Department of Metallurgical and Materials Engineering

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MSE 4941
Advanced Structural Steels
Lecture 4

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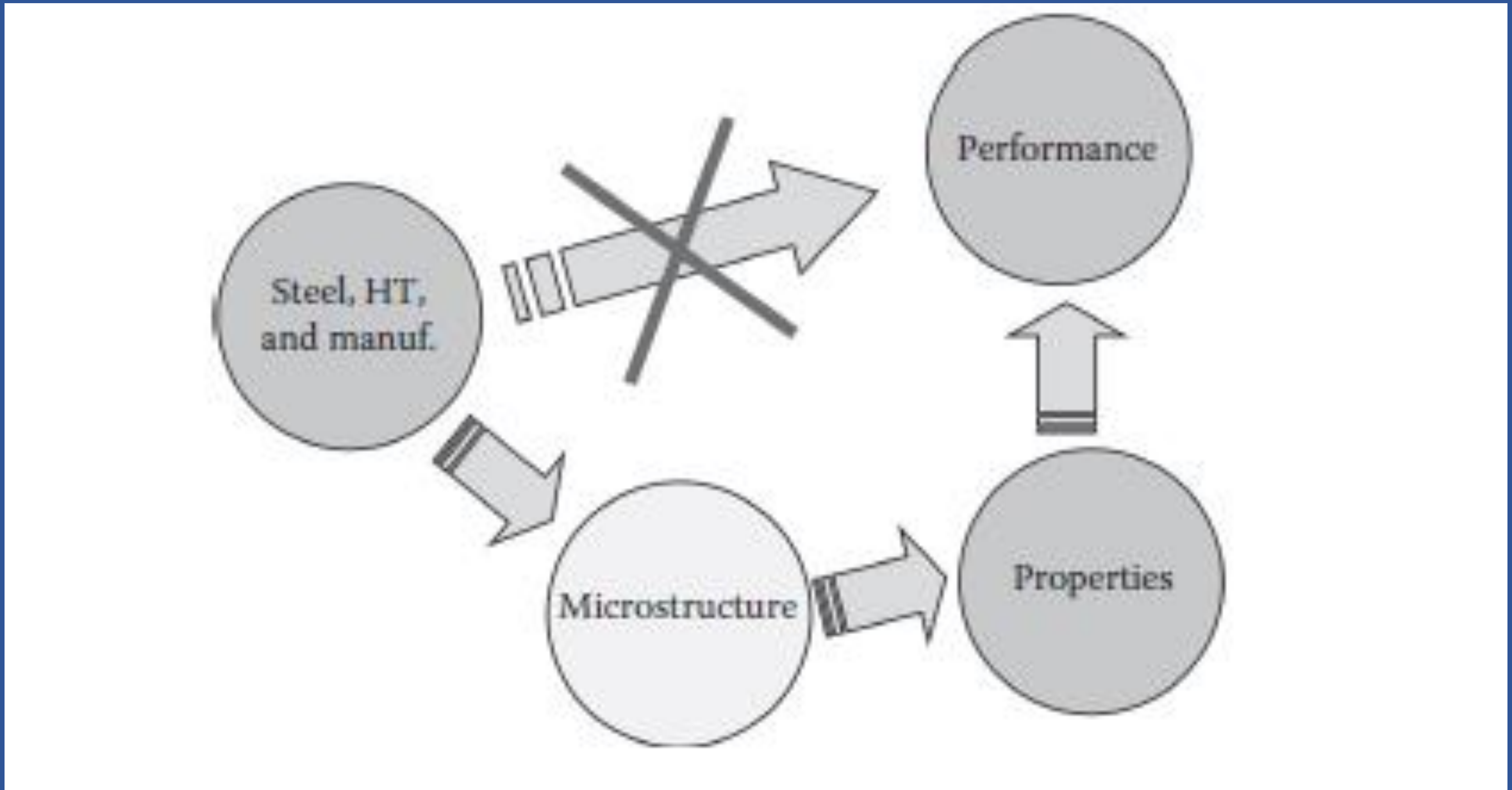
Table 1-1 Important dates in the development of high-speed tool steels

Date	Development
1200 B.C.	First documented hardened steel tool
350 B.C.	Wootz steels of India
A.D. 540	Damascus layered steel blades
A.D. 900	Japanese layered steel blades
Dark Ages	Steel production by carburizing of iron
1740	Crucible melting of steel: Huntsman
1868	Air-hardening tungsten alloy steel: Mushet
1898	High-speed steel high-heat hardening: Taylor/White
1903	0.70C-14W-4C prototype of modern high-speed steel
1904	Alloying with 0.3% V
1906	Electric furnace melting introduced
1910	18W-4Cr-1V (18-4-1) steel (T1) introduced
1912	3 to 5% C additions for added red hardness
1923	12% C for higher-speed machining
1939	High C high V superhigh-speed steels (M4 and T15)
1940	Start of substitution of molybdenum for tungsten
1953	Sulfurized free-machining high-speed steel
1961	Rockwell C 70 high-speed steel (M40 series)
1970	Introduction of powdered metal high-speed steels
1973	Higher silicon and nickel contents of M7 to increase hardness
1980	Development to cobalt-free superhigh-speed steels
1980	Titanium nitride ceramic coating of tool steels
1982	Aluminum-modified high-speed tool steels

Source: Modified from previous editions of *Tool Steels*, with additions from Ref 12


Performance
Steel, HT,
and manuf.
Microstructure
Properties

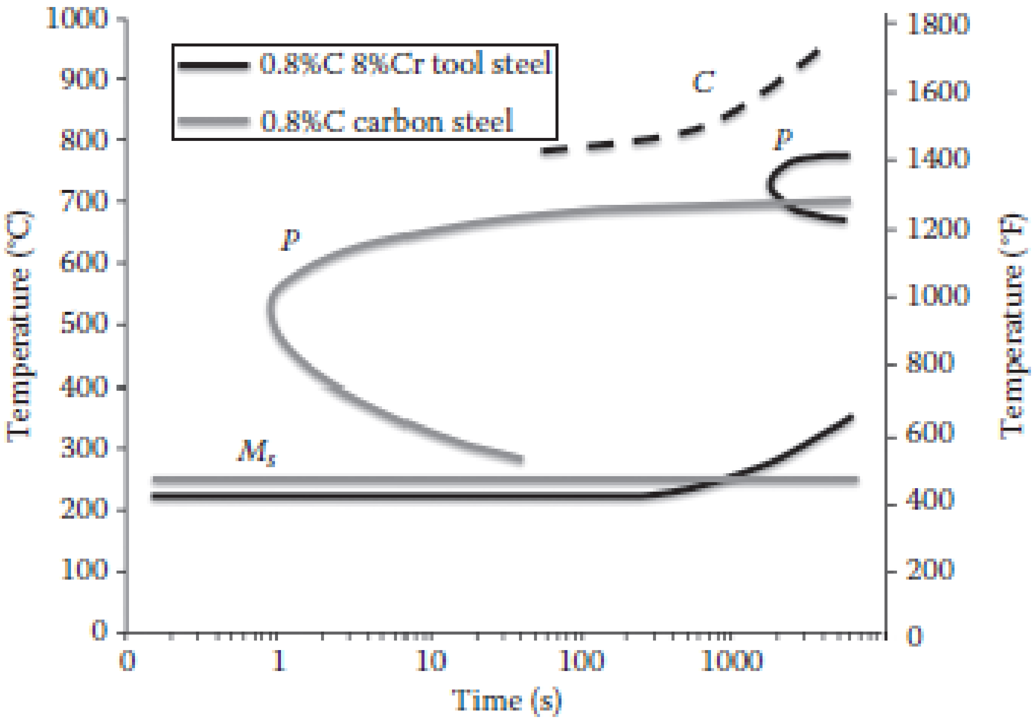


FIGURE 3.14 Continuous cooling transformation (CCT) diagram for a 0.8%C carbon steel and for a high-alloy tool steel (0.8%C, 8%Cr, 2%Mo, 0.5%V). P represents the pearlite transformation, M martensite, and C the precipitation of proeutectoid carbide. Observe that the pearlite nose shifts from 1 to more than 1000 s due to the effect of alloying elements in solid solution. Also notice that the martensite temperature increases after the precipitation of proeutectoid carbides in the high-alloy steel, as an effect of the decrease of alloying elements in solid solution. Curves were drawn from data in Reference 9 for the 1080 carbon steel and References 10 through 12 for 8%Cr steel (commercial names Sleipner, K340, and VF800AT, respectively).

Classification of Tool Steel:

They are classified according to:

Quenching Medium	Alloy Content	Application of T. S
1 – Water quenching Steel	1 – Carbon Tool Steel	1 – Hot work Steel
2 – Oil quenching Steel	2 – Low Alloy Tool Steel	2 – Shock resisting Steel
3 – Air hardening Steel	3 – Medium Alloy Tool Steel	3 – High speed Steel
		4 – Cold work Steel

Classification of Tool Steels

Cold Work Tool Steels

This is a group of three tool steels: oil-hardening, air-hardening, and high carbon-chromium. The steels in the group have high hardenability and wear resistance, with average toughness. Typically they are in the production of larger parts or parts that have a minimum distortion requirement when being hardened.

Both Oil quenching and Air-hardening both reduce the distortion and higher stress caused by the quick water quenching. Because of this they are less likely to crack.

