, low; O, medium	Medium	60-65	Medium	Low	Very high	**Very high**
M30	Low	Deep	A or S, low; O, medium	Medium	60-65	Medium	Low	Highest	**Very high**
M33	Low	Deep	A or S, low; O, medium	Medium	60-65	Medium	Low	Highest	**Very high**

M34	Low	Deep	A or S, low; O, medium	Medium	60-65	Medium	Low	Highest	**Very high**
M35	Low	Deep	A or S, low; O, medium	Medium	60-65	Medium	Low	Highest	**Very high**
M36	Low	Deep	A or S, low; O, medium	Medium	60-65	Medium	Low	Highest	**Very high**
M41	Low	Deep	A or S, low; O, medium	Medium	65-70	Medium	Low	Highest	**Very high**
M42	Low	Deep	A or S, low; O, medium	Medium	65-70	Medium	Low	Highest	**Very high**
M43	Low	Deep	A or S, low; O, medium	Medium	65-70	Medium	Low	Highest	**Very high**
M44	Low	Deep	A or S, low; O, medium	Medium	62-70	Medium	Low	Highest	**Very high**
M46	Low	Deep	A or S, low; O, medium	Medium	67-69	Medium	Low	Highest	**Very high**
M47	Low	Deep	A or S, low; O, medium	Medium	65-70	Medium	Low	Highest	**Very high**
M48	Low	Deep	A or S, low; O, medium	Medium	65-70	Low	Low	Highest	**Highest**
M62	Low	Deep	A or S, low; O, medium	Medium	62-68	Medium	Low	Highest	**Very high**

Tungsten high-speed steels									
T1	High	Deep	A or S, low; O, medium	High	60-65	Medium	Low	Very high	**Very high**
T2	High	Deep	A or S, low; O, medium	High	61-66	Medium	Low	Very high	**Very high**
T4	Medium	Deep	A or S, low; O, medium	Medium	62-66	Medium	Low	Highest	**Very high**
T5	Low	Deep	A or S, low; O, medium	Medium	60-65	Medium	Low	Highest	**Very high**
T6	Low	Deep	A or S, low; O, medium	Medium	60-65	Low to medium	Low	Highest	**Very high**
T8	Medium	Deep	A or S, low; O, medium	Medium	60-65	Medium	Low	Highest	**Very high**
T15	Medium	Deep	A or S, low; O, medium	Medium	63-68	Low to medium	Low	Highest	**Highest**
Intermediate high-speed steels									
M50	Low	Deep	A or S, low; O, medium	Medium	58-63	Medium	Low	High	**High**
M52	Low	Deep	A or S, low; O, medium	Medium	58-64	Medium	Low	High	**High**
Chromium hot-work steels									

H10	Medium	Deep	Very low	Highest	39-56	Medium to high	High	High	**Medium**
H11	Medium	Deep	Very low	Highest	38-54	Medium to high	Very high	High	**Medium**
H12	Medium	Deep	Very low	Highest	38-55	Medium to high	Very high	High	**Medium**
H13	Medium	Deep	Very low	Highest	38-53	Medium to high	Very high	High	**Medium**
H14	Medium	Deep	Low	Highest	40-47	Medium	High	High	**Medium**
H19	Medium	Deep	A, low; O, medium	High	40-57	Medium	High	High	**Medium to high**
Tungsten hot-work steels									
H21	Medium	Deep	A, low; O, medium	High	36-54	Medium	High	High	**Medium to high**
H22	Medium	Deep	A, low; O, medium	High	39-52	Medium	High	High	**Medium to high**
H23	Medium	Deep	Medium	High	34-47	Medium	Medium	Very high	**Medium to high**
H24	Medium	Deep	A, low; O, medium	High	45-55	Medium	Medium	Very high	**High**
H25	Medium	Deep	A, low; O, medium	High	35-44	Medium	High	Very high	**Medium**
H26	Medium	Deep	A or S, low; O, medium	High	43-58	Medium	Medium	Very high	**High**

Molybdenum hot-work steels									
H42	Medium	Deep	A or S, low; O, medium	Medium	50-60	Medium	Medium	Very high	**High**
Air-hardening, medium-alloy, cold-work steels									
A2	Medium	Deep	Lowest	Highest	57-62	Medium	Medium	High	**High**
A3	Medium	Deep	Lowest	Highest	57-65	Medium	Medium	High	**Very high**
A4	Medium to high	Deep	Lowest	Highest	54-62	Low to medium	Medium	Medium	**Medium to high**
A6	Medium to high	Deep	Lowest	Highest	54-60	Low to medium	Medium	Medium	**Medium to high**
A7	Medium	Deep	Lowest	Highest	57-67	Low	Low	High	**Highest**
A8	Medium	Deep	Lowest	Highest	50-60	Medium	High	High	**Medium to high**
A9	Medium	Deep	Lowest	Highest	35-56	Medium	High	High	**Medium to high**
A10	Medium to high	Deep	Lowest	Highest	55-62	Medium to high	Medium	Medium	**High**
High-carbon, high-chromium, cold-work steels									
D2	Medium	Deep	Lowest	Highest	54-61	Low	Low	High	**High to very high**
D3	Medium	Deep	Very low	High	54-61	Low	Low	High	**Very high**

D4	Medium	Deep	Lowest	Highest	54-61	Low	Low	High	**Very high**
D5	Medium	Deep	Lowest	Highest	54-61	Low	Low	High	**High to very high**
D7	Medium	Deep	Lowest	Highest	58-65	Low	Low	High	**Highest**
Oil-hardening cold-work steels									
O1	High	Medium	Very low	Very high	57-62	High	Medium	Low	**Medium**
O2	High	Medium	Very low	Very high	57-62	High	Medium	Low	**Medium**
O6	High	Medium	Very low	Very high	58-63	Highest	Medium	Low	**Medium**
O7	High	Medium	O, very low; W, high	W, low; O, very high	58-64	High	Medium	Low	**Medium**
Shock-resisting steels									
S1	Medium	Medium	Medium	High	40-58	Medium	Very high	Medium	**Low to medium**
S2	Low	Medium	High	Low	50-60	Medium to high	Highest	Low	**Low to medium**
S5	Low	Medium	Medium	High	50-60	Medium to high	Highest	Low	**Low to medium**
S6	Low	Medium	Medium	High	54-56	Medium	Very high	Low	**Low to medium**

S7	Medium	Deep	A, lowest; O, low	O, high; A, highest	45-57	Medium	Very high	High	**Low to Medium**
Low-alloy special-purpose steels									
L2	High	Medium	O, medium; W, low	O, medium; W, high	45-63	High	Very high(c)	Low	**Low to medium**
L6	High	Medium	Low	High	45-62	Medium	Very high	Low	**Medium**
Low-Carbon mold steels									
P2	High	Medium	Low	High	58-64(c)	Medium to high	High	Low	**Medium**
P3	High	Medium	Low	High	58-64(c)	Medium	High	Low	**Medium**
P4	High	High	Very low	High	58-64(c)	Low to medium	High	Medium	**High**
P5	High	. . .	O, low; W, high	High	58-64(c)	Medium	High	Low	**Medium**
P6	High	. . .	A, very low; O, low	High	58-61(c)	Medium	High	Low	**Medium**
P20	High	Medium	Low	High	28-37	Medium to high	High	Low	**Low to medium**
P21	High	Deep	Lowest	Highest	30-40(d)	Medium	Medium	Medium	**Medium**
Water-hardening steels									
W1	Highest	Shallow	High	Medium	50-64	Highest	High(e)	Low	**Low to medium**

W2	Highest	Shallow	High	Medium	50-64	Highest	High[e]	Low	**Low to medium**
W5	**Highest**	**Shallow**	**High**	**Medium**	**50-64**	**Highest**	**High**[e]	**Low**	**Low to medium**

Source: Ref 3

(a) A, air cool; B, brine quench; O, oil quench; S, salt bath quench; W, water quench.

