Wrought Stainless Steels: Metallographic Techniques and Microstructures

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<Previous section in this article

Atlas of Microstructures for Wrought Stainless Steels

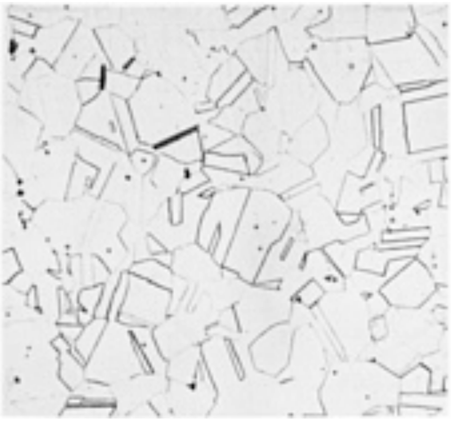

Fig. 1 Type 201 stainless steel strip, annealed 5 min at 1065 °C (1950 °F) and rapidly cooled to room temperature. The structure is equiaxed austenite grains and annealing twins. 10 mL HNO_3, 10 mL acetic acid, 15 mL HCl, and 2 drops glycerol. 250×

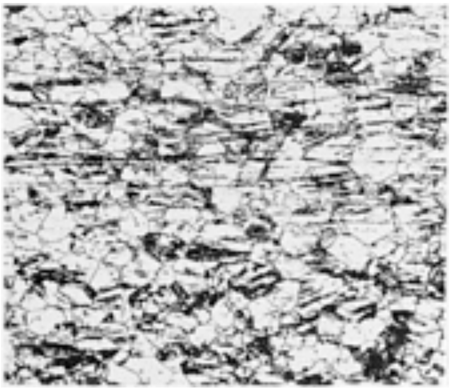

Fig. 2 Type 301 stainless steel, mill annealed at 1065 °C (1950 °F) and cold worked. Some martensite (dark) has formed in the austenitic matrix. Electrolytic: HNO_3-acetic acid, then 10% oxalic acid. 200×

Fig. 3 Type 301 sheet cold rolled to 10% reduction (quarter hard), showing martensite formation in deformed austenite grains. Stringers and pits are etched-out inclusions. Electrolytic: 10% oxalic acid. 250×

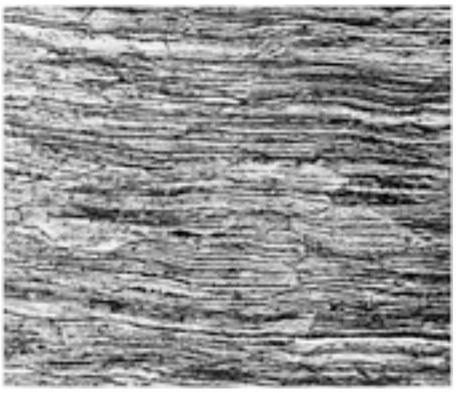

Fig. 4 Type 301 sheet, cold rolled to 40% reduction (full hard), showing almost complete transformation to martensite in severely deformed austenite grains. Electrolytic: 10% oxalic acid. 250×

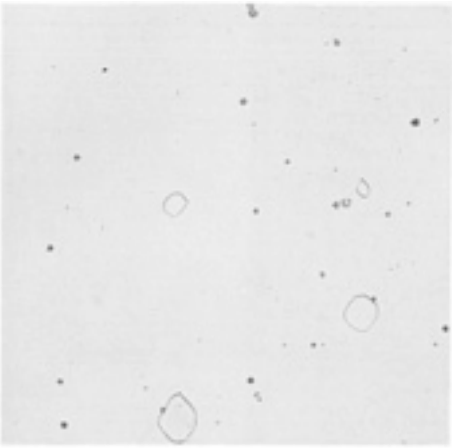

Fig. 5 Type 302 stainless steel strip, 1.6 mm (0.06 in.) thick, annealed at 1065 °C (1950 °F) and rapidly cooled to room temperature. The structure consists of ferrite pools (globules) in an austenitic matrix. Electrolytic: 10% NaCN. 500×

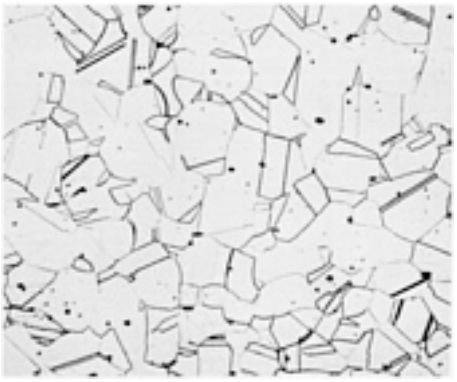

Fig. 6 Type 304 stainless steel strip, annealed 5 min at 1065 °C (1950 °F), cooled in air. Structure consists of equiaxed austenite grains and annealing twins. 10 mL HNO_3, 10 mL acetic acid, 15 mL HCl, and 2 drops glycerol. 250×

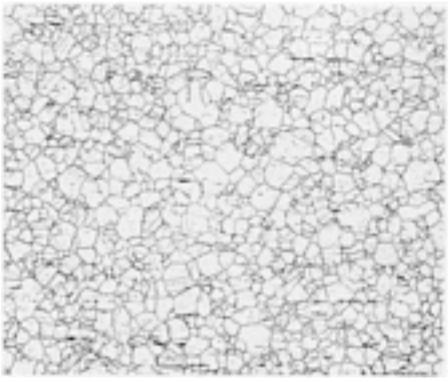

Fig. 7 Type 304 strip, annealed 2 min at 1065 °C (1950 °F) and air cooled. Structure is equiaxed austenite grains, annealing twins, and small stringer inclusions. Electrolytic: HNO_3-acetic acid, then 10% oxalic acid. 100×

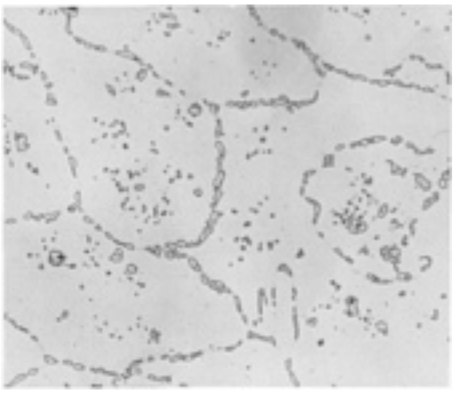

Fig. 8 Type 310 stainless steel plate, hot rolled and annealed at 1065 °C (1950 °F), water quenched in less than 3 min, exposed 27 months at 760 °C (1400 °F), and slowly air cooled. Structure is σ-phase precipitates in an austenitic matrix. Electrolytic: saturated NaOH, 1.5 V dc, 6 s. 250×