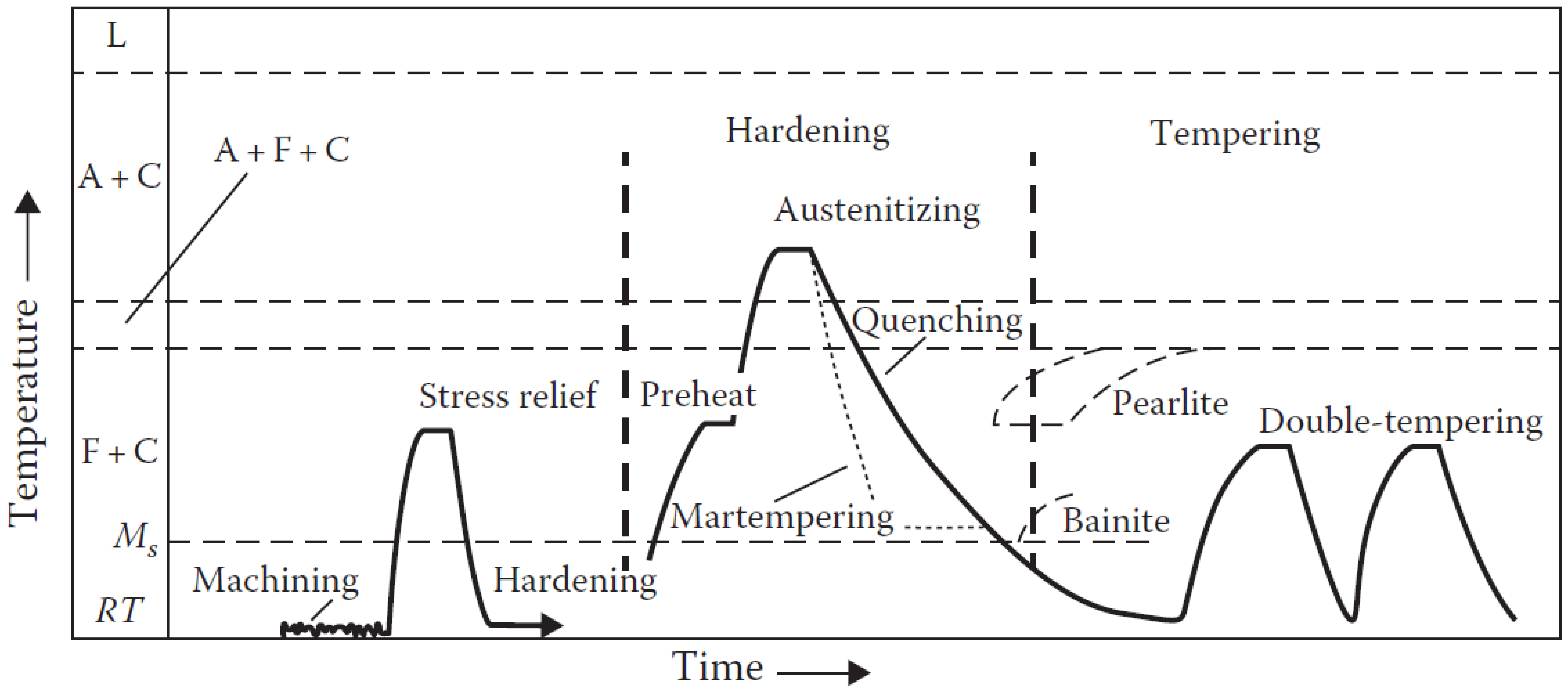
Hot Work Tool Steels

H-group tool steels were specifically developed to maintain strength and hardness while exposed to prolonged elevated temperatures.

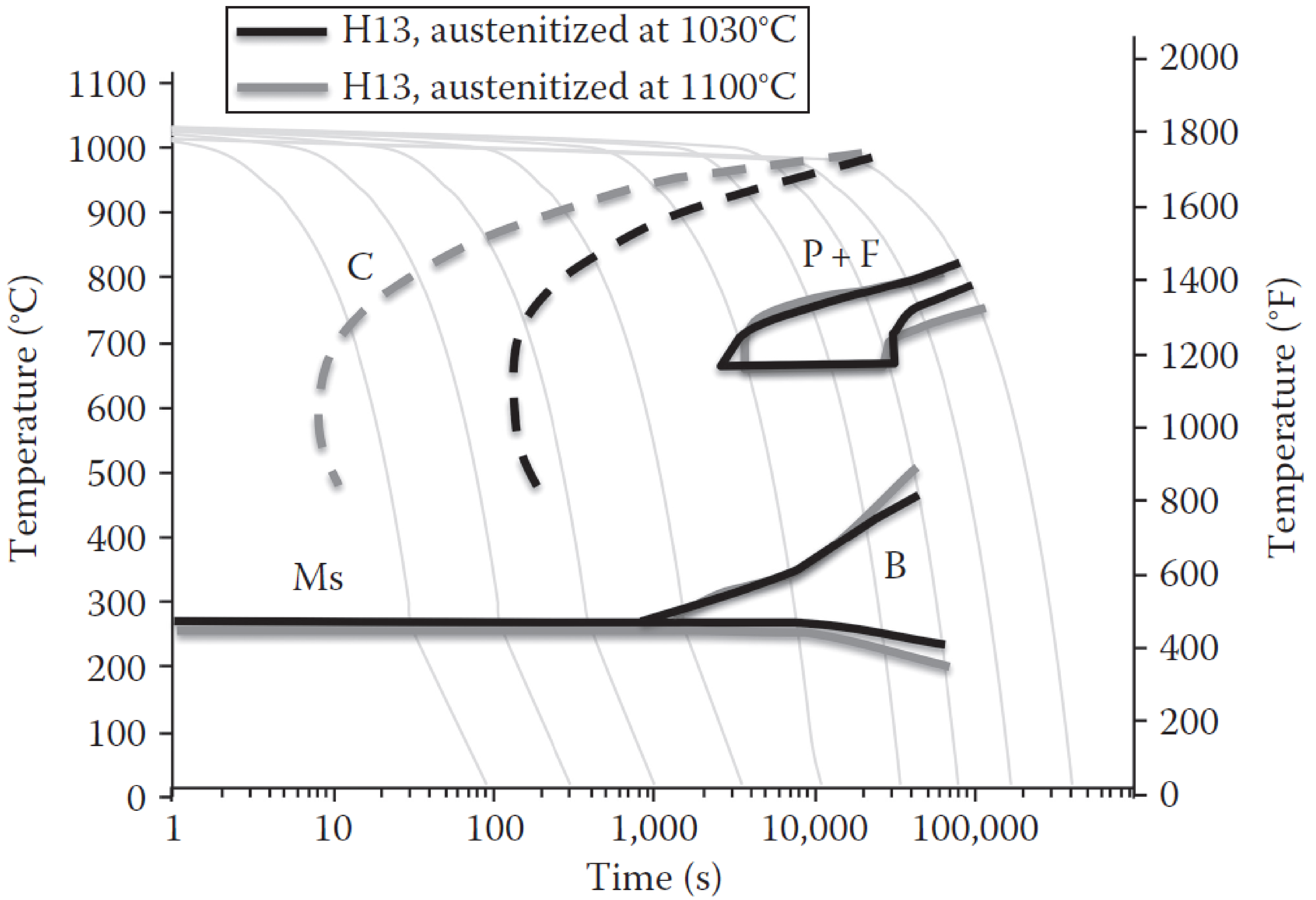
Hot-working steels are a group of steel used to cut or shape material at high temperatures. H-group tool steels were developed for strength and hardness during prolonged exposure to elevated temperatures. These tool steels are low carbon and moderate to high alloy that provide good hot hardness and toughness and fair wear resistance due to a substantial amount of carbide. H1 to H19 are based on a chromium content of 5%; H20 to H39 are based on a tungsten content of 9-18% and a chromium content of 3–4%; H40 to H59 are molybdenum based.

High Speed Steels

High-speed steel is a subset of tool steels, commonly used in tool bits and cutting tools. It is often used in power-saw blades and drill bits. It is superior to the older high-carbon steel tools used extensively through the 1940s in that it can withstand higher temperatures without losing its temper (hardness). This property allows HSS to cut faster than high carbon steel, hence the name high-speed steel. At room temperature, in their generally recommended heat treatment, HSS grades generally display high hardness (above HRC60) and abrasion resistance (generally linked to tungsten and vanadium content often used in HSS) compared with common carbon and tool steels.



L
A + C
A + F + C
F + C
M_s
RT
Temperature
Time
Machining
Stress relief
Hardening
Hardening
Preheat
Austenitizing
Quenching
Martempering
Pearlite
Bainite
Tempering
Double-tempering



H13, austenitized at 1030°C
H13, austenitized at 1100°C
Temperature (°C)
1100
1000
900
800
700
600
500
400
300
200
100
0
C
P + F
B
Ms
1
10
100
1,000
10,000
100,000
Time (s)
Temperature (°F)
2000
1800
1600
1400
1200
1000
800
600
400
200
0

