Carbon and Alloy Steels: Metallographic Techniques and Microstructures
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Atlas of Microstructures for Carbon and Alloy Steels

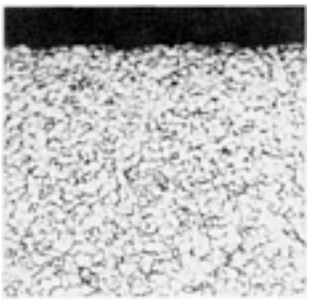

Fig. 45 Rimmed steel (0.08C), as rolled. The structure is ferrite grains; note the slight difference in grain size from case (top) to core. 3% nital. 100×

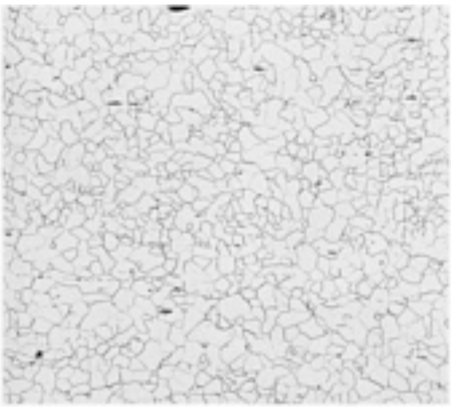

Fig. 46 Rimmed steel (0.013% C), finish rolled at 940 °C (1720 °F) and coiled at 725 °C (1340 °F). The relatively fine ferrite grain is unusual for a steel rolled at a temperature this high. Nital. 100×

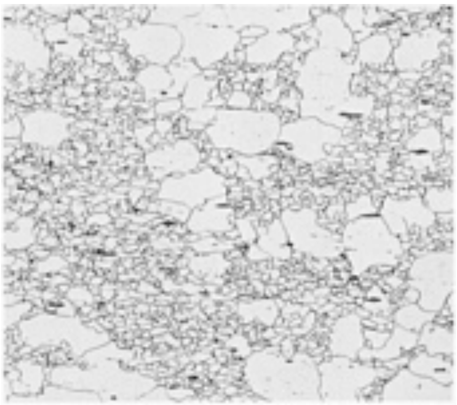

Fig. 47 Same as Fig. 46, except finish rolled at 845 °C (1550 °F) and coiled at 695 °C (1280 °F). At this rolling temperature, low carbon content contributed to development of a duplex ferrite grain. Nital. 100×

Fig. 48 Rimmed steel (0.012% C), finish rolled at 820 °C (1510 °F) and coiled at 680 °C (1260 °F). Strain imparted by rolling at low finishing temperature enhances grain growth at coiling temperature. Nital. 100×

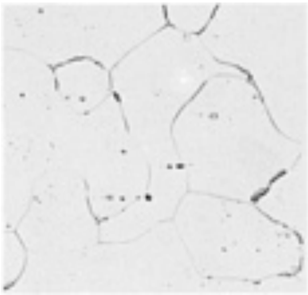

Fig. 49 Low-carbon (0.05% C) steel, showing Fe_3C carbide at ferrite grain boundaries. 2% nital, 3 s, followed by Marshall's reagent, 3 s. 340 ×

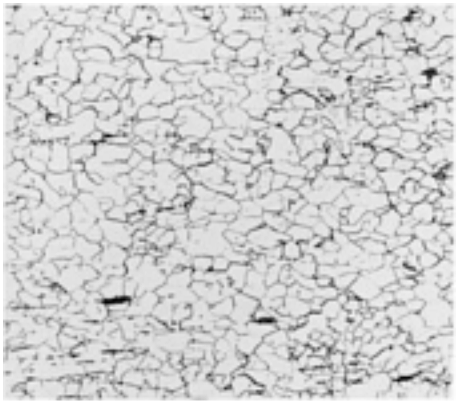

Fig. 50 Rimmed steel (0.06 %C), finish rolled at 845 °C (1550 °F) and coiled at 620 °C (1150 °F). A fine-grain ferrite developed. Nital. 100×

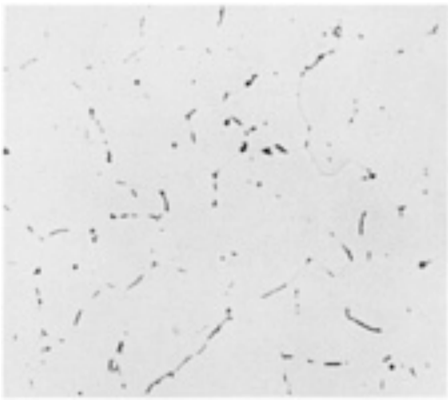

Fig. 51 Same material and processing as Fig. 50, but at a higher magnification showing particles of

cementite at the ferrite grain boundaries. Picral. 500×

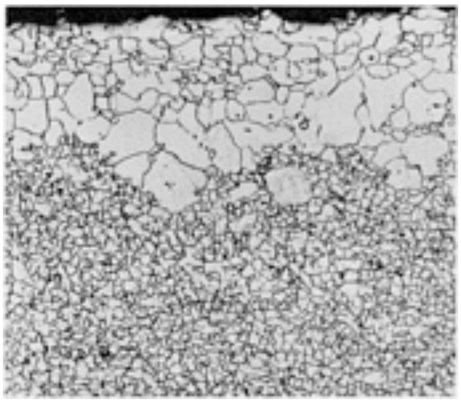

Fig. 52 Same as Fig. 50, except finish rolled at 790 °C (1450 °F) and coiled at 620 °C (1150 °F). The rolling temperature developed fine grains, but self-annealing caused surface grain enlargement. Nital. 100×

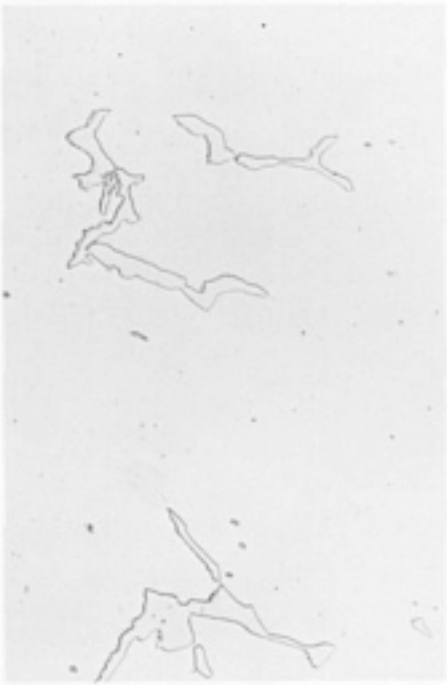

Fig. 53

Fig. 54

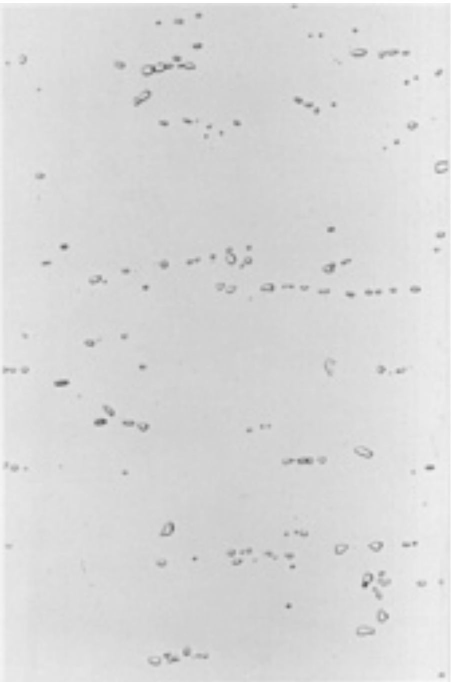

Fig. 55

Low-carbon (0.06% C) steel, cold rolled and annealed. Fig. 53: massive carbide particles. Fig. 54: medium size carbide particles. Fig. 55: small, dispersed carbides. Picral. All 1000×

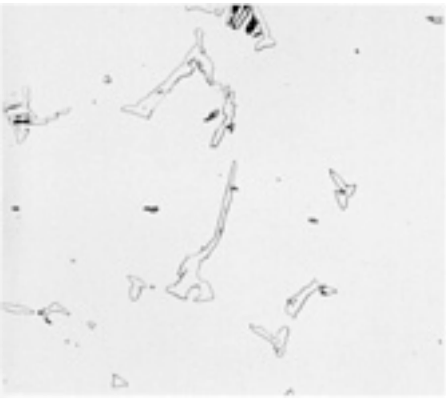

Fig. 56 Rimmed steel (0.06% C), finish rolled at 890 °C (1630 °F) and coiled at 655 °C (1210 °F). Ferrite matrix contains cementite particles (light, outlined) and traces of pearlite. Picral. 1000×

Fig. 57 Same as Fig. 56, except the steel was subsequently cold rolled to 60% reduction. Cold rolling fragmented the cementite particles. Picral. 500×

Fig. 58 Same as Fig. 57, but decarburized in wet hydrogen at 705 °C (1300 °F), The cementite particles were depleted of carbon, resulting in the formation of voids in the ferrite matrix. Picral. 500×

Fig. 59 Sheet steel (0.06C-0.35Mn-0.04Si-0.40Ti), tint etched to color ferrite grains. Color depends on grain orientation. Beraha's tint etchant. 100×

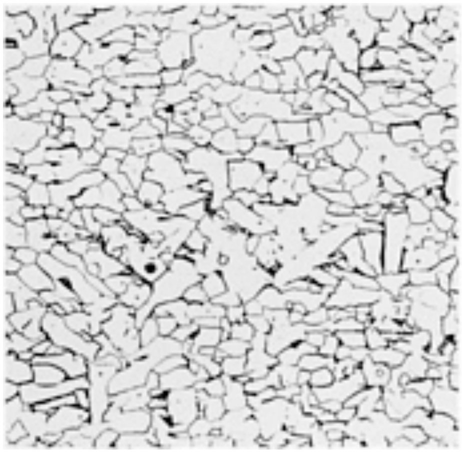

Fig. 60

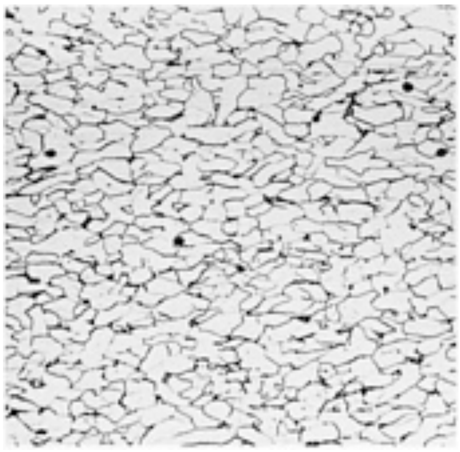

Fig. 61

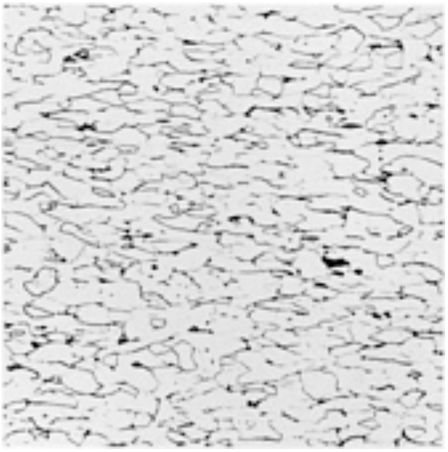

Fig. 62

Capped 1008 steel, finished hot, coiled cold, then hot rolled from a thickness of 3 mm (0.13 in.). Note increasing grain elongation as reduction increases. Fig. 60: 10% reduction. Fig. 61: 20% reduction. Fig. 62: 30% reduction. 4% nital. 250×

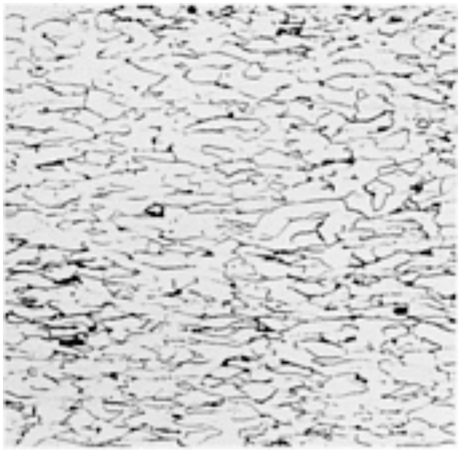

Fig. 63

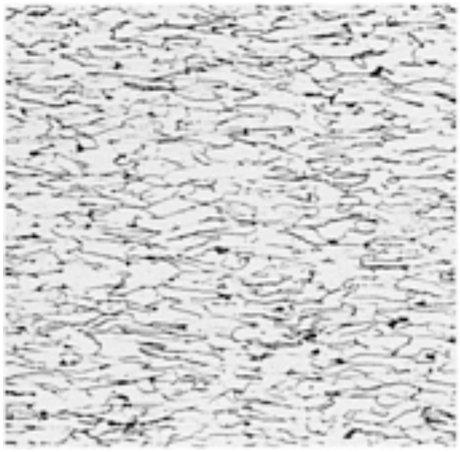

Fig. 64

Fig. 65

Same as Fig. 60, 61, and 62. Fig. 63: 40% reduction. Fig. 64: 50% reduction. Fig. 65: 60% reduction. 4% nital. All 250×

Fig. 66

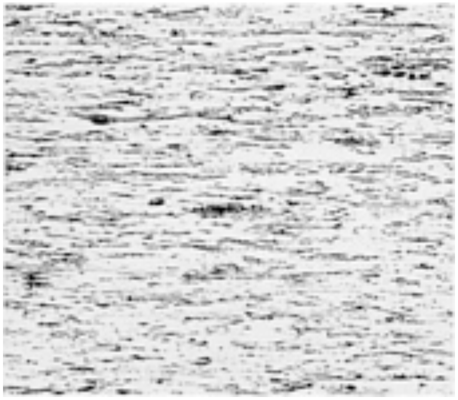

Fig. 67

Fig. 68

Same as Fig. 60, 61, 62, 63, 64, and 65. Fig. 66: 70% reduction. Fig. 67: 80% reduction. Fig. 68: 90% reduction. 4% nital. All 250×

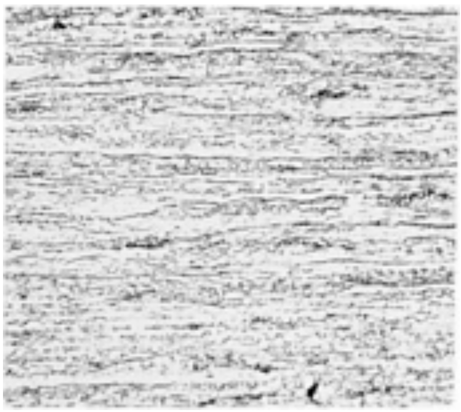

Fig. 69 Low-carbon steel (0.10% C), cold rolled 90% to a thickness of 0.25 mm (0.01 in.) with

HR30-T = 80 and annealed 106 s at 550 °C (1025 °F). Recrystallized 10%; HR30-T reduced to 79. Nital. 1000×

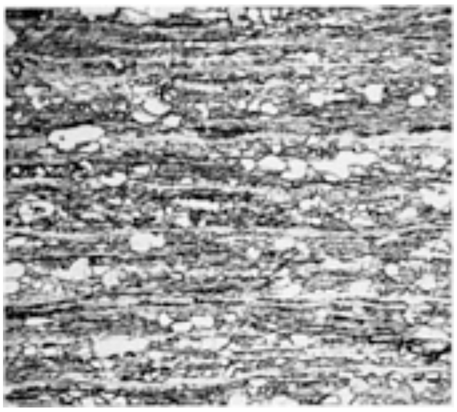

Fig. 70 Same steel and cold rolling as Fig. 69, but annealed 7 min at 550 °C (1025 °F). Recrystallization increased to 40%; HR30-T reduced to 76. Nital. 1000×

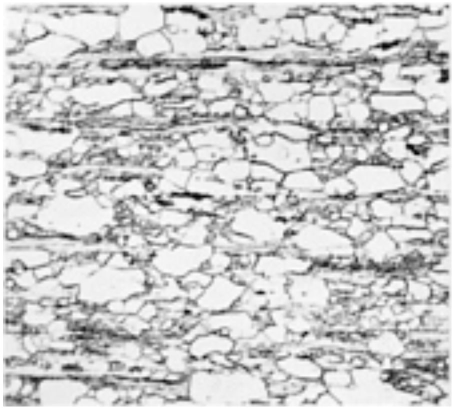

Fig. 71 Same steel and cold rolling as Fig. 69, but annealed 14.5 min at 550 °C (1025 °F). Recrystallization is 80%; HR30-T reduced to 70. Nital. 1000×

