Titanium and Titanium Alloys: Metallographic Techniques and Microstructures
Rodney R. Boyer, Senior Research Engineer, Boeing Commercial Airplane Company

<Previous section in this article

Atlas of Microstructures for Titanium and Titanium Alloys

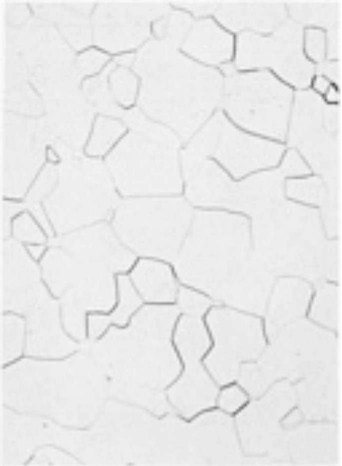

Fig. 2 High-purity (iodide-process) unalloyed titanium sheet, cold rolled, and annealed 1 h at 700 °C (1290 °F). Equiaxed, recrystallized grains of α. Kroll's reagent (ASTM 192). 250×

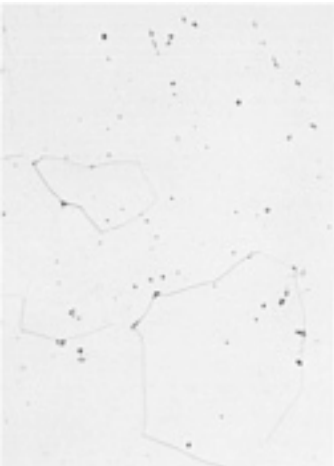

Fig. 3 Commercial-purity unalloyed titanium, hydrogenated to 20 ppm H. Annealed 1 h at 850 °C (1560 °F), air cooled. TiH (black) in equiaxed grains of α. Kroll's reagent (ASTM 192). 250×

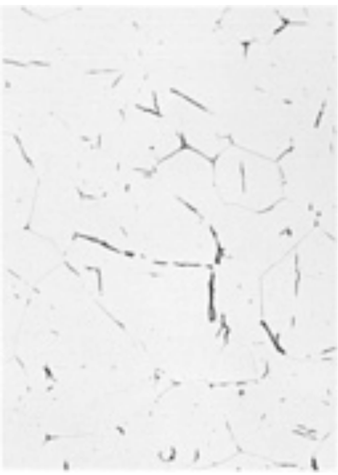

Fig. 4 Same as Fig. 3, except hydrogenated to 80 ppm H, producing a greater amount of TiH (black needles) at grain boundaries and in the α grains. Kroll's reagent (ASTM 192). 250×

[graphic]

Fig. 5 Same as Fig. 3 and 4, except hydrogenated to 230 ppm H, producing needles of TiH (black) that are larger and more numerous than those shown in Fig. 3. Kroll's reagent (ASTM 192). 250×

Fig. 6 Commercial-purity (99.0%) unalloyed titanium sheet, as-rolled to 1.0 mm (0.040 in.) thick at 760 °C (1400 °F). Grains of α, which have been elongated by cold working. See also Fig. 7, 8, and 9. Kroll's reagent (ASTM 192). 250×

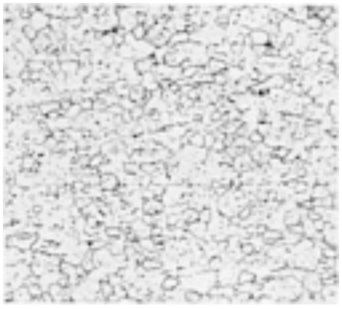

Fig. 7 Same as Fig. 6, but annealed 2 h at 700 °C (1290 °F) and air cooled. Recrystallized α grains; particles of TiH (black); and particles of β (also black) stabilized by impurities. Kroll's reagent (ASTM 192). 250×

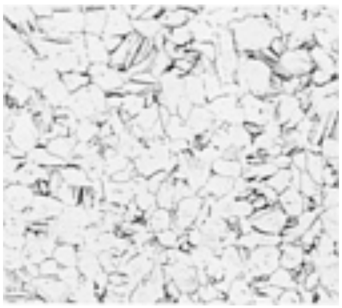

Fig. 8 Same as Fig. 6, but annealed 1 h at 900 °C (1650 °F)--just below the β transus--and air cooled. Recrystallized grains of "primary" α and transformed β containing acicular α Kroll's reagent