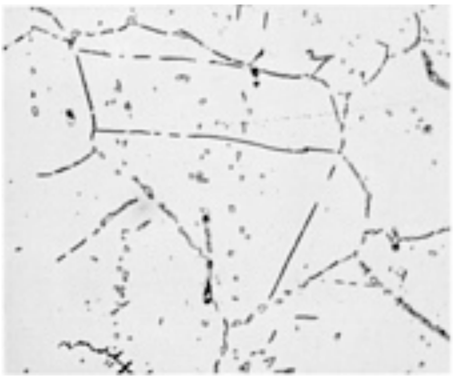

Fig. 9 Type 316 stainless steel, annealed 30 min at 1080 °C (1975 °F) and exposed 3000 h at 815 °C (1500 °F). Prolonged exposure at temperature has resulted in the formation of islands of σ and χ phases at austenite grain boundaries. Picral and HCl. 500×

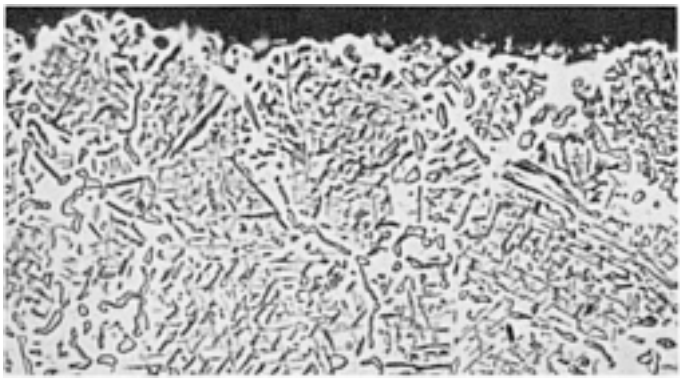

Fig. 10 Type 316 tubing, packed with boron nitride powder and held 2285 h at 840 °C (1540 °F). The gray phase at grain boundaries and Widmanstätten platelets within grains are chromium nitride. The matrix is austenite. 12 mL lactic acid, 38 mL HCl, and 2 mL HNO_3. 500×

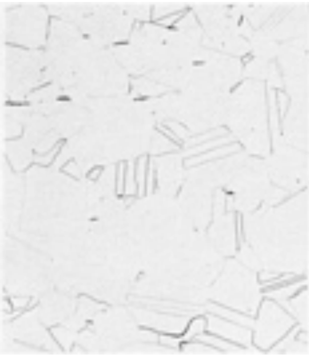

Fig. 11 Type 316 stainless steel, solution annealed at 1035 °C (1900 °F) and water quenched. Etching has revealed most of the austenite grain and annealing twin boundaries. 10 mL HNO_3, 10 mL acetic acid, 15 mL HCl, and 5 mL glycerol. 100×

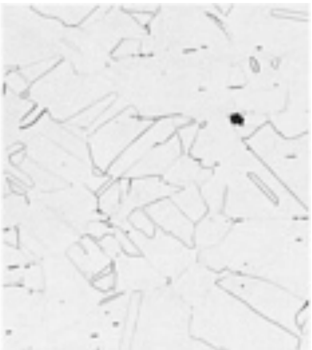

Fig. 12 Same steel and processing as Fig. 11, etched electrolytically to reveal austenite grain boundaries. Not all of the boundaries are visible. Electrolytic: 10% aqueous oxalic acid, 6 V dc, 15 s. 100×

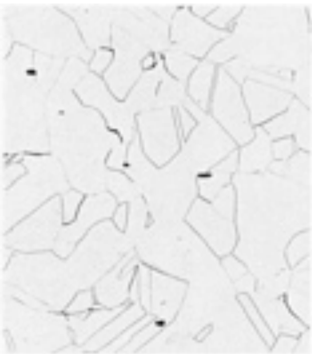

Fig. 13 Same steel and processing as Fig. 11, etched to reveal austenite grain boundaries. Not all of

the boundaries are revealed. Compare with Fig. 12 and 14. Marble's reagent. 100×

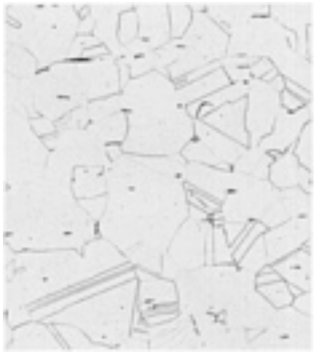

Fig. 14 Same steel and processing as Fig. 11, etched to reveal austenite grain boundaries. Not all of the boundaries are visible. Compare with Fig. 12 and 13. Equal parts H_2O, HCl, and HNO_3. 100×

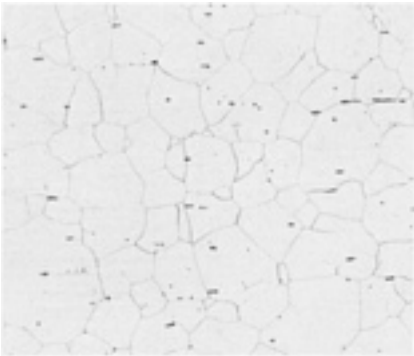

Fig. 15 Same steel and processing as Fig. 11, etched to reveal austenite grain boundaries. Note that twins are not etched. Electrolytic: 60% aqueous HNO_3, 0.6 V dc, 2 min (platinum cathode). 100×

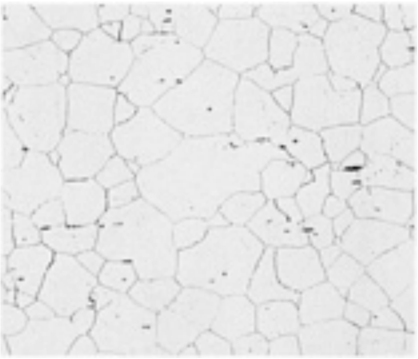

Fig. 16 Same steel as fig. 11, solution annealed and sensitized. Twins are not etched, because no carbide was precipitated at the twins. Equal parts H_2O, HCl, and HNO_3. 100×

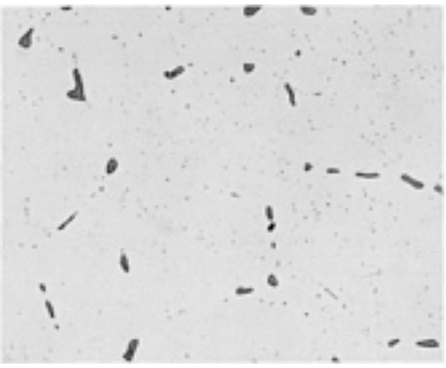

Fig. 17 Annealed type 321 stainless steel furnace part, after 16 months service at 900 °C (1650 °F) in hydrogen. Sigma-phase islands at austenite grain boundaries and fine, dispersed chromium carbide. Electrolytic: 40% aqueous NaOH. 300×

