Tool Steels: Metallographic Techniques and Microstructures

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<Previous section in this article

Atlas of Microstructures for Tool Steels

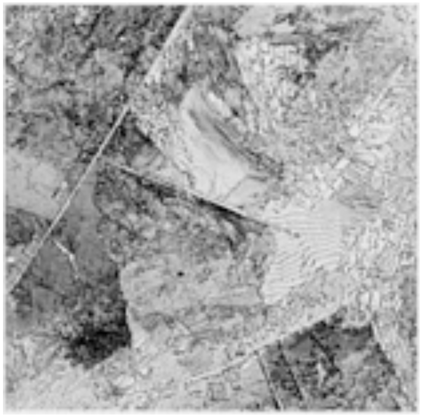

Fig. 1 AISI W1 (1.3% C), as-rolled, containing pearlite and acicular cementite. 4% picral. 500×

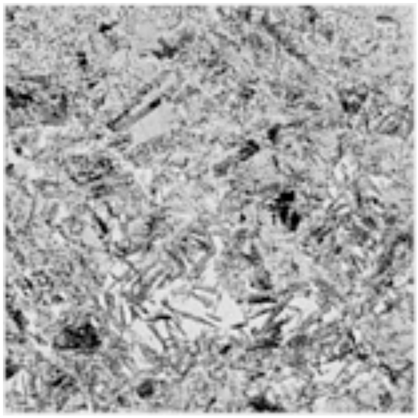

Fig. 2 AISI L6, as-rolled, containing bainite and martensite (white). 2% nital. 500×

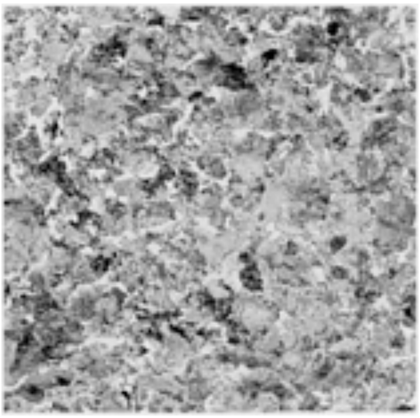

Fig. 3 AISI S4, as-rolled, containing ferrite (white) and pearlite. 4% picral. 500×

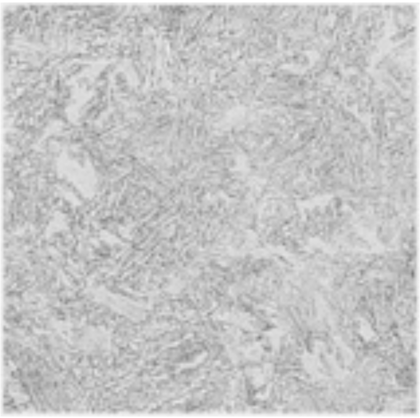

Fig. 4 AISI S4, as-rolled, containing bainite and martensite (featureless patches). This bar was cooled at a faster rate after rolling than the one in Fig. 3. 4% picral. 500×

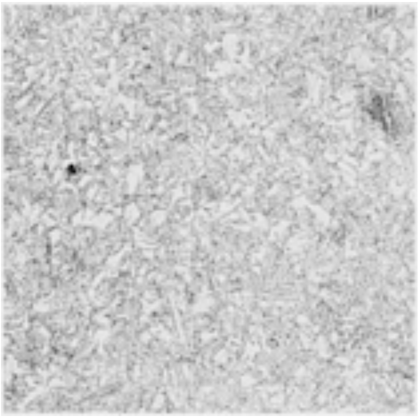

Fig. 5 AISI S5, as-rolled, containing bainite and martensite (white). 2% nital. 500×

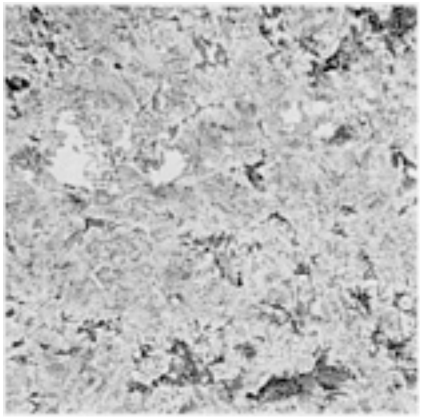

Fig. 6 AISI O1, as-rolled, containing bainite and martensite (white patches). The dark patches are pearlite. 4% picral. 500×

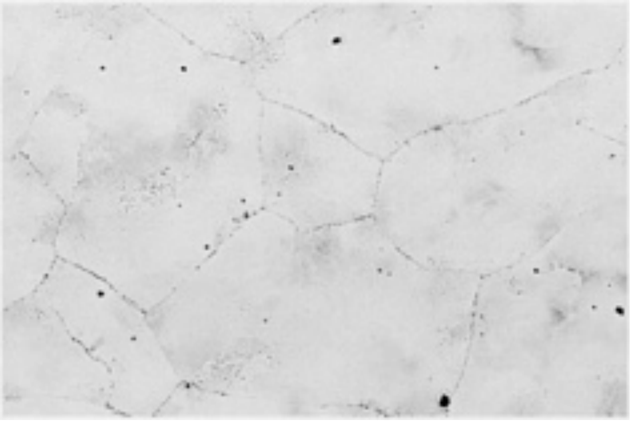

Fig. 7 AISI L1, as-rolled, containing pearlite and a grain boundary cementite network. Boiling alkaline sodium picrate. 100×

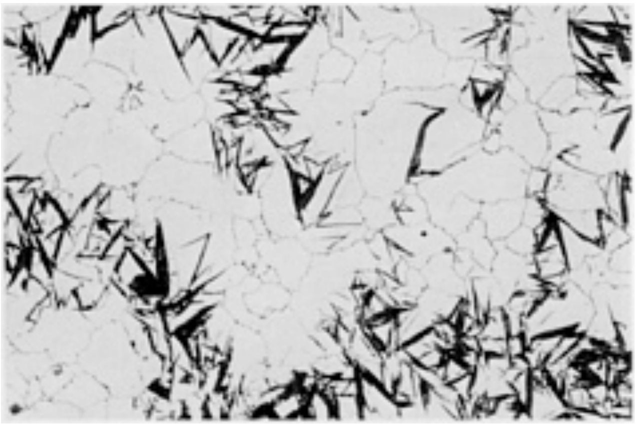

Fig. 8 AISI A2, as-rolled, containing plate martensite (black) and retained austenite (white). 2% nital. 500×