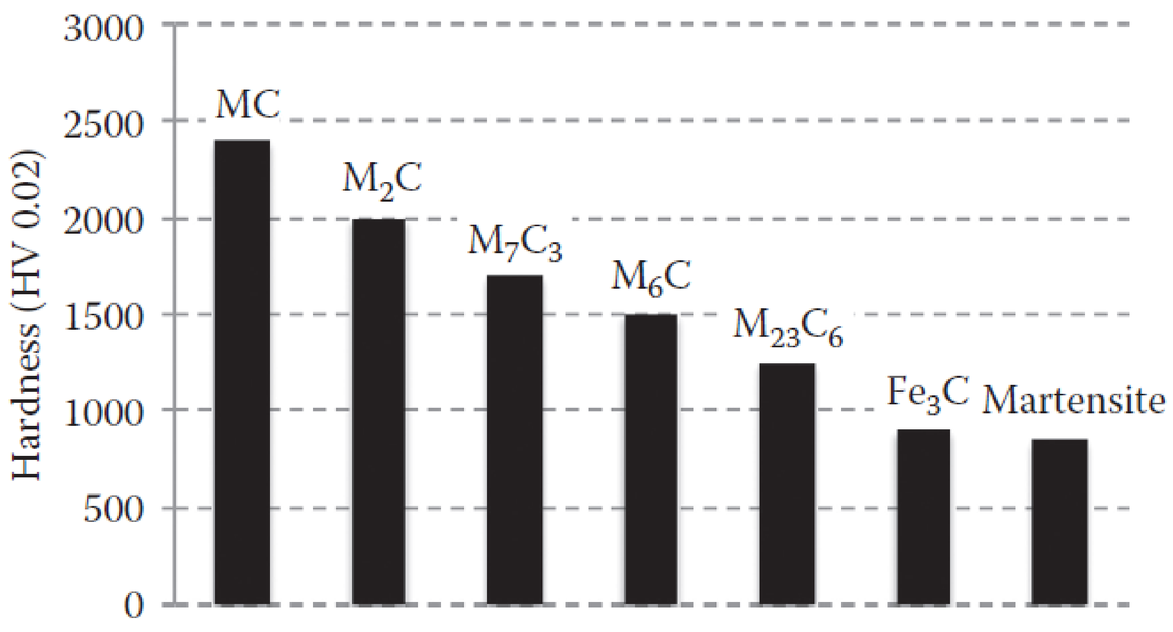
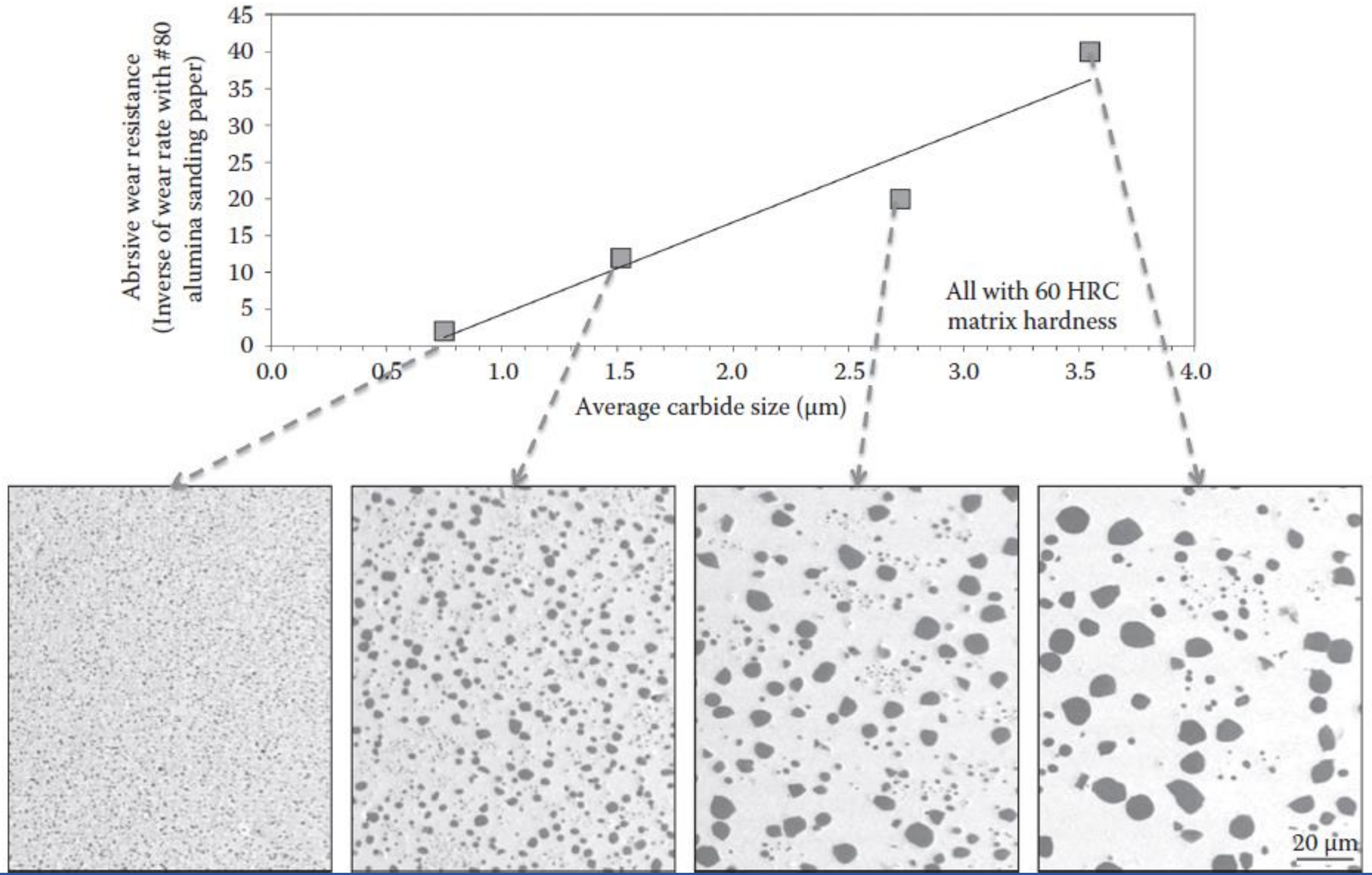


FIGURE 3.24 Typical hardness of different types of complex carbides. The carbides are shown in the M_xC_y form, where M is usually a mixture of Fe and alloying elements and never a pure carbide. However, each stoichiometry is based on the crystal structure and usually has a high content of one of the alloying elements: MC → Nb or V; M_2C and M_6C → W or Mo; $M_{23}C_6$ and M_7C_3 → Cr; M_3C → Fe. (From Brandis, H. et al., Metallurgical aspects of carbides in high speed steels, *Processing and Properties of High Speed Tool Steels*, Wells, M.G.H. and Lherbier, L.W., eds., TMS-AIME, Warrendale, PA, 1980, pp. 1–18; Tarasov, L.P., *Metal Prog.*, 54(6), 846, 1948; Elsen, E. et al., *Metall*, 19, 334, 1965; Brook, G.B. and Crompton, J.M.G., Fulmer Report R 319/4, Fulmer Research Institute, 1971, Apud: Karagoz, S. and Fischmeister, H., *Metallurg. Trans. A*, 19Z, 1935, 1988.)



Abrsive wear resistance
(Inverse of wear rate with #80
alumina sanding paper)
45
40
35
30
25
20
15
10
5
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Average carbide size (μm)
All with 60 HRC
matrix hardness
20 μm

Cold Work Tool Steels

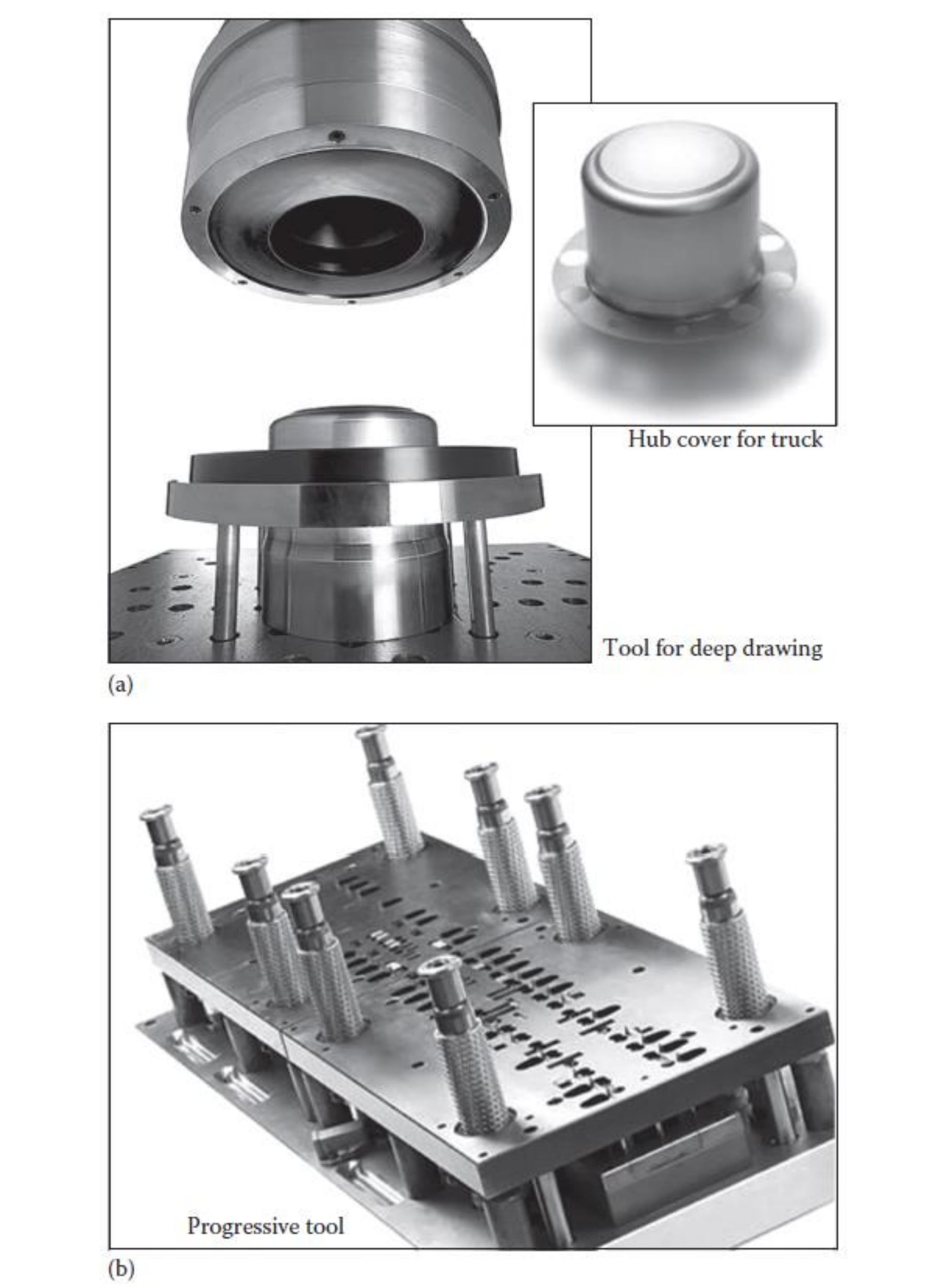


FIGURE 5.1 Examples of cold work tools: (a) deep drawing tool set and example of produced part. (b) A progressive tool, for high-speed production of several forming operations (e.g., punching, coining, bending or cutting), combined with an automatic feeding system. (From Uddeholm Tool Steel for Cold Work Tooling, Available at: http://www.uddeholm.com/files/, Accessed January 2016.)