(b) After tempering in temperature range normally recommended for this steel.

(c) Carburized case hardness.

(d) After aging at 510 to 550 °C (950 to 1025 °F).

(e) Toughness decreases with increasing carbon content and depth of hardening.

More detailed heat-treating information for each of these steels is available in *Heat Treating,* Volume 4 of *ASM Handbook*. Additional detailed information on resistance to softening at elevated temperatures is summarized in Fig. 1, which presents curves of hardness versus tempering temperature. Similar curves for most of the tool steels covered in this article are presented in Ref 5.

Technical representatives of tool steel producers can supply more specific information on the properties developed by specific heat treatments in the steels produced by their companies. They should be consulted regarding the type of steel and heat treatment best suited to meet all service requirements at the least overall cost.

The physical properties, specifically, density, thermal expansion, and thermal conductivity, of selected tool steels are given in Tables 11 and 12.

Table 11 Density and thermal expansion of selected tool steels

Type	**Density**		Thermal expansion									
			µm/m · K from 20 °C to					µin./in. · °F from 70 °F to				
	g/cm^3	**lb/in.^{3}**	**100 °C**	**200 °C**	**425 °C**	**540 °C**	**650 °C**	**200 °F**	**400 °F**	**800 °F**	**1000 °F**	1200 °F
W1	7.84	0.282	10.4	11.0	13.1	13.8(a)	14.2(b)	5.76	6.13	7.28	7.64(a)	**7.90(b)**
W2	7.85	0.283	. . .	. . .	14.4	14.8	14.9	. . .	. . .	8.0	8.2	**8.3**
S1	7.88	0.255	12.4	12.6	13.5	13.9	14.2	6.9	7.0	7.5	7.7	**7.9**
S2	7.79	0.281	10.9	11.9	13.5	14.0	14.2	6.0	6.6	7.5	7.8	**7.9**
S5	7.76	0.280	. . .	. . .	12.6	13.3	13.7	. . .	. . .	7.0	7.4	**7.6**
S6	7.75	0.279	. . .	. . .	12.6	13.3	. . .	. . .	. . .	7.0	7.4	**. . .**
S7	7.76	0.280	. . .	12.6	13.3	13.7(a)	13.3	. . .	7.0	7.4	7.6(a)	**7.4**
O1	7.85	0.283	. . .	10.6(c)	12.8	14.0(d)	14.4(d)	. . .	5.9(c)	7.1	7.8(d)	**8.0(d)**
O2	7.66	0.277	11.2	12.6	13.9	14.6	15.1	6.2	7.0	7.7	8.1	**8.4**
O6	7.70	0.277	. . .	11.2	12.6	12.9	13.7	. . .	6.2	7.0	7.2	**7.6**
O7	7.8	0.282	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	**. . .**
A2	7.86	0.284	10.7	10.6(c)	12.9	14.0	14.2	5.96	5.9(c)	7.2	7.8	**7.9**
A6	7.84	0.283	11.5	12.4	13.5	13.9	14.2	6.4	6.9	7.5	7.7	**7.9**

A7	7.66	0.277	. . .	. . .	12.4	12.9	13.5	. . .	. . .	6.9	7.2	**7.5**
A8	7.87	0.284	. . .	. . .	12.0	12.4	12.6	. . .	. . .	6.7	6.9	**7.0**
A9	7.78	0.281	. . .	. . .	12.0	12.4	12.6	. . .	. . .	6.7	6.9	**7.0**
A10	7.68	0.278	12.8	13.3	. . .	. . .	. . .	7.1	7.4	. . .	. . .	**. . .**
D2	7.70	0.278	10.4	10.3	11.9	12.2	12.2	5.8	5.7	6.6	6.8	**6.8**
D3	7.70	0.278	12.0	11.7	12.9	13.1	13.5	6.7	6.5	7.2	7.3	**7.5**
D4	7.70	0.278	. . .	. . .	12.4	. . .	. . .	. . .	. . .	6.9	. . .	**. . .**
D5	. . .	. . .	. . .	. . .	. . .	12.0	. . .	. . .	. . .	. . .	6.7	**. . .**
H10	7.81	0.281	. . .	. . .	12.2	13.3	13.7	. . .	. . .	6.8	7.4	**7.6**
H11	7.75	0.280	11.9	12.4	12.8	12.9	13.3	6.6	6.9	7.1	7.2	**7.4**
H13	7.76	0.280	10.4	11.5	12.2	12.4	13.1	5.8	6.4	6.8	6.9	**7.3**
H14	7.89	0.285	11.0	. . .	. . .	. . .	. . .	6.1	. . .	. . .	. . .	**. . .**
h19	7.98	0.288	11.0	11.0	12.0	12.4	12.9	6.1	6.1	6.7	6.9	**7.2**
H21	8.28	0.299	12.4	12.6	12.9	13.5	13.9	6.9	7.0	7.2	7.5	**7.7**
H22	8.36	0.302	11.0	. . .	11.5	12.0	12.4	6.1	. . .	6.4	6.7	**6.9**
H26	8.67	0.313	. . .	. . .	. . .	12.4	. . .	. . .	. . .	. . .	6.9	**. . .**
H42	8.15	0.295	. . .	. . .	. . .	11.9	. . .	. . .	. . .	. . .	6.6	**. . .**
T1	8.67	0.313	. . .	9.7	11.2	11.7	11.9	. . .	5.4	6.2	6.5	**6.6**
T2	8.67	0.313	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	**. . .**
T4	8.68	0.313	. . .	. . .	. . .	11.9	. . .	. . .	. . .	. . .	6.6	**. . .**
T5	8.75	0.316	11.2	. . .	. . .	11.5	. . .	6.2	. . .	. . .	6.4	**. . .**