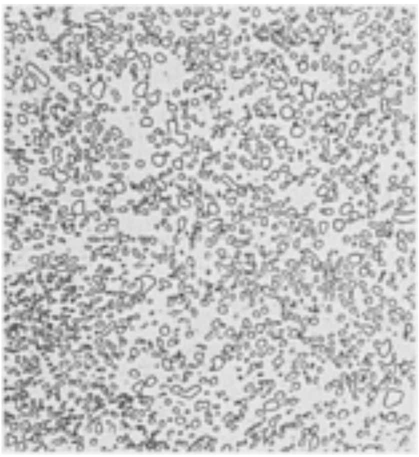

Fig. 9

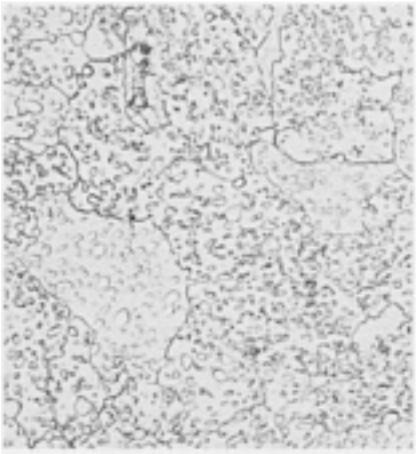

Fig. 10

[graphic]

Fig. 11

AISI W2 (1.05% C) spheroidize annealed. Fig. 9: etched with 4% picral to outline only cementite (uniform dissolution of the ferrite matrix). Fig. 10: etched with 2% nital, which reveals ferrite grain boundaries and outlines cementite. Note that the ferrite in some grains is not attacked, and the carbides within these grains are barely visible. Fig. 11: etched lightly with 4% picral, then tint-etched with Klemm's I reagent to color the ferrite (blue and red). 1000×

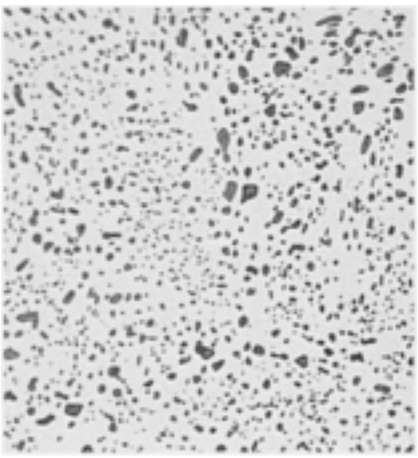

Fig. 12

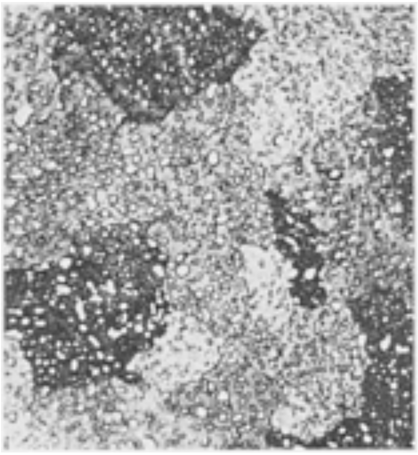

Fig. 13

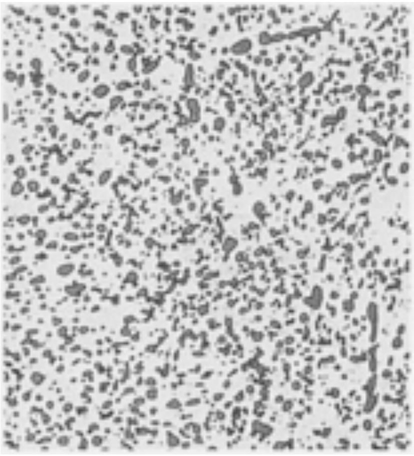

Fig. 14

AISI W2 (1.05% C), spheroidize annealed. Fig. 12: etched with boiling alkaline sodium picrate for 60 s to color the cementite brown. Fig. 13: etched lightly with 4% picral and tint etched with Beraha's $Na_2S_2O_3/K_2S_2O_5$ reagent to color the ferrite (wide range of colors). Fig. 14: etched lightly with 4% picral and tint etched with Beraha's Na_2MoO_4 reagent to color the cementite dark orange. See also Fig. 9, 10, and 11. 1000×

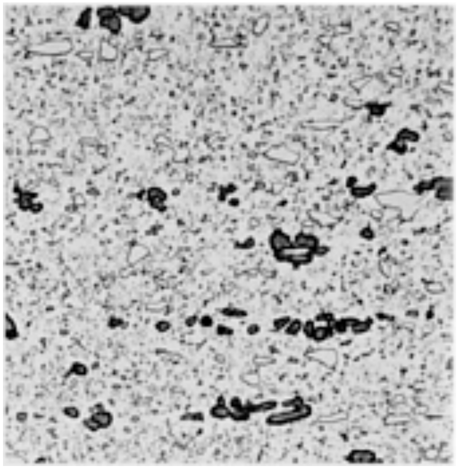

Fig. 15 A7 tool steel, as-received (mill annealed), longitudinal section. Dark particles are chromium carbide; light particles, vanadium carbide; matrix ferrite. 4 g NaOH, 4 g $KMnO_4$, 100 mL H_2O. 500×

[graphic]

Fig. 16 W4 water-hardening tool steel (0.98C-0.74Mn-0.14Cr-0.19Ni), as-received (mill annealed). 187 HB. Spheroidal cementite in a matrix of ferrite; a considerable amount of lamellar pearlite is also present. 4% picral. 1000×

[graphic]

Fig. 17 W4 water-hardening tool steel (0.96C-0.66Mn-0.23Cr), as-received (full annealed). 170 HB. Structure consists of spheroidal cementite in a ferrite matrix; no lamellar constituent is present. Compare with Fig. 16. 4% picral. 1000×

[graphic]

Fig. 18 W1 water-hardening tool steel (0.94C-0.21Mn), as-received (mill annealed). 170 HB. Structure: mixture of lamellar pearlite and spheroidal cementite in a matrix of ferrite, with a few large, globular carbide particles. 3% nital. 1000×

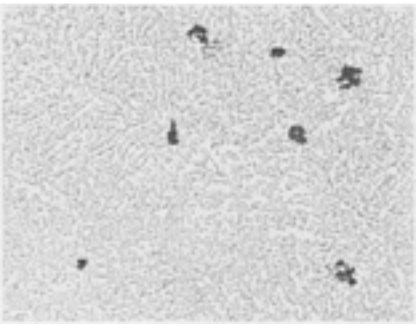

Fig. 19 AISI O6, spheroidize annealed, transverse section. Note the globular appearance of the graphite (black). 4% picral. 500×

[graphic]

Fig. 20 AISI O6, spheroidize annealed, longitudinal section. Note that the graphite is elongated in the rolling direction. 4% picral. 500×

[graphic]

Fig. 21

[graphic]

Fig. 22

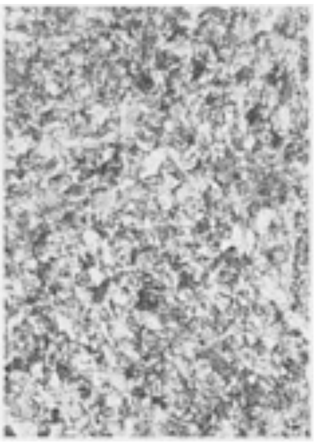

Fig. 23

[graphic]