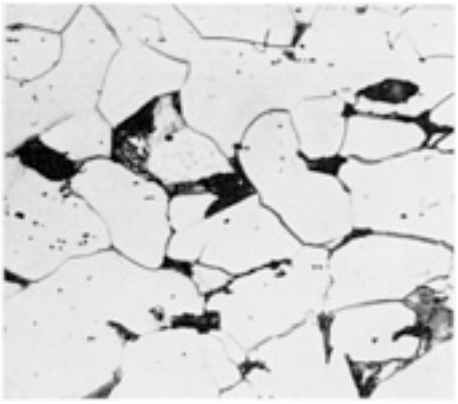

Fig. 72 Aluminum-killed 1008 steel, normalized after 60% cold reduction to a final thickness of 0.8 mm (0.03 in.). The ferritic structure contains fine pearlite (dark areas) at the grain boundaries. 4% nital. 1000×

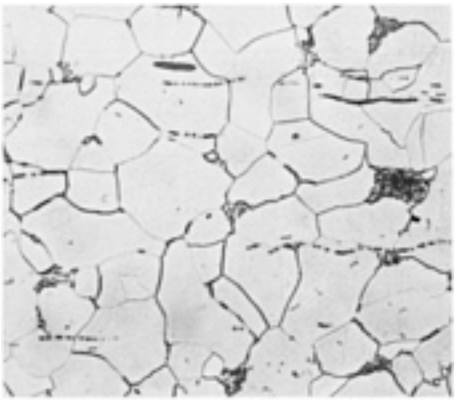

Fig. 73 Same as Fig. 72, except process annealed at 595 °C (1100 °F) after normalizing. Ferritic structure contains some fine pearlite and some spheroidized cementite at the grain boundaries. 4% nital. 1000×

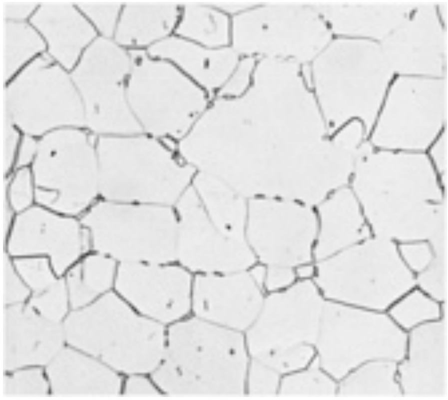

Fig. 74 Same as Fig. 72, except process annealed at 705 °C (1300 °F) after normalizing. The ferritic structure contains some cementite particles at the grain boundaries. 4% nital. 1000×

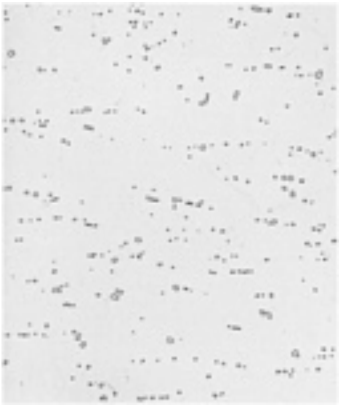

Fig. 75 Rimmed 1008 steel, coiled at 570 °C (1060 °F), cold rolled, heated rapidly in a vacuum to 690 °C (1270 °F), held 20 h, and cooled slowly. Structure is ferrite and finely spheroidized cementite. Picral. 500×

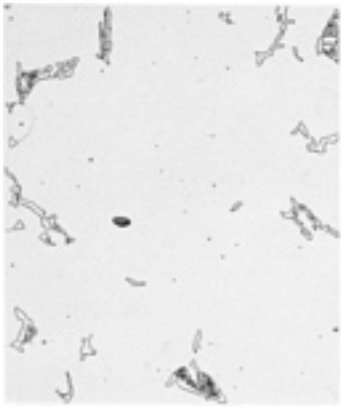

Fig. 76 Same as Fig. 75, except after cold rolling the sheet was heated rapidly to 740 °C (1360 °F), held 20 h, then cooled slowly. Structure is ferrite, cementite particles, and pearlite. Picral. 500×

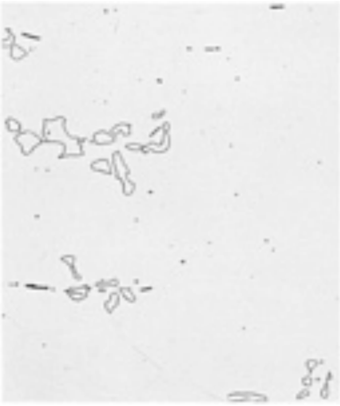

Fig. 77 Same as Fig. 75, except the steel was coiled at 680 °C (1260 °F) cold rolled, heated rapidly to 690 °C (1270 °F), held for 20 h, and cooled slowly. Structure is ferrite and coarse cementite. Picral. 500×

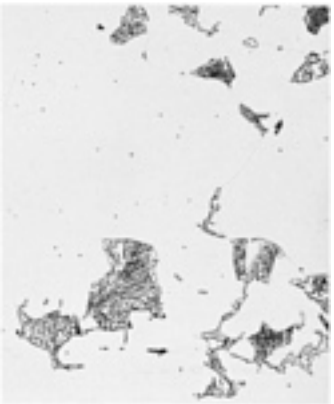

Fig. 78 Same as Fig. 75, except coiled at 680 °C (1260 °F), cold rolled 70%, heated rapidly to 740 °C (1360 °F), cooled slowly to 690 °C (1270 °F), held 20 h, and cooled slowly. The structure is ferrite and pearlite. Picral. 500×

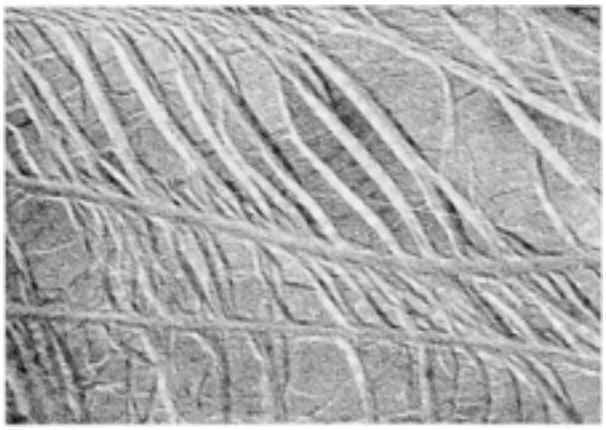

Fig. 79 Rimmed 1008 steel with stretcher strains (Lüders lines) on the surface resulting from the sheet being stretched beyond the yield point during forming. Not polished, not etched. 0.875×

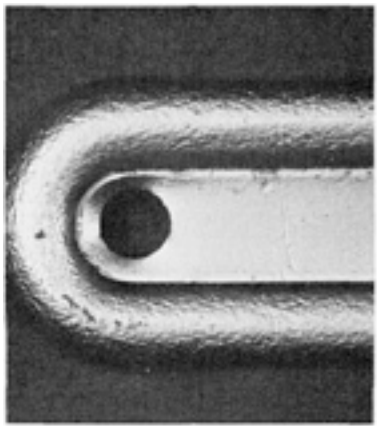

Fig. 80 Rimmed 1008 steel part, formed from sheet, with surface roughness (orange peel). See also Fig. 81. Not polished, not etched. Actual size

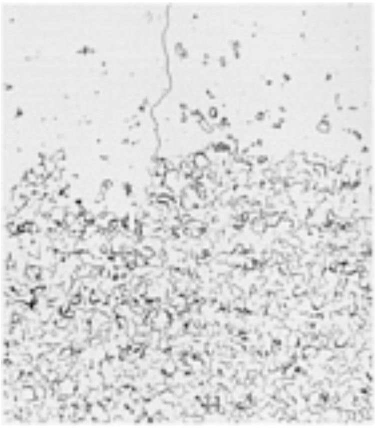

Fig. 81 Same as Fig. 80. Magnified cross section shows the coarse surface grain that caused the orange peel. Nital. 50×

Fig. 82 Aluminum-killed, hot-rolled 1008 steel, with an open skin lamination that appeared on the surface after drawing. Not polished, not etched. 2×

Fig. 83 Aluminum-killed, hot-rolled 1008 steel sheet, with a pickled surface having a concentration of "arrowhead" defects. See also Fig. 84. Not polished, not etched. Actual size

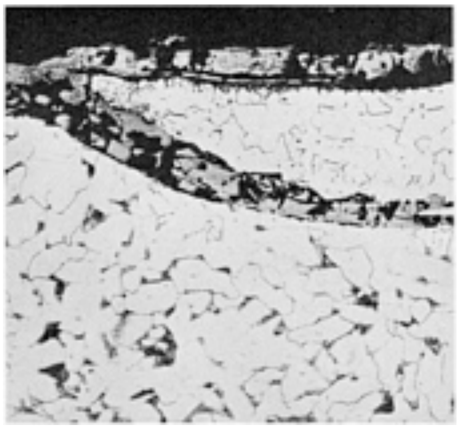

Fig. 84 Section through an "arrowhead" defect seen in Fig. 83. Oxidized and decarburized slivers, rolled back into the surface, caused these defects. Nital. 200×

Fig. 85 Cold-rolled 1008 steel sheet. The surface defect is mill scale that was rolled into the sheet at the hot mill. See also Fig. 86 and 87. Not polished, not etched. 3×

Fig. 86 Same as Fig. 85, but at higher magnification to show the darker shading and different texture of the mill scale. See also Fig. 87. Not polished, not etched. 15×

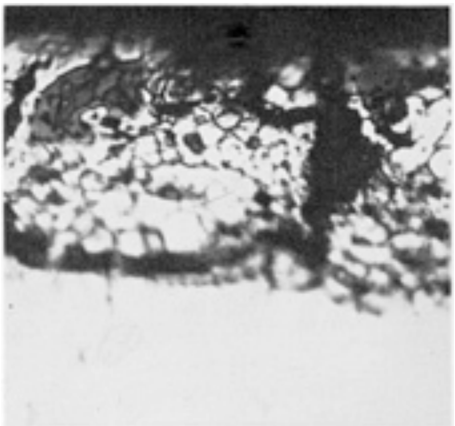

Fig. 87 Same as Fig. 85. Magnified cross section through the surface defect shows the hot-mill scale pressed into the sheet surface. Nital. 1250×

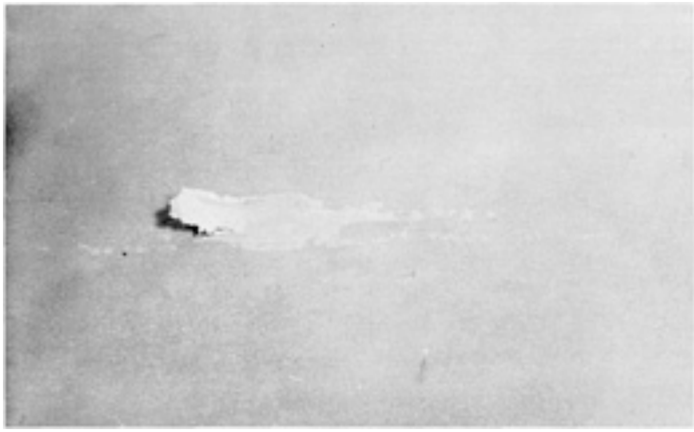

Fig. 88 Cold-rolled 1008 steel sheet. Sliver on the surface, the result of an ingot scab, is partially welded to the surface. See also Fig. 89. Not polished, not etched. Actual size

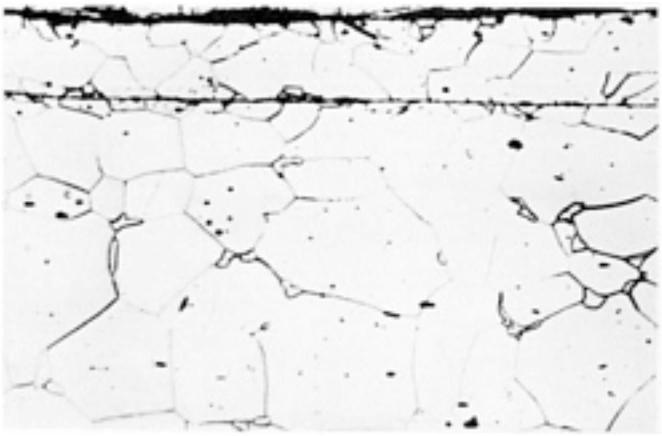

Fig. 89 Same as Fig. 88. Cross section through the part of the sliver adhering to the surface shows a thin film of oxide separating it from the sheet. Nital. 500×

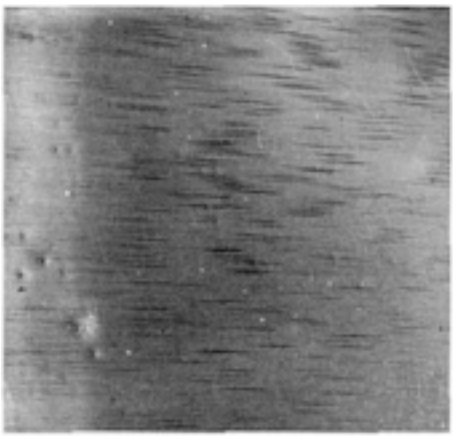

Fig. 90 Cold-rolled 1008 steel, with longitudinal streaks on the surface that were caused by slippage between rolls in the tandem mill. See also Fig. 91. Not polished, not etched. 0.25×

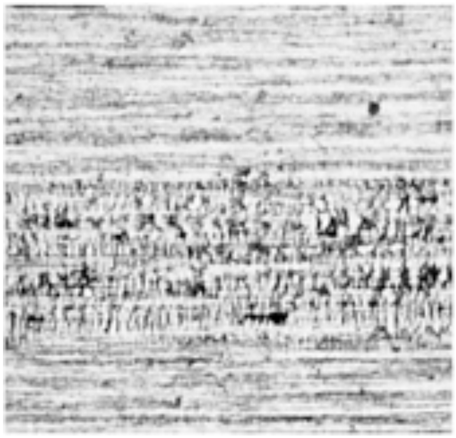

Fig. 91 Same as Fig. 90, at moderate magnification. A single streak reveals the distinctive texture typical of all streaks on the sheet. See also Fig. 92. Nital. 28×

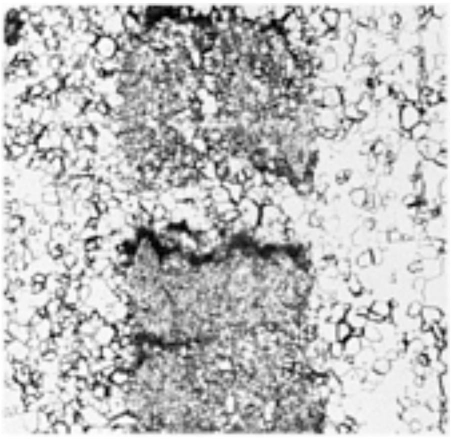

Fig. 92 Same as Fig. 90. After light polishing, the surface streak shows a dark-etching area of very fine grain. Nital. 500×

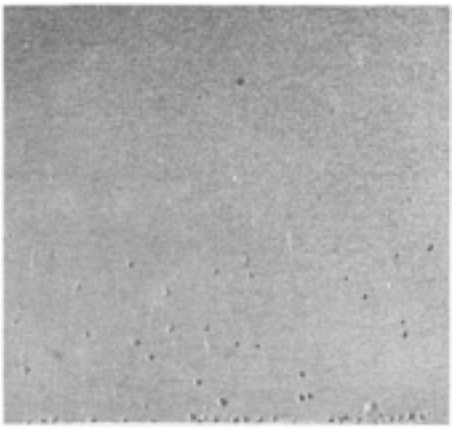

Fig. 93 Cold-rolled 1008 steel sheet, with numerous surface pits caused by rolled-in sand. See also Fig. 94. Not polished, not etched. 2.5×

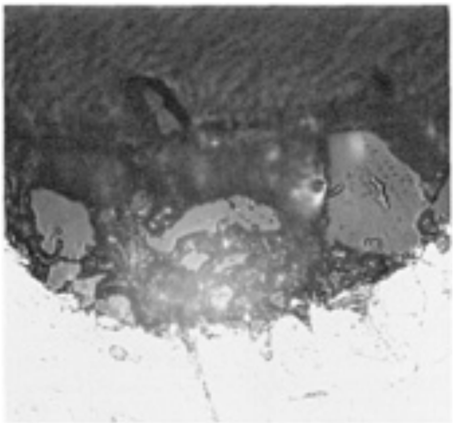

Fig. 94 Same as Fig. 93. A cross section through one of the pits shows a grain of sand rolled into the sheet during temper rolling. See also Fig. 95. Nital. 1000×