T6	8.89	0.321	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	**. . .**
T8	8.43	0.305	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	**. . .**
T15	8.19	0.296	. . .	9.9	11.0	11.5	. . .	. . .	5.5(c)	6.1	6.4	**. . .**
M1	7.89	0.285	. . .	10.6(c)	11.3	12.0	12.4	. . .	5.9(c)	6.3	6.7	**6.9**
M2	8.16	0.295	10.1	9.4(c)	11.2	11.9	12.2	5.6	5.2(c)	6.2	6.6	**6.8**
M3, class 1	8.15	0.295	. . .	. . .	11.5	12.0	12.2	. . .	. . .	6.4	6.7	**6.8**
M3, class 2	8.16	0.295	. . .	. . .	11.5	12.0	12.8	. . .	. . .	6.4	6.7	**7.1**
M4	7.97	0.288	. . .	9.5(c)	11.2	12.0	12.2	. . .	5.3(c)	6.2	6.7	**6.8**
M7	7.95	0.287	. . .	9.5(c)	11.5	12.2	12.4	. . .	5.3(c)	6.4	6.8	**6.9**
M10	7.88	0.255	. . .	. . .	11.0	11.9	12.4	. . .	. . .	6.1	6.6	**6.9**
M30	8.01	0.289	. . .	. . .	11.2	11.7	12.2	. . .	. . .	6.2	6.5	**6.8**
M33	8.03	0.290	. . .	. . .	11.0	11.7	12.0	. . .	. . .	6.1	6.5	**6.7**
M36	8.18	0.296	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	**. . .**
M41	8.17	0.295	. . .	9.7	10.4	11.2	. . .	. . .	5.4	5.8	6.2	**. . .**
M42	7.98	0.288	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	**. . .**
M46	7.83	0.283	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	**. . .**
M47	7.96	0.288	10.6	11.0	11.9	. . .	12.6	5.9	6.1	6.6	. . .	**7.0**
L2	7.86	0.284	. . .	. . .	14.4	14.6	14.8	. . .	. . .	8.0	8.1	**8.2**
L6	7.86	0.284	11.3	12.6	12.6	13.5	13.7	6.3	7.0	7.0	7.5	**7.6**
P2	7.86	0.284	. . .	. . .	13.7	. . .	. . .	. . .	. . .	7.6	. . .	**. . .**
P5	7.80	0.282	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	**. . .**

P6	7.85	0.284	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	**. . .**
P20	**7.85**	**0.284**	**. . .**	**. . .**	**12.8**	**13.7**	**14.2**	**. . .**	**. . .**	**7.1**	**7.6**	**7.9**

(a) From 20 °C to 500 °C (70 °F to 930 °F).

(b) From 20 °C to 600 °C (70 °F to 1110 °F).

(c) From 20 °C to 260 °C (70 °F to 500 °F).

(d) From 40 ° (100 °F)

Table 12 Thermal conductivity of selected tool steels

Temperature		Thermal conductivity	
°C	**°F**	**W/m · K**	Btu/ft · h · °F
Type W1			
95	200	48.3	**27.9**
260	500	41.5	**24.0**
400	750	38.1	**22.0**
540	1000	34.6	**20.0**
675	1250	29.4	**17.0**
815	1500	24.2	**14.0**
Type H11			
95	200	42.2	**24.4**
260	500	36.3	**21.0**
400	750	33.4	**19.3**

540	1000	31.5	**18.2**
675	1250	30.1	**17.4**
815	1500	28.6	**16.5**
Type H13			
215	420	28.6	**16.5**
350	660	28.4	**16.4**
475	890	28.4	**16.4**
605	1120	28.7	**16.6**
Type H21			
95	200	27.0	**15.6**
260	500	29.8	**17.2**
400	750	29.8	**17.2**
540	1000	29.4	**17.0**
675	1250	29.1	**16.8**
Type T1			
95	200	19.9	**11.5**
260	500	21.6	**12.5**
400	750	23.2	**13.4**
540	1000	24.7	**14.3**
Type T15			
95	200	20.9	**12.1**

200	500	24.1	**13.9**
400	750	25.4	**14.7**
540	1000	26.3	**15.2**
Type M2			
95	200	21.3	**12.3**
200	500	23.5	**13.6**
400	750	25.6	**14.8**
540	1000	27.0	**15.6**
675	**1250**	**28.9**	**16.7**

References cited in this section

3. "Tool Steels," Products Manual, American Iron and Steel Institute, March 1978
5. *Source Book on Industrial Alloys and Engineering Data,* American Society for Metals, 1978, p 251-292

Wrought Tool Steels

Revised by Alan M. Bayer, Teledyne Vasco, and Lee R. Walton, Latrobe Steel Company

Testing of Tool Steels

Because of the difficulty of obtaining reliable correlations between the properties of tool steels as measured by laboratory tests and the performance of these steels in service or in fabrication, these properties are usually presented as general comparisons rather than as specific data.

Performance in Service

The basic properties of tool steels that determine their performance in service are resistance to wear, deformation, and breakage; toughness; and, in many instances, resistance to softening at elevated temperatures. These properties are listed in Table 13 and compared in Fig. 6. Often, these characteristics can be measured by, or inferred from, the measurement of hardness. The hardness of tool steels is most commonly measured and reported on the Rockwell C scale (HRC) in the United States and on the Vickers scale (diamond pyramid hardness, or HV) in Great Britain and Europe. It is significant that the conversion from HRC to HV, or vice versa, is not linear (see Fig. 7). For example, an increase from 67 to 68 HRC corresponds to a 40-point increase on the HV scale, whereas increases from 57 to 58 HRC and from 49 to 50 HRC correspond, respectively, to 20-point and 10-point increases on the HV scale.

Table 13 General properties of tool steels

AISI designation	**Major factors(a)**			Minor factors				
	Wear resistance(b)	**Toughness(c)**	**Hot hardness**	**Usual working hardness, HRC**	**Depth of hardening(d)**	**Finest grain size at full hardness, Shepherd standard**	**As-quenched surface hardness, HRC**	Core hardness (25 mm, or 1 in., diam round), HRC
Molybdenum high-speed steels								
M1	7	3	8	63-65	D	$9\frac{1}{2}$	64-66	**64-66**
M2	7	3	8	63-65	D	$9\frac{1}{2}$	64-66	**64-66**
M3, class 1	8	3	8	63-66	D	$9\frac{1}{2}$	64-66	**64-66**
M3, class 2	8	3	8	63-66	D	$9\frac{1}{2}$	64-66	**64-66**
M4	9	3	8	63-66	D	$9\frac{1}{2}$	65-67	**65-67**
M7	8	3	8	63-66	D	$9\frac{1}{2}$	64-66	**64-66**
M10	7	3	8	63-65	D	$9\frac{1}{2}$	64-66	**64-66**
M30	7	2	8	63-65	D	$9\frac{1}{2}$	64-66	**64-66**
M33	8	1	9	63-65	D	$9\frac{1}{2}$	64-66	**64-66**
M34	8	1	9	63-65	D	$9\frac{1}{2}$	64-66	**64-66**

M35	7	2	8	63-65	D	$9\frac{1}{2}$	64-66	**64-66**
M36	7	1	9	63-65	D	$9\frac{1}{2}$	64-66	**64-66**
M41	8	1	9	66-70	D	$9\frac{1}{2}$	63-65	**63-65**
M42	8	1	9	66-70	D	$9\frac{1}{2}$	63-65	**63-65**
M43	8	1	9	66-70	D	$9\frac{1}{2}$	63-65	**63-65**
M44	8	1	9	66-70	D	$9\frac{1}{2}$	63-65	**63-65**
M46	8	1	9	66-69	D	$9\frac{1}{2}$	63-65	**63-65**
M47	8	1	9	66-70	D	$9\frac{1}{2}$	63-65	**63-65**
Intermediate high-speed steels								
M50	6	3	6	61-63	D	$8\frac{1}{2}$	63-65	**63-65**
M52	6	3	6	62-64	D	$8\frac{1}{2}$	63-65	**63-65**
Tungsten high-speed steels								
T1	7	3	8	63-65	D	$9\frac{1}{2}$	64-66	**64-66**
T2	8	3	8	63-66	D	$9\frac{1}{2}$	65-67	**65-67**
T4	7	2	8	63-65	D	$9\frac{1}{2}$	63-66	**63-66**