Fig. 24

AISI W1 (1.05% C). Influence of starting structure on spheroidization. Fig. 21: as-rolled, contains coarse and fine pearlite. Fig. 22: after spheroidization (heat to 760 °C, or 1400 °F, cool at a rate of 11 °C/h, or 20 °F/h to 595 °C, or 1100 °F, air cool). Fig. 23: austenitized at 870 °C (1600 °F) and oil quenched to produce fine pearlite. Fig. 24: austenitized as in Fig. 23; annealed as in Fig. 22. Note the more uniform spherical carbide shape compared to Fig. 22. 4% picral. 500×

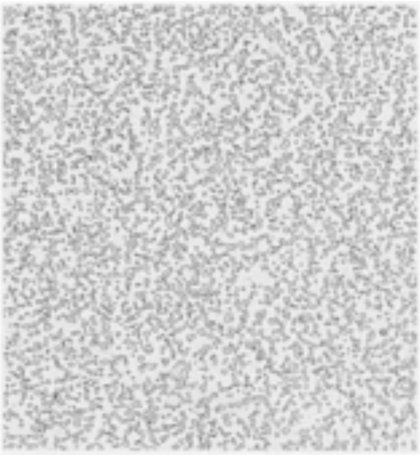

Fig. 25 AISI L1, spheroidize annealed. Note the very well formed spheroidal carbides. 4% picral. 500×

[graphic]

Fig. 26 AISI S2, spheroidize annealed. 4% picral. 1000×

[graphic]

Fig. 27 AISI S5, spheroidize annealed. 4% picral. 500×

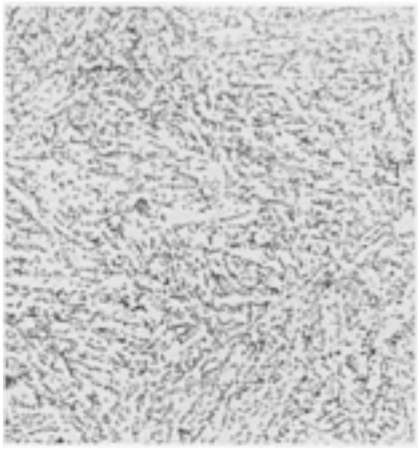

Fig. 28 AISI S7, spheroidize annealed. 4% picral. 1000×

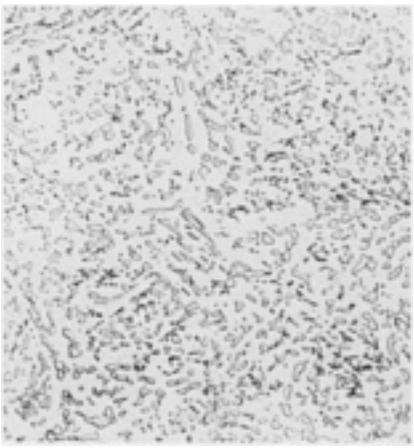

Fig. 29 AISI A6, spheroidize annealed. 4% picral. 1000×

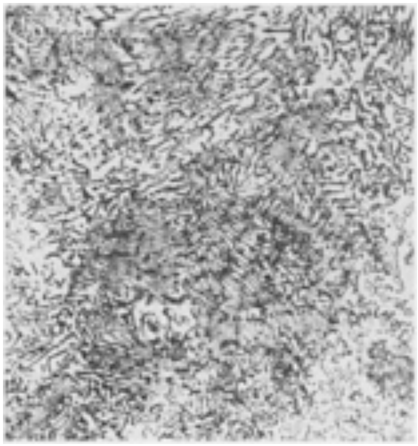

Fig. 30 AISI A6, partially spheroidized. Note lamellar pearlite. 4% picral. 1000×

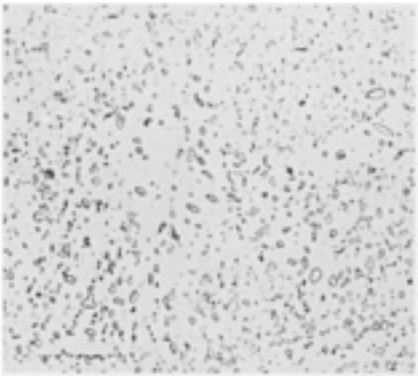

Fig. 31 AISI H13 chromium hot-worked tool steel, spheroidize annealed. 4% picral. 1000×

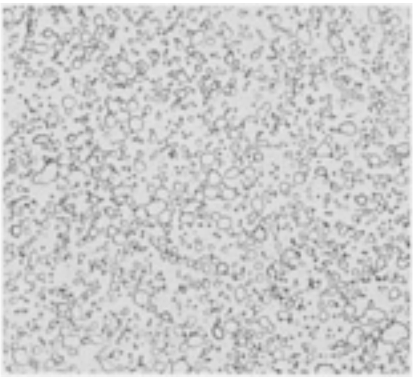

Fig. 32 AISI M2 molybdenum high-speed tool steel, spheroidize annealed. 4% picral. 1000×

[graphic]

Fig. 33 A7 tool steel, box annealed at 900 °C (1650 °F) for 1 h per 25 mm (1.0 in.) of container thickness and cooled at no more than 28 °C/h (50 °F/h). Massive alloy carbide and spheroidal carbide in a ferrite matrix. 4% nital. 1000×

[graphic]

Fig. 34 A10 tool steel as-received (mill annealed). Section transverse to rolling direction. At the magnification used, the structure is poorly resolved. Nital. 100×

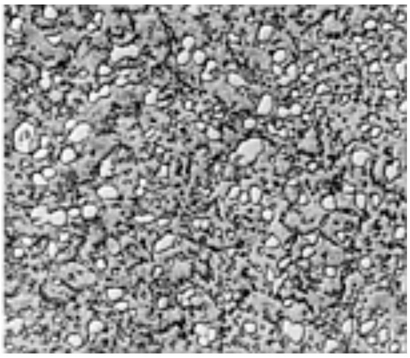

Fig. 35 H23 tool steel, annealed by austenitizing at 870 °C (1600 °F) for 2 h and cooling at 28 °C/h (50 °F/h) to 540 °C (1000 °F), then air cooling. 98 HRB. Structure consists of tiny spheroidal and some larger alloy carbide particles in a matrix of ferrite. Kalling's reagent. 500×

[graphic]

Fig. 36 H26 tool steel, annealed by austenitizing at 900 °C (1650 °F), cooling at 8.5 °C/ h (15 °F/h) to 650 °C (1200 °F), then air cooling. 22 to 23 HRC. Structure consists of a dispersion of fine particles of alloy carbide in a matrix of ferrite. Picral with HCl, 10 s. 500×

[graphic]