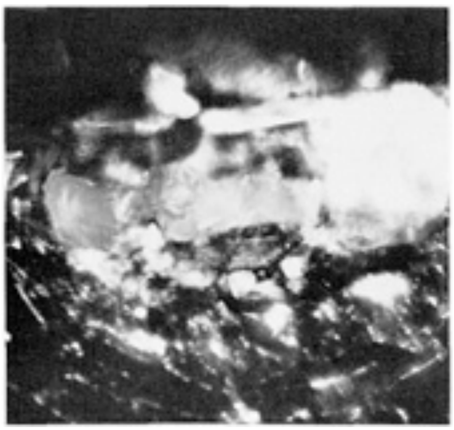

Fig. 95 Same as Fig. 93. Polarized light illumination confirms the defect. The sand was picked up from the seals at the annealing pit. Nital. 1000×

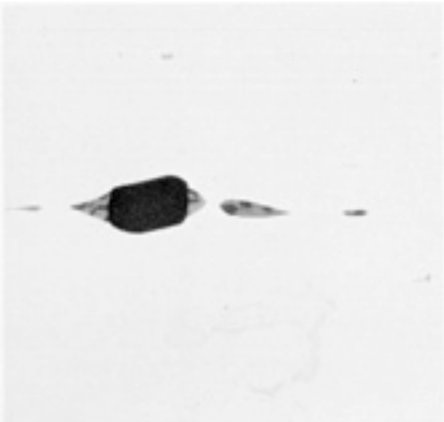

Fig. 96 Manganese oxide (dark) with manganese sulfide tails (light) and thin stringers of sulfide. As-polished. 1000×

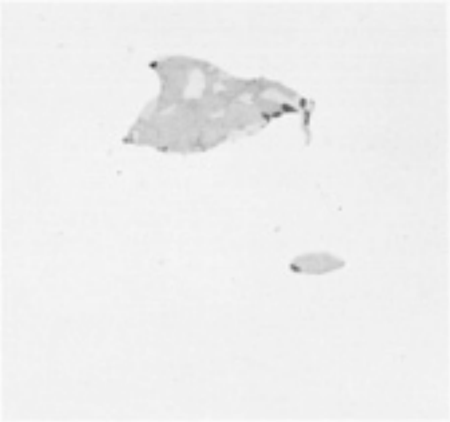

Fig. 97 Mixed sulfides of iron and manganese containing a few small oxide spots (dark areas at the edge of the inclusions). As-polished. 1000×

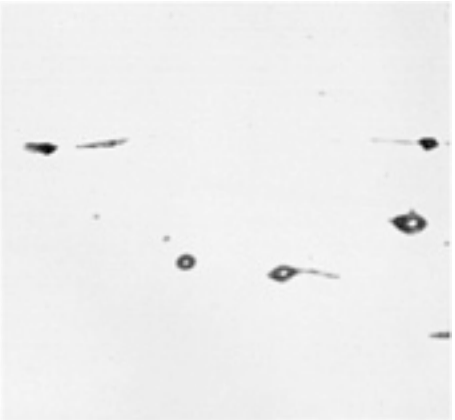

Fig. 98 The major inclusions are globular, glassy silicates. The tails attached to the silicates are sulfides. As-polished. 1000×

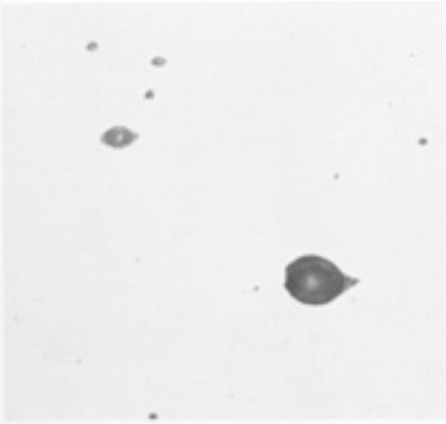

Fig. 99 Iron oxide with manganese oxide causing internal reflection. Tails are probably manganese sulfide. As-polished. 1000×

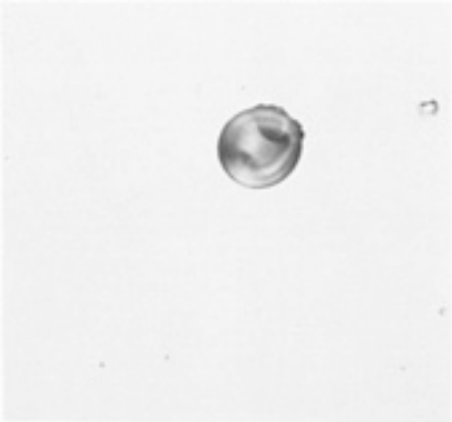

Fig. 100 Glassy globules of SiO_2 showing internal reflections. Under polarized light, these globules produce an optical cross. As-polished. 1000×

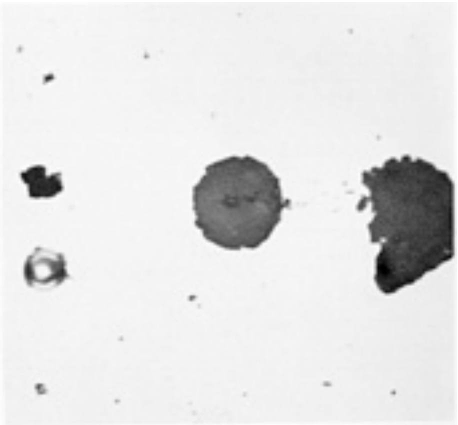

Fig. 101 The glassy inclusion at the left is SiO_2. The irregular-shaped inclusions above it and to the right are $FeO-SiO_2$. As-polished. 1000×

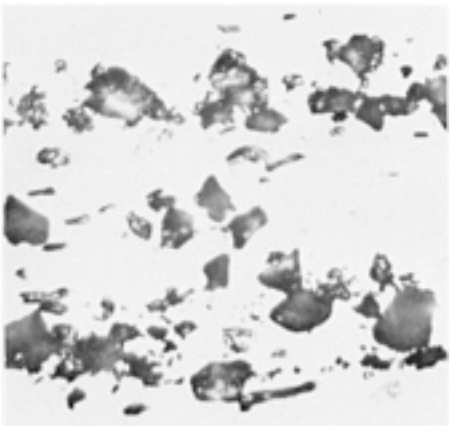

Fig. 102 These mixed inclusions are Al_2O_3, which is colorless under polarized light, and hercynite. As-polished. 1000×

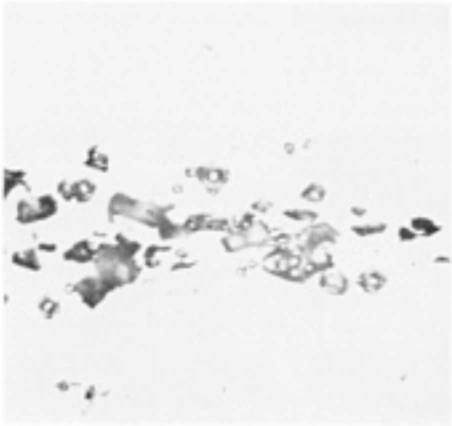

Fig. 103 A complex mixture consisting of Al_2O_3, hercynite, silica, and mullite. As-polished. 1000×

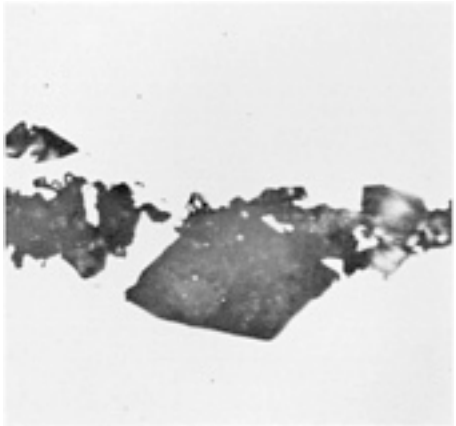

Fig. 104 These irregularly shaped masses are typical of refractory brick. Under polarized light illumination, they emit reddish blue-gray tinges. As-polished. 1000×

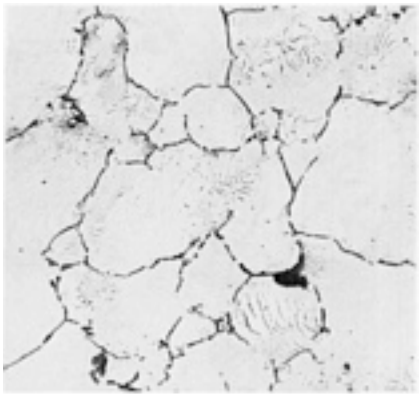

Fig. 105 AISI 1020 steel, carburized. Prior austenite grain boundaries are revealed by an etchant that darkens Fe_3C in the boundaries. Hot (100 °C, or 212 °F) alkaline sodium picrate. 500×

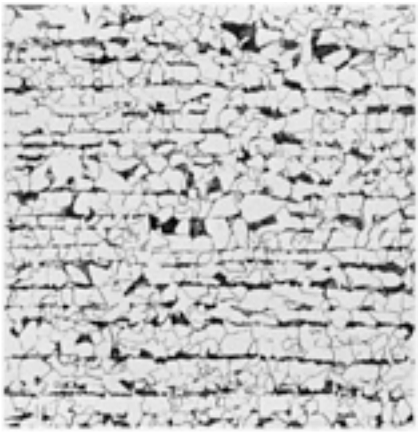

Fig. 106 High-strength low-alloy steel (0.2% C), hot rolled. The structure is ferrite and pearlite. 4% picral, then 2% nital. 200×

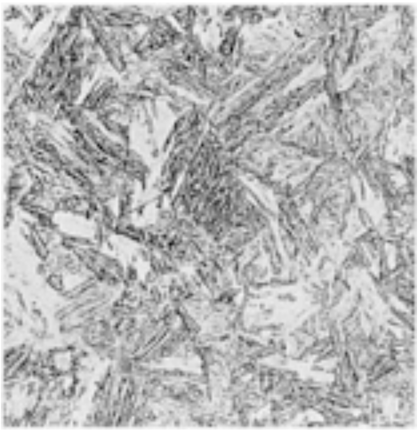

Fig. 107 0.20% C steel, water quenched. The structure is lath martensite. 8% $Na_2S_2O_5$. 500×. (R.L. Perry)

Fig. 108 0.20C-1.0Mn steel, as-quenched. The structure is pearlite (dark), martensite (light), and ferrite (white). 10% $Na_2S_2O_5$. 1000×. (M. Scott)

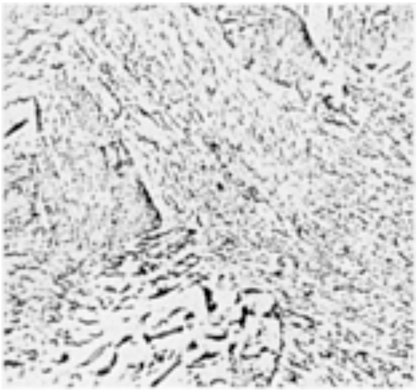

Fig. 109 Steel specimen (Fe-0.22C-0.88Mn-0.55Ni-0.50Cr-0.35Mo) taken 38 mm (1.5 in.) from the quenched end of a Jominy bar. The structure is bainite. 4% picral. 1000×

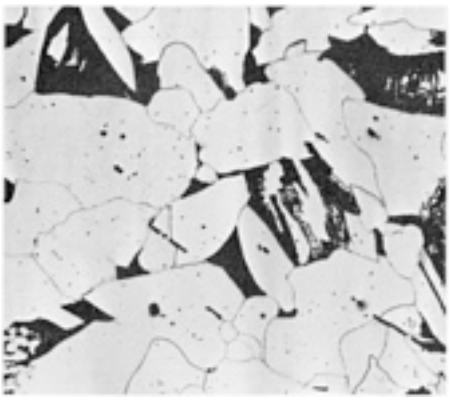

Fig. 110 1025 steel, normalized by austenitizing at 1095 °C (2000 °F) and air cooling. Coarse grain structure is pearlite (black) in a ferrite matrix. See also Fig. 111. Picral. 500×

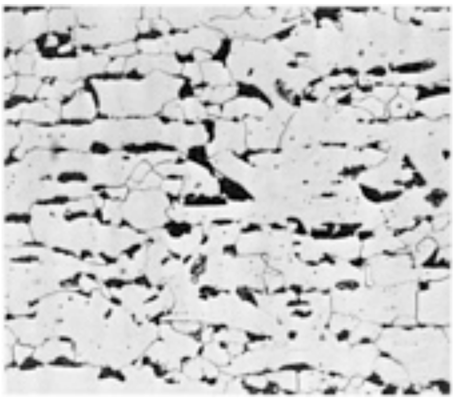

Fig. 111 Same as Fig. 110, except normalized by austenitizing at 930 °C (1700 °F) and air cooling. The lower austenitizing temperature is responsible for the finer grain size of the steel. Picral. 500×

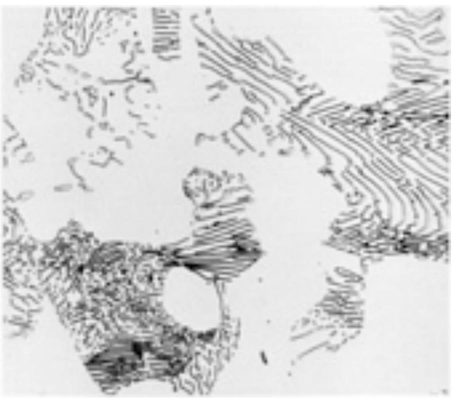

Fig. 112 1030 steel, austenitized 1 h at 930 °C (1700 °F) then 2 h 40 min at 775 °C (1430 °F), and held at 705 °C (1300 °F) for isothermal transformation of austenite and brine quenched. Structure is coarse pearlite and ferrite. Picral. 1000×

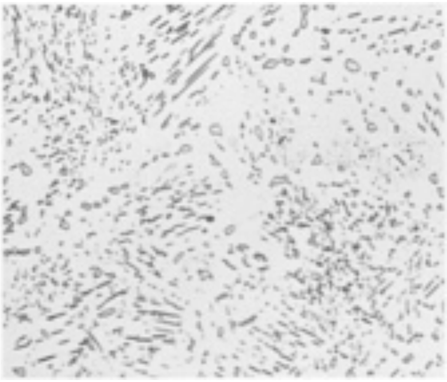

Fig. 113 1030 steel, austenitized 40 min at 800 °C (1475 °F), held 15 min at 705 °C (1300 °F) for isothermal transformation, then heated to 705 °C (1305 °F) and held 192 h. Partly spheroidized pearlite in a ferrite matrix. Picral. 1000×

Fig. 114 10B35 steel, austenitized 1 h at 850 °C (1560 °F), quenched in still water, and tempered 1 h at 175 °C (350 °F). Structure is ferrite (small white areas) and lower bainite (dark acicular areas) in tempered martensite. 1% nital. 550×

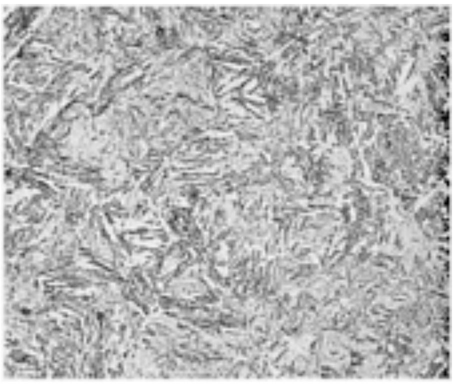

Fig. 115 Same steel and austenitizing as Fig. 114, but quenched in agitated water and tempered 1 h at 230 °C (450 °F). The more severe quench suppressed formation of ferrite and bainite. The structure is tempered martensite. 1% nital. 500×

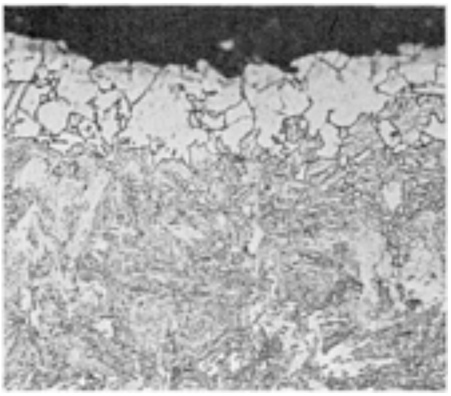

Fig. 116 Same steel as Fig. 114, austenitized 1 h at 870 °C (1600 °F), water quenched, and tempered 1 h at 230 °C (450 °F). Core is tempered martensite; the surface of the specimen (ferrite) is severely decarburized (white area at top). 1% nital. 500×