TABLE 5.1

Chemical Composition of the Main Cold Work Tool Steels Applied in Industry, Showing the Commonly Observed Target Values

Hot Work Tool Steels			Most Common Chemical Composition (wt.%)							
ASTM	EN/DIN	UNS	C	Si	Mn	Cr	V	W	Mo	Other
O1	1.2510	T31501	0.9	0.3	1.2	0.5	0.1	0.5	—	—
W1	1.1545	T72301	1.0	0.2	0.2	—	—	—	—	—
W2	1.1645	T72302	1.0	0.2	0.2	—	0.25	—	—	—
A2	1.2363	T30102	1.0	0.3	0.7	5.0	0.25	—	1.1	—
D2	1.2379	T30402	1.5	0.3	0.3	12.0	0.9	—	0.9	—
D3	1.2080	T30403	2.1	0.3	0.3	12.0	—	—	—	—
D6	1.2436	—	2.1	0.3	0.3	12.0	0.1	0.7	—	—
8%Cr (not standardized)			0.9	0.9	0.5	8.0	0.5	—	2.2	+Nb or Al

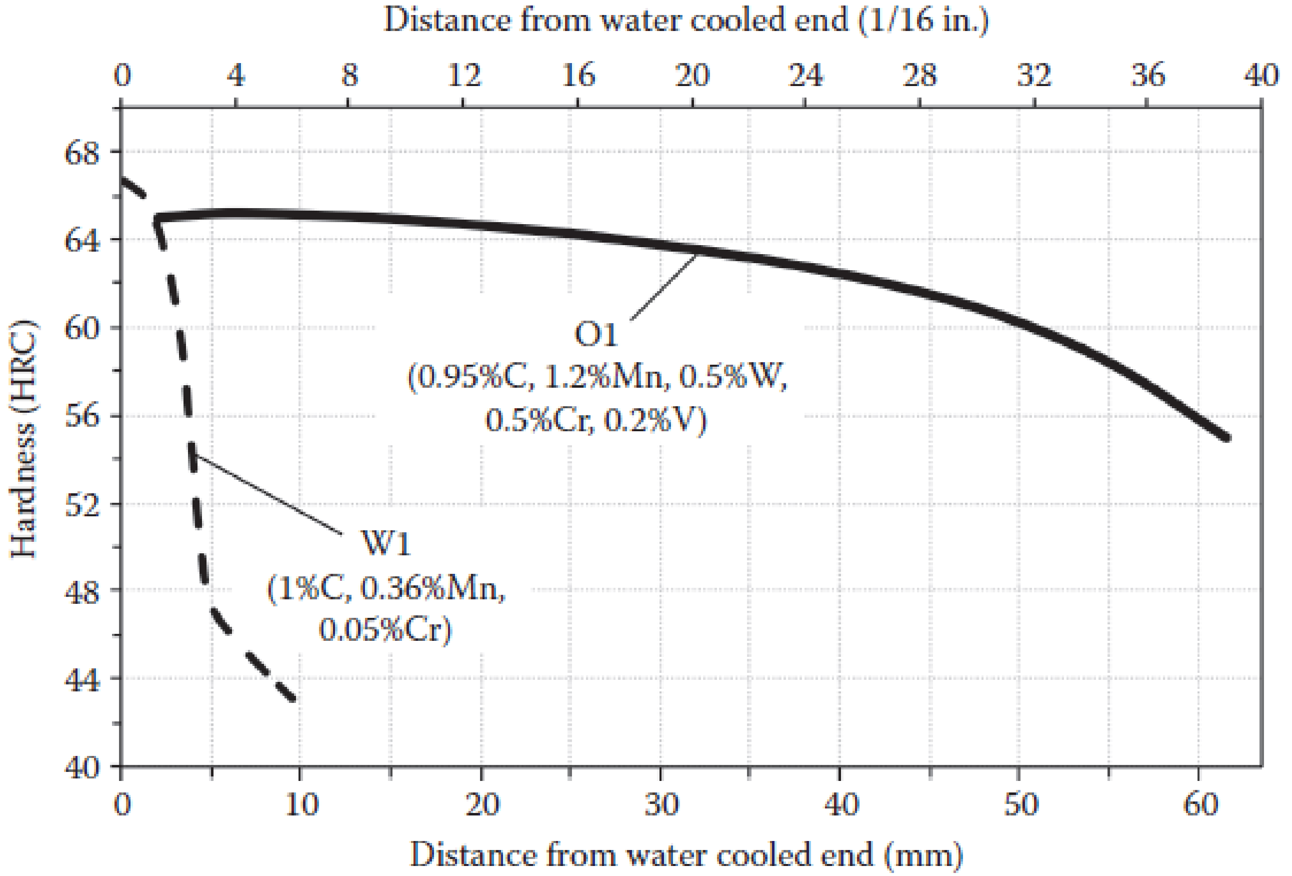
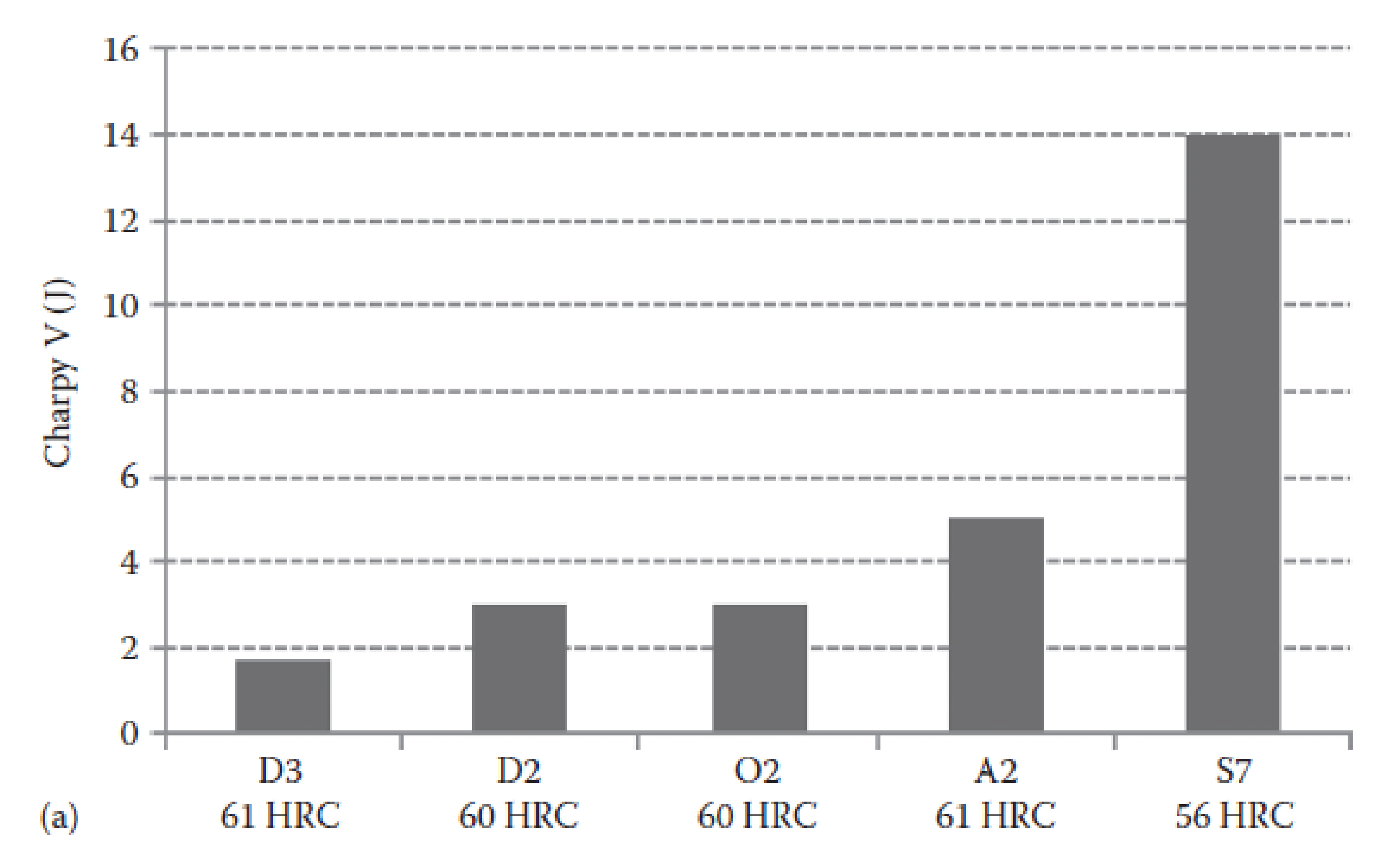


FIGURE 5.19 Typical hardenability curves for O1 and W1 steel. O1 was hardened at 830°C (1520°F) and the measurements refer to the Jominy end-quench test. W1 specimens are 19 mm cylinders, quenched in water. In comparative terms, the quenching is slower for O1, and if both steels were tested in the same method, the difference would be even higher. (Adapted from Roberts, G. et al., *Tool Steels*, 5th edn., ASM International, Materials Park, OH, 1998, pp. 133, 187.)