Fig. 37

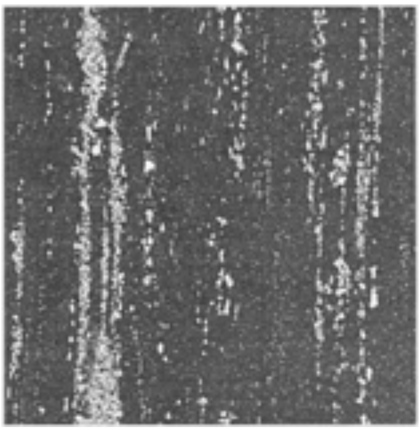

Fig. 38

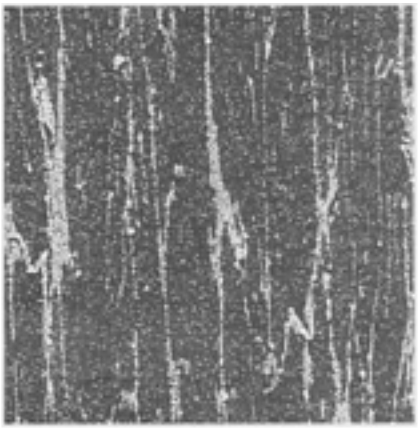

Fig. 39

AISI M2, round bars. Carbide segregation at the center of round bars of different diameters. Fig. 37: 27-mm ($1\frac{1}{16}$-in.) diam. Fig. 38: 67-mm ($2\frac{5}{8}$-in.) diam. Fig. 39: 105-mm ($4\frac{1}{8}$-in.) diam. 10% nital. 100×

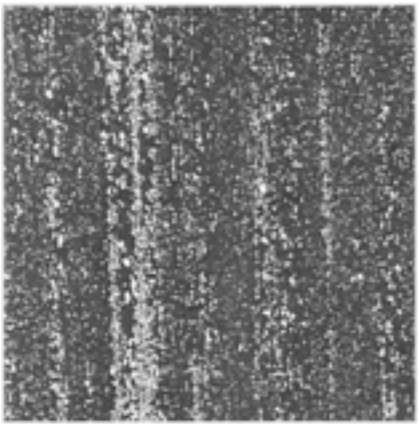

Fig. 40

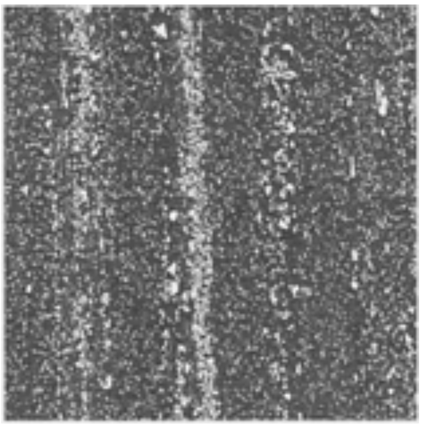

Fig. 41

[graphic]

Fig. 42

AISI T1, round bars. Carbide segregation at the center of round bars of different diameters. Fig. 40: 35-mm ($1\frac{3}{8}$-in.) diam. Fig. 41: 64-mm ($2\frac{1}{2}$-in.) diam. Fig. 42: 83-mm ($3\frac{1}{4}$-in.) diam. 10% nital. 100×

Fig. 43

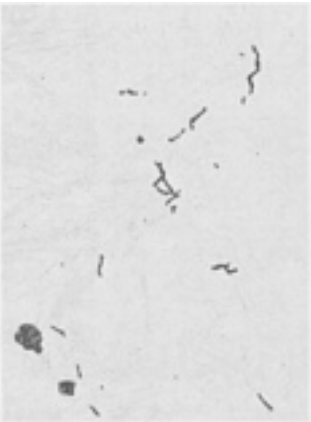

Fig. 44

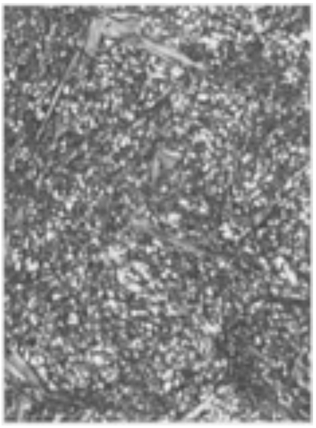

Fig. 45

[graphic]

Fig. 46

AISI W1 (1% C), overaustenitized at 925 °C (1700 °F) and water quenched, producing martensite, retained austenite, and small patches of pearlite. Influence of etchant on revealing as-quenched martensite. Fig. 43: 2% nital etch reveals martensite and pearlite (black). Fig. 44: 4% picral etch reveals pearlite, but only faintly reveals martensite. Fig. 45: 5% aqueous sodium metabisulfite etch produces a strong contrast between the martensite and retained austenite (white). Fig. 46: Beraha's $Na_2S_2O_3/K_2S_2O_5$ reagent produces similar results to Fig. 45, but pearlite is more visible. 500×

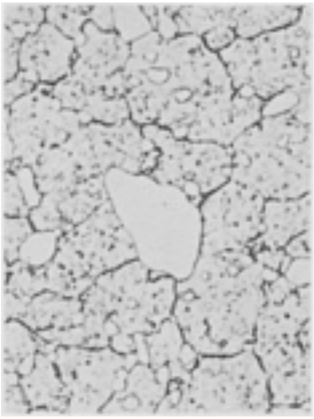

Fig. 47

[graphic]

Fig. 48

[graphic]

Fig. 49

[graphic]

Fig. 50

AISI D2, austenitized at 1040 °C (1900 °F), air quenched and tempered at 200 °C (400 °F). Influence of etchant on revealed martensite. Fig. 47: 10% nital etch reveals grain boundaries, carbides, and martensite (light). Fig. 48: 4% picral plus HCl etch reveals carbides and martensite (light). Fig. 49: heat tinted at 540 °C (1000 °F) for 5 min after 10% nital etch to produce greater contrast and reveal the retained austenite. Fig. 50: superpicral etch reveals retained austenite as white, but carbide also appears white. 1000×

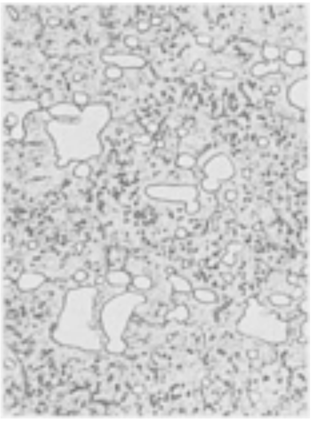

Fig. 51

[graphic]

Fig. 52

[graphic]

Fig. 53

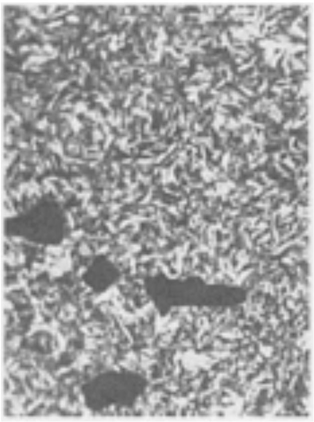

Fig. 54

Fig. 51, 52: AISI D2, quenched and tempered, Fig. 53, 54: AHT tool steel, quenched and tempered. Use of vapor-deposited zinc selenicle to accentuate carbide detection and retained austenite. Samples were etched first with 4% picral plus HCl (Fig. 51, 53) to outline the carbides, then coated with a thin layer of zinc selenide (Fig. 52, 54) to reveal the carbides (dark violet), retained austenite (white), and martensite (dark). 1000×