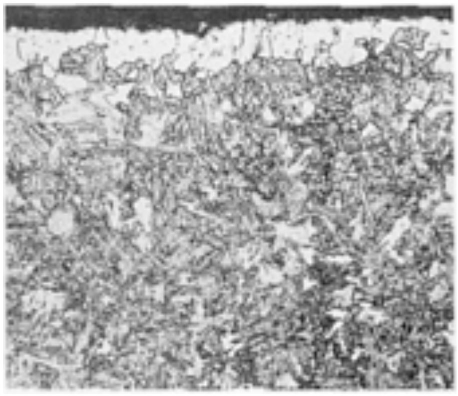

Fig. 117 Same steel and heat treatment as Fig. 116, but austenitized in on atmosphere with a carbon potential closer to that of the steel. Surface (top) is less severely decarburized. 1% nital. 550×

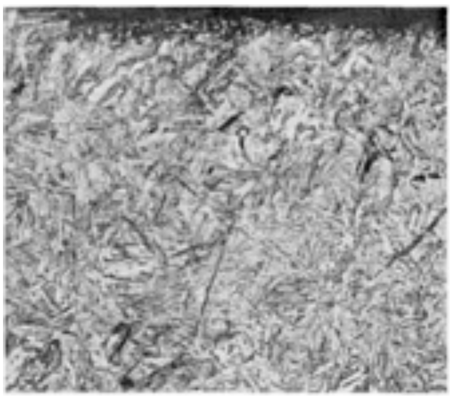

Fig. 118 Same steel and heat treatment as Fig. 116 and 117, except tempered 1 h at 175 °C (350 °F). Austenitizing was carried out in an atmosphere of correct carbon potential. No decarburization at the surface (top). 1% nital. 500×

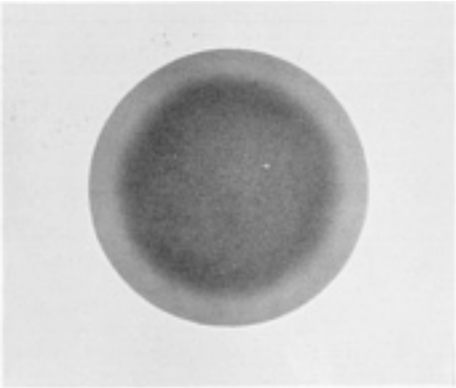

Fig. 119 1035 steel bar, austenitized 1 h at 850 °C (1560 °F), water quenched, and tempered 1 h at 175 °C (350 °F). Cross section shows light outer zone of martensite and a dark core of softer transformation products. 10% nital and 1% picral. Actual size

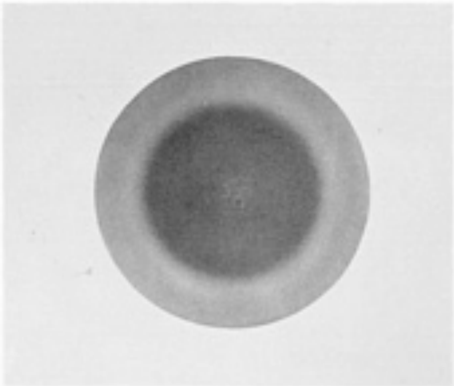

Fig. 120 10B35 steel bar (same as 1035, but boron treated) after same heat treatment as bar shown in Fig. 119. Effect of boron on hardenability is evident from the greater depth of the martensite zone. 10% nital and 1% picral. Actual size

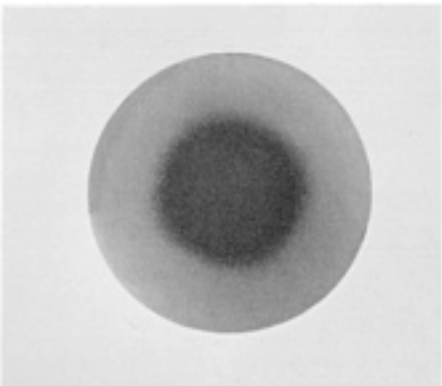

Fig. 121 Same steel as Fig. 120, modified for even greater hardenability. After same heat treatment as Fig. 119, the martensite zone is still deeper than in Fig. 120. 10% nital and 1% picral. Actual size

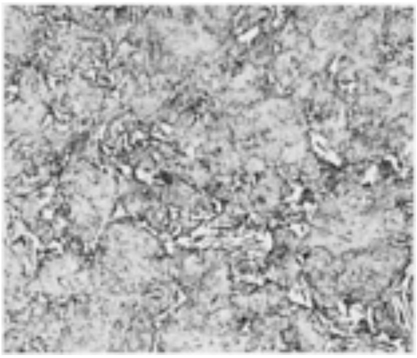

Fig. 122 1040 steel bar (25-mm, or 1-in., diam), austenitized 30 min at 915 °C (1675 °F), oil quenched, and tempered 2 h at 205 °C (400 °F). Structure consists of tempered martensite (gray) and ferrite (white). Nital. 500×

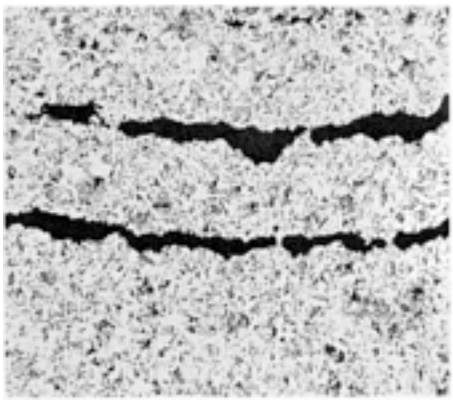

Fig. 123 1038 steel bar, as-forged. Longitudinal section displays secondary pipe (black areas) that was carried along from the original bar stock into the forged piece. Gray areas are pearlite; white areas, ferrite. 2% nital. 50×

Fig. 124 1038 steel, as-forged. Transverse section of severely overheated specimen shows initial stage of "burning." Ferrite (white) outlines prior austenite grains, and the matrix consists of ferrite (white) and pearlite (black). 2% nital. 100×

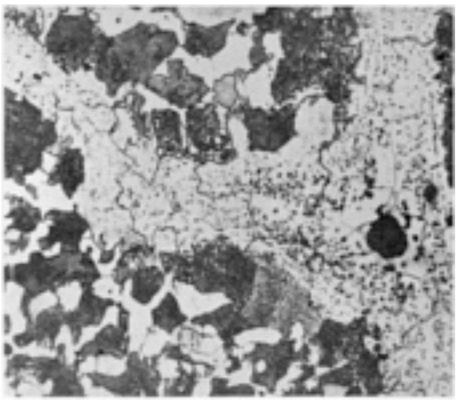

Fig. 125 Same as Fig. 124, but at a higher magnification. Massive ferrite outlines prior austenite grains and contains particles of oxide (block dots). The matrix consists of ferrite (white) and pearlite (black). 2% nital. 550×

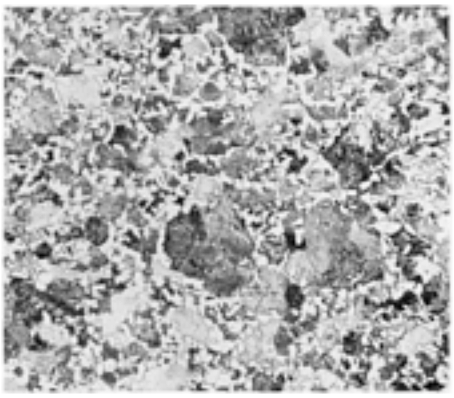

Fig. 126 1040 steel bar, 25 mm (1 in.) in diameter, austenitized 30 min at 915 °C (1675 °F) and cooled slowly in the furnace. White areas are ferrite; dark areas, pearlite. See also Fig. 127. Nital. 200×

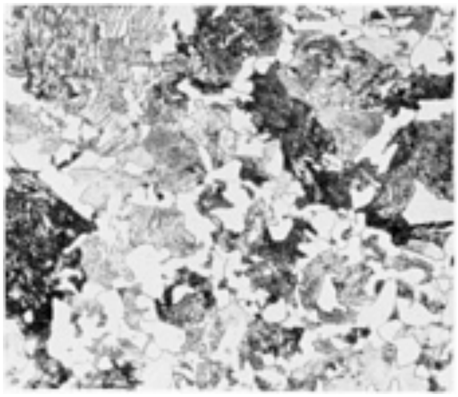

Fig. 127 Same as Fig. 126, but at higher magnification to resolve more clearly the pearlite and ferrite groins. Wide difference in grain size is evident here and in Fig. 126. Nital. 500×

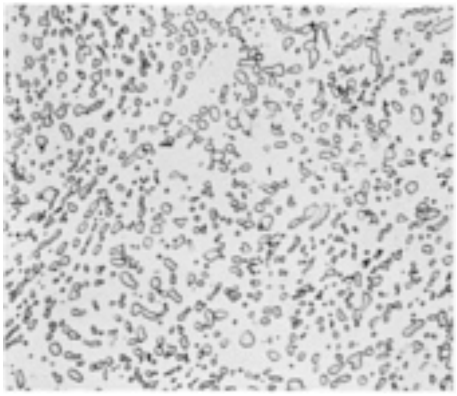

Fig. 128 1040 steel, austenitized 40 min at 800 °C (1475 °F) and held 6 h at 705 °C (1305 °F) for isothermal transformation. Structure is spheroidized carbide in a ferrite matrix. Picral. 1000×

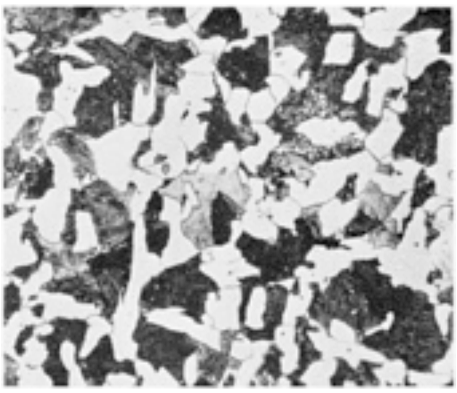

Fig. 129 25 mm (1-in.) 1045 steel bar, normalized by austenitizing at 845 °C (1550 °F) and air cooling and tempered 2 h at 480 °C (900 °F). Structure is fine lamellar pearlite (dark) and ferrite (light). 2% nital. 500×

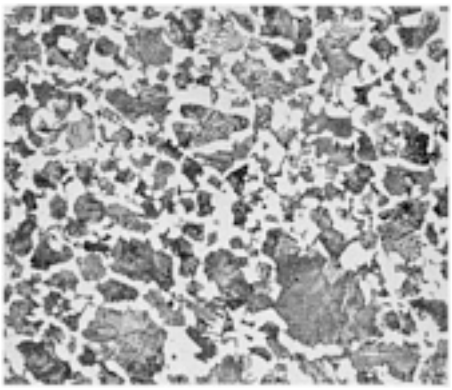

Fig. 130 1045 steel sheet. 3 mm (0.13 in.) thick, normalized by austenitizing at 1095 °C (2000 °F) and cooling in air. Structure consists of pearlite (dark gray) and ferrite (light). Picral. 500×

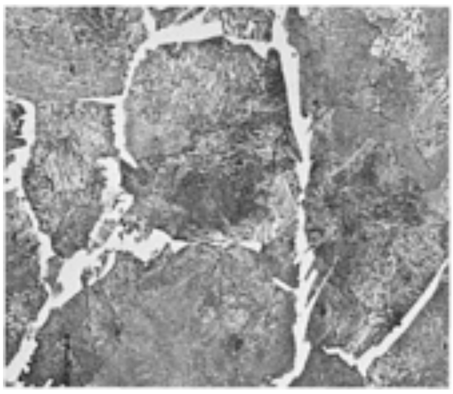

Fig. 131 1045 steel bar, normalized same as Fig. 130. Grain size is much larger than that in Fig. 130. Structure is pearlite (gray), with a network or grain-boundary ferrite (white) and a few plates of ferrite. Picral. 500×

Fig. 132 1045 steel forging, as air cooled from the forging temperature of 1205 °C (2200 °F). Structure consists of envelopes of proeutectoid ferrite at prior austenite grain boundaries, with emerging spines of ferrite, in a matrix of pearlite. Picral. 330×

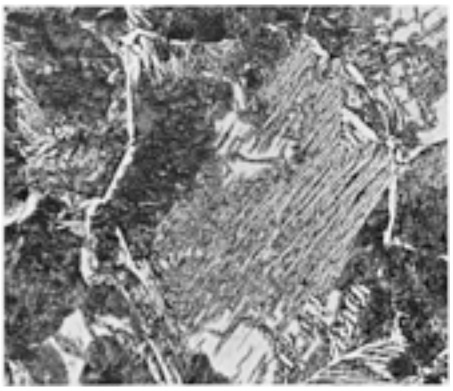

Fig. 133 1045 steel, 51-mm (2-in.) bar stock, austenitized 2 h at 845 °C (1550 °F), oil quenched 15 s, air cooled 5 min, and oil quenched to room temperature. Ferrite at prior austenite grain boundaries; acicular structure is probably upper bainite. The matrix is pearlite. 4% picral. 500×

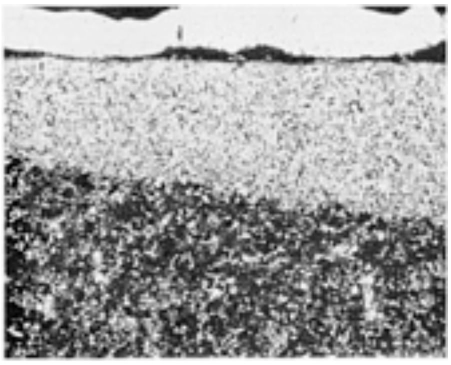

Fig. 134 1045 steel forging, austenitized 3 h at 900 °C (1650 °F), air cooled, and tempered 2 h at 205 °C (400 °F). At top is a layer of chromium plate; below it is martensite formed due to overheating during abrasive cutoff. The remainder of the structure is ferrite and pearlite. 2% nital. 100×

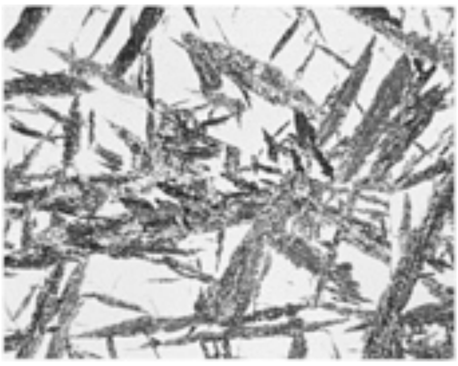

Fig. 135 1045 steel austenitized 10 min at 1205 °C (2200 °F), held 10 min at 340 °C (640 °F) for partial isothermal transformation, and cooled in air to room temperature. Lower bainite (dark) in a matrix of martensite (white). Picral. 500×

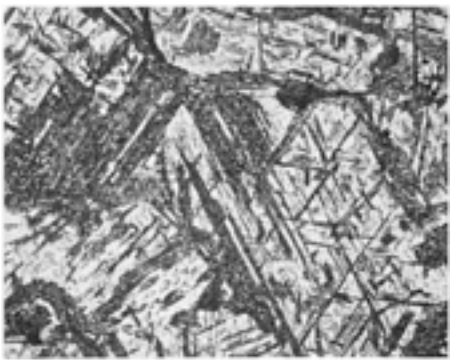

Fig. 136 51-mm (2-in.) 1045 steel bar, austenitized 2 h at 845 °C (1550 °F), oil quenched 15 s, air cooled 3 min, and water quenched to room temperature. Specimen taken 3 mm (0.13 in.) below surface. Dark stripes at prior austenite grain boundaries are probably upper bainite; the matrix is martensite. 2% nital. 500×