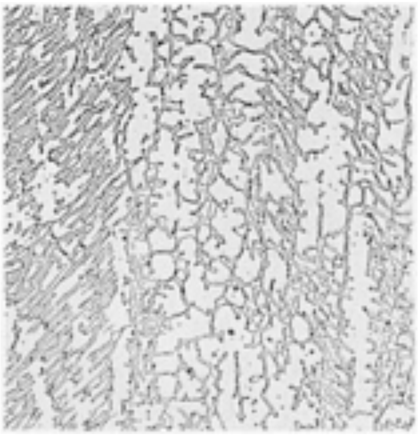

Fig. 18

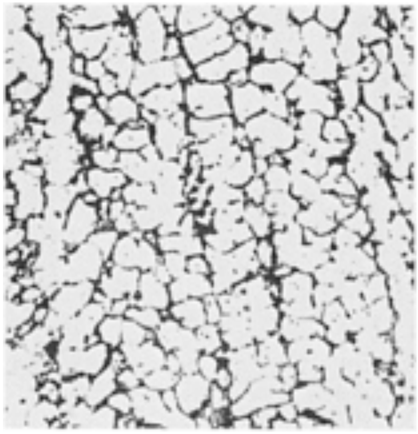

Fig. 19

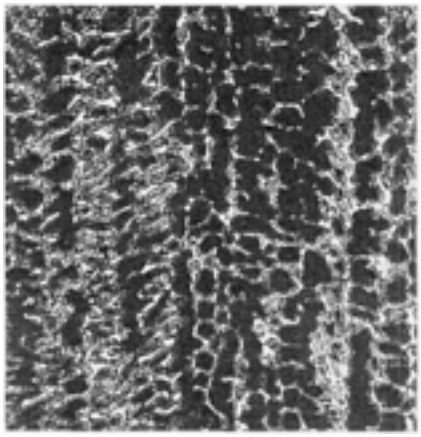

Fig. 20

The use of different etchants to reveal δ-ferrite in austenitic stainless steel weld metal. Fig. 18: etched in Vilella's reagent. Fig. 19: etched 15 s in modified Murakami's reagent (30 g $K_3Fe(CN)_6$, 30 g KOH, and 150 mL H_2O) at 95 °C (200 °F) to color δ-ferrite brown. Fig. 20: heat tinted at 595 °C (1100 °F) to color austenite red and δ-ferrite cream. See also Fig. 21, 22, and 23. 500×

Fig. 21

Fig. 22

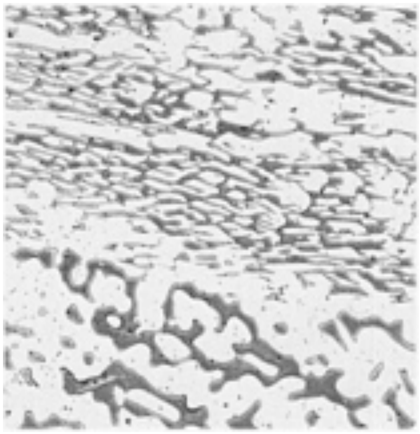

Fig. 23

Different etchants used to reveal δ-ferrite in austenitic stainless steel weld metal. Fig. 21: electrolytic etch 10 s in 10 *N* KOH, 2.5 V dc. Fig. 22: electrolytic etch 25 s in 20% aqueous NaOH, 20 V dc. Fig. 23: etched 15 min in boiling Murakami's reagent. 500×

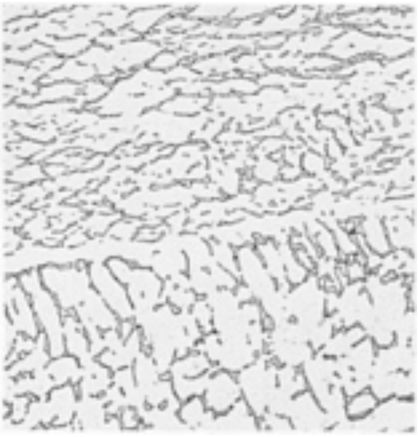

Fig. 24

Fig. 25

Fig. 26

Austenitic stainless steel weld metal, etched using different reagents to reveal σ phase. Fig. 24: electrolytic etch in 10 *N* KOH, 2.5 V dc, 10 s. Fig. 25: electrolytic etch in 20% aqueous NaOH, 20 V, 25 s. Fig. 26: etched 3 min in Murakami's reagent, room temperature. 500×

Fig. 27 22-13-5 austenitic stainless steel (400 HV), solution annealed and cold drawn. Note the uniform grain structure. 10 mL HNO_3, 10 mL acetic acid, 15 mL HCl, and 2 drops glycerol. 200×

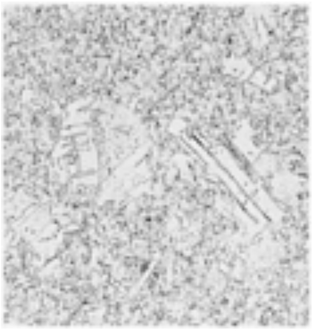

Fig. 28 22-13-5 stainless steel, solution annealed and cold drawn as in Fig. 27. In this case, a duplex grain structure developed. 10 mL HNO_3, 10 mL acetic acid, 15 mL HCl, and 2 drops glycerol. 100×

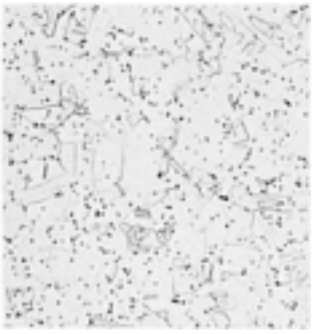

Fig. 29 Type 308 stainless steel, solution annealed and cold worked. The grain structure is difficult to reveal by chemical etching. 10 mL HNO_3, 10 mL acetic acid, 15 mL HCl, and 2 drops glycerol. 400×

Fig. 30 Same material and processing as Fig. 29, examined under differential interference contrast illumination to reveal surface topography. 10 mL HNO_3, 10 mL acetic acid, 15 mL HCl, and 2 drops glycerol. 400×

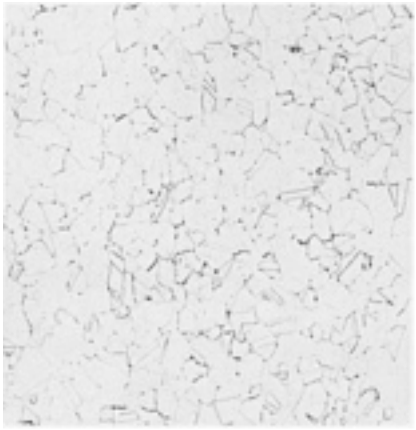

Fig. 31

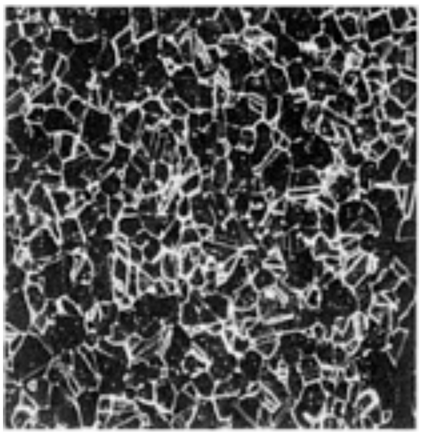

Fig. 32

Fig. 33

20Cb-3 austenitic stainless steel, solution annealed. The use of different illumination modes to reveal the chemically etched grain structure. Fig. 31: bright-field illumination. Fig. 32: dark-field illumination. Fig. 33: differential interference contrast. 10 mL HNO_3, 10 mL acetic acid, 15 mL HCl, and 2 drops glycerol. 400×