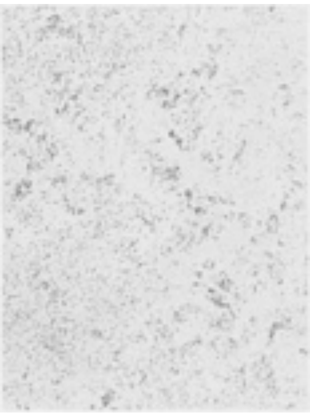

Fig. 55

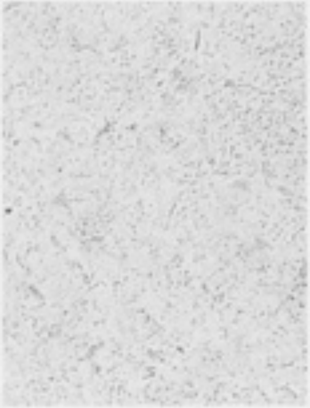

Fig. 56

[graphic]

Fig. 57

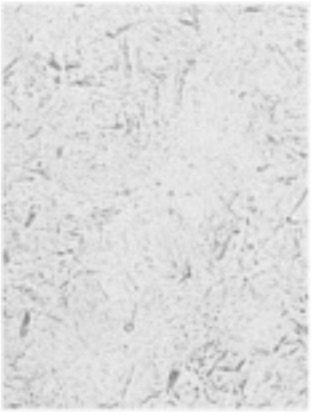

Fig. 58

AISI S7 (0.5% C). Influence of austenitizing temperature. Fig. 55: austenitized at 915 °C (1675 °F) 1 h for every 25 mm (1.0 in.) of thickness and air quenched. Sample is underaustenitized. Fig. 56: austenitized at 925 °C (1700 °F). Slightly underaustenitized. Fig. 57: austenitized at the preferred temperature of 940 °C (1725 °F). Fig. 58: austenitized at 955 °C (1750 °F). Slightly overaustenitized, note coarsening, no visible carbide. 4% picral. 500×

Fig. 59

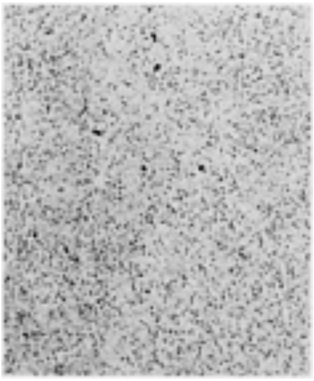

Fig. 60

[graphic]

Fig. 61

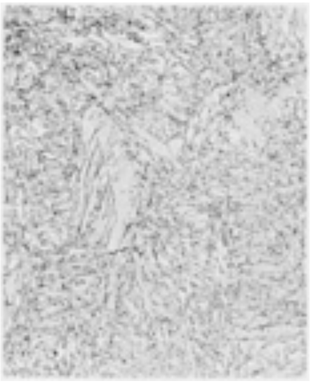

Fig. 62

AISI O1. Influence of austenitizing temperature on microstructure. Fig. 59: austenitized at 800 °C (1475 °F) 1 h for every 25 mm (1.0 in.) of thickness. 65 HRC, grain size 9.5. Specimen properly austenitized. Fig. 60: austenitized at 870 °C (1600 °F). 65 HRC, grain size 9. Overaustenitized. Fig. 61: austenitized at 980 °C (1800 °F). 64 HRC, grain size 7. Very overaustenitized; all carbide dissolved. Fig. 62: austenitized at 1100 °C (2010 °F). 64 HRC, grain size 3. Severely overaustenitized, note retained austenite (white). 4% picral. 500×

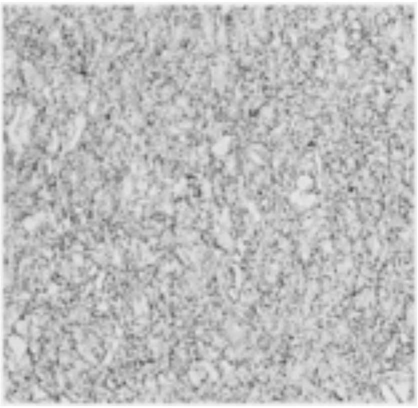

Fig. 63

[graphic]

Fig. 64

[graphic]

Fig. 65

AISI A2. Influence of austenitizing temperature on microstructure. Fig. 63: underaustenitized at 870 °C (1600 °F), air quenched. 48 HRC. 2% nital. 500×. Fig. 64: austenitized at 950 °C (1750 °F) air quenched and tempered at 200 °C (400 °F). 61 HRC. Correctly austenitized. Vilella's reagent. 1000×. Fig. 65: overaustenitized at 1095 °C (2000 °F), air quenched. Most of the carbides have been dissolved, and the grains are quite large. Retained austenite is faintly visible. 2% nital. 500×

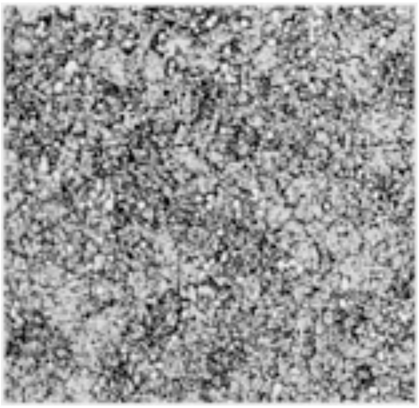

Fig. 66 AISI M2, normal quenched and tempered condition. 1200 °C (2200 °F) for 5 min in salt, oil quench, double tempered at 595 °C (1100 °F). 64 to 65 HRC. 3% nital. 500×

[graphic]

Fig. 67 AISI M2. Heat treated at 1220 °C (2225 °F) for 5 min in salt, oil quench, 1175 °C (2150 °F) for 5 min in salt, oil quench. 64 HRC. Grain growth due to rehardening without annealing between heat treatments. 10% nital. 400×

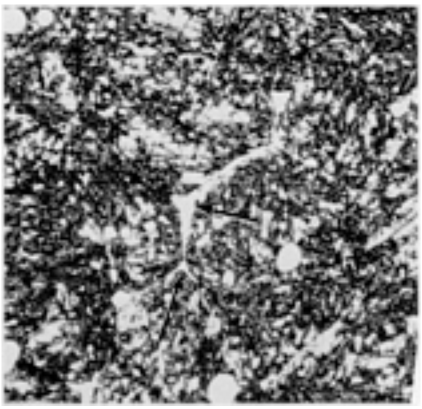

Fig. 68 AISI M2. Heat treated at 1260 °C (2300 °F) for 5 min in salt, oil quench, double tempered at 540 °C (1000 °F). 66 HRC. Overaustenitization and onset of grain boundary melting (arrow). 3% nital/Vilella's reagent. 1000×

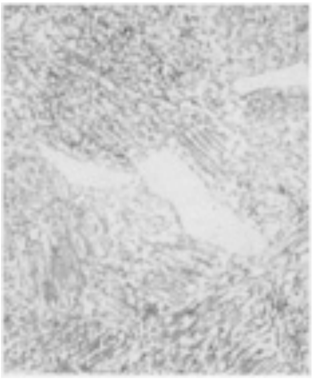

Fig. 69 AISI S5 austenitized and isothermally transformed at 650 °C (1200 °F) for 4 h (air cooled) to form ferrite and coarse pearlite. 23 to 24 HRC. 4% picral. 1000×

[graphic]

Fig. 70 AISI S5 austenitized, isothermally transformed at 595 °C (1100 °F) for 8 h and air cooled to form ferrite and fine pearlite. 36 HRC. 4% picral. 1000×

[graphic]

Fig. 71 AISI S5 austenitized, isothermally transformed (partially) at 540 °C (1000 °F) for 8 h, and water quenched to form upper bainite (dark); balance of austenite formed martensite. 4% picral/2% nital. 1000×

[graphic]

Fig. 72 AISI S5 austenitized, isothermally transformed at 400 °C (750 °F) for 1 h, and air cooled to form lower bainite. 37 to 38 HRC. 4% picral/2% nital. 1000×.