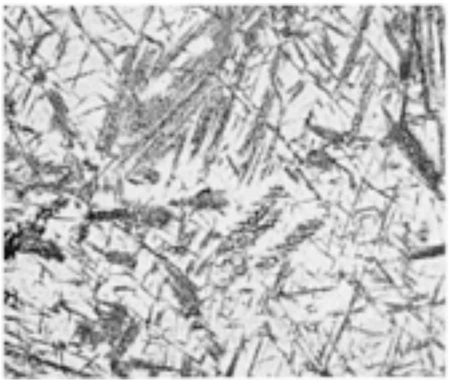

Fig. 137 51-mm (2-in.) 1045 steel bar stock, austenitized 2.5 h at 845 °C (1550 °F), water quenched 4 s, air cooled 3 min, and water quenched to room temperature. Specimen is from 3 mm (0.13 in.) below the surface. The dark acicular structure is probably lower bainite; the matrix is martensite. 4% picral. 500×

Fig. 138 Same steel, bar size, and heat treatment as Fig. 137, but a different structure developed. The gray aggregates are probably upper bainite; the fine acicular dispersion is probably lower bainite. The matrix is martensite. 4% picral. 500×

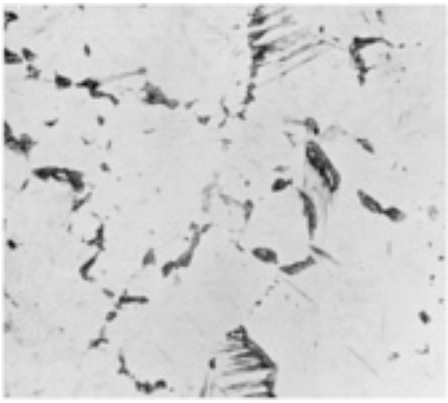

Fig. 139 1050 steel, austenitized 30 min at 870 °C (1600 °F) and oil quenched. The quench was slow enough to permit formation of some grain-boundary ferrite and bainite (feathery constituent). The matrix is martensite. Nital. 825×

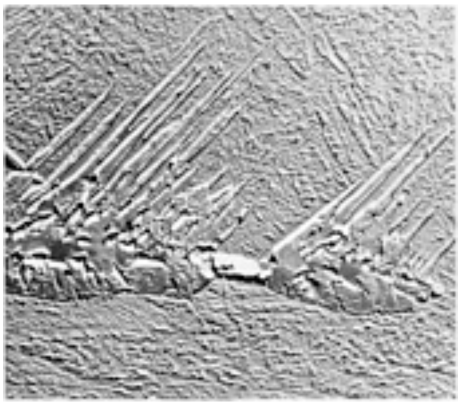

Fig. 140 Replica electron micrograph of same steel as Fig. 139 after identical processing. Structure is proeutectoid ferrite at a prior austenite grain boundary, and emerging spines of bainite, in a martensite matrix. Nital. 9130×

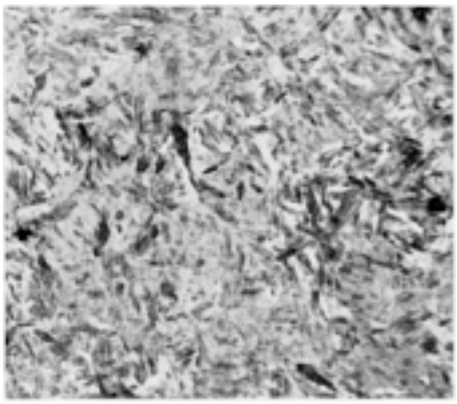

Fig. 141 1050 steel, austenitized 1 h at 870 °C (1600 °F), water quenched, and tempered 1 h at 260 °C (500 °F). The structure is fine tempered martensite. No free ferrite is visible, indicating an effective quench. Nital. 825×

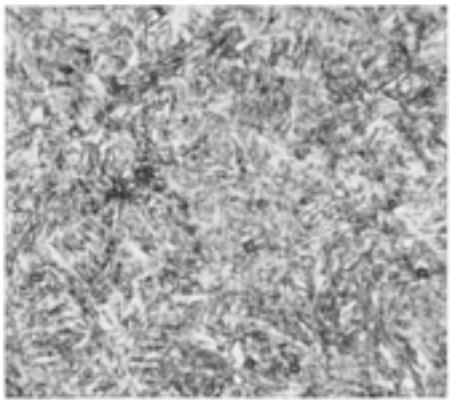

Fig. 142 Same steel and heat treatment as Fig. 141, except the steel was tempered 1 h at 370 °C (700 °F). The structure is tempered martensite. See also Fig. 145. Nital. 825×

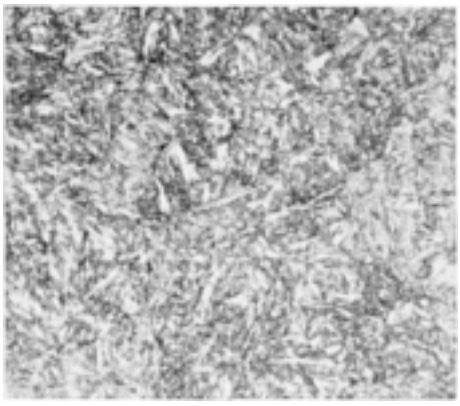

Fig. 143 Same steel and heat treatment as Fig. 141, but tempered 1 h at 480 °C (900 °F). Structure is tempered martensite, with ferrite and carbide constituents barely resolved. See also Fig. 146. Nital. 825×

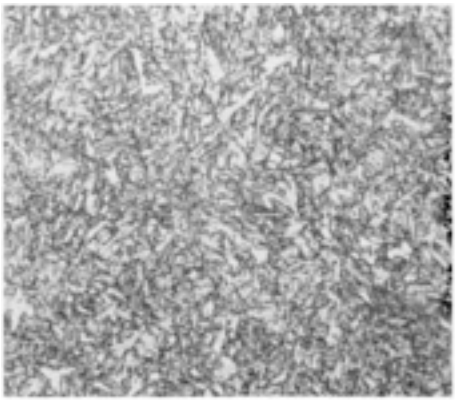

Fig. 144 Same steel and heat treatment as Fig. 141, but tempered 1 h at 595 °C (1100 °F). Structure is tempered martensite. Ferrite and carbide are better resolved than in Fig. 143. See also Fig. 147. Nital. 825×

Fig. 145 Replica electron micrograph of specimen in Fig. 142. The tempered martensite is typical of a thoroughly quenched structure. Nital. 9130×

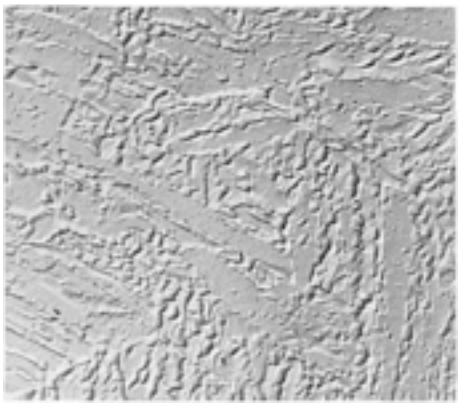

Fig. 146 Replica electron micrograph of the specimen in Fig. 143. The structure is typical of a thoroughly quenched structure. Nital. 9130×

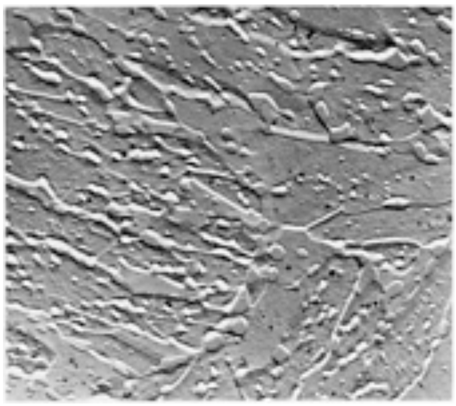

Fig. 147 Replica electron micrograph of the specimen in Fig. 144. Resolution of ferrite and carbide has increased markedly. Nital. 9130×

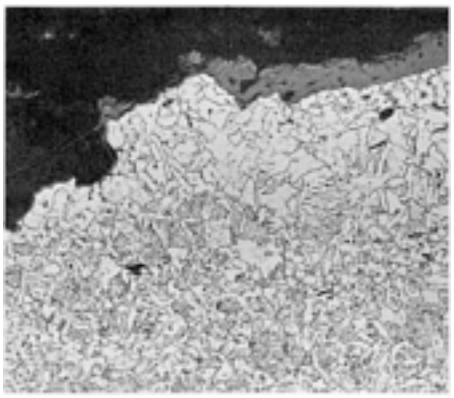

Fig. 148 1052 steel forging, austenitized 1 h at 850 °C (1560 °F), water quenched, and tempered 1 h at 570 °C (1060 °F). Top to bottom: a dark layer of iron oxide, a lighter gray area of decarburization, and a core of ferrite and tempered martensite. The dark particles in the core are manganese sulfide. 1% nital. 250×

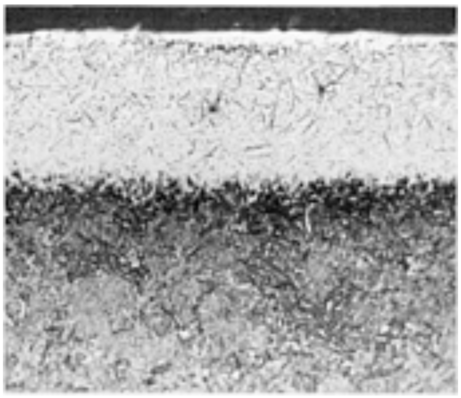

Fig. 149 1052 steel forging, austenitized 2 h at 850 °C (1560 °F), water quenched, and tempered 2 h at 650 °C (1200 °F). Heat of friction in service produced a layer of martensite (white crust) and retained austenite (white) between martensite needles; the core is ferrite (white) in tempered martensite. 1% nital. 275×

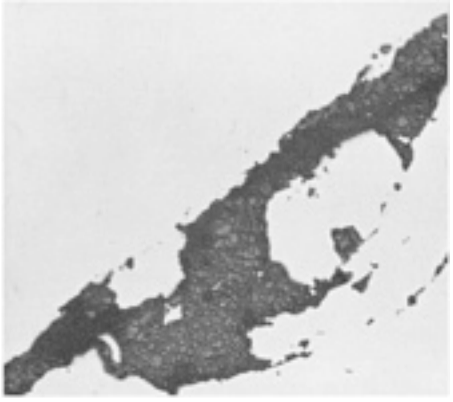

Fig. 150 1052 steel forging. Structure is a massive inclusion with a matrix of Al_2O_3, SiO_2, magnesium oxide, and calcium oxide. Rectangular particles in the matrix are Al_2O_3 with iron oxide; others are Al_2O_3 with magnesium oxide. See Fig. 151 for a higher magnification view of a similar inclusion. As-polished. 100×

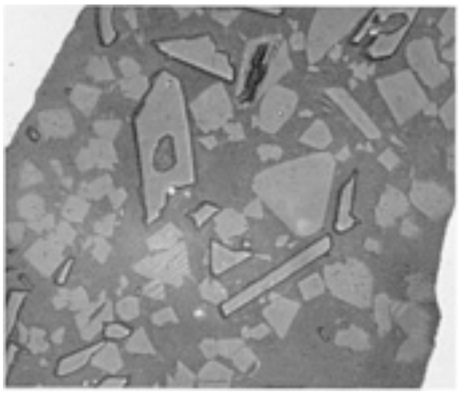

Fig. 151 Massive, stringer-type inclusion in a 1052 steel forging. Particles in the matrix of the inclusion are clearly resolved. As-polished. 500×

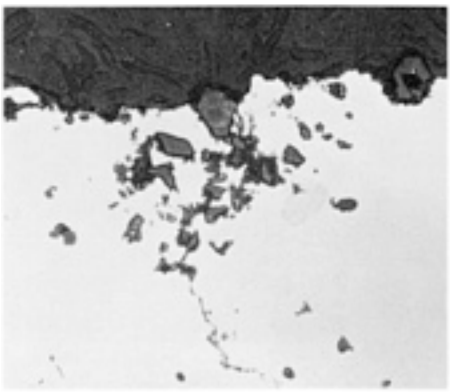

Fig. 152 1052 steel forging, with massive iron aluminide inclusions at the surface. Note the crack extending downward from the inclusions. As-polished. 500×

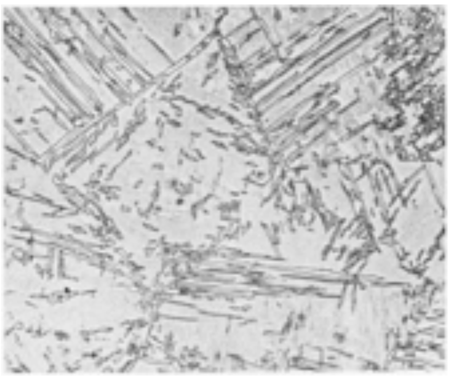

Fig. 153 1541 steel forged at 1205 °C (2200 °F) and cooled in an air blast. Structure is Widmanstätten platelets of ferrite nucleated at prior austenite grain boundaries and within grains. The matrix is martensite. Nital. 330×

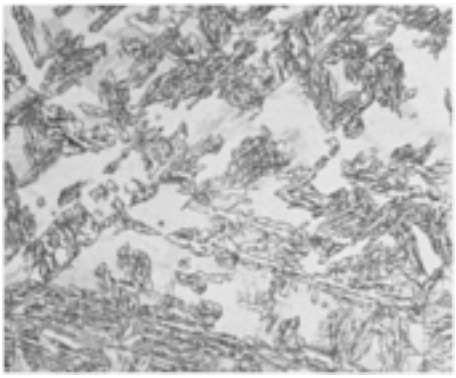

Fig. 154 Same steel and forging temperature as Fig. 153, but cooled in a milder air blast. The slower cooling rate resulted in the formation of upper bainite (dark). The matrix is martensite. Nital. 550×

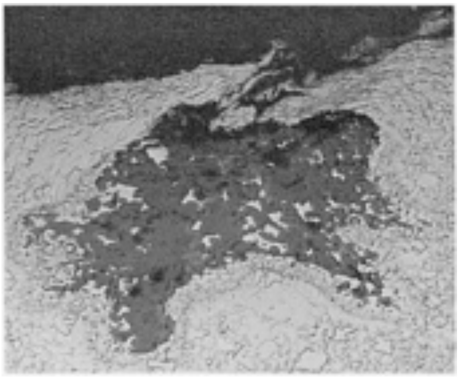

Fig. 155 Forging lap in 1541 steel, austenitized 2 h at 870 °C (1600 °F), water quenched, and tempered 2 h at 650 °C (1200 °F). The dark area is iron oxide; the adjacent lighter area is ferrite and tempered martensite. Core: ferrite and tempered martensite. 1% nital. 100×

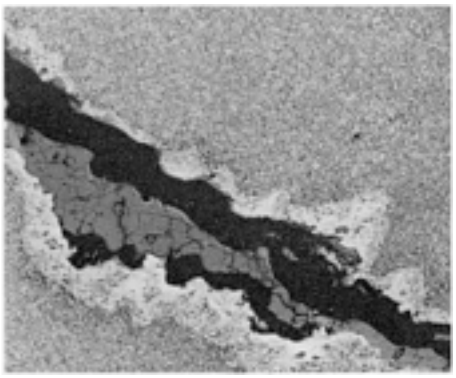

Fig. 156 Elongated forging lap in 1541 steel that was austenitized, water quenched, and tempered to 25 to 30 HRC. The dark area is iron oxide; the white area surrounding the lap is the result of decarburization. The remainder of the structure is tempered martensite. 1% nital. 100×

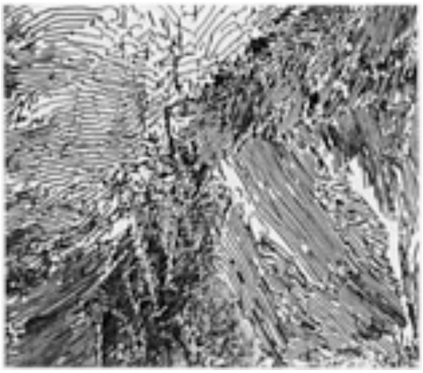

Fig. 157 High carbon steel (Fe-0.75C) that was held 2A h at 1095 °C (2000 °F) and air cooled. Slow cooling from the austenite region produced this pearlite structure. 4% picral. 500×

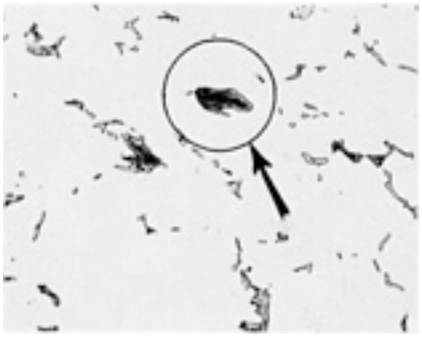

Fig. 158 Dual-phase steel (0.11C-1.40Mn-0.58Si-0.12Cr-0.08Mo), heat treated at 790 °C (1450 °F) and air cooled. The structure is ferrite and pearlite. See Fig. 159. 4% picral. 1000×