TABLE 5.2

Data for Undissolved Carbides Typically Found in Cold Work Tool Steels

Phase	Rich in	Pure Carbide (Reference)	Crystallographic System	Lattice Parameters (Reference)	Hardness (Reference)
MC	Nb	NbC	Face centered cubic	$a = 4.47$ Å [37]	2300 HV [44]
MC	V	V_4C_3	Cubic	$a = 4.16$ Å [38]	2000 HV [45]
M_2C	Mo	Mo_2C	Hexagonal	$a = 3.01$ Å; $c = 4.74$ Å [39]	1800 HV [46]
M_6C	W or Mo	Fe_3Mo_3C	Cubic	$a = 11.12$ Å [40]	1500 HV [47]
M_7C3	Cr	Cr_7C_3	Hexagonal	$a = 13.9$ Å; $c = 4.52$ Å [41]	1600 HV [48]
M_3C	Fe	Fe_3C	Orthorhombic	$a = 5.06$ Å; $b = 6.74$ Å; $c = 4.50$ Å [42]	1100 HV [49]
Martensite	0.8%C steel	—	Tetragonal	$a = 2.85$ Å; $c = 2.95$ Å [43]	900 HV (65 HRC)


Charpy V (J)
16
14
12
10
8
6
4
2
0
D3
61 HRC
D2
60 HRC
O2
60 HRC
A2
61 HRC
S7
56 HRC
(a)

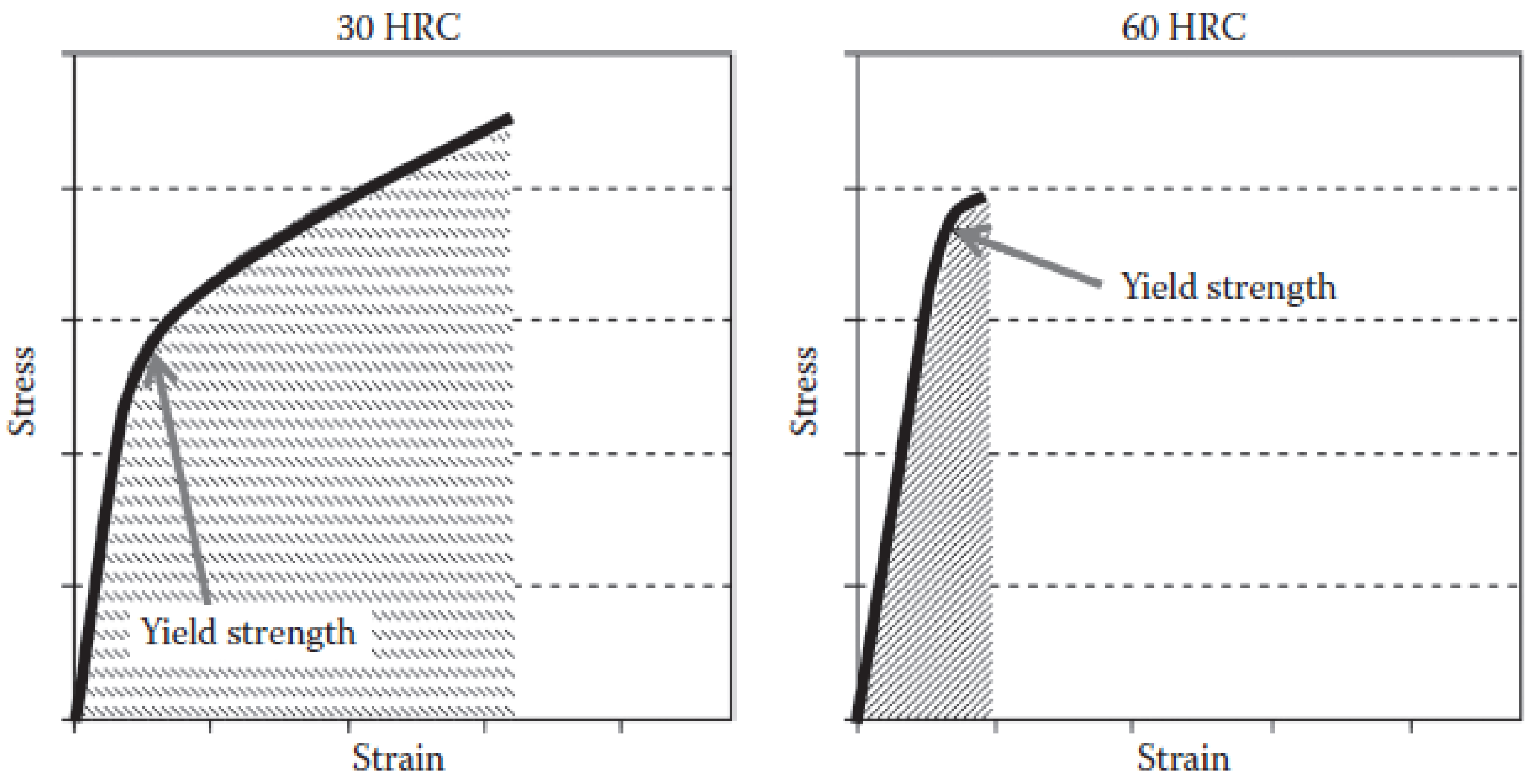


FIGURE 5.3 Schematic stress–strain diagram for cold work tool steels. Observe that the increase in hardness has a direct effect on the increase of yield strength but an inverse effect on the area under the curve, which represents the absorbed energy and so the toughness.

High Speed Steels

TABLE 7.1
Chemical Composition of the Main High-Speed Steels, Showing the Commonly Observed Target Values

High-Speed Steels			Most Common Chemical Composition (wt.%)							
ASTM	EN/DIN	UNS	C	Si	Mn	Cr	V	W	Mo	Other
M1	1.3346	T11301	0.82	0.3	0.3	4.0	1.0	1.5	8.0	—
M2	1.3343	T11302	0.89	0.3	0.3	4.0	1.9	6.0	5.0	—
M3:2	1.3344	T11323	1.20	0.3	0.3	4.0	3.0	6.0	5.0	—
M35	1.3243	T11335	0.89	0.3	0.3	4.0	1.0	6.0	5.0	Co = 5.0
M42	1.3247	T11342	1.10	0.3	0.3	4.0	1.1	1.5	9.5	Co = 8.0
M50	1.3551	T11350	0.84	0.4	0.4	4.0	1.0	—	4.2	
T1	1.3355	T12001	0.75	0.3	0.3	4.0	1.0	18	—	—
T15	1.3202	T12015	1.55	0.3	0.3	4.0	5.0	12	—	Co = 5.0