(ASTM 192). 250×

Fig. 9 Same as Fig. 6, but annealed 2 h at 1000 °C (1830 °F) and air cooled. Colonies of serrated α plates; particles of TiH and retained β (both black) between the plates of α. Kroll's reagent (ASTM 192). 250×

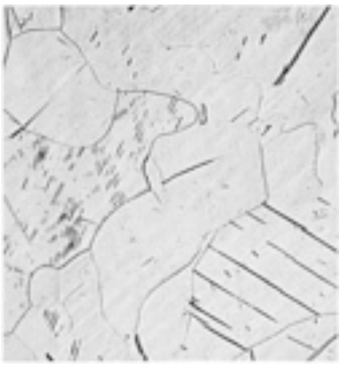

Fig. 10 Commercial-purity unalloyed titanium bar, annealed for 1 h at 705 °C (1300 °F). The structure consists of equiaxed α grains exhibiting same twin bands (parallel straight lines). 10 mL HF, 5 mL HNO_3, 85 mL H_2O. 250×

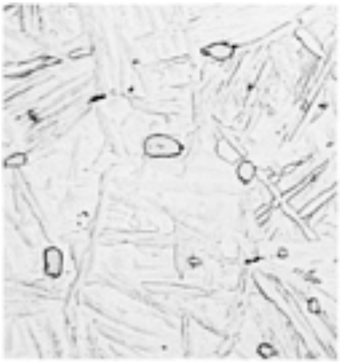

Fig. 11 Commercial-purity unalloyed titanium containing 0.14% C and 0.12% Fe. Annealed for 1 h at 1095 °C (2000 °F), water quenched. TiC particles (gray) in matrix of coarse, acicular α. Kroll's reagent (ASTM 192). 500×

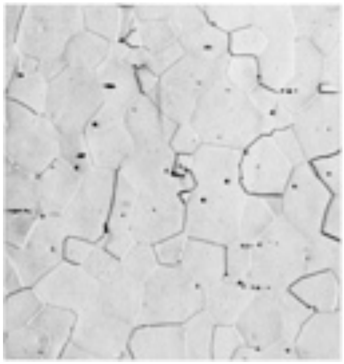

Fig. 12 Ti-0.2Pd sheet, hot rolled with starting temperature of 760 °C (1400 °F), annealed for 2 h at 705 °C (1300 °F), and slowly cooled. Equiaxed grains of α; iron-stabilized β (black dots). 2 mL HF, 10 mL HNO_3, 88 mL H_2O. 250×

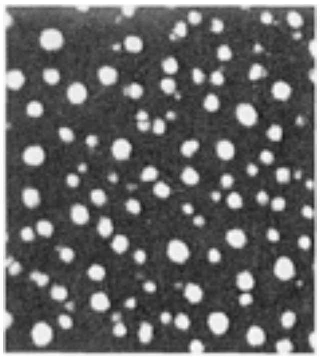

Fig. 13 Ti-8Al (with 1800 PPM O_2) sheet aged to precipitate the ordered α_2 phase. The dark-field transmission electron micrograph illustrates α_2 precipitates (light) in an α matrix. 105600×. (J.C. Williams)

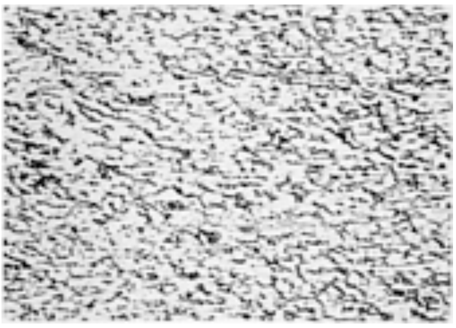

Fig. 14 Ti-6Al-2Nb-1Ta-0.8Mo plate, hot rolled with starting temperature below the β transus of about 1000 °C (1830 °F), annealed for 30 min at 900 °C (1650 °F) and air cooled. Structure: slightly elongated α grains (light) and intergranular β (dark). 10 mL HF, 5 mL HNO_3, 85 mL H_2O. 100×

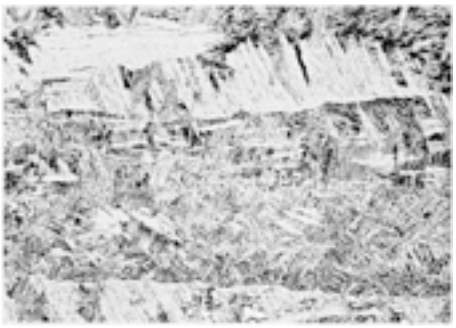

Fig. 15 Ti-6Al-2Nb-1Ta-0.8Mo plate, hot rolled with a starting temperature of 1150 °C (2100 °F), which is above the β transus. Structure: acicular α (light), intergranular β (dark), with boundaries of elongated β grains. 10 mL HF, 5 mL HNO_3, 85 mL H_2O. 100×