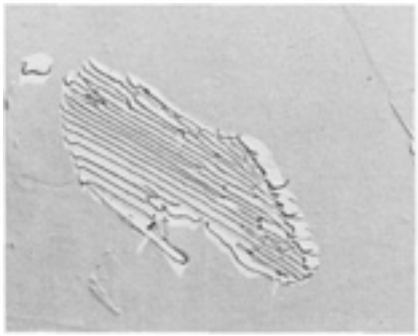

Fig. 159 Replica electron micrograph of the area circled in Fig. 158. The pearlite is resolved at this higher magnification. 4% picral. 4970×

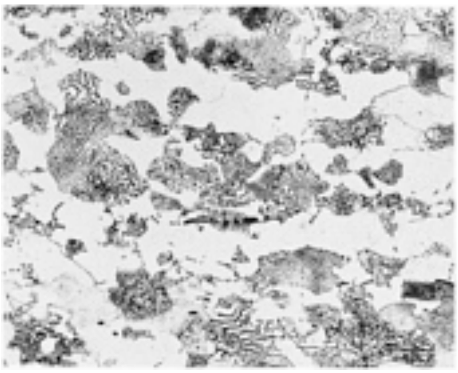

Fig. 160 4130 steel normalized by austenitizing at 870 °C (1600 °F) and air cooling to room temperature. Structure consists of ferrite (white) and lamellar pearlite (dark). 2% nital. 500×

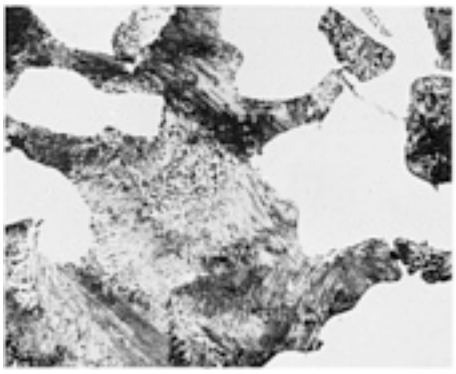

Fig. 161 4130 hot-rolled steel bar, 25 mm (1 in.) in diameter, annealed by austenitizing at 845 °C (1550 °F) and cooling slowly in the furnace. The structure consists of coarse lamellar pearlite (dark) in a matrix of ferrite (light). 2% nital, 750×

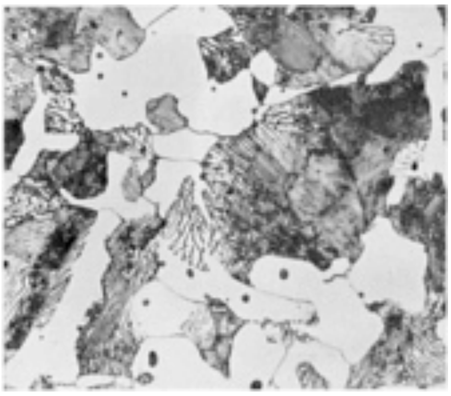

Fig. 162 Resulfurized 4140 steel forging normalized by austenitizing 30 min at 900 °C (1650 °F) and air cooling, and annealed by heating 1 h at 815 °C (1500 °F), furnace cooling to 540 °C (1000 °F), and air cooling. The structure is blocky ferrite and lamellar pearlite. The black dots are sulfide. 2% nital. 825×

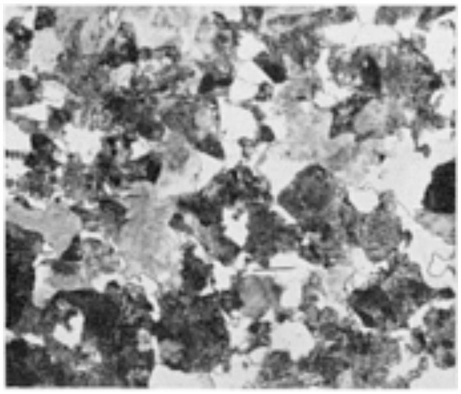

Fig. 163 25-mm (1-in.) diam 4140 steel bar, austenitized 1 h at 845 °C (1550 °F), cooled to 650 °C (1200 °F) and held 1 h for isothermal transformation, then cooled to room temperature. White areas are ferrite; gray and black areas, pearlite with fine and coarse lamellar spacing. Nital. 500×

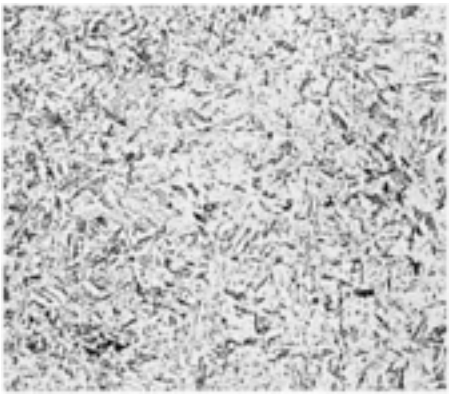

Fig. 164 25-mm (1-in.) diam 4140 steel bar, austenitized 1 h at 845 °C (1550 °F) and water quenched. The structure consists entirely of fine, homogeneous untempered martensite. Tempering at 150 °C (300 °F) would result in a darker-etching structure. 2% nital. 500×

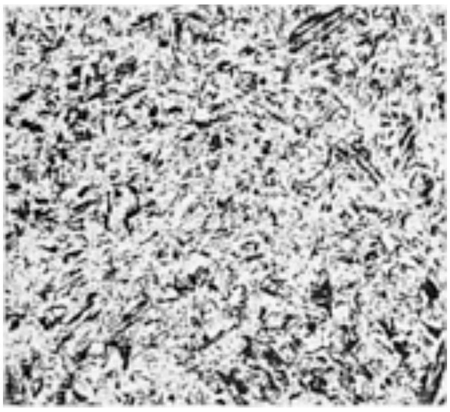

Fig. 165 Same material and processing as Fig. 164, except quenched in oil instead of water; this resulted in the formation of bainite (black) along with the martensite (light). 2% nital. 500×

Fig. 166 4140 steel bar, austenitized at 845 °C (1550 °F), oil quenched to 65 °C (150 °F), and tempered 2 h at 620 °C (1150 °F). Structure is a martensite-ferrite-carbide aggregate. 2% nital. 750×

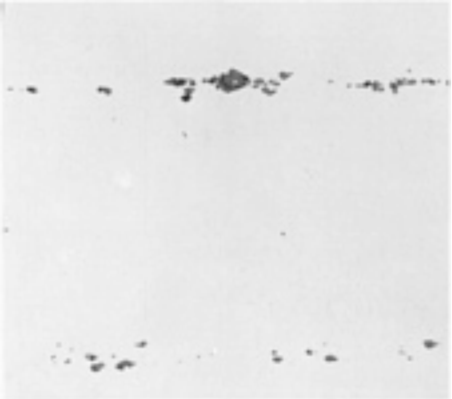

Fig. 167 Oxide inclusions (stringers) in a 25-mm (1-in.) diam 4140 steel bar. The stringers are parallel to the direction of rolling on the as-polished surface of the bar. As-polished. 200×

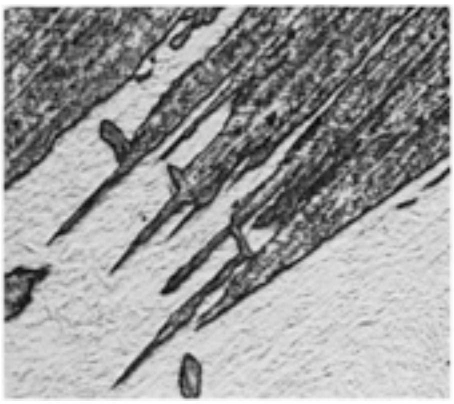

Fig. 168 4350 steel bar austenitized at 845 °C (1550 °F), quenched to 455 °C (850 °F) and held 4 min for partial isothermal transformation, and water quenched. Dark areas are upper bainite, with aligned carbide particles. The light areas are martensite. Nital. 1500×

Fig. 169 4350 steel bar austenitized at 845 °C (1550 °F), quenched to 345 °C (650 °F) and held 12 min for partial isothermal transformation, and water quenched. Dark areas are lower bainite with carbide particles aligned at 60°; light areas are martensite. Nital. 11,000×

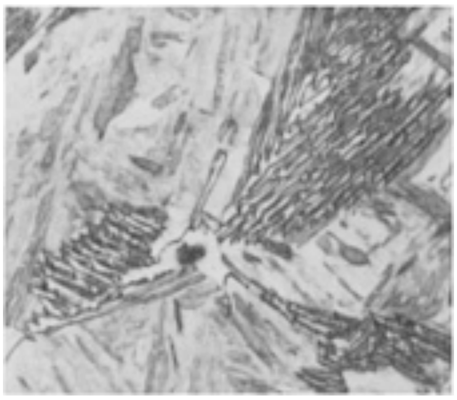

Fig. 170 5132 steel forging austenitized at 845 °C (1550 °F) and water quenched. Structure consists of some blocky ferrite (light) and bainite (dark) in a martensite matrix. Nital. 1650×

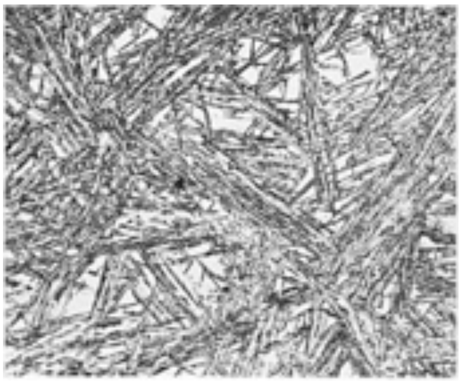

Fig. 171 AMS 6419 steel center of a 102-mm (4-in.) thick section austenitized 1.5 h at 860 °C (1575 °F), salt quenched 30 min at 290 °C (550 °F), then quenched in oil to room temperature. Structure is self-tempered martensite and some bainite. 2% nital. 500×

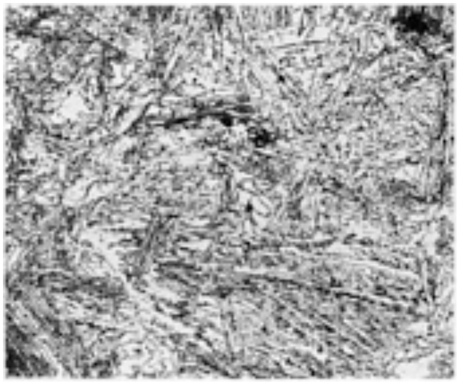

Fig. 172 Same steel and processing as Fig. 171, except air cooled to room temperature after salt bath. Structure is a mixture of bainite, tempered martensite, and untempered martensite. 2% nital. 500×

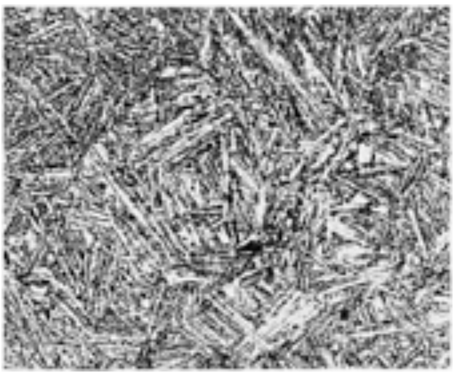

Fig. 173 Same steel as Fig. 171, but quenched 15 min from the austenitizing temperature in a salt bath at 290 °C (550 °F), placed 1 h in an air furnace at 205 °C (400 °F), and air cooled. Structure is tempered martensite and probably some retained austenite. 2% nital. 500×

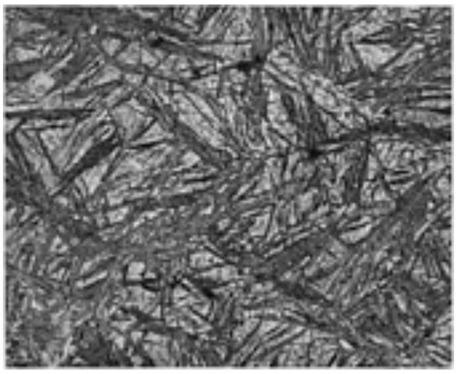

Fig. 174 Same as Fig. 171, but quenched 15 min from the austenitizing temperature in a salt bath at 290 °C (550 °F), then 20 min in oil at 80 °C (175 °F), then air cooled. The structure is tempered martensite and probably some retained austenite. 2% nital. 500×

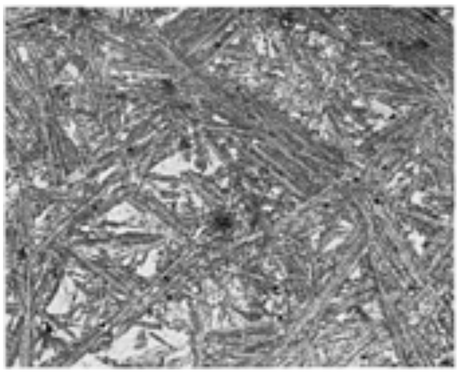

Fig. 175 Same steel and austenitizing as Fig. 171, but quenched 15 min in a salt bath at 290 °C (550 °F), then air cooled to room temperature. The structure is tempered martensite and probably some retained austenite. 2% nital. 500×

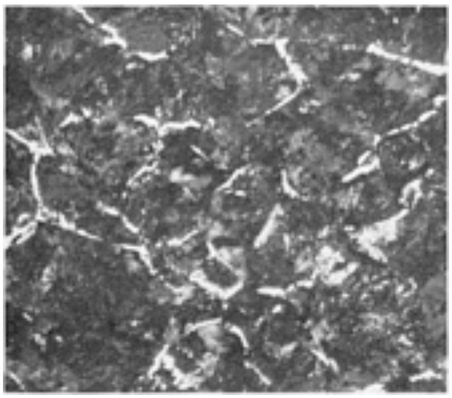

Fig. 176 6.5-mm (0.25-in.) diam 1055 steel rod, patented by austenitizing 2 min 20 s in a lead bath at 550 °C (1020 °F) and air cooling. Structure is unresolved pearlite (dark) with ferrite (white) at prior austenite grain boundaries. Picral. 1000×

Fig. 177 1055 steel wire, 3 mm (0.13 in.) in diameter, patented by austenitizing 1.5 min at 1030 °C (1890 °F) and air cooling in strand form. Fine lamellar pearlite with discontinuous precipitation of ferrite at prior austenite grain boundaries. Picral. 1000×

Fig. 178 1060 steel rod, 6.7 mm (0.26 in.) diam, air cooled from hot rolling in a 454-kg (1000-lb) coil. Dark areas are unresolved pearlite, with some distinct lamellar pearlite; white areas are ferrite partly outlining prior austenite grain boundaries. Picral. 1000×

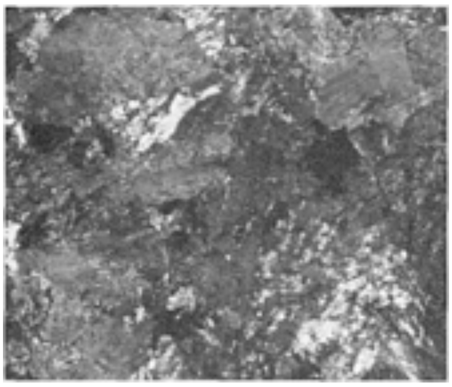

Fig. 179 6.5-mm (0.25-in.) diam 1060 steel rod, cooled from hot rolling in a single strand by a high-velocity air blast. The structure is mostly unresolved pearlite, with some distinctly lamellar pearlite. The scattered white areas are ferrite partly outlining prior austenite grain boundaries. Picral. 1000×

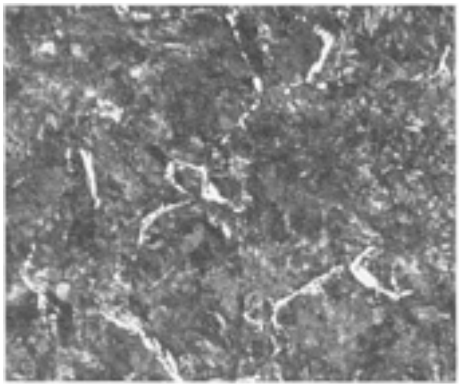

Fig. 180 6.7-mm (0.26-in.) diam 1060 steel rod, patented by austenitizing 2.5 min at 945 °C (1730 °F), quenching 55 s in a lead bath at 530 °C (990 °F), and air cooling. The structure is pearlite (dark) and ferrite (light) at prior austenite grain boundaries. Picral. 1000×