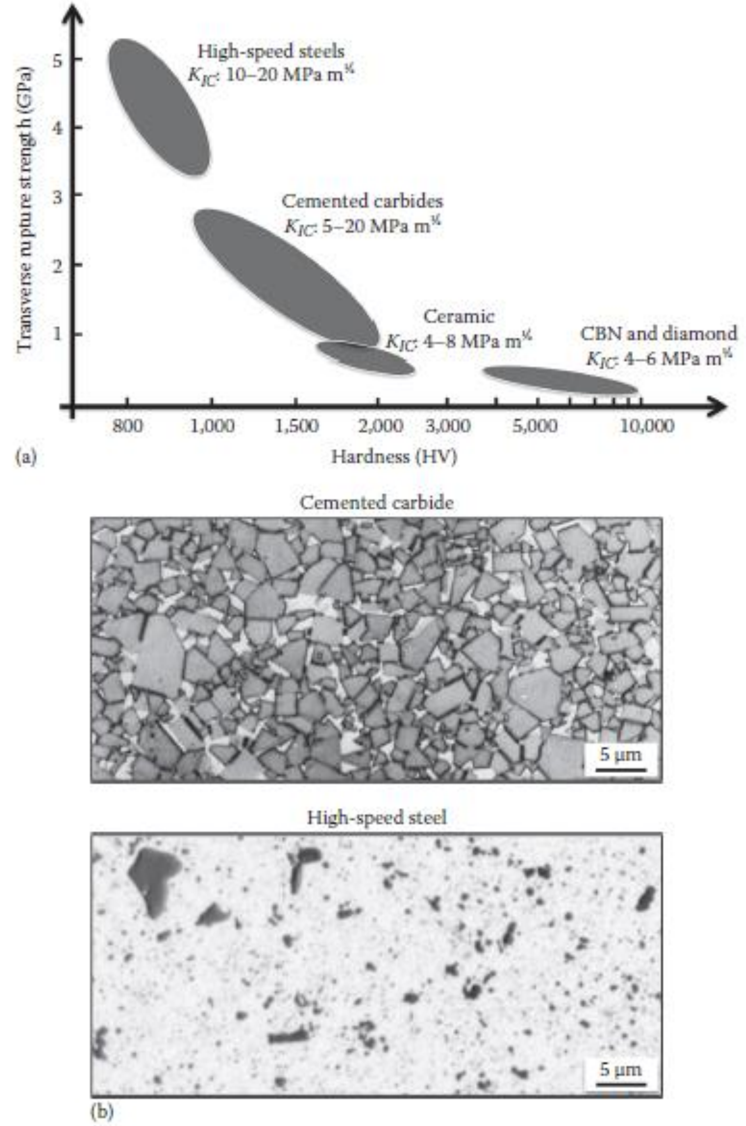
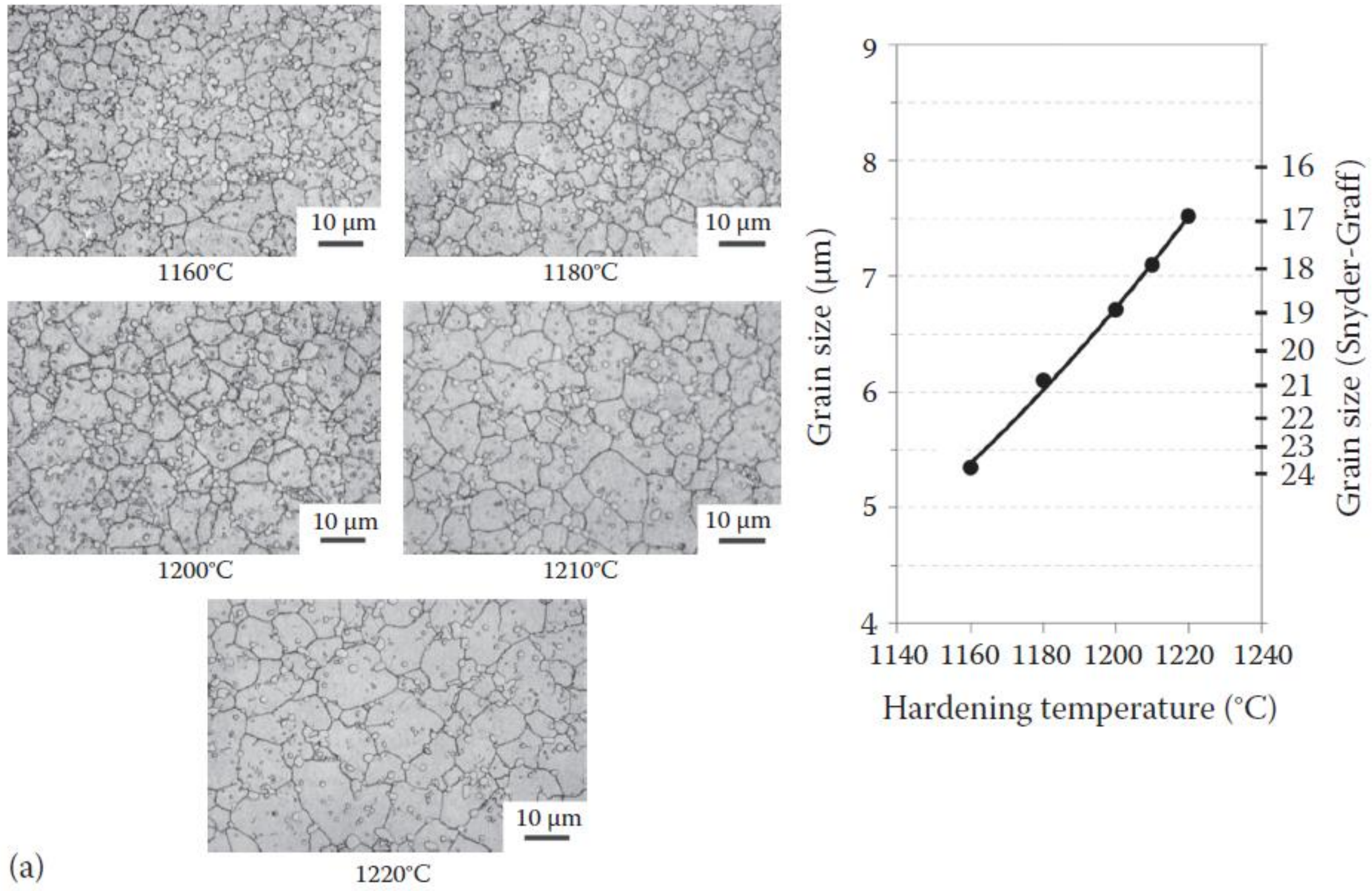
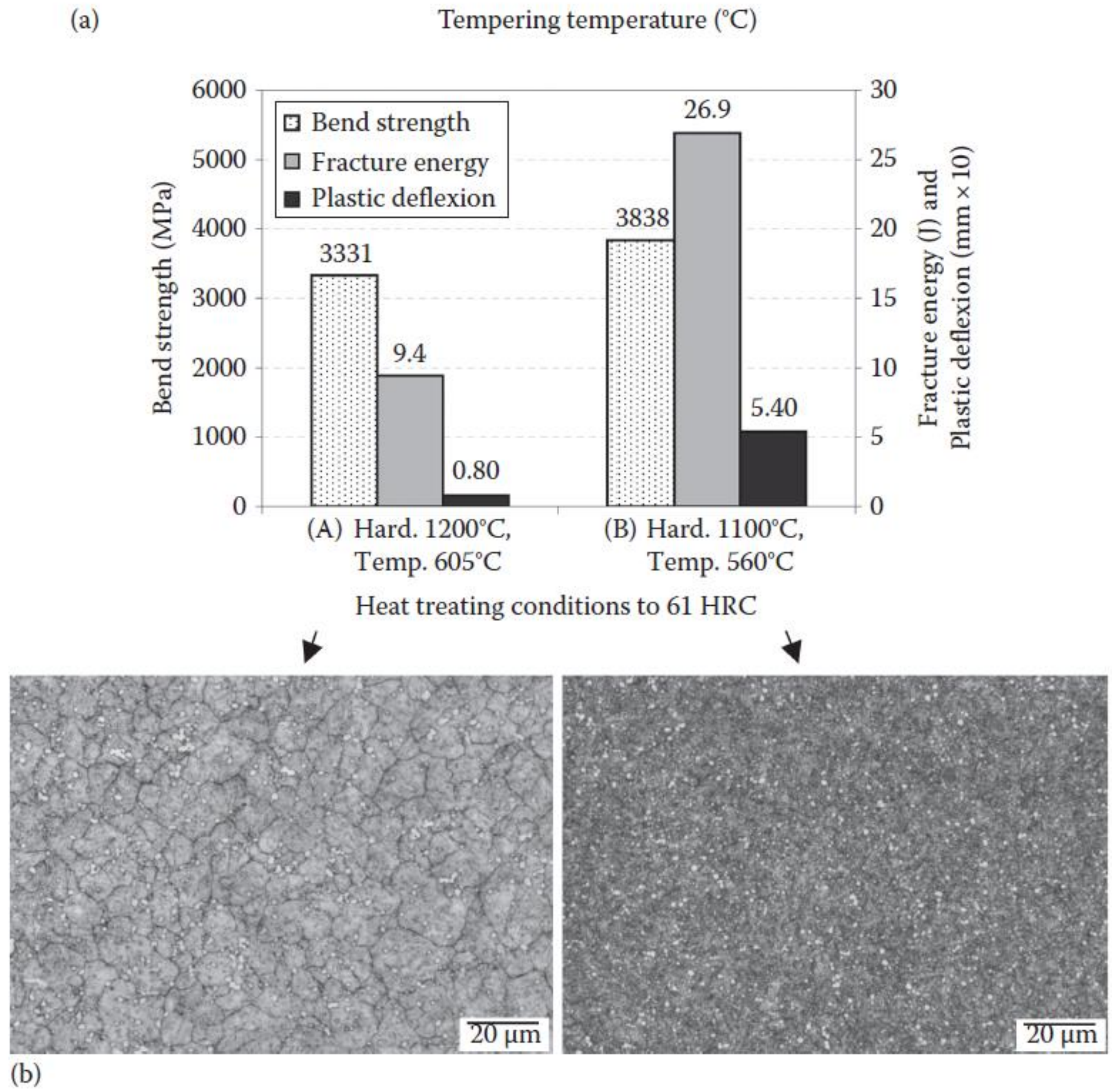


FIGURE 7.1 General comparison of materials used for cutting tools. (a) Diagram showing the bend strength, hardness, and K_{IC} values for the different classes of materials. (b) Examples of the microstructures for cemented carbides and high-speed steels, showing the larger amount of carbides (in gray) for the cemented carbides. (Chart built with data from Trent, E.M. and Wright, P.K., *Metal Cutting*, 4th edn., Butterworth-Heinemann, Boston, MA, 2000, pp. 132–249.) The image of cemented carbide is adapted from Reference 1. High-speed steel is from unpublished material from the author, where the carbides were viewed by deep etching and the image was color-inverted, in such a way that the white carbides become gray and the matrix white.