T5	7	1	9	63-65	D	$9\frac{1}{2}$	64-66	**64-66**
T6	8	1	9	63-65	D	$9\frac{1}{2}$	64-66	**64-66**
T8	8	2	8	63-65	D	$9\frac{1}{2}$	64-66	**64-66**
T15	9	1	9	64-68	D	$9\frac{1}{2}$	65-68	**65-68**
Chromium hot-work steels								
H10	3	9	6	39-56	D	8	52-59	**52-59**
H11	3	9	6	38-55	D	8	53-55	**53-55**
H12	3	9	6	38-55	D	8	53-55	**53-55**
H13	3	9	6	40-53	D	8	51-54	**51-54**
H14	4	6	7	40-54	D	8	53-57	**53-56**
H19	5	6	7	40-55	D	$8\frac{1}{2}$	48-57	**48-57**
Tungsten hot-work steels								
H21	4	6	8	40-55	D	9	45-63	**45-63**
H22	5	5	8	36-54	D	9	48-56	**48-56**
H23	5	5	8	38-48	D	7	34-40	**34-40**
H24	5	5	8	40-55	D	9	52-56	**52-56**
H25	4	6	8	35-45	D	9	33-46	**33-46**
H26	6	4	8	50-58	D	9	51-59	**51-59**

Molybdenum hot-work steels								
H24	6	4	7	45-62	D	$8\frac{1}{2}$	54-62	**54-62**
Air-hardening, medium-alloy, cold-work steels								
A2	6	4	5	57-62	D	$8\frac{1}{2}$	63-65	**63-65**
A3	7	3	5	58-63	D	$8\frac{1}{2}$	63-65	**63-65**
A4	5	4	4	54-62	D	$8\frac{1}{2}$	61-63	**61-63**
A5	5	4	4	54-60	D	$8\frac{1}{2}$	60-62	**60-62**
A6	4	5	4	54-60	D	$8\frac{1}{2}$	60-62	**60-62**
A7	9	1	6	58-66	D	$8\frac{1}{2}$	64-66	**64-66**
A8	4	8	6	48-57	D	8	60-62	**60-62**
A9	4	8	6	40-56	D	8	55-57	**55-57**
A10	3	3	3	55-62	D	8	60-63	**60-63**
High-carbon, high-chromium, cold-work steels								
D2	8	2	6	58-64	D	$7\frac{1}{2}$	61-64	**61-64**
D3	8	1	6	58-64	D	$7\frac{1}{2}$	64-66	**64-66**
D4	8	1	6	58-64	D	$7\frac{1}{2}$	64-66	**64-66**

D5	8	2	7	58-63	D	$7\frac{1}{2}$	61-64	**61-64**
D7	9	1	6	58-66	D	$7\frac{1}{2}$	64-68	**64-68**
Oil-hardening cold-work steels								
O1	4	3	3	57-62	M	9	61-64	**59-61**
O2	4	3	3	57-62	M	9	61-64	**59-61**
O6	3	3	2	58-63	M	9	65-67	**50-55**
O7	5	3	3	58-64	M	9	61-64	**59-61**
Shock-resisting steels								
S1	4	8	5	50-58	M	8	55-58	**55-58**
S2	2	8	2	50-60	M	8	61-63	**56-60**
S5	2	8	3	50-60	M	9	61-63	**58-62**
S6	2	8	3	50-56	M	8	56-58	**56-58**
S7	3	8	5	47-57	D	8	59-61	**59-61**
Low-alloy special-purpose steels								
L2	1	7	2	45-62	M	$8\frac{1}{2}$	56-62	**54-58**
L6	3	6	2	45-62	M	8	58-63	**58-62**
Low-carbon mold steels								
For hubbed and/or carburized cavities								
P2	1(e)	9	2(e)	58-64(e)	S	. . .	62-65(a)	**15-21**

P3	1(e)	9	2(e)	58-64(e)	S	. . .	62-64(a)	**15-21**
P4	1(e)	9	4(e)	58-64(e)	M	. . .	62-65(a)	**33-35**
P5	1(e)	9	2(e)	50-64(e)	S	. . .	62-65(a)	**20-25**
P6	1(e)	9	3(e)	58-61(e)	M	. . .	60-62(a)	**35-37**
For machined cavities								
P20	1(e)	8	2(e)	30-50	M	$7\frac{1}{2}$	52-54	**45-50**
P21	1	8	4	36-39(e)	D	. . .	22-26	**22-26**
Water-hardening tool steels								
W1	2-4	3-7	1	58-65	S	9	65-67	**38-43**
W2	2-4	3-7	1	58-65	S	9	65-67	**38-43**
W5	**3-4**	**3-7**	**1**	**58-65**	**S**	**9**	**65-67**	**38-43**

Source: Ref 6

(a) Rating range from 1 (low) to 9 (high).

(b) Wear resistance increases with increasing carbon content.

(c) Toughness decreases with increasing carbon content and depth of hardening.

(d) S, shallow; M, medium; and D, deep.

(e) After carburizing.

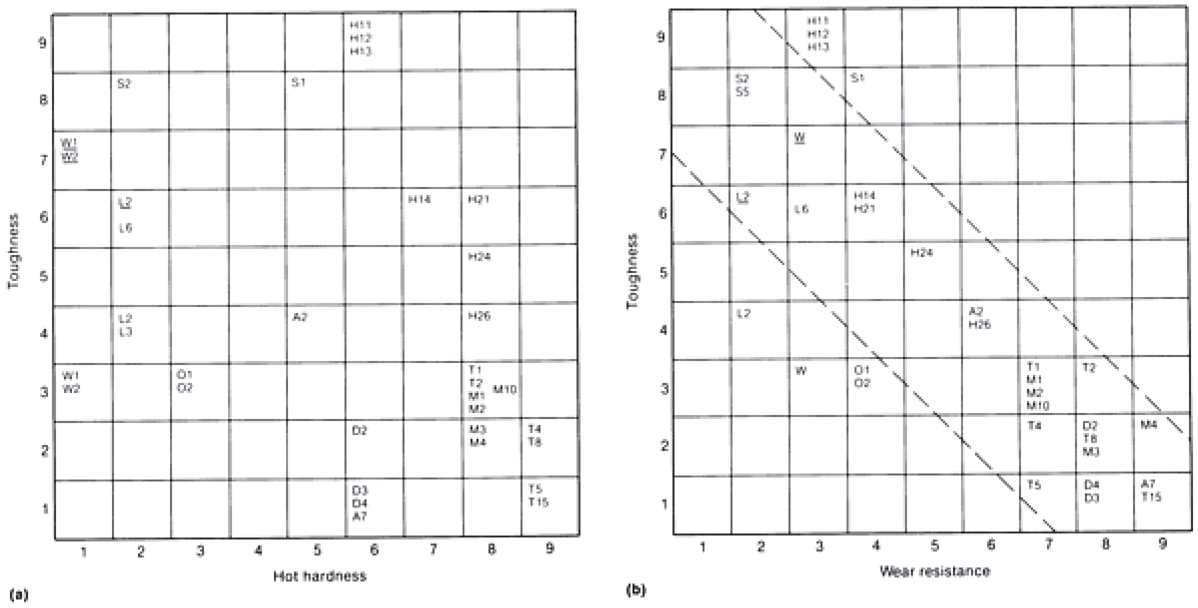

Fig. 6 Plots of toughness against (a) hot hardness and (b) wear resistance for tool steels. Types underlined indicate shallow-hardened tool steels. The area between the dashed lines in (b) represents average values.