[graphic]

Fig. 73

[graphic]

Fig. 74

[graphic]

Fig. 75

AISI S7. Continuous cooling transformations. Some very fine undissolved carbide is present in all specimens in this series. Fig. 73: austenitized at 940 °C (1725 °F) and cooled at 2780 °C/h (5000 °F/h). 62 HRC. Structure is martensite plus a small amount of bainite. Fig. 74: cooled at 1390 °C/h (2500 °F/h) to produce a greater amount of bainite. 61.5 HRC. Fig. 75: cooled at 830 °C/h (1500 °F/h). 56.5 HRC. Structure is mostly bainite plus some martensite (light). 4% picral. 500×

[graphic]

Fig. 76

[graphic]

Fig. 77

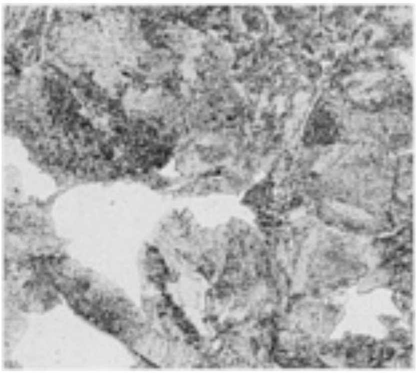

Fig. 78

AISI S7. Continuous cooling transformations. Some very fine carbide is present in all specimens in this series. Fig. 76: austenitized at 940 °C (1725 °F) and cooled at 445 °C/h (800 °F/h). 51.5 HRC. Structure is nearly all bainite with some small patches of martensite (white). Fig. 77: cooled at 220 h (400 °F/h). 45 HRC. Structure is mostly bainite with fine pearlite at the prior-austenite grain boundaries. Fig. 78: cooled at 28 °C/h (50 °F/h) to 620 °C (1150 °F), then water quenched. Austenite present at 620 °C (1150 °F) was transformed to martensite. Structure is mostly fine pearlite with patches of martensite (white). See also Fig. 73, 74, and 75. 4% picral. 500×

Fig. 79

[graphic]

Fig. 80

[graphic]

Fig. 81

Fig. 82

AISI O1. Influence of tempering temperature. All specimens austenitized at 800 °C (1475 °F), oil quenched, and tempered at different temperatures. Fig. 79: 200 °C (400 °F). 60 HRC. Fig. 80: 315 °C (600 °F). 55 HRC. Fig. 81: 425 °C (800 °F). 49 HRC. Fig. 82: 540 °C (1000 °F). 43 HRC. 4% picral. 500×

[graphic]

Fig. 83

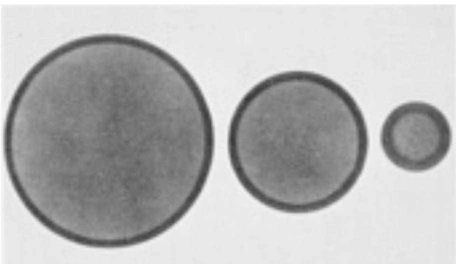

Fig. 84

[graphic]

Fig. 85

AISI W1. Austenitized at 800 °C (1475 °F), brine quenched, and tempered 2 h at 150 °C (300 °F). Black rings are hardened zones in 75-, 50-, and 25-mm (3-, 2-, and 1 -in.) diam bars. Core hardness decreases with increasing bar diameter. Fig. 83: shallow-hardening grade. Case, 65 HRC; core, 34 to 43 HRC. Fig. 84: medium-hardening grade. Case, 64.5 HRC: core, 36 to 41 HRC. Fig. 85: deep-hardening grade. Case, 65 HRC; core, 36.5 to 45 HRC. Hot 50% HCl. One half actual size.

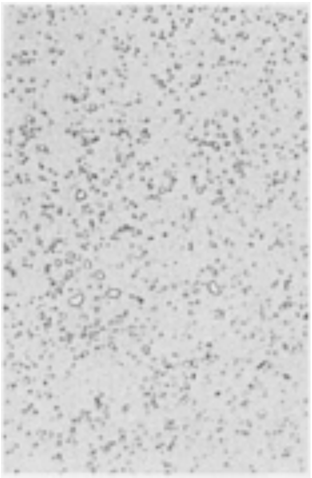

Fig. 86

[graphic]

Fig. 87

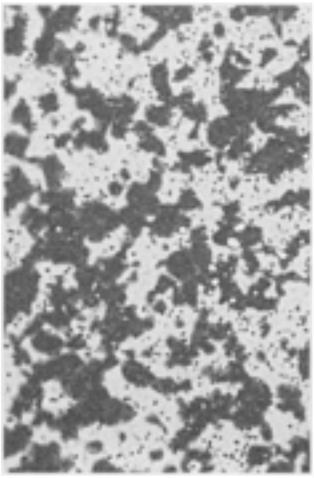

Fig. 88

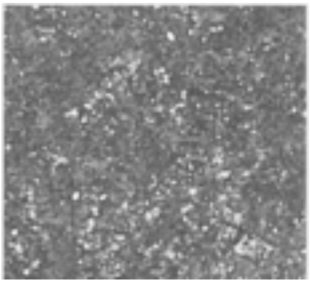

Fig. 89

AISI W1 (1.05% C), 19-mm (0.75-in.) diam bars; brine quenched. Fig. 86: hardened case microstructure. 64 HRC. Case contains as-quenched martensite and undissolved carbides. 4% picral. Fig. 87: 2% nital etch reveals martensite as dark rather than light. Fig. 88: transition zone. 55 HRC. Martensite is light, undissolved, carbide is outlined, and pearlite is dark. 4% picral. Fig. 89: core microstructure. 42 to 44 HRC. 4% picral etch reveals fine pearlite matrix (black) containing some patches of martensite (white) and undissolved carbides (outlined white particles). 1000×

[graphic]

Fig. 90

[graphic]

Fig. 91

[graphic]

Fig. 92

AISI F2, heated to 870 °C (1600 °F), water quenched, and tempered at 150 °C (300 °F). Fig. 90: case microstructure. 63 HRC. 2% nital. Fig. 91: transition region. Martensite (light) and pearlite (dark) are present between the surface and center. 4% picral. Fig. 92: core microstructure. 48 HRC. 4% picral etch reveals pearlite, carbides, and some martensite. 1000×