10 μm
1160°C
10 μm
1180°C
10 μm
1200°C
10 μm
1210°C
10 μm
1220°C
(a)
Grain size (μm)
9
8
7
6
5
4
Grain size (Snyder-Graff)
16
17
18
19
20
21
22
23
24
1140 1160 1180 1200 1220 1240
Hardening temperature (°C)


(a)
Tempering temperature (°C)
Bend strength
Fracture energy
Plastic deflexion
Bend strength (MPa)
Fracture energy (J) and Plastic deflexion (mm × 10)
6000
5000
4000
3000
2000
1000
0
30
25
20
15
10
5
0
3331
9.4
0.80
3838
26.9
5.40
(A) Hard. 1200°C, Temp. 605°C
(B) Hard. 1100°C, Temp. 560°C
Heat treating conditions to 61 HRC
20 μm
20 μm
(b)

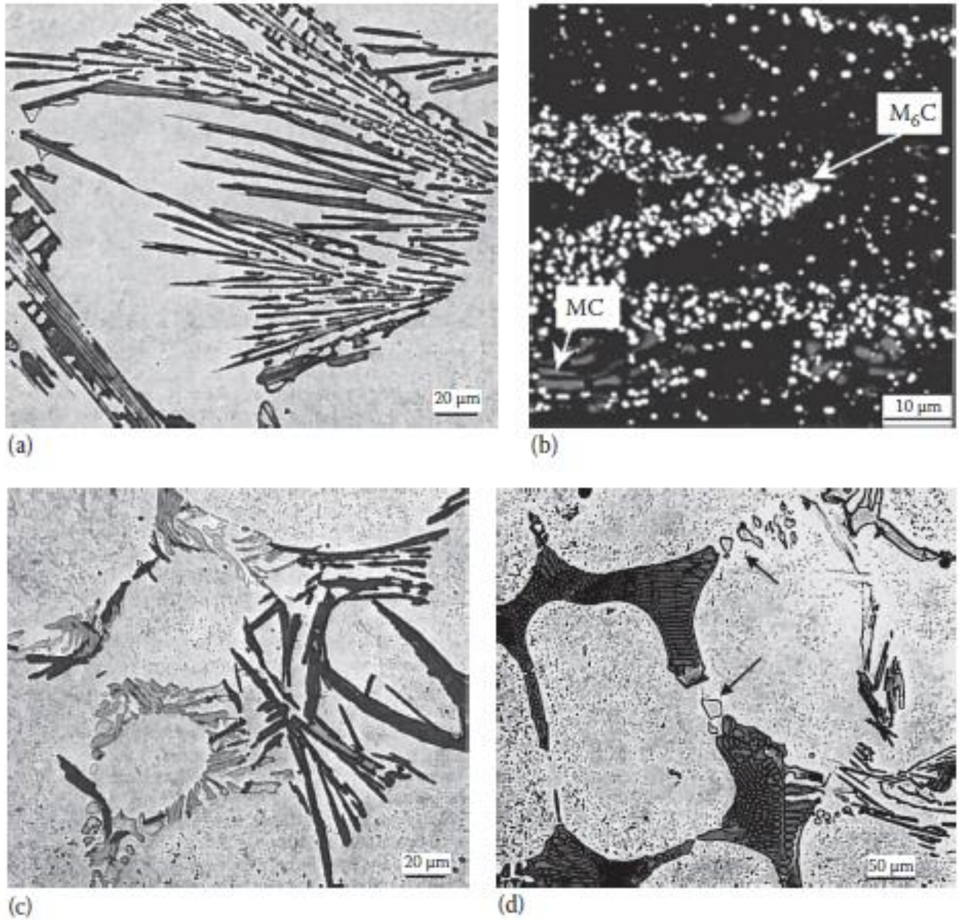
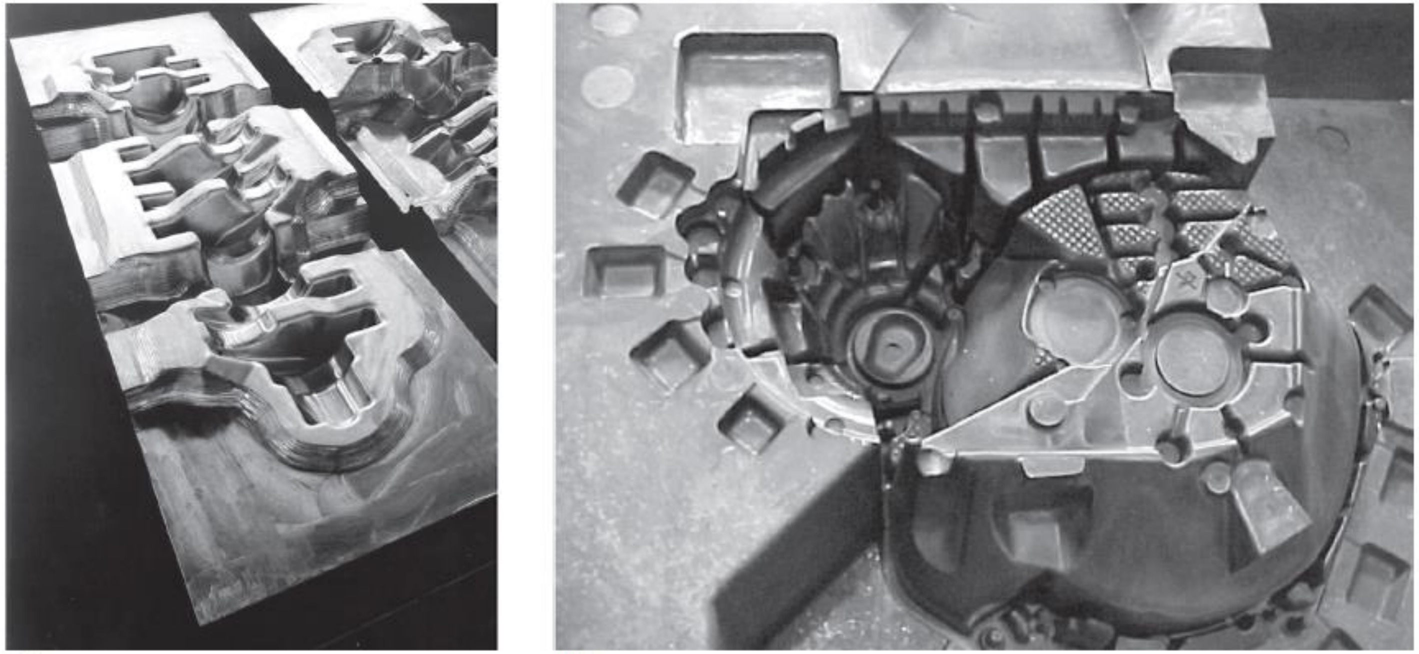


FIGURE 7.6 Examples of as-cast microstructures in M2 tool steels, showing (a) the feather-like morphology of M_2C carbides and (b) the transformation of those feathers, after reheating to forging or rolling, into M_6C and small amounts of MC. In (c), both M_2C (dark) and MC (light) eutectics are shown, after special etching with $KMnO_4$. And in (d), the primary MC carbides are pointed by the arrows; those carbides are larger and of cuboid morphology because they precipitate in the liquid phase and tend to grow in all directions following the most stable crystallographic planes, rather than getting elongated when formed by an eutectic reaction. Some of those MC carbides are also shown in (b). (Images from (a), (c), and (d) are from light microscopy and obtained from Barkalow, R.H. et al., *Metal. Trans.*, 3, 919, 1972.) The image in (b) is a backscattered image from scanning electron microscopy, where the phases with heavier elements become lighter, which is the case of the M_6C carbides rich in Mo and W.

Hot Work Tool Steels



(a) (b)

FIGURE 4.1 Examples of hot-working dies, for application in (a) hot forging, used to produce crankshaft, and (b) die-casting, to cast an aluminum gearbox cover. (From Canale, L.C.F. et al. (eds.), Failure analysis of heat treated steel components, in: *Failure Analysis in Tool Steels*, Mesquita, R.A. and Barbosa, C.A., eds., American Society for Metals (ASM), Materials Park, OH, 2008, vol. 1. Chapter 11, pp. 311–350.)

TABLE 4.1

Chemical Composition of the Main Tool Steels Applied in Industry Showing the Commonly Observed Target Values

Hot Work Tool Steels			Most Common Chemical Composition (wt.%)							
ASTM	EN/DIN	UNS	C	Si	Mn	Cr	V	W	Mo	Other
6F3 mod	1.2714	T61206	0.56	0.3	0.8	1.1	0.1	—	0.5	Ni = 1.7
H10	1.2365 mod	T20810	0.34	1.0	0.3	3.2	0.4	—	2.5	—
H10 mod	1.2367	—	0.38	0.3	0.3	5.0	0.5	—	3.0	—
H11	1.2343	T20811	0.36	1.0	0.3	5.0	0.4	—	1.3	—
Low Si H11	1.2343 mod	—	0.36	0.3	0.3	5.0	0.4	—	1.3	P < 0.015
H12	1.2606	T20812	0.36	1.0	0.3	5.0	0.3	1.5	1.5	—
H13	1.2344	T20813	0.38	1.0	0.3	5.0	0.9	—	1.3	—
H19	1.2678	T20819	0.40	0.3	0.3	4.2	2.0	4.2	0.2	Co = 4.25
H21	1.2581	T20821	0.32	0.3	0.3	3.5	0.4	9.0	—	—