Fig. 34

Fig. 35

Fig. 36

Type 316L stainless steel, cold drawn, using different illumination modes. The structure is revealed more clearly with dark-field illumination and differential interference contrast than with bright-field illumination. Fig. 34: bright-field illumination. Fig. 35: dark-field illumination. Fig. 36: differential interference contrast. 10 mL HNO_3, 10 mL acetic acid, 15 mL HCl, and 2 drops glycerol. 100×

Fig. 37

Fig. 38

Fig. 39

Proprietary austenitic stainless steel, not recrystallized after hot working. The structure is revealed more clearly using dark-field illumination and differential interference contrast than by bright-field illumination. Fig. 37: bright-field illumination. Fig. 38: dark-field illumination. Fig. 39: differential interference contrast. 10 mL HNO_3, 10 mL acetic acid, 15 mL. HCl, and 2 drops glycerol. 100×

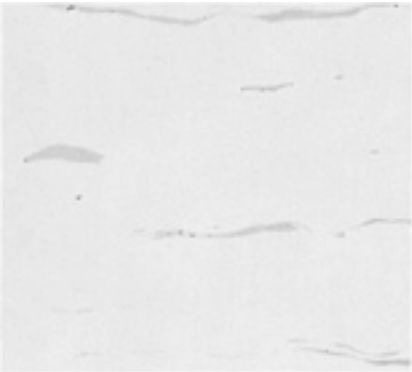

Fig. 40 Stringer-type manganese sulfide inclusions in resulfurized type 303 stainless steel. Free-machining additives such as MnS permit higher machining speeds, lower power consumption, and promote longer tool life. See also Fig. 41. As-polished. 500×

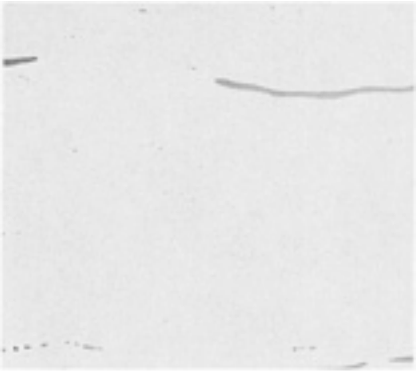

Fig. 41 Mixed manganese sulfide and manganese selenide inclusions in type 303 selenium-treated stainless steel (0.21% Se). Selenium has beneficial effects similar to sulfur (see Fig. 40), but also imparts greater ductility to free-machining stainless steels than does sulfur. As-polished. 500×

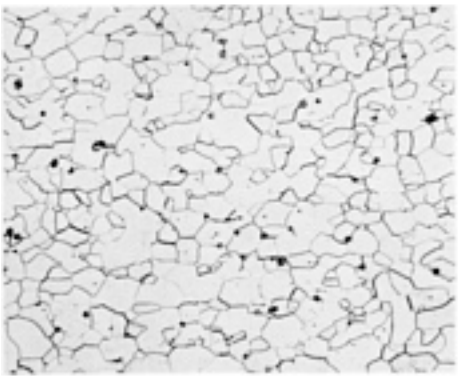

Fig. 42 Muffler-grade type 409 stainless steel (0.045C-11Cr-0.50Ti) strip, annealed 1 h per inch of thickness at 870 °C (1600 °F) and air cooled to RT. Equiaxed ferrite grains and dispersed titanium carbide particles. 10 ml. HNO_3, 10 mL acetic acid, 15 mL HCl, and 2 drops glycerol. 100×

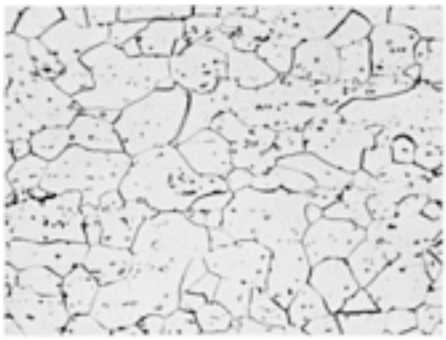

Fig. 43 Type 430 stainless steel strip, annealed at 845 °C (1550 °F) and cooled in air. The structure consists of equiaxed ferrite grains and randomly dispersed chromium carbide particles. Vilella's reagent. 500×

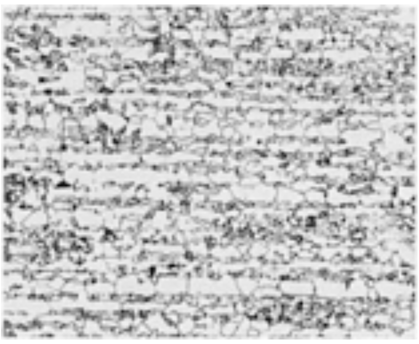

Fig. 44 Type 430 ferritic stainless steel. This grade can sometimes be partially hardenable, depending on composition balance and amount of segregation. The structure in this longitudinal section is streaks of martensite (dark) and ferrite (white). See Fig. 45. Glyceregia. 100×

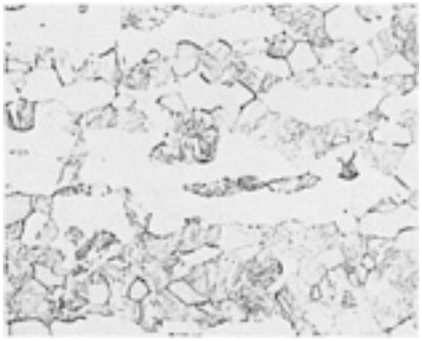

Fig. 45 Same as Fig. 44, but a higher magnification to resolve the structure more clearly. Ferrite (white constituent) is approximately 235 HV; martensite (dark), 360 HV. Same etchant as Fig. 44. 400×

Fig. 46 Type 430F (resulfurized free-machining 430, 254 HV) ferritic stainless steel. Longitudinal section shows dispersed manganese sulfide stringers in a ferrite matrix. As-polished. 200×

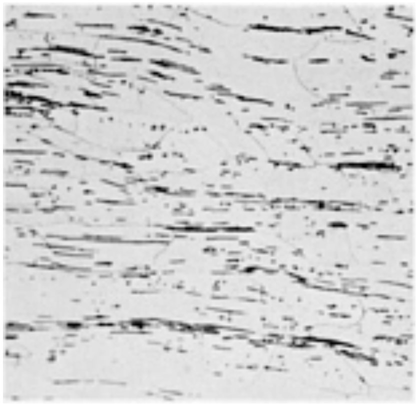

Fig. 47 182-FM (18Cr-2Mo) resulfurized free-machining stainless steel (230 HV). The structure is carbide and sulfides in a ferritic matrix. Ralph's reagent. 200×