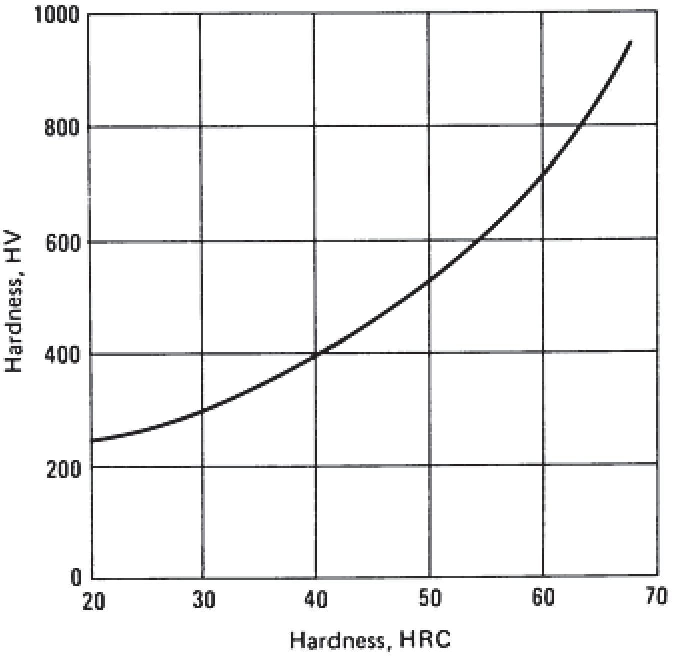

Fig. 7 Relationship of Vickers and Rockwell hardness scales

For a given tool steel at a given hardness, wear resistance may vary widely depending on the wear mechanism involved and the heat treatment used. It is important to note also that among tool steels with widely differing compositions but identical hardnesses, wear resistance may vary widely under identical wear conditions.

For all practical purposes, the resistance to elastic deformation (modulus of elasticity) of all tool steels in all conditions is about 210 GPa (30 × 10^6 psi) at room temperature. This decreases uniformly to about 185 GPa (27 × 10^6 psi) at 260 °C (500 °F) and about 150 GPa (22 × 10^6 psi) at 540 °C (1000 °F).

Except for special grades, the compositions and heat treatments of most tool steels are selected to provide very high resistance to plastic deformation. This course of action leaves the metal with very little ability to absorb deformation; in other words, it leaves the metal very brittle. Therefore, it is difficult to determine reliable values of strength at maximum hardness by tensile testing, even when specially designed clamping fixtures are used to provide accurate alignment.

Compression tests have been used to some extent to measure resistance to deformation. Bending tests using either three- or four-point supports can provide useful comparative information on tool steels with high hardness levels, but the results are often difficult to evaluate. Torsion tests have been used effectively to measure the toughness of tool steels, particularly those to be used in drills and other tools loaded in torsion during service.

The amount of energy absorbed when a notched bar of fully hardened tool steel (except for certain grades) is broken in impact (Charpy test) is so small that it is very difficult to measure the differences in toughness that may make it possible to predict service performance. Attempts havebeen made to perform impact tests on unnotched tool steel bars, but excessive deformation of supporting fixtures makes it very difficult to obtain reproducible results. Torsion impact testing yields useful, reproducible data on the effects of variations in the composition and heat treatment of tool steels; however, it is difficult to correlate the results of such testing with service experience. Fatigue tests have been useful for research, but only in some instances have the results correlated well with field experience.

In general, the ability of tool steels to withstand the rapid application of high loads without breaking increases with decreasing hardness. With hardness held constant, wide differences can be observed among tool steels of different compositions, or among steels of the same nominal composition made by different melting practices or heat treated according to different schedules.

The ability of a tool steel to resist softening at elevated temperatures is related to its ability to develop secondary hardening and to the amount of special phases, such as excess alloy carbides, in the microstructure. Useful information on the ability of tool steels to resist softening at elevated temperatures can be obtained from tempering curves such as those in Fig. 1. Hardness testing at elevated temperatures (see Fig. 8 and 9) also can provide useful information. Table 14 lists the hot hardness of selected high-speed and die steels.

Table 14 Hot hardness of selected high-speed tool steels and die steels

AISI designation	Hardness, HRC				
	Room temperature	Hot hardness[(a)]			
		315 °C (600 °F)	**425 °C (800 °F)**	**540 °C (1000 °F)**	650 °C (1200 °F)
High-speed tool steels					
M1	65	61	58	54	**32**
M2	65	62	59	55	**36**
M3, class 1	65	63	60	56	**36**
M3, class 2	65	63	60	56	**36**
M4	66	63	60	56	**37**
M7	65	61	58	54	**35**
M10	65	60	57	52	**33**
M30	65	63	58	55	**35**
M33	65	64	60	57	**40**
M36	65	64	60	57	**40**
M42	68	66	65	62	**44**

M50	64	59	57	52	...
M52	64	60	57	53	...
T1	65	61	57	53	**33**
T4	65	61	59	55	**38**
T5	66	62	60	56	**40**
T15	68	64	61	57	**42**
Cold-work die steels					
A2	60	52	46	35	...
A8	58	55	52	45	...
D2	60	53	47	38	...
D4	62	52	46	37	...
Hot-work die steels					
A8	58	55	52	45	...
H11	54	49	47	42	**22**
H12	54	49	47	42	**22**
H13	55	49	47	42	**22**
H19	54	51	47	42	**31**
H21	54	52	49	45	**29**
H23	41	32	30	28	**25**
H26	**58**	**54**	**50**	**46**	**31**

Source: Ref 7

(a) Small-diameter bars tested according to the recommended heat treatment.

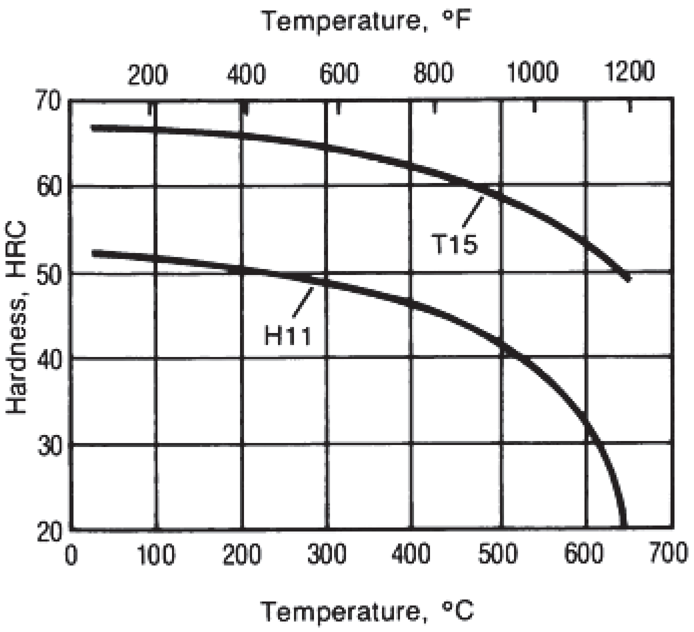

Fig. 8 Hot hardness of H11 and T15 tool steels. Type H11 has high resistance to softening at elevated temperatures; T15 has the highest resistance to softening. For these tests, H11 was air cooled from 1010 °C (1850 °F) and tempered 2 + 2 h at 565 °C (1050 °F); T15 was oil quenched from 1230 °C (2250 °F) and tempered 2 + 2 h at 550 °C (1025 °F). After hot-hardness testing at 650 °C (1200 °F), T15 had a room-temperature hardness of 63.4 HRC.