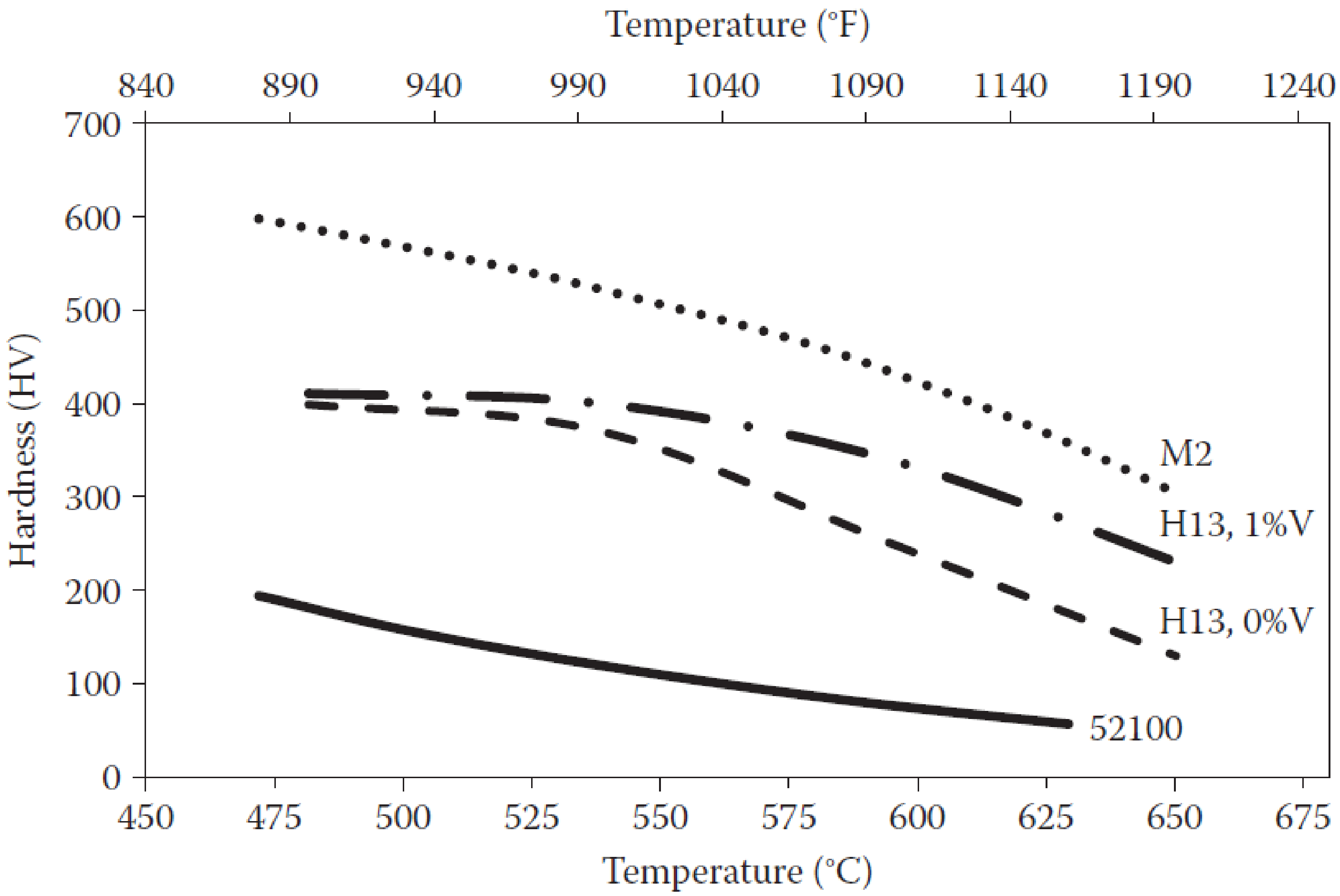
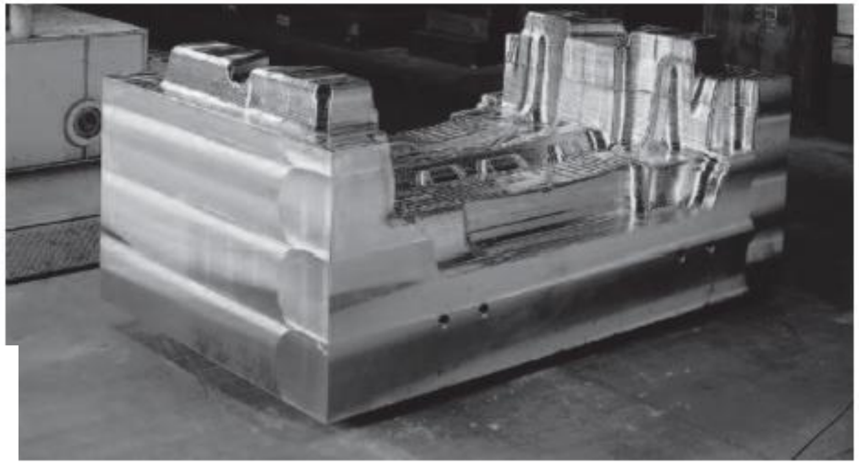


FIGURE 4.2 Hot hardness of selected alloyed steels: 52100 (1%C, 1.4%Cr); H13, 0%V (0.33%C, 5%Cr, 0.8%Si, 1.35%Mo); H13, 1%V (0.33%C, 5%Cr, 0.8%Si, 1.3%Mo, 1%V); M2: (0.9%C, 5%Mo, 6%W, 2%V). (The charts for M2 and 52100 were built with data extracted from Jatczak, C.F., *Metal Prog*., 70, 1978; H13 data from Roberts, G.A. and Cary, R.A., *Tool Steels*, 4th edn., American Society for Metals, Beachwood, OH, 1980, pp. 645–653.)

Plastic Mold Steels

TABLE 6.1
Chemical Composition of the Main Plastic Mold Steels, Showing the Commonly Observed Target Values

Plastic Mold Tool Steels			Most Common Chemical Composition (wt.%)							
ASTM	EN/DIN	UNS	C	Si	Mn	Cr	V	W	Mo	Other
P20	—	T51620	0.35	0.4	0.5	1.7	—	—	0.4	—
P20 Mod	1.2738	—	0.38	0.3	1.5	2.0	—	—	0.2	Ni = 1.0
P20 Mod	1.2311	—	0.38	0.3	1.5	2.0	—	—	0.2	—
P20 Mod	1.2312	—	0.38	0.3	1.5	2.0	—	—	0.2	S = 0.070
6F2 Mod	1.2711		0.52	0.2	0.7	0.8	0.1	—	0.3	Ni = 1.7
420	1.2083	S42000	0.42	0.4	0.4	13.0	—	—	—	—
422 Mod	1.2316	—	0.36	0.3	0.7	16.0	—	—	1.1	Ni = 0.80



(b)

FIGURE 6.3 ***(Continued)*** (b) Examples of rough machined cavities for car bumpers, with weight of more than 10 tons. Observe that those cavities were massive blocks, from which all volume was removed by sawing and machining (rough milling). (From Hippenstiel, F. et al., *Handbook of Plastic Mould Steels*, Edelstahlwerke Buderus AG, Wetzlar, Germany, 2001, pp. 17, 40, 67, 125–149, 248–251.)

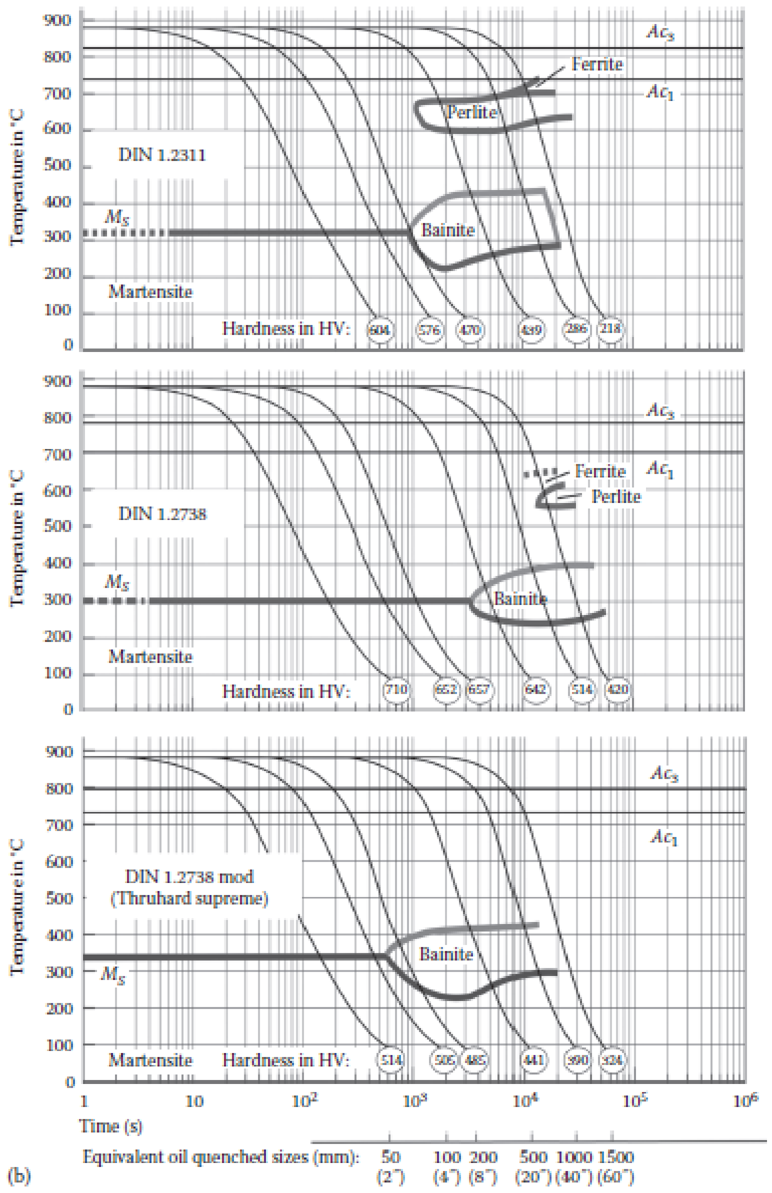


FIGURE 6.5 (*Continued*) The challenges in large molds. (b) Continuous cooling transformation (CCT) diagram for 1.2738 and 1.2711 steels, showing the occurrence of pearlite in earlier times for the 1.2711 steel, which explains the decrease of core hardness in the large-diameter blocks. Thruhard Supreme is a developed composition by Buderus Edelstahl. (Results adapted from Hippenstiel, F. et al., *Handbook of Plastic Mould Steels*, Edelstahlwerke Buderus AG, Wetzlar, Germany, 2001, pp. 17, 40, 67, 125–149, 248–251.)