Fig. 48 Type 434 modified free-machining ferritic stainless steel (260 HV). Longitudinal section shows carbides and sulfide stringers in a matrix of ferrite. Ralph's reagent. 100×

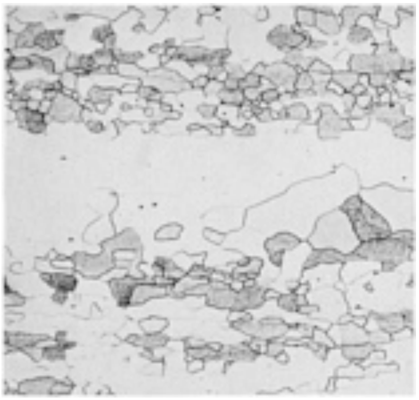

Fig. 49 E-Brite (26Cr-1Mo) ferritic stainless steel plate (180 HV), 6 mm (0.25 in.) thick. Longitudinal section shows ferrite grains. 10 mL HNO_3, 10 mL acetic acid, 15 mL HCl, and 2 drops glycerol. 50×

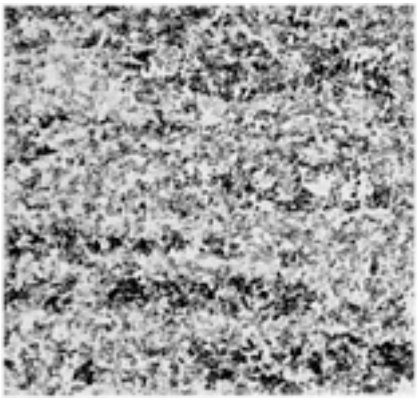

Fig. 50 Type 403 martensitic stainless steel (320 HV) in the quenched and tempered condition. Longitudinal section shows a structure of tempered martensite. Vilella's reagent. 400×

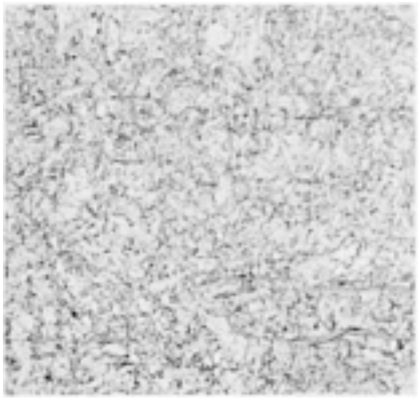

Fig. 51 Type 410 stainless steel (300 HV), with sulfur added for machinability, in the quenched and tempered condition. Structure is tempered martensite with some manganese sulfide stringers. Vilella's reagent. 400×

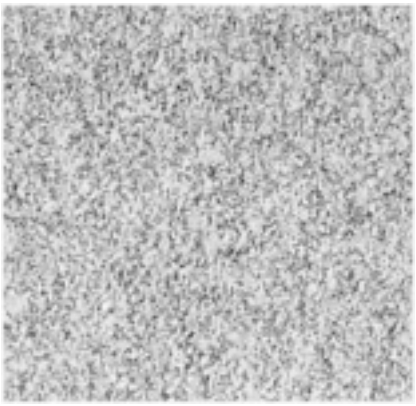

Fig. 52 Type 420 stainless steel, quenched and tempered. Structure is tempered martensite. Vilella's reagent. 100×

Fig. 53 Type 420 stainless steel (306 HV), quenched and tempered with sulfur added to improve machinability. Tempered martensite with some sulfide inclusions. Vilella's reagent. 400×

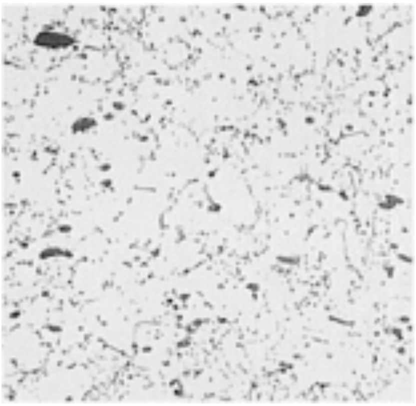

Fig. 54 Free-machining type 416 stainless steel (160 HV), annealed. The gray particles are sulfides. Vilella's reagent. 400×

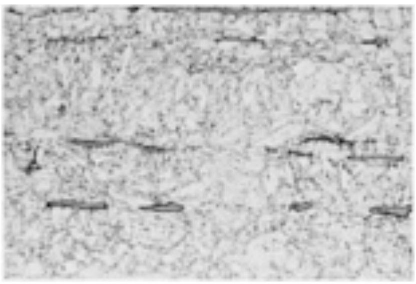

Fig. 55 Same free-machining stainless steel as shown in Fig. 54, but in the quenched and tempered condition. Longitudinal section shows δ-ferrite stringers (white), tempered martensite, and sulfides. Vilella's reagent. 400×

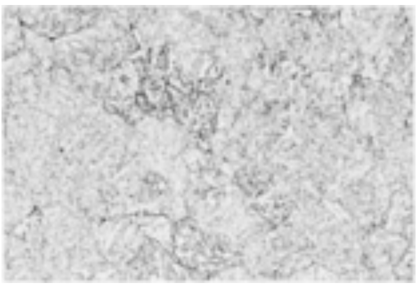

Fig. 56 Type 431 Stainless steel (335 HV) in the quenched and tempered condition. Structure is tempered martensite. This martensitic alloy has a nickel addition (1.25-2.50%) for enhanced corrosion resistance. Vilella's reagent. 200×

Fig. 57 Type 440A stainless steel in the annealed condition. Longitudinal section shows chromium carbide particles in a ferritic matrix. See Fig. 58 for effects of austenitizing/air cooling/tempering heat treatment on the structure of this alloy. 5% picric acid and 3% hydrochloric acid in alcohol. 500×

Fig. 58 Type 440A stainless steel, austenitized 30 min at 1010 °C (1850 °F), air cooled and tempered 30 min at 595 °C (1100 °F). The structure is partly spheroidized particles of chromium carbide in a martensitic matrix. Compare with the annealed structure shown in Fig. 57. 1% picric acid and 5% HCl in alcohol. 500×