Fig. 93

[graphic]

Fig. 94

[graphic]

Fig. 95

[graphic]

Fig. 96

AISI S2, heated to 845 °C (1550 °F), water quenched, and tempered at 150 °C (300 °F). Fig. 93: 59.5 HRC. Structure consists of martensite and some very fine undissolved carbide. 2% nital. 1000×. Fig. 94: surface of part that was decarburized, then carburized and heat treated. Note white ferrite grains below the dark surface layer. 3% nital. 200×. Fig. 95: as in Fig. 94, but at 400×. Ferrite at 260 HK, martensite in surface layer at 665 HK, martensite beneath ferrite increased from 400 to 635 HK going away from ferrite. Fig. 96: core structure. 580 HK. Martensite (dark), some undissolved carbides and ferrite (white) formed during quenching. 3% nital. 1000×

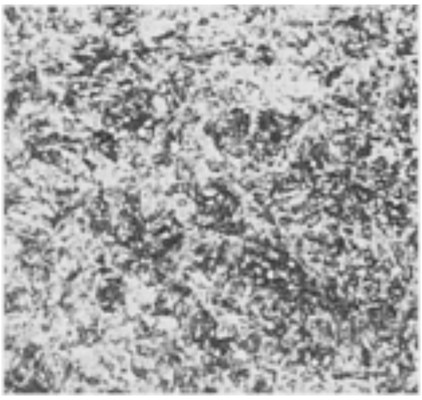

Fig. 97 AISI L6, heated to 840 °C (1550 °F), oil quenched and tempered at 150 °C (300 °F). 61 HRC. Martensite and undissolved carbides are revealed. 2% nital. 1000×

[graphic]

Fig. 98 AISI O2, heated to 850 °C (1500 °F), oil quenched and tempered at 175 °C (350 °F). 61 HRC. Martensite and a small amount of undissolved carbide are revealed. 2% nital. 1000×

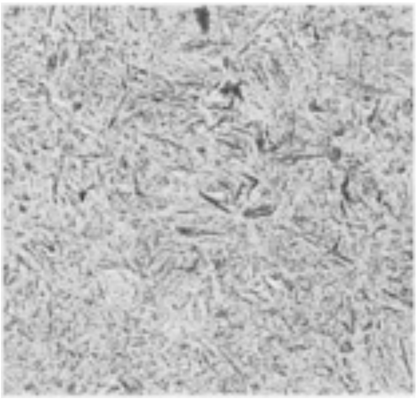

Fig. 99 AISI S1, heated to 955 °C (1750 °F), oil quenched and tempered at 150 °C (300 °F). 58 to 59 HRC. Only martensite is visible. 2% nital. 500×

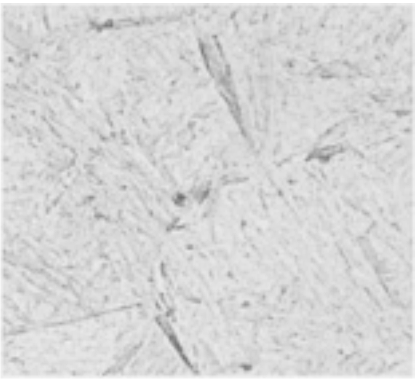

Fig. 100 AISI S5, heated to 870 °C (1600 °F) and oil quenched. 62 HRC. Only martensite is visible. 4% picral/2% nital. 1000×

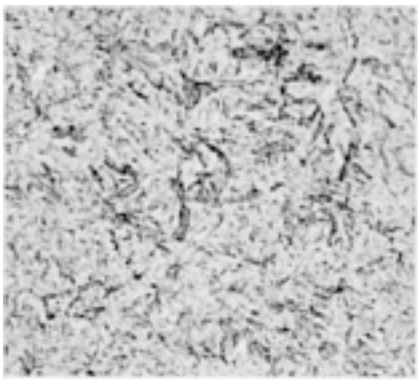

Fig. 101 AISI S5 heated to 870 °C (1600 °F), oil quenched and tempered at 175 °C (350 °F). 60

HRC. Only martensite is visible. 2% nital. 1000×

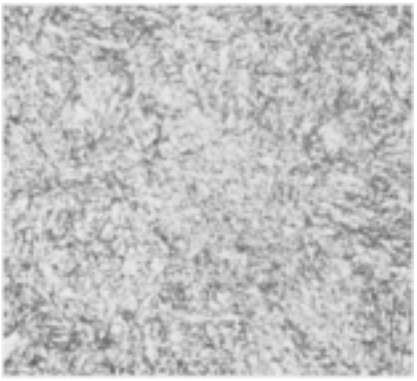

Fig. 102 AISI S5 heated to 870 °C (1600 °F), oil quenched and tempered at 480 °C (900 °F). 51 to 52 HRC. Only martensite is visible. 2% nital. 1000×

Fig. 103 AISI S7, heated to 940 °C (1725 °F), air quenched and tempered at 200 °C (400 °F). 58 HRC. Martensite and a small amount of undissolved carbides are observed. Vilella's reagent. 1000×

[graphic]

Fig. 104 AISI S7 heated to 940 °C (1725 °F), air quenched and tempered at 495 °C (925 °F). 52 HRC. Martensite and a small amount of undissolved carbide are observed. Vilella's reagent. 1000×

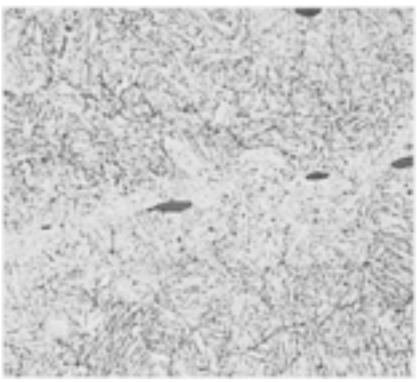

Fig. 105 AISI P20 heated to 900 °C (1650 °F), water quenched and tempered at 525 °C (975 °F). 32 HRC. Matrix is martensite. Dark particles are manganese sulfides. Contrast process orthochromatic film. 2% nital. 500×