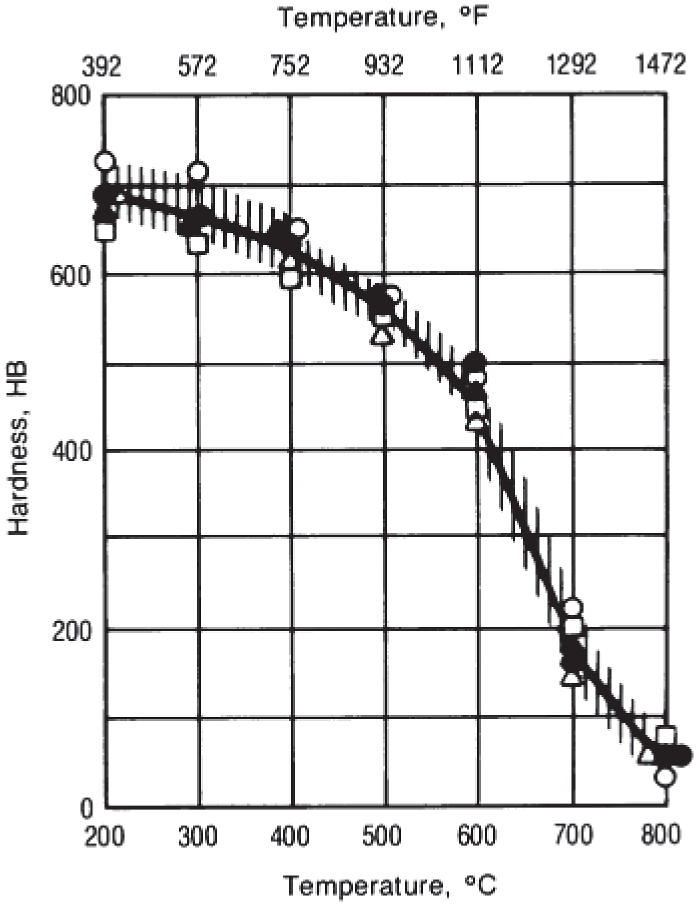

Fig. 9 Hot hardness (mutual indentation Brinell) of high-speed steel as a function of the temperature of testing. Average results of a series of tests on T1 tool steel. Ref 6

Fabrication

The properties that influence the ease of fabrication of tool steels include machinability; grindability; weldability; hardenability; and extent of distortion, safety (freedom from cracking), and tendency to decarburize during heat treatment.

Machinability of tool steels can be measured by the usual methods applied to constructional steels. Results are reported as percentages of the machinability of water-hardening tool steels (see Table 15); 100% machinability in tool steels is equivalent to about 30% machinability in constructional steels, for which 100% machinability would be that of a free-machining, constructional steel such as B1112. Improving the machinability of a tool steel by altering either the composition or preliminary heat treatment can be very important if a large amount of machining is required to form the tool and a large number of tools are to be made.

Table 15 Approximate machinability ratings for annealed tool steels

Type	Machinability rating
O6	**125**
W1, W2, W5	**100**[(a)]
A10	**90**

P2, P3, P4, P5, P6	**75-90**
P20, P21	**65-80**
L2, L6	**65-75**
S1, S2, S5, S6, S7	**60-70**
H10, H11, H13, H14, H19	**60-70**(b)
O1, O2, O7	**45-60**
A2, A3, A4, A6, A8, A9	**45-60**
H21, H22, H24, H25, H26, H42	**45-55**(b)
T1	**40-50**
M2	**40-50**
T4	**35-40**
M3, class 1	**35-40**
D2, D3, D4, D5, D7, A7	**30-40**
T15	**25-30**
M15	**25-30**

(a) Equivalent to approximately 30% of the machinability of B1112.

(b) For hardness range 150 to 200 HB

Grindability. One measure of grindability is the ease with which the excess stock on heat-treated tool steel can be removed using standard grinding wheels. The grinding ratio (grindability index) is the volume of metal removed per volume of wheel wear. The higher the grindability index, the easier the metal is to grind. The index is valid only for specific sets of grinding conditions. Table 16 gives grinding ratios for several high-speed steels. It should be noted that the grindability index does not indicate the susceptibility to cracking during or after grinding, the ability to produce the required surface (and subsurface) stress distribution, or the ease of obtaining the required surface smoothness.

Table 16 Typical grinding ratios for high-speed steels using three selected grinding wheels

Type	**Hardness, HRC**	Grinding ratio[(a)]		
		32A46-H8VBE	**32A60-H8VBE**	32A80-H8VBE
T15	65.7	0.49	0.62	**0.51**
M44	67.7	0.97	0.99	**0.88**
M41	68.7	1.2	1.6	**1.4**
M43	67.5	1.4	2.2	**1.7**
M42	68.8	4.8	6.5	**3.8**
M2	64.9	6.1	7.2	**6.7**
M1	**64.9**	**7.8**	**8.0**	**11.9**

(a) For the following conditions: work, 152 mm (6 in.) long by 38 mm (1.5 in.) wide; wheel size, 203 mm (8 in.) in diameter by 12.7 mm (0.5 in.) wide; wheel speed (idling), 30 m/s (6000 table speed, 0.3 m/s (60 sfm); unit cross feed, 1.27 mm (0.050 in.) after each table traverse; unit downfeed, 0.025 mm (0.001 in.) after each complete cross feed; total down feed, 0.25 mm (0.010 in.) preceded by four unit down feeds to break wheel in after dressing with a diamond tool; grinding fluid, 1.25% water emulsion of general-purpose soluble oil

Weldability. The ability to construct, alter, or repair tools by welding without causing the material to crack may be an important factor in the selection of a tool material, especially if the tool is large. It is only rarely of importance in selecting materials for small tools. Weldability is largely a function of composition, but welding method and procedure also influence weld soundness. Generally, tool steels that are deep hardening and that are classified as having relatively high safety in hardening are among the more readily welded tool steel compositions. These are generally the lower-alloy tool steel grades.