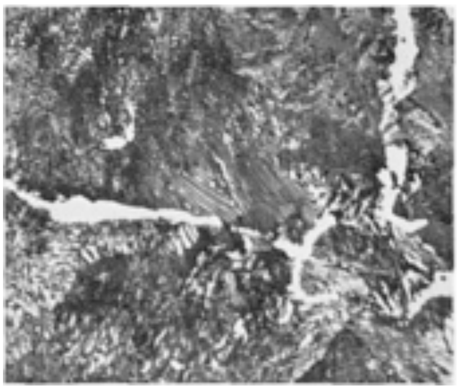

Fig. 181 7.1-mm (0.28-in.) diam 1060 steel wire, air patented by austenitizing 3 min at 1055 °C (1930 °F) and air cooling in strand form. The dark areas are partly resolved pearlite; white areas are ferrite at prior austenite grain boundaries. Picral. 1000×

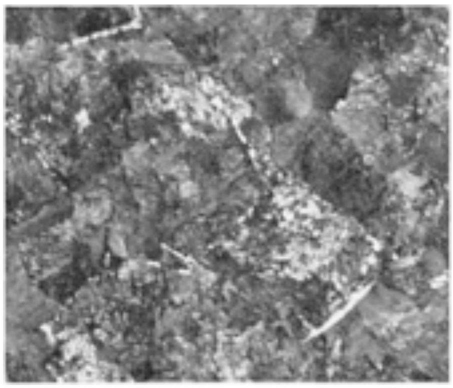

Fig. 182 2.5-mm (0.10-in.) diam 1060 steel wire, air patented by austenitizing 1 min at 1015 °C (1860 °F) and air cooling in strand form. Structure is fine pearlite (dark), mostly unresolved, and some ferrite at prior austenite grain boundaries. Picral. 1000×

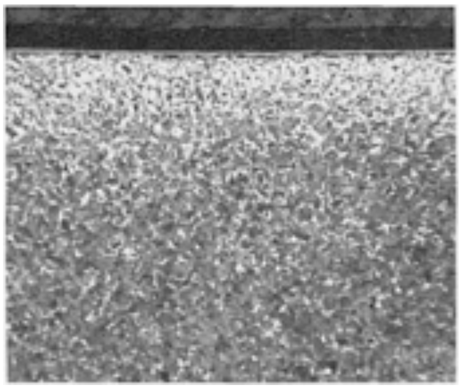

Fig. 183 Decarburized 1060 steel, heated 1 h at 1205 °C (2000 °F) before rolling to size. Note the thin layer of scale at the surface (top) and the decarburized layer (white, near top). Below that is unresolved pearlite and ferrite. Picral. 100×

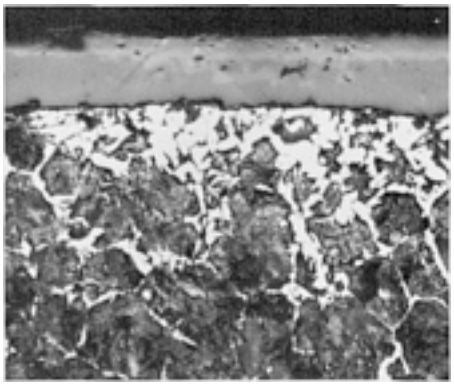

Fig. 184 Decarburized 1060 steel, heated 12 min at 870 to 930 °C (1600 to 1700 °F) and cooled in air. Top to bottom: Scale, a decarburized layer, pearlite, and some grain-boundary ferrite. Picral. 500×

Fig. 185 1064 cold-rolled steel strip, heated to 745 °C (1370 °F), furnace cooled to 650 °C (1200 °F), and air cooled to room temperature. Structure is fine spheroidal cementite in a matrix of ferrite. This structure is preferred for subsequent heat treatment. Picral. 500×

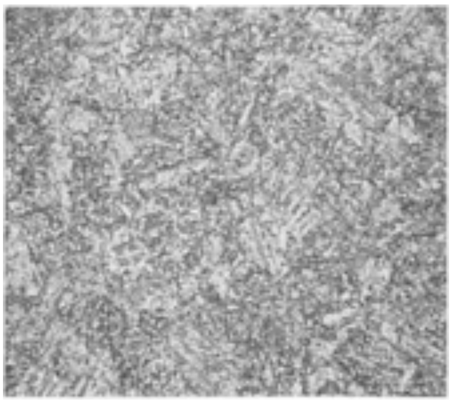

Fig. 186 1064 cold-rolled steel strip, austenitized at 815 °C (1500 °F), quenched to 315 °C (600 °F) and held to complete isothermal transformation, air cooled, and tempered at 370 °C (700 °F). The structure is a mixture of bainite and tempered martensite. Picral. 500×

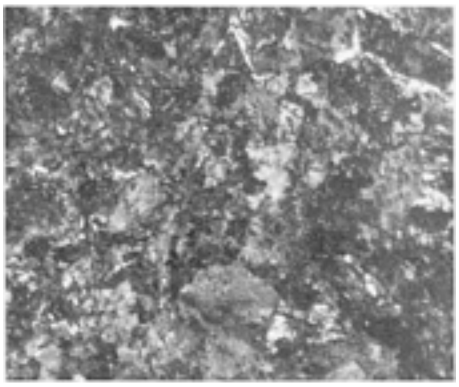

Fig. 187 1065 steel wire, 3.4 mm (0.14 in.) in diameter, patented by austenitizing 1.5 min at 930 °C (1710 °F), quenching 30 s in a lead bath at 545 °C (1010 °F), and air cooling. The structure is mostly unresolved pearlite with some grain-boundary ferrite. Picral. 500×

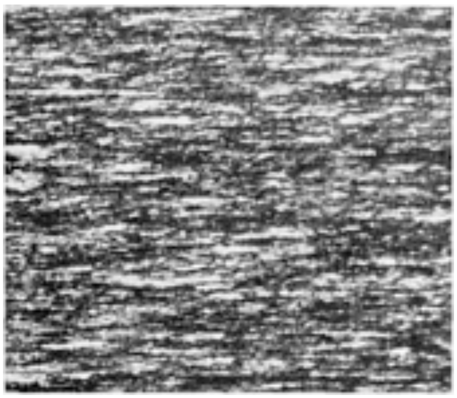

Fig. 188 1070 hard drawn steel valve-spring wire, tensile strength of 1690 MPa (245 ksi) obtained by 80% reduction. Longitudinal section has a structure of deformed pearlite. 2% nital. 100×

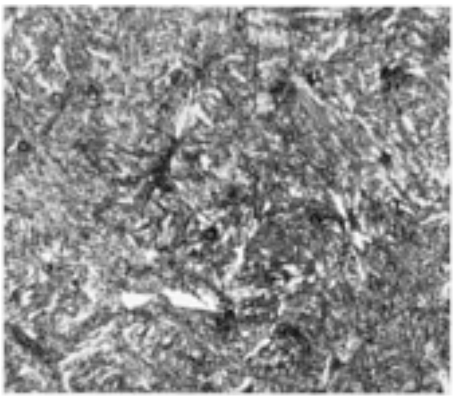

Fig. 189 1070 steel valve-spring wire, quenched and tempered. Austenitized at 870 °C (1600 °F), oil quenched, and tempered at 455 °C (850 °F). Structure is mainly tempered martensite, with some free ferrite (white). 2% nital. 1000×

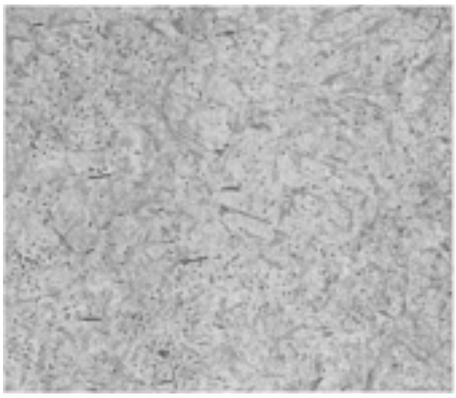

Fig. 190 1074 cold-rolled steel sheet, austenitized 5 min at 815 °C (1500 °F) and oil quenched. Structure is predominantly untempered martensite, with scattered, poorly resolved cementite. Picral. 500×

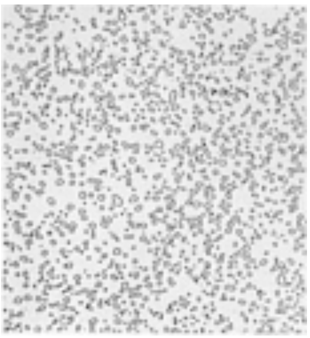

Fig. 191 AISI 1074 steel, cold rolled, then batch annealed 10 h at 695 °C (1285 °F). The structure is spheroidized carbides in a ferrite matrix. 4% picral. 500×. (J.E. Gatehouse)

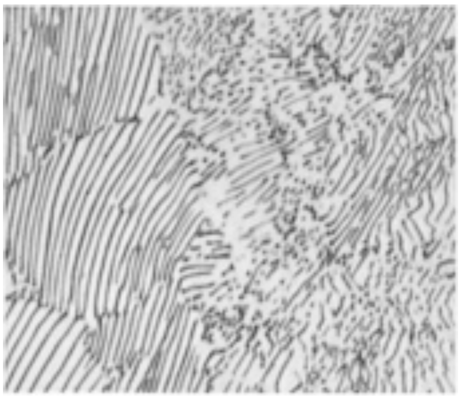

Fig. 192 1080 hot-rolled steel at, austenitized 30 min at 1050 °C (1920 °F) and furnace cooled to room temperature at 28 °C (50 °F) per h. The structure is mostly pearlite, with some spheroidal cementite particles. Picral. 2000×

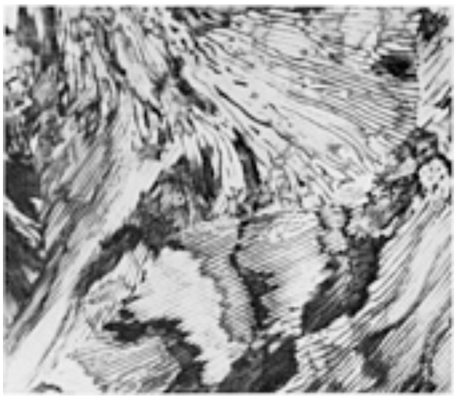

Fig. 193 Thin-foil transmission electron micrograph of the same steel and heat treatment as in Fig. 192, but the cooling rate was increased to 55 °C (100 °F) per h. The structure is almost entirely fine lamellar pearlite. 2000×

Fig. 194 1095 steel wire, austenitized at 940 °C (1725 °F) and oil quenched. The dark areas are a mixture of fine pearlite and lower bainite; light areas are untempered martensite. This structure resulted from slack quenching. 2% nital. 500×

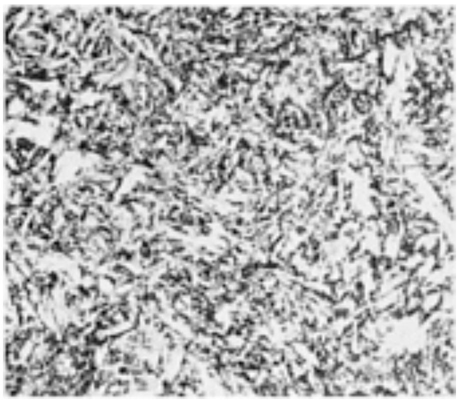

Fig. 195 1095 steel, austenitized at 870 °C (1600 °F) and air cooled (normalized) then austenitized at 815 °C (1500 °F) and water quenched. Fine untempered martensite caused by a more severe quench than in Fig. 194 and some spheroidal cementite. Picral. 1000×

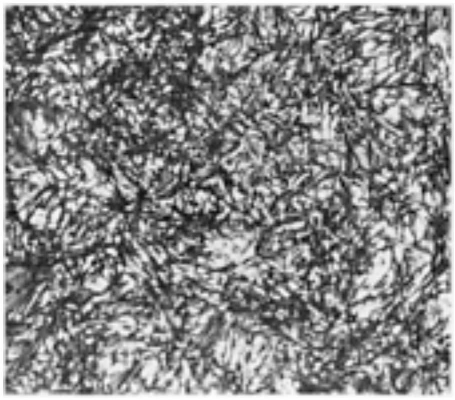

Fig. 196 Same steel and heat treatment as Fig. 195, but tempered at 150 °C (300 °F) after quenching. The structure is tempered martensite (darker than that in Fig. 195) and some spheroidal cementite particles. Picral. 1000×

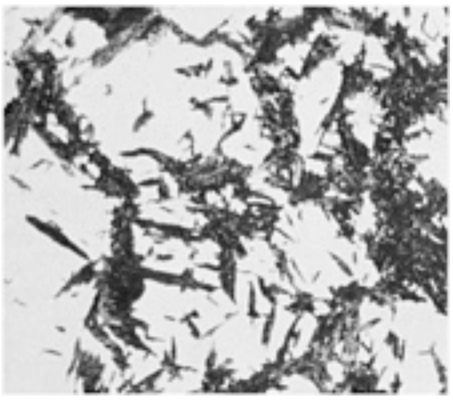

Fig. 197 1095 steel wire, austenitized 30 min at 885 °C (1625 °F) quenched to 330 °C (625 °F), held 5 min, and oil quenched. The structure is lower bainite (dark) and untempered martensite. 2% nital. 550×

Fig. 198 Same steel and austenitizing treatment as Fig. 197, but held 20 min in 330 °C (625 °F) quench and air cooled. Dark areas are lower bainite; light areas, untempered martensite. 2% nital. 550×

Fig. 199 Same steel and austenitizing treatment as Fig. 197, but held 1 h in a 455 °C (850 °F) quench and air cooled (austempered). The structure is mainly upper bainite. 2% nital. 550×

Fig. 200 Iron-carbon alloy (1.4% austenitized at 1010 °C (1850 °F), furnace cooled to 315 °C (600 °F), and air cooled. The structure is ferrite (dark) and cementite (light). Beraha's tint etchant. 320×

Fig. 201 Same alloy as Fig. 200, austenitized at 1095 °C (2000 °F) and water quenched. Structure is acicular martensite, with some retained austenite (white). 2% nital. 1000×

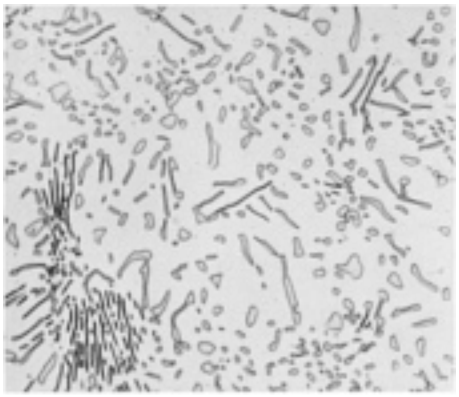

Fig. 202 0.55C-2.40Mn steel, held 2 h 40 min at 750 °F (1380 °C), cooled to 680 °C (1255 °F), and held 48 h. Structure is spheroidized carbide particles and lamellar pearlite in a ferrite matrix. Picral. 1000×

Fig. 203 Hot-rolled alloy steel bar (1.2C-0.5Cr-0.9Mo-0.2V), austenitized 30 min at 925 °C (1700 °F) and oil quenched. Structure is untempered martensite (dark, needlelike) and retained austenite (white). Picral. 550×

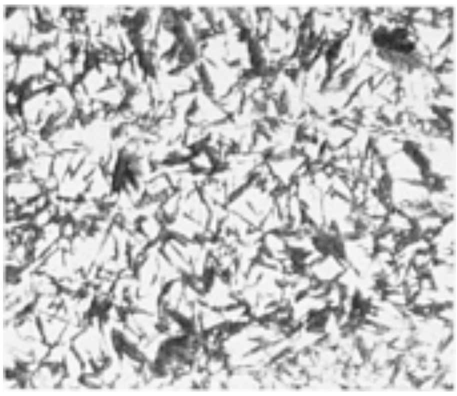

Fig. 204 Same steel and heat treatment as Fig. 203, but at a higher magnification. The large amount of retained austenite (white) indicates that the austenitizing temperature was too high for this steel. Picral. 1100×