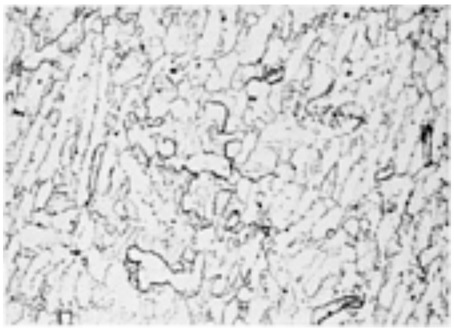

Fig. 16 Ti-5Al-2.5Sn, forged with starting temperature of 1010 °C (1850 °F), which is below the β-transus temperature, annealed for 1 h at 815 °C (1500 °F), and air cooled. Slightly elongated grains of "primary" α (light) in matrix of acicular α (mottled). Kroll's reagent (ASTM 192). 100×

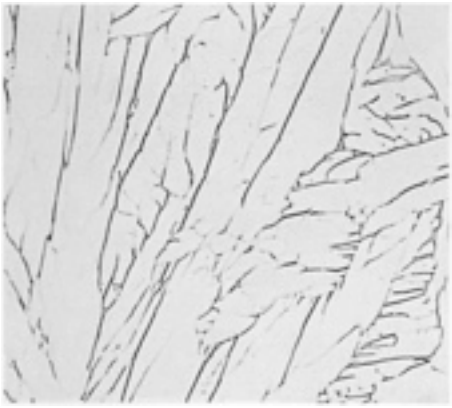

Fig. 17 Ti-5Al-2.5Sn, hot worked below the α transus, annealed 30 min at 1175 °C (2150 °F), which is above the β transus, furnace cooled to 790 °C (1450 °F) in 6 h, and furnace cooled to room temperature in 2 h. Coarse, platelike α. See also Fig. 18 and 19. Kroll's reagent (ASTM 192). 100×

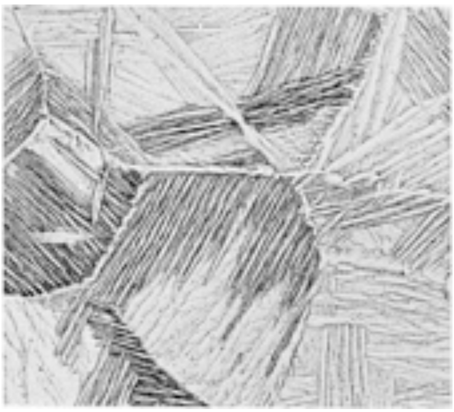

Fig. 18 Same as Fig. 17, but air cooled from the annealing temperature instead of furnace cooled. The faster cooling rate produced acicular α that is finer than the platelike α in Fig. 17. Prior-β grains are outlined by the α that was first to transform. Kroll's reagent (ASTM 192). 100×

[graphic]

Fig. 19 Same as Fig. 17, but water quenched from the annealing temperature instead of furnace cooled and shown at a higher magnification. The rapid cooling produced fine acicular α. A prior-β grain boundary can be seen near the center of the micrograph. Kroll's reagent (ASTM 192). 250×

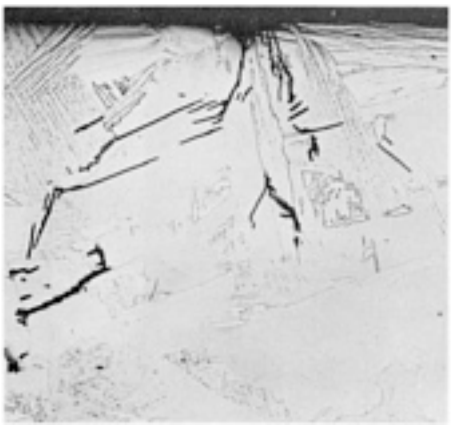

Fig. 20 Stress-corrosion cracks (black) at the surface of a Ti-5Al-2.5Sn part. These transgranular cracks were caused by exposure to chlorides at 815 °C (1500 °F). Kroll's reagent (ASTM 192). 100×