Hardenability includes both the maximum hardness obtainable when the quenched steel is fully martensitic and the depth of hardening obtained by quenching in a specific manner. In this context, depth of hardening must be defined, generally as a specific value of hardness or a specific microstructural appearance. As a very general rule, maximum hardness of a tool steel increases with increasing carbon content; increasing the austenitic grain size and the amount of alloying elements reduces the cooling rate required to produce maximum hardness (increases the depth of hardening). The Jominy end-quench test, which is applied extensively to measure hardenability of constructional steels (see the articles in the Section "Hardenability of Carbon and Low-Alloy Steels" in this Volume), has limited application to tool steels. This test gives useful information only for oil-hardening grades. Air-hardening grades are so deep hardening that the standard Jominy test is not sufficient to evaluate hardenability.

An air-hardenability test has been developed that is based on the principles involved in the Jominy test, but which uses only still-air cooling and a 152 mm (6 in.) diam end block to produce the very slow cooling rates of large sections. Such tests provide useful information for research but are of limited use for devising production heat treatments. By contrast, water-hardening grades of tool steel are so shallow hardening that the Jominy test is not sensitive enough. Special tests, such as the Shepherd PF test, are useful for research and for special applications of water-hardening tool steels.

In the Shepherd PF test, a bar 19 mm ($\frac{3}{4}$ in.) in diameter, in the normalized condition, is brine quenched from 790 °C (1450 °F) and fractured; the case depth (penetration, P) is measured in 0.4 mm ($\frac{1}{64}$ in.) intervals, and the fracture grain size of the case (F) is determined by comparison with standard specimens. A PF value of 6 to 8 indicates a case depth of 2.4 mm ($\frac{6}{64}$ in.) and a fracture grain size of 8. Fine-grain water-hardening tool steels are those with fracture grain sizes (F values) of 8 or more. Deep-hardening steels of this type have P values of 12 or more; medium-hardening steels, 9 to 11; and shallow-hardening steels, 6 to 8.

Distortion and Safety in Hardening. Minimal distortion in heat treating is important for tools that must remain within close size limits. In general, the amount of distortion and the tendency to crack increase as the severity of quenching increases.

Resistance to decarburization is an important factor in determining whether a protective atmosphere is required during heat treating. In a decarburizing atmosphere, the rate of decarburization increases rapidly with increasing austenitizing temperature, and, for a given austenitizing temperature, the depth of decarburization increases in direct proportion to holding time. Some types of tool steel decarburize much more rapidly than others under the same conditions of atmosphere, austenitizing temperature, and time.

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Wrought Tool Steels

Revised by Alan M. Bayer, Teledyne Vasco, and Lee R. Walton, Latrobe Steel Company

Machining Allowances

The standard machining allowance is the recommended total amount of stock that the user should remove from the as-supplied mill form to provide a surface free from imperfections that might adversely affect the response to heat treatment or the ability of tools to perform properly.

The decarburization resulting from oxidation at the exposed surfaces during the forging and rolling of the tool steel is a major factor in determining the amount of stock that should be removed. Although extra care is used in producing tool steels, scale, seams, and other surface imperfections that may be present must be removed.

Table 17 gives the standard machining allowances for various sizes of hot-rolled square and flat bars. Similar tables are available for other shapes and other methods of forming and finishing in ASTM specifications A 600, A 6881, and A 686.

Table 17 Standard machining allowances for hot-rolled square and flat bars

Specified width		Machining allowances[(a)]			
		Top and bottom surfaces		Edges	
mm	**in.**	**mm**	**in.**	**mm**	in.

Specified thickness, <12.7 mm ($\frac{1}{2}$ in.)					
0-12.7	0-$\frac{1}{4}$	0.64	0.025	0.64	**0.025**
>12.7-25.4	>$\frac{1}{4}$-1	0.64	0.025	0.89	**0.035**
>25.4-50.8	>1-2	0.76	0.030	1.02	**0.040**
>50.8-76.2	>2-3	0.89	0.035	1.27	**0.050**
>76.2-101.6	>3-4	1.02	0.040	1.65	**0.065**
>101.6-127.0	>4-5	1.14	0.045	2.03	**0.080**
>127.0-152.4	>5-6	1.27	0.050	2.41	**0.095**
>152.4-177.8	>6-7	1.40	0.055	2.67	**0.105**
>177.8-203.2	>7-8	1.52	0.060	3.05	**0.120**
>203.2-228.6	>8-9	1.52	0.060	3.30	**0.130**
>228.6-304.8	>9-12	1.52	0.060	3.56	**0.140**
Specified thickness, >12.7-25.4 mm (>$\frac{1}{4}$-1 in.)					
>12.7-25.4	>$\frac{1}{4}$-1	1.14	0.045	1.14	**0.045**
>25.4-50.8	>1-2	1.14	0.045	1.27	**0.050**
>50.8-76.2	>2-3	1.27	0.050	1.52	**0.060**
>76.2-101.6	>3-4	1.40	0.055	1.90	**0.075**
>101.6-127.0	>4-5	1.52	0.060	2.41	**0.095**

>127.0-152.4	>5-6	1.65	0.065	2.92	**0.115**
>152.4-177.8	>6-7	1.78	0.070	3.30	**0.130**
>177.8-203.2	>7-8	1.90	0.075	3.81	**0.150**
>203.2-228.6	>8-9	1.90	0.075	3.94	**0.155**
>228.6-304.8	>9-12	1.90	0.075	3.94	**0.155**
Specified thickness, >25.4-50.8 mm (>1-2 in.)					
>25.4-50.8	>1-2	1.65	0.065	1.65	**0.065**
>50.8-76.2	>2-3	1.65	0.065	1.78	**0.070**
>76.2-101.6	>3-4	1.78	0.070	2.16	**0.085**
>101.6-127.0	>4-5	1.78	0.070	2.67	**0.105**
>127.0-152.4	>5-6	1.90	0.075	3.18	**0.125**
>152.4-177.8	>6-7	2.030	0.080	3.68	**0.145**
>177.8-203.2	>7-8	2.03	0.080	4.19	**0.165**
>203.2-228.6	>8-9	2.41	0.095	4.32	**0.170**
>228.6-304.8	>9-12	2.54	0.100	4.32	**0.170**
Specified thickness, >50.8-76.2 mm (>2-3 in.)					
>50.8-76.2	>2-3	2.16	0.085	2.16	**0.085**
>76.2-101.6	>3-4	2.16	0.085	2.54	**0.100**
>101.6-127.0	>4-5	2.16	0.085	3.05	**0.120**
>127.0-152.4	>5-6	2.16	0.085	3.43	**0.135**
>152.4-177.8	>6-7	2.29	0.090	3.94	**0.155**

>177.8-203.2	>7-8	2.54	0.100	4.32	**0.170**
>203.2-228.6	>8-9	2.54	0.100	4.83	**0.190**
>228.6-304.8	>9-12	2.54	0.100	4.83	**0.190**
Specified thickness, >76.2-101.6 mm (>3-4 in.)					
>76.2-101.6	>3-4	2.92	0.115	2.92	**0.115**
>101.6-127.0	>4-5	2.92	0.115	3.18	**0.125**
>127.0-152.4	>5-6	2.92	0.115	3.56	**0.140**
>152.4-177.8	>6-7	2.92	0.115	4.32	**0.170**
>177.8-203.2	>7-8	3.18	0.125	4.83	**0.190**
>203.2-228.6	>8-9	3.18	0.125	4.83	**0.190**
>228.6-304.8	**>9-12**	**3.18**	**0.125**	**4.83**	**0.190**

(a) Minimum allowance per side for machining prior to heat treatment. Maximum decarburization limit, 80% of machining allowance

In addition to the standard machining allowance, sufficient stock must be provided to permit the cleanup of any decarburization or distortion that may occur during final heat treatment. The amount varies with the type of tool steel, the type of heat treating equipment, and the size and shape of the tool.