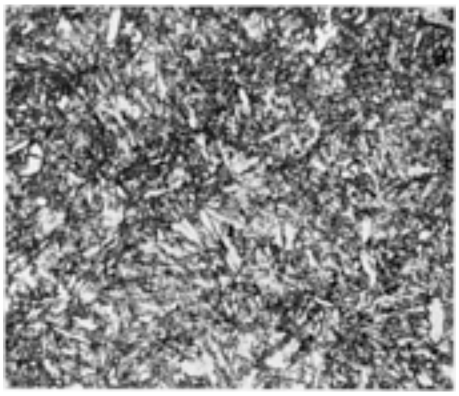

Fig. 205 51B60 hot-rolled steel bar 32 mm (1.25 in.) in diameter, austenitized at 870 °C (1600 °F), air cooled (normalized), austenitized at 815 °C (1500 °F), and water quenched. Structure is untempered martensite, some retained austenite, and fine spheroidal carbide. Picral. 1000×

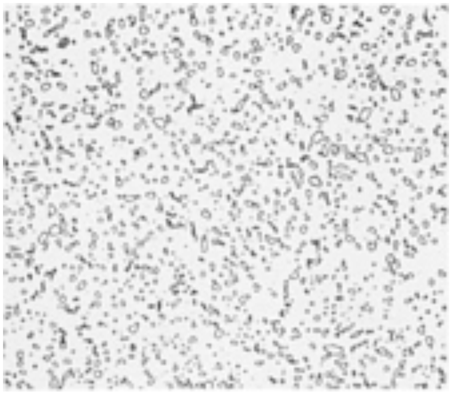

Fig. 206 51B60 hot-rolled steel bar, 32 mm (1.25 in.) in diameter, austenitized and quenched to obtain a martensitic structure, then tempered 15 h at 675 °C (1250 °F). Structure consists of spheroidal carbide particles in a ferrite matrix. Nital. 1000×

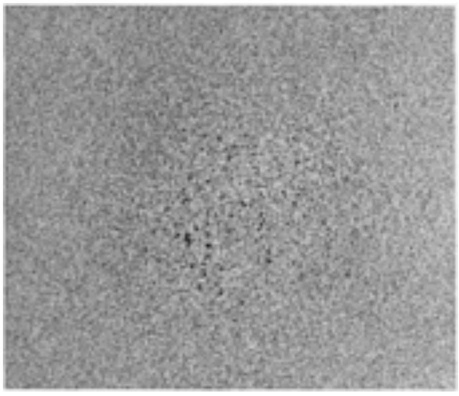

Fig. 207 52100 steel bar, 124 mm (4.8 in.) in diameter, hot rolled at 1175 to 925 °C (2150 to 1700 °F) and air cooled to room temperature. Cross section shows pits (cluster of small dark spots); in center are inclusions. 50% aqueous HCl. Actual size

Fig. 208 Microstructure of specimen taken from bar section in Fig. 207. The structure is predominantly pearlite (light and dark gray), with thin films of carbide (black lines) outlining the prior austenite grain boundaries. Equal parts 4% picral and 4% nital. 100×

Fig. 209 Same specimen as Fig. 208, but at a higher magnification. The grain-boundary carbide rejected from solid solution during cooling is resolved and appears as white lines. Equal parts 4% picral and 4% nital. 500×

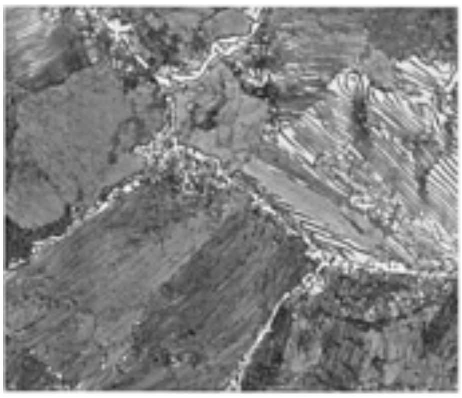

Fig. 210 Same specimen as in Fig. 208, but a still higher magnification to show the grain-boundary carbide as areas rather than thin lines. The matrix is pearlite. Equal parts 4% picral and 4% nital. 1000×

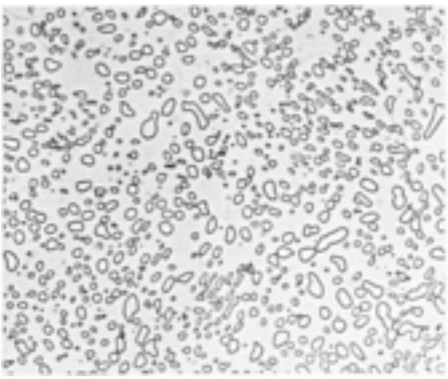

Fig. 211 52100 steel bar, 124 mm (4.8 in.) in diameter, heated to 770 °C (1420 °F) in 10 h, held 5 h, cooled at 10 °C (20 °F) per h to 650 °C (1200 °F), furnace cooled to 27 °C (80 °F). Fine dispersion of spheroidal carbide in a matrix of ferrite. See also Fig. 212, 213, 214, 215, 216, 217, 218, and 219. 4% picral + 0.05% HCl. 1000×

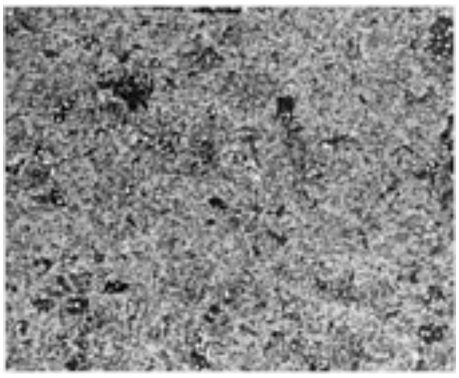

Fig. 212 Same steel as Fig. 211, except austenitized 30 min at 790 °C (1450 °F), oil quenched, and tempered 1 h at 175 °C (350 °F). The black areas are bainite, the gray areas are tempered martensite, and the white dots are carbide particles that did not dissolve during austenitizing. Equal parts 4% picral and 4% nital. 500×

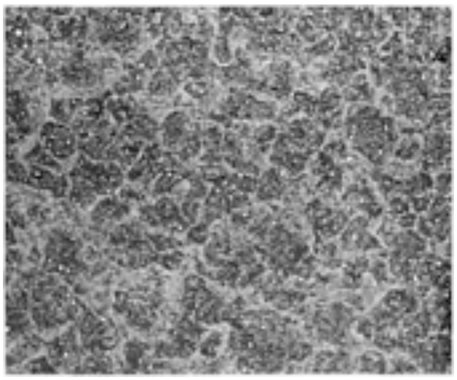

Fig. 213 Same steel as Fig. 211, except austenitized 30 min at 845 °C (1550 °F), oil quenched, and tempered same as in Fig. 212. Structure is tempered martensite, along with carbide particles (white) that were not dissolved during austenitizing. Equal parts 4% picral and 4% nital. 500×

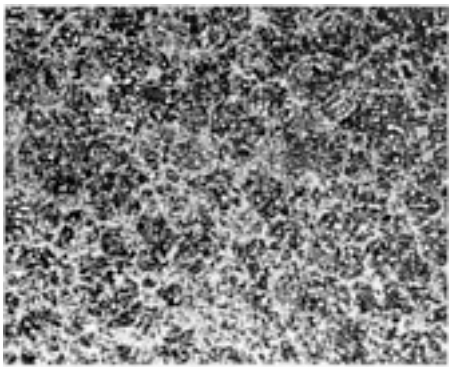

Fig. 214 Same steel as Fig. 211, except austenitized 30 min at 855 °C (1575 °F), oil quenched, and tempered 1 h at 260 °C (500 °F). The structure is tempered martensite and undissolved carbide particles. Equal parts 4% picral and 4% nital. 500×

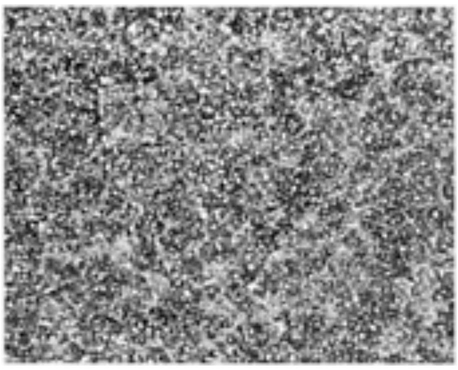

Fig. 215 Same steel as Fig. 211, except austenitized 30 min at 845 °C (1550 °F), oil quenched, and tempered 1 h at 400 °C (750 °F). Structure is tempered martensite and a dispersion of carbide particles not dissolved during austenitizing. Equal parts 4% picral and 4% nital. 500×

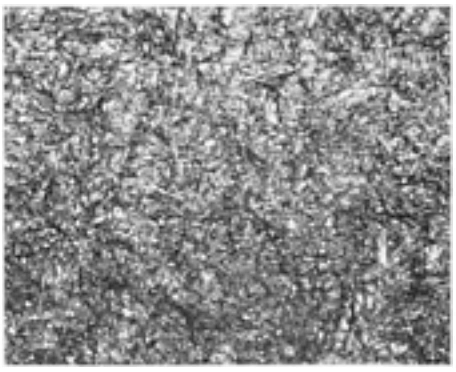

Fig. 216 Same steel as Fig. 211, except austenitized 30 min at 925 °C (1700 °F), oil quenched, and tempered 1 h at 175 °C (350 °F). The structure is mainly tempered martensite. High austenitizing temperature has resulted in some retained austenite and a few carbide particles. Equal parts 4% picral and 4% nital. 500×

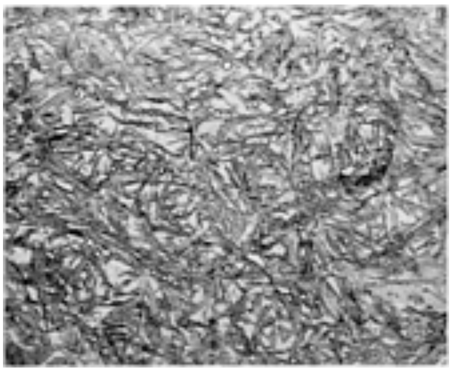

Fig. 217 Same specimen as Fig. 216, except at a higher magnification. Dark areas are tempered martensite; retained austenite (angular, light gray) is well resolved. A few undissolved carbide particles remain from the original structure. Equal parts 4% picral and 4% nital. 1000×

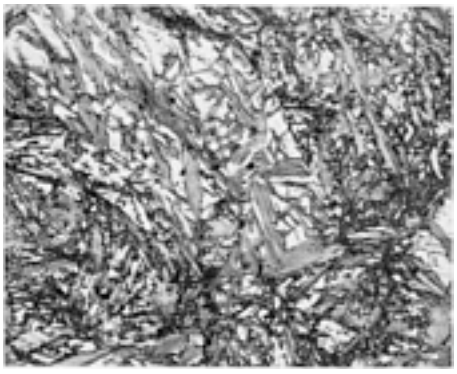

Fig. 218 Same steel as Fig. 211, except austenitized 30 min at 980 °C (1800 °F), oil quenched, and tempered 1 h at 175 °C (350 °F). Structure is coarse plates (needles) of tempered martensite and retained austenite (white). Carbides are almost completely dissolved. Equal parts 4% picral and 4% nital. 1000×

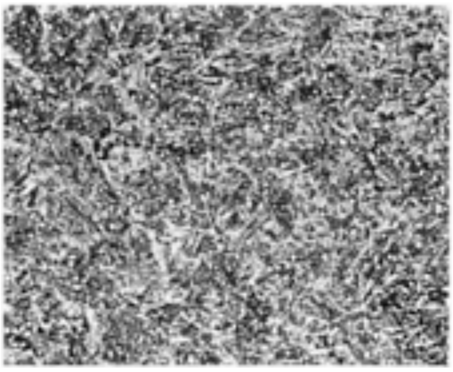

Fig. 219 Same steel as Fig. 211, except austenitized 30 min at 855 °C (1575 °F), quenched in a salt bath at 260 °C (500 °F), held 30 min, and air cooled to room temperature. Structure consists of spheroidal carbide particles in lower bainite and some retained austenite. Equal parts 4% picral and 4% nital. 500×

Fig. 220 52100 steel rod, austenitized 20 min at 900 °C (1650 °F) and slack quenched in oil to room temperature. The dark areas are a mixture of fine pearlite and bainite. Light areas are untempered martensite. 4% nital. 500×

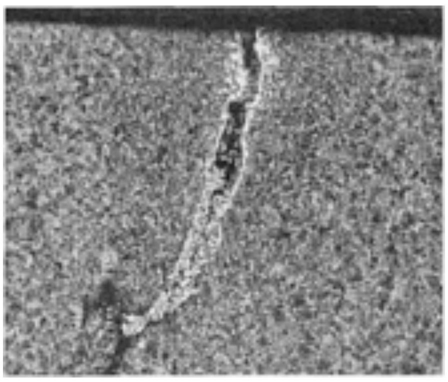

Fig. 221 Crack in a 52100 steel roller after austenitizing, water quenching, and tempering. The crack, extending down from the surface, was caused by a seam in the bar stock. The structure is martensite. See also Fig. 222. 1% nital. 100×

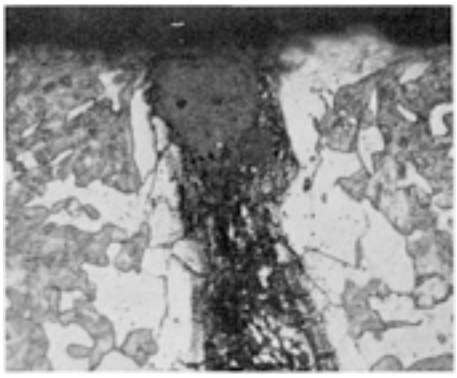

Fig. 222 Same crack as Fig. 221, but at a higher magnification. Decarburization (white areas) along the crack is evidence that the crack preceded heat treatment (surface is not decarburized). 1% nital. 750×

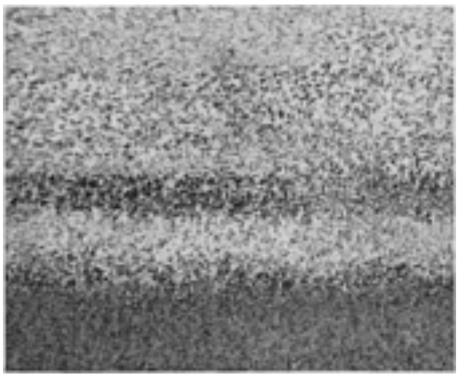

Fig. 223 Hardened 52100 steel, damaged by an abrasive cutoff wheel. Dark areas are martensite tempered by overheating; light areas, untempered martensite, which had been reaustenitized by frictional heat. 1% nital. 100×

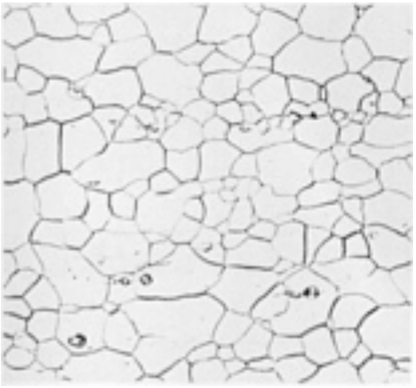

Fig. 224 Electrical sheet steel, decarburized. The structure consists of ferrite grains. Marshall's reagent. 500×

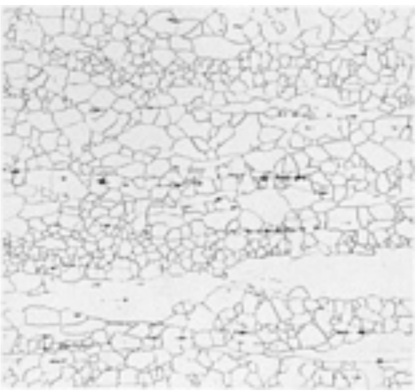

Fig. 225 Same steel as Fig. 224, but not decarburized. The structure consists of ferrite grains. Marshall's reagent. 200×

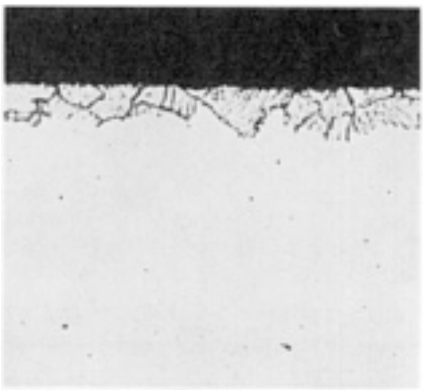

Fig. 226 Same steel and processing as Fig. 224, showing internal oxidation. 4% picral. 1000×. (S.A. Wright)

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