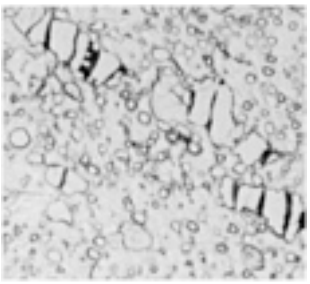

Fig. 59

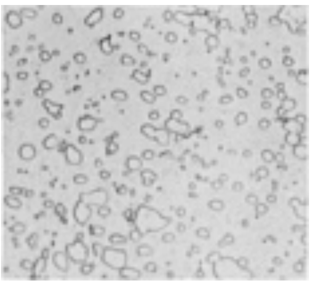

Fig. 60

Type 440B martensitic stainless steel (245 HV) in the spheroidize annealed condition. Fig. 59: specimen was polished incorrectly; note resulting cracks in and around the carbide particles. Fig. 60: some specimen as shown in Fig. 59 but polished properly. No cracking is evident in this specimen. See the article "Mechanical Grinding, Abrasion, and Polishing" in this Volume for detailed information on procedures. Vilella's reagent. 1000×

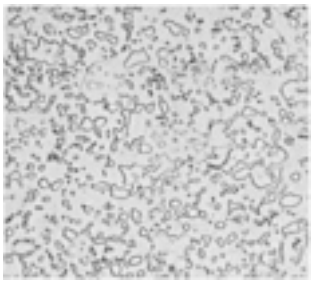

Fig. 61 Type 440C stainless steel (255 HV) in the spheroidize annealed condition. Structure is chromium-rich carbide particles in a ferrite matrix. See also Fig. 62 and 63 for the effects of alternate heat treatments on the structure of this martensitic alloy. Vilella's reagent. 1000×

Fig. 62 Type 440C martensitic stainless steel, austenitized 1 h at 1010 °C (1850 °F), air cooled, and tempered 2 h at 230 °C (450 °F). The structure is carbide particles in a martensitic matrix. Vilella's reagent. See also Fig. 63. 500×

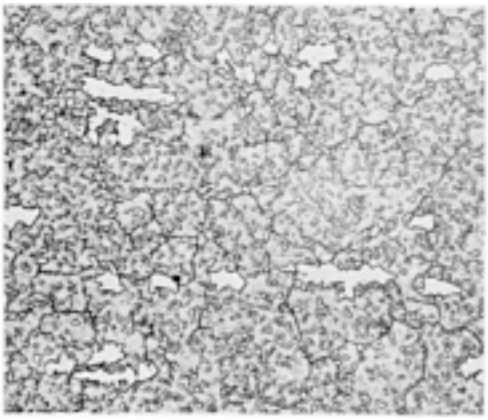

Fig. 63 Type 440C stainless steel bar, preheated 30 min at 760 °C (1400 °F), austenitized 30 min at 1025 °C (1875 °F), air cooled to 65 °C (150 °F), and double tempered (2 h each) at 425 °C (800 °F). Primary and secondary carbides (islands and particles) in tempered martensite. Superpicral. 500×

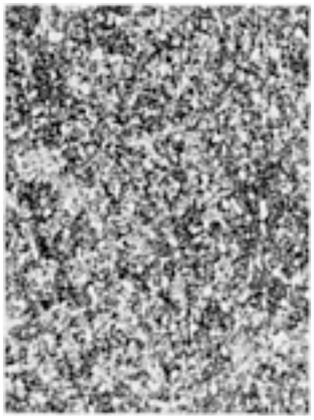

Fig. 64

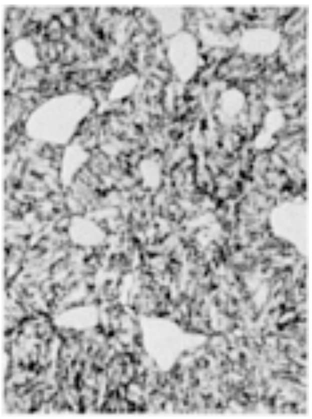

Fig. 65

AM350 semiaustenitic precipitation-hardenable stainless steel, containing a small amount of ferrite (white patches) in a martensitic matrix. Some retained austenite is also present. This grade and AM355 (see Fig. 66, 67, 68), while classed as precipitation-hardenable alloys, do not have true precipitation reactions. Fry's reagent. Fig. 64: 100×. Fig. 65: 1000×

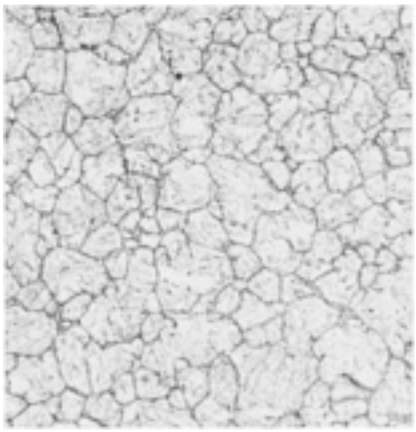

Fig. 66

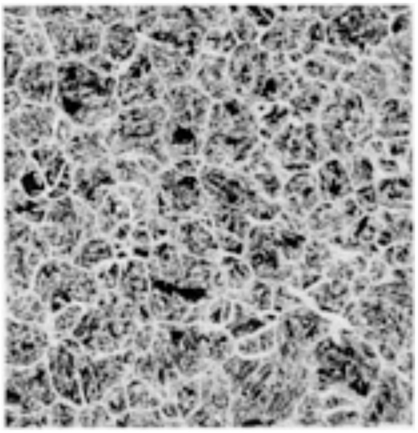

Fig. 67

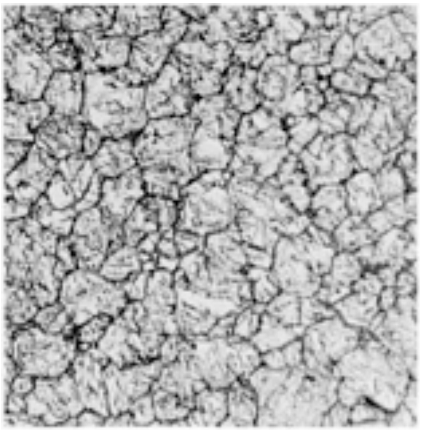

Fig. 68

AM355 precipitation-hardenable stainless steel (525 HV), heat treated. The structure is martensite, but etching has revealed prior austenite grain boundaries. Fig. 66: bright-field illumination. Fig. 67: dark-field illumination. Fig. 68: Differential interference contrast. Vilella's reagent. 400×

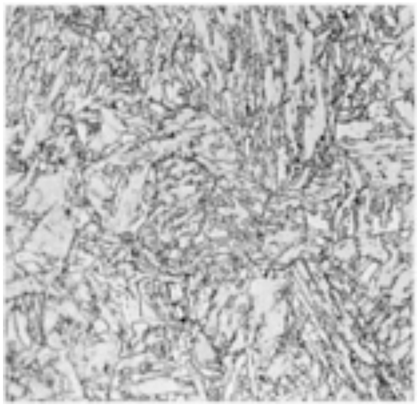

Fig. 69 PH13-8Mo precipitation-hardenable stainless steel (475 HV), solution annealed and aged. The structure is tempered martensite. Fry's reagent. 1000×