Group W and group O tool steels are considered highly resistant to decarburization. Group M steels, cobalt-containing group T steels, group D steels, and types H42, A2, and S5 are rated poor for resisting decarburization.

Decarburization during final heat treatment is undesirable because it alters the composition of the surface layer, thereby changing the response to heat treatment of this layer and usually adversely affecting the properties resulting from heat treatment. Decarburization can be controlled or avoided by heat treating in a salt bath or in a controlled atmosphere or vacuum furnace. When heat treating is accomplished in vacuum, a vacuum of 13 to 27 Pa (100 to 200 μm Hg) is satisfactory for most tools if the furnace is in good operating condition and has a very low leak rate. However, it is recommended that a vacuum of 7 to 13 Pa (50 to 100 μm Hg) be used wherever possible.

If special heat-treating equipment is not available, appreciable decarburization can be avoided by wrapping the tool in stainless steel foil. Type 321 stainless steel foil can be used at austenitizing temperatures up to about 1010 °C (1850 °F); either type 309 or type 310 foil is required at austenitizing temperatures from 1010 to 1205 °C (1850 to 2200 °F).

Wrought Tool Steels

Revised by Alan M. Bayer, Teledyne Vasco, and Lee R. Walton, Latrobe Steel Company

Precision Cast Hot-Work Tools

Precision casting of tools to nearly finished size offers important cost advantages through reductions in waste and machining. Casting is a particular advantage when pattern-making costs can be distributed over a large number of tools.

Experience with cast forging and extrusion dies has shown that cast tools are more resistant to heat checking. Minute cracks do occur, but they grow at much lower rates than in wrought material of the same grade and hardness. The slower propagation of thermal-fatigue cracks generally extends die life significantly. The mechanical testing of cast and wrought H13 indicates that yield and tensile strengths are virtually identical from room temperature to 595 °C (1100 °F), but that ductility is moderately lower in cast material. Hot hardness of cast H13 is higher than that of wrought H13 at temperatures above about 315 °C (600 °F); this hardness advantage increases with temperature, as illustrated in Fig. 10, and measures about eight points on the Rockwell C scale at 650 °C (1200 °F).

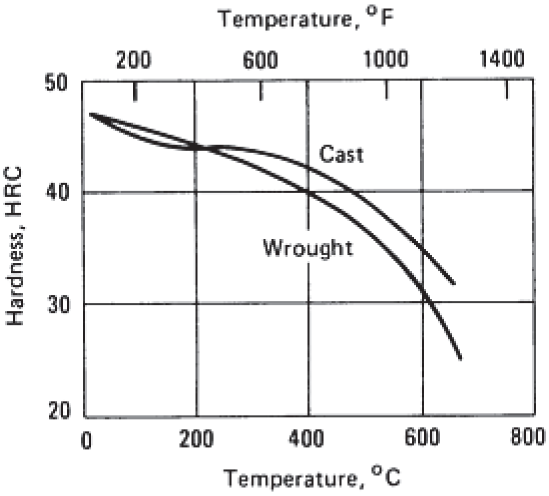

Fig. 10 Comparison of hot hardness for cast and wrought H13 tool steel. Source: Latrobe Steel Company

Because cast dies exhibit uniform properties in all directions, no problem of directionality (anisotropy) exists. The dimensional control of castings is very consistent after an initial die is made and any necessary corrections are incorporated in the pattern. Reasonable finishing allowances are 0.25 to 0.38 mm (0.010 to 0.015 in.)on the impression faces, 0.8 to 1.6 mm ($\frac{1}{32}$ to $\frac{1}{16}$ in.) at the parting line of the mold, and 1.6 to 3.2 mm ($\frac{1}{16}$ to $\frac{1}{8}$ in.) on the back and outside surfaces. The hot-work tool steels most commonly cast include H12, H13, H21, and H25.

Wrought Tool Steels

Revised by Alan M. Bayer, Teledyne Vasco, and Lee R. Walton, Latrobe Steel Company

Surface Treatments

In many applications, the service life of high-speed steel tools can be increased by surface treatments.

Oxide coatings, provided by treatment of the finish-ground tool in an alkali-nitrate bath or by steam oxidation, prevent or reduce adhesion of the tool to the workpiece. Oxide coatings have doubled tool life, particularly that of tools used to machine gummy materials such as soft copper and nonfree-cutting low-carbon steels.

Plating of finished high-speed steel tools with 0.0025 to 0.0125 mm (0.1 to 0.5 mil) of chromium also prolongs tool life by reducing adhesion of the tool to the workpiece. Chromium plating is relatively expensive, and precautions must be taken to prevent tool failure in service due to hydrogen embrittlement.

Carburizing is not recommended for high-speed steel cutting tools because the cases on such tools are extremely brittle. However, carburizing is useful for applications such as cold-work dies that require extreme wear resistance and that are not subjected to impact or highly concentrated loading. Carburizing is done at 1040 to 1065 °C (1900 to 1950 °F) for short periods of time (10 to 60 min) to produce a case 0.05 to 0.25 mm (0.002 to 0.010 in.) deep. The carburizing treatment also serves as an austenitizing treatment for the whole tool. A carburized case on high-speed steels has a hardness of 65 to 70 HRC, but does not have the high resistance to softening at elevated temperatures exhibited by normally hardened high-speed steel.

Nitriding successfully increases the life of all types of high-speed steel cutting tools. However, gas nitriding in dissociated ammonia produces a case that is too brittle for most applications. Liquid nitriding for about 1 h at 565 °C (1050 °F) provides a light case, increasing both surface hardness and resistance to adhesion. For nitrided high-speed steel taps, drills, and reamers used in machining annealed steel, fivefold increases in life have been reported, with average increases of 100 to 200%. Obviously, if this nitrided case is removed when the tool is reground, the tool must then be retreated, thereby reducing the cost advantage of the process.

Other special surface treatment processes, such as aerated nitriding baths, improve resistance to adhesive wear without producing excessive brittleness. Sulfur-containing nitriding baths provide a high-sulfur surface layer for additional resistance to seizing.

Titanium nitride coating is the most common of the newer types of wear-resistant coatings that are applied to tool steels. This shallow layer of titanium nitride, formed by physical vapor deposition process, has increased tool life in many instances by as much as 400%. This is primarily attributed to the increased lubricity of the coating due to a coefficient of friction that is one-third that of the bare metal surface of the tool. This increase in tool life justifies the application of the coating, despite the increase in cost. Additional information on the benefits of titanium nitride coatings used on tool steels is available in the article "High-Speed Tools Steels" in *Machining,* Volume 16 of *ASM Handbook,* formerly 9th Edition of *Metals Handbook.*

Sulfide Treatment. A low-temperature (190 °C, or 375 °F) electrolytic process using sodium and potassium thiocyanate provides a seizing-resistant iron sulfide layer. This process can be used as a final treatment for all types of hardened tool steels without great danger of overtempering.

Wrought Tool Steels

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