[graphic]

Fig. 21 Strain-induced porosity near surface of a Ti-5Al-2.5Sn part. Pores (black), caused by severe forming, in equiaxed grains of α (few grain boundaries show). Kroll's reagent (ASTM 192). 100×

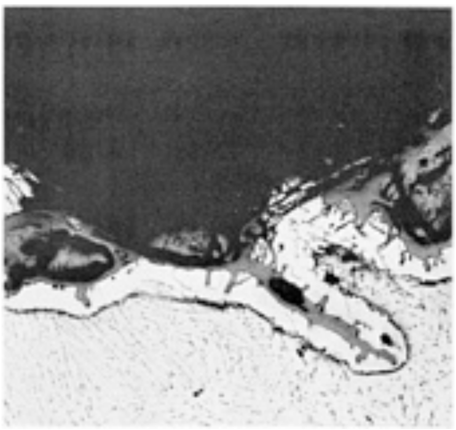

Fig. 22 Lap, or fold, in the surface of a Ti-5Al-2.5Sn forging. Oxide (gray) on the surface and in the cracks of the white, brittle layer (case) of oxygen-stabilized α. Kroll's reagent (ASTM 192). 100×

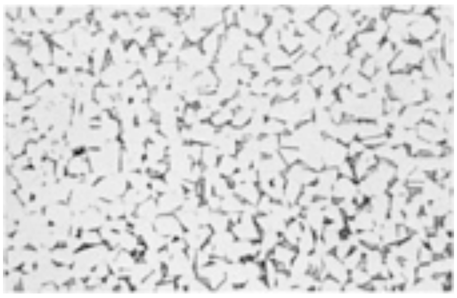

Fig. 23 Ti-8Al-1Mo-1V, forged with a starting temperature of 900 °C (1650 °F), which is below the normal temperature range for forging this alloy. Structure: equiaxed α grains (light) in a matrix of transformed β (dark). See also Fig. 24 and 25. Kroll's reagent (ASTM 192). 250×

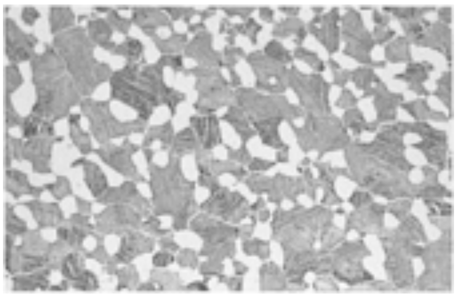

Fig. 24 Same as Fig. 23, but forged with starting temperature of 1005 °C (1840 °F), which is within the normal range, and air cooled. Equiaxed grains of "primary" α (light) in a matrix of transformed β (dark) containing fine acicular α. See also Fig. 25. Kroll's reagent (ASTM 192). 250×

Fig. 25 Same as Fig. 23, except the starting temperature for forging was 1095 °C (2000 °F), which is above the β-transus temperature, and the finished forging was rapidly air cooled. The structure consists of transformed β containing coarse and fine acicular α (light). Kroll's reagent (ASTM 192). 250×

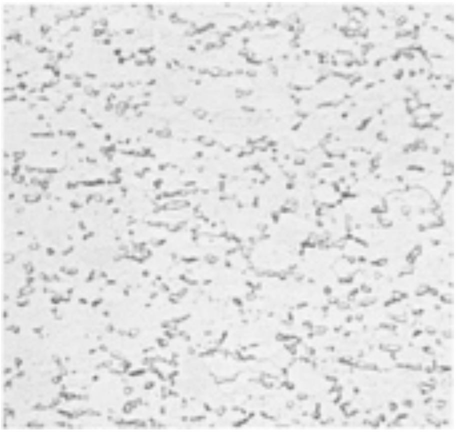

Fig. 26 Ti-8Al-1Mo-1V sheet, duplex annealed by holding 8 h at 760 °C (1400 °F), furnace cooling to room temperature, holding 20 min at 790 °C (1450 °F), and air cooling. Equiaxed α grains and outlined intergranular β. 2 mL HF, 8 mL HNO_3, 90 mL H_2O. 850×