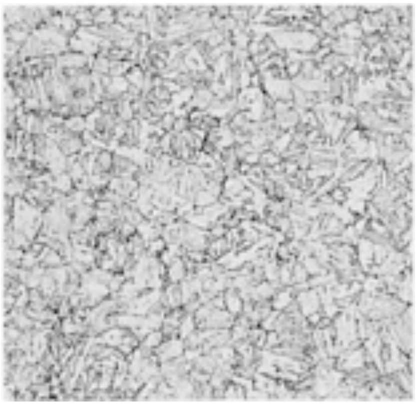

Fig. 70 17-4PH stainless steel, solution annealed and aged. Structure is tempered martensite (no δ-ferrite). Compare with Fig. 81, 82, 83, 84. Fry's reagent. 200×

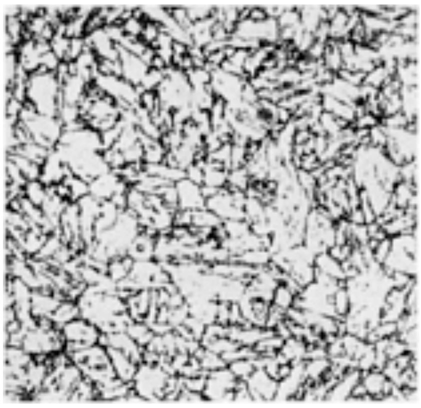

Fig. 71 Custom 450 precipitation-hardenable stainless steel (360 HV), solution annealed and aged (H1050). The structure is tempered martensite. Fry's reagent. 1000×

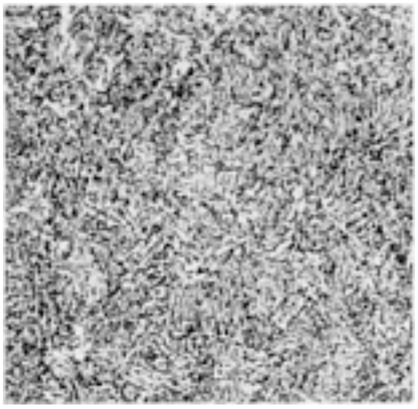

Fig. 72 Custom 450 precipitation-hardenable stainless steel (320 HV), solution annealed and aged (H1150). The structure is tempered martensite and reverted austenite. Fry's reagent. 1000×

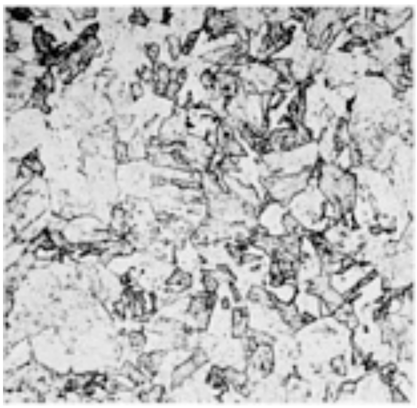

Fig. 73 Custom 455 precipitation-hardenable stainless steel (51 HRC), solution annealed and aged (H850). The structure is martensitic. Fry's reagent. 1000×

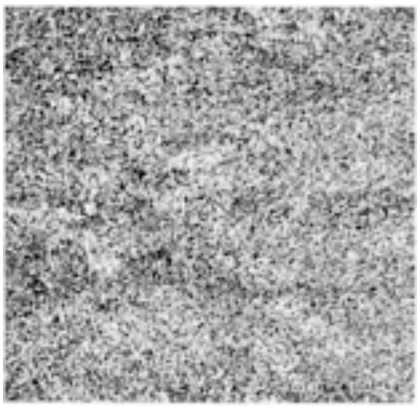

Fig. 74 Custom 455 precipitation-hardenable stainless steel (36 HRC) in the solution annealed and aged condition (H1100). The structure is martensitic, Fry's reagent. 1000×

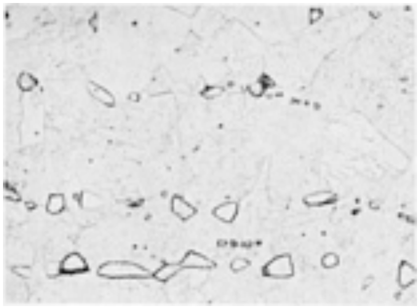

Fig. 75

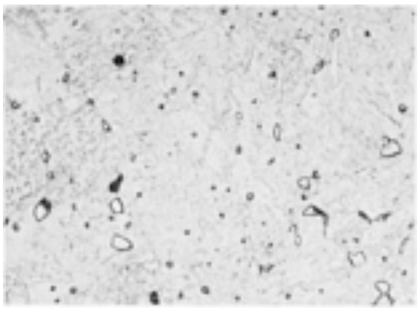

Fig. 76

17-7PH semiaustenitic precipitation-hardenable stainless steel (165 HV) that was hot rolled and annealed. The outlined particles shown in this photomicrograph are δ-ferrite. Fig. 75: a longitudinal section. Fig. 76: a transverse section. Figures 77 and 78 show this alloy in the solution-annealed/air-cooled condition. Figure 79 illustrates a heat-treated, cold-rolled structure. Vilella's reagent. 1000×

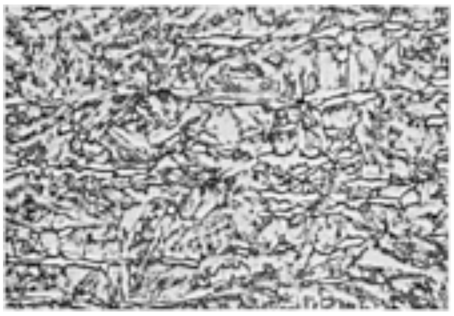

Fig. 77 17-7PH stainless, solution annealed at 1065 °C (1950 °F), then held 10 min at 955 °C (1750 °F), air cooled, held 8 h at -75 °C (-100 °F), held 1 h at 510 °C (950 °F), and air cooled. Ferrite stringers in a martensitic matrix. Vilella's reagent. 1000×

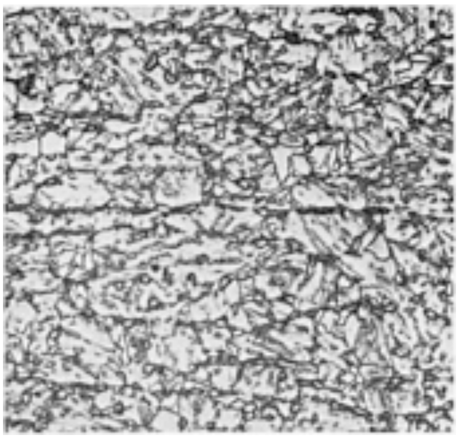

Fig. 78 Same as Fig. 77, but reheated and held 1.5 h at 760 °C (1400 °F), air cooled to 15 °C (60 °F) and held 30 min, heated to 565 °C (1050 °F) and held 1.5 h, and air cooled. The structure is the same as Fig. 77, but this steel is more ductile. Vilella's reagent. 1000×