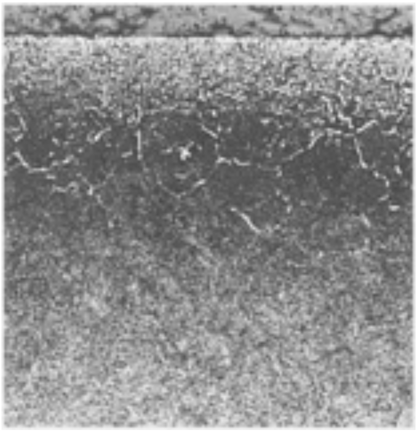

Fig. 106

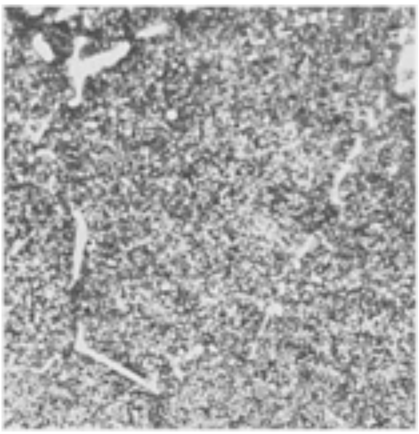

Fig. 107

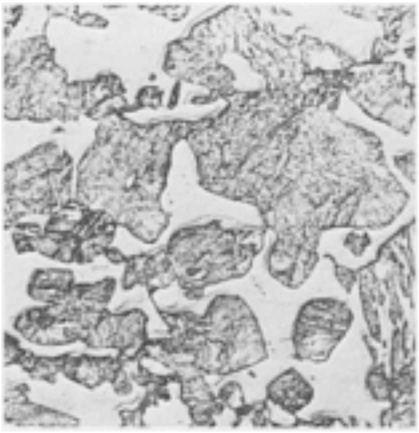

Fig. 108

AISI P5, heat treated. Case, 59.5 HRC; core, 22 HRC. Fig. 106: carburized case. Note the carbide enrichment and networking in the case region. Matrix is martensite. 100×. Fig. 107: carburized case microstructure. 1000×. Fig. 108: differential interference contrast micrograph, core microstructure. Austenitization temperature used to harden the case is too low for the core; note the ferrite (white) and martensite (dark) in the underaustenitized core. 2% nital. 400×

[graphic]

Fig. 109 AISI A6, heated to 840 °C (1550 °F), air quenched and tempered at 150 °C (300 °F). 61.5 HRC. Martensite plus a small amount of undissolved carbide are observed. 2% nital. 1000×

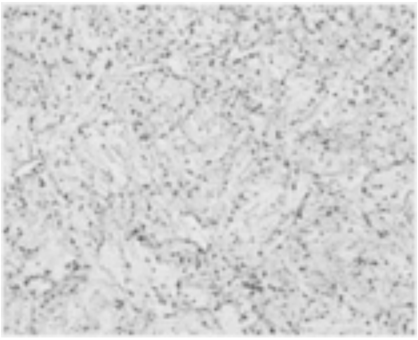

Fig. 110 AISI H11, heated to 1010 °C (1850 °F), air quenched and double tempered at 510 °C (950 °F). 52 HRC. Martensite plus a small amount of very fine carbide are visible. Vilello's reagent. 1000×

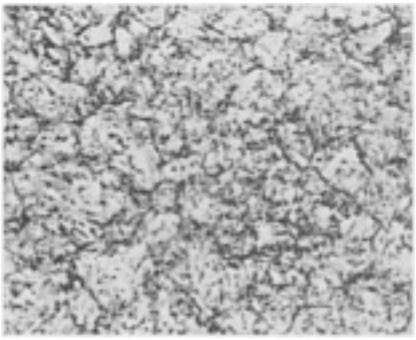

Fig. 111 AISI H13, heated to 1025 °C (1875 °F), air quenched and double tempered at 595 °C (1100 °F). 42 HRC. All martensite plus a small amount of very fine undissolved carbide. 2% nital. 1000×

[graphic]

Fig. 112 AISI H21, heated to 1200 °C (2200 °F), oil quenched and tempered at 595 °C (1100 °F). 53.5 HRC. Martensite and undissolved carbide are observed. 2% nital/Vilella's reagent. 1000×

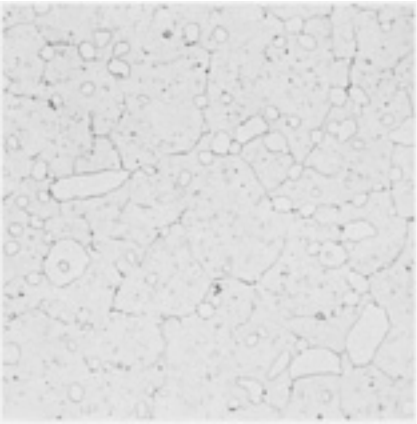

Fig. 113 AISI D2, heated to 1010 °C (1850 °F), air quenched and tempered at 200 °C (400 °F). 59.5 HRC. Martensite plus substantial undissolved carbide; note the prior-austenite grain boundaries. 2% nital. 1000×

[graphic]

Fig. 114 AISI D3, heated to 980 °C (1800 °F), oil, quenched and tempered at 200 °C (400 °F). 60.5 HRC. Martensite plus substantial undissolved carbide are visible. 2% nital/Vilella's reagent. 1000×

[graphic]

Fig. 115 AISI Ml, heated to 1175 °C (2150 °F), oil quenched and triple tempered at 480 °C (900 °F). 62 HRC. Martensite plus undissolved carbide are revealed. 2% nital. 1000×

[graphic]

Fig. 116 AISI M2, heated to 1120 °C (2050 °F), oil quenched and double tempered at 480 °C (900 °F). 62 HRC. Martensite plus undissolved carbide are revealed. Vilella's reagent. 1000×

[graphic]

Fig. 117 AISI M4, heated to 1220 °C (2225 °F), oil quenched and double tempered at 480 °C (900 °F). 62 HRC. Martensite plus undissolved carbide are revealed. Vilella's reagent. 1000×

[graphic]

Fig. 118 AISI M42, heated to 1175 °C (2150 °F), oil quenched and triple tempered at 565 °C (1050 °F). 65 HRC. Martensite plus undissolved carbide are observed. Vilella's reagent. 1000×

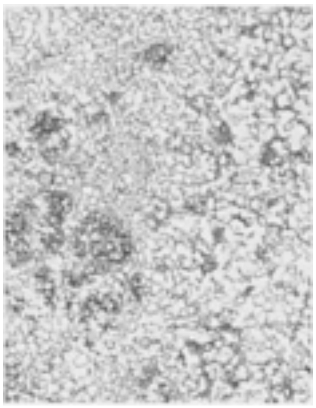

Fig. 119 AISI T15, powder-made. Sample was slow cooled after hot isostatic pressing. 28 HRC. Structure is partially annealed. 3% nital. 1000×

[graphic]

Fig. 120 AISI T15, powder-made. Sample was hot isostatically pressed, forged, and annealed. 24 HRC. Structure is fully annealed. 3% nital. 1000×

[graphic]

Fig. 121 AISI T15, powder-made. Processed as in Fig. 120, then hardened: heated to 1230 °C (2250 °F) for 5 min in salt, oil quenched, triple tempered 2 h each at 540 °C (1000 °F). 65 HRC. 3% nital. 1000×

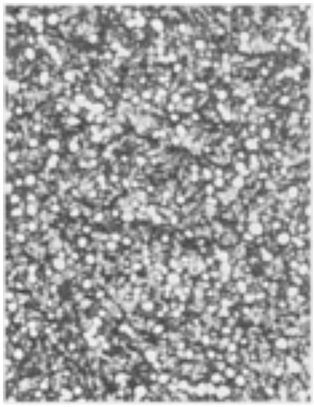

Fig. 122 AISI T15, powder-made. Same sample as in Fig. 121, but etched in 100 mL H_2O, 1 mL HCl, 1 g $K_2S_2O_5$, and 1 g $NH_4F \cdot HF$. 1000×

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