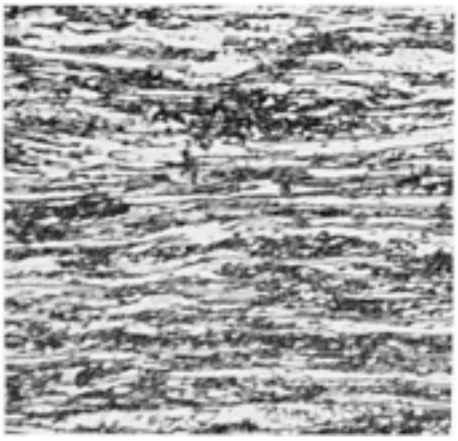

Fig. 79 17-7PH stainless steel, cold rolled at the mill, then held 1 h at 480 °C (900 °F) and air cooled. Structure is essentially martensite; austenite was transformed by cold rolling. Electrolytic: HNO_3 acetic acid, then 10% aqueous oxalic acid. 1000×

Fig. 80 15-5PH martensitic precipitation-hardenable stainless steel (41 HRC), solution annealed and aged. Structure is tempered martensite. Vilella's reagent. 200×

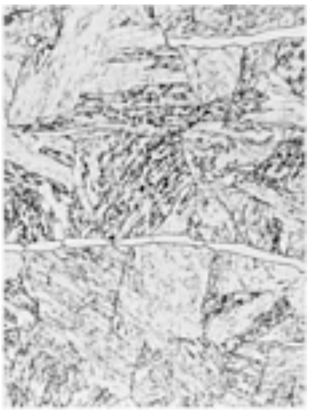

Fig. 81

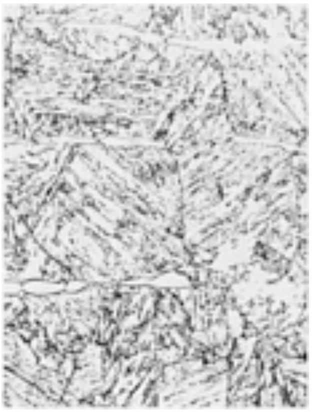

Fig. 82

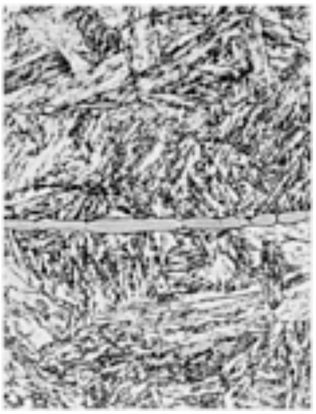

Fig. 83

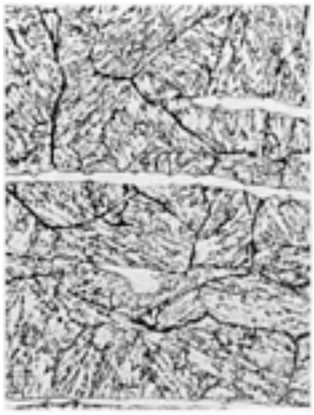

Fig. 84

17-4PH precipitation-hardenable stainless steel, heat treated. The effect of different etchants in revealing the structure, which consists of δ-ferrite stringers in a martensitic matrix. Fig. 81: etched using Fry's reagent. Fig. 82: etched using Vilella's reagent. Fig. 83: etched using Marble's reagent. Fig. 84: etched using superpicral. 500×

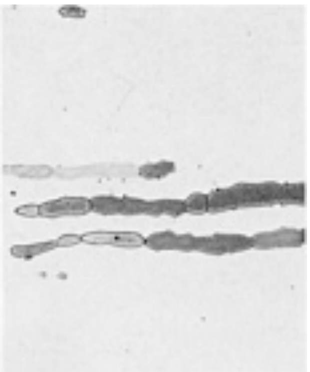

Fig. 85

Fig. 86

Same stainless steel as Fig. 81, 82, 83, and 84, etched electrolytically to reveal δ-ferrite stringers. Fig. 85: etched 10 s in 10 *N* KOH at 2.5 V dc. Fig. 86: etched 21 s in 20% aqueous NaOH at 20 V dc. 500×

Fig. 87 Stainless W in the solution annealed and aged condition; δ-ferrite stringers in tempered martensite elongated in the rolling direction. Superpicral. 500×

Fig. 88 Type 312 duplex stainless steel (250 HV) in the solution annealed and aged condition. Transverse section shows austenite in a matrix of ferrite. Glyceregia. 200×

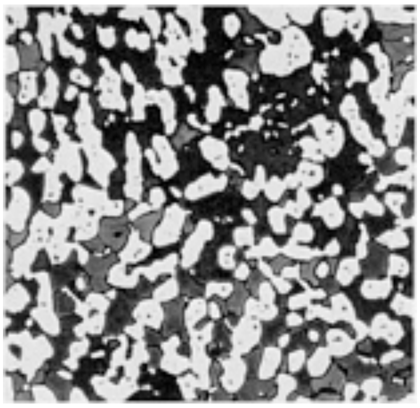

Fig. 89 Same stainless steel and processing as Fig. 88 but tint etched to color the ferrite phase. The austenite remains white. 10% aqueous HCl and 1% aqueous $K_2S_2O_5$. 200×

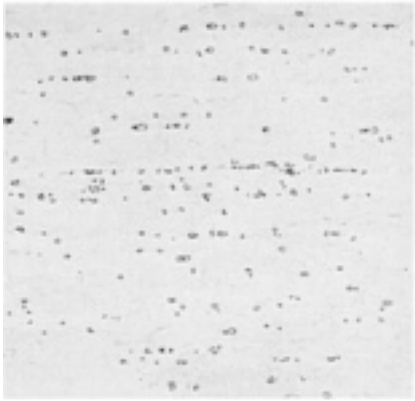

Fig. 90 Proprietary duplex stainless steel (250 HV). The specimen has been etched to reveal carbide phase; the matrix is only faintly visible in this longitudinal section. Vilella's reagent. 200×

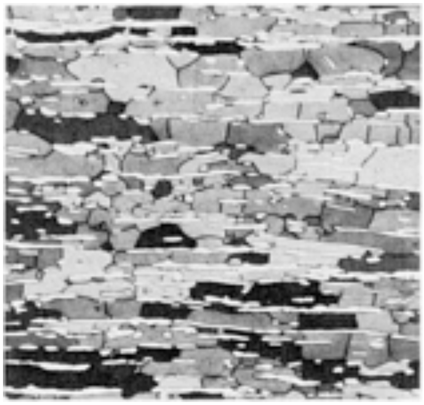

Fig. 91 Same duplex stainless steel as in Fig. 90, tint etched. Ferrite in the matrix is colored; austenite is unaffected. 10% aqueous HCl and 1% aqueous $K_2S_2O_5$. 200×

<Previous section in this article