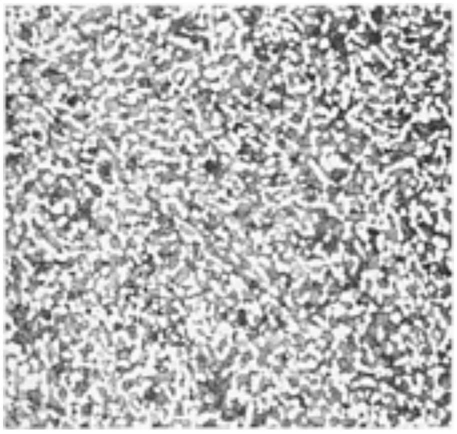

Fig. 27 Ti-8Al-1Mo-1V forging, solution treated 1 h at 1010 °C (1850 °F), oil quenched, aged 8 h at 595 °C (1100 °F), and air cooled. Structure: same as shown in Fig. 24 (effect of the aging treatment is not resolvable at this magnification). Kroll's reagent (ASTM 192). 100×

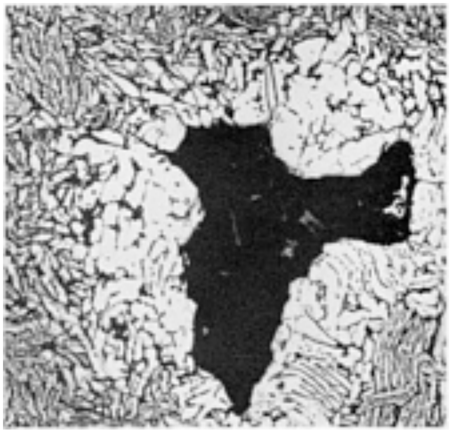

Fig. 28 Ti-8Al-1Mo-1V, as-forged. Ingot void (black), surrounded by a layer of oxygen-stabilized α (light). The remaining structure consists of elongated α grains in a dark matrix of transformed β. Kroll's reagent (ASTM 192). 25×

[graphic]

Fig. 29 Ti-8Al-1Mo-1V sheet, solution treated 10 min at 1010 °C (1850 °F), air cooled, aged 20 min at 745 °C (1375 °F), then exposed to cadmium plate (top) for 1000 h at 260 °C (500 °F) while stressed at 620 MPa (90 ksi). Intergranular stress-corrosion cracks. 2 mL HF, 8 mL HNO_3, 90 mL H_2O. 200×

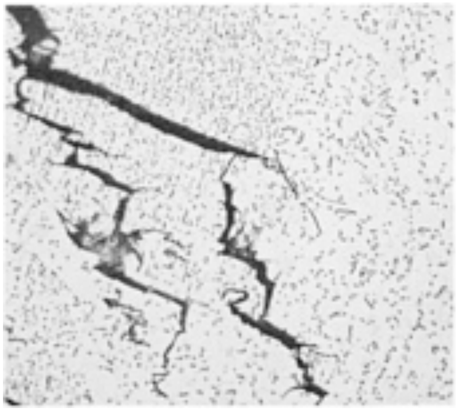

Fig. 30 Ti-8Al-1Mo-1V sheet, annealed for 8 h at 790 °C (1450 °F) and furnace cooled. Transgranular stress-corrosion cracks, which occurred in a salt-water environment. The microstructure consists of equiaxed grains of α and small, outlined particles of β. Kroll's reagent (ASTM 192). 500×

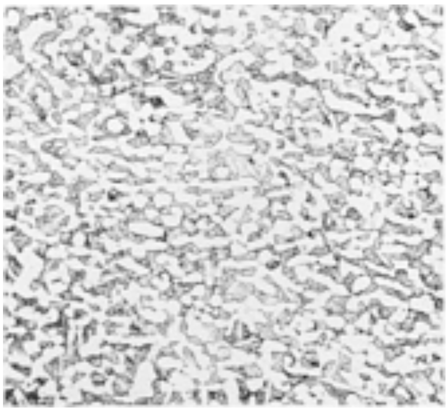

Fig. 31 Ti-6Al-5Zr-0.5Mo-0.5Si, forged with a starting temperature of 1040 °C (1900 °F), solution treated 1 h at 980 °C (11800 °F), oil quenched, aged 24 h at 495 °C (920 °F), and air cooled. Structure: slightly elongated light α grains in a dark matrix of transformed β. Kroll's reagent (ASTM 192). 100×

Fig. 32 Ti-6Al-2Sn-4Zr-2Mo forged ingot, held 1 h at 1010 °C (1850 °F), air cooled, heated to 970 °C (1775 °F), and immediately air cooled. Acicular α (transformed β); prior β grain boundaries. See also Fig. 33. Kroll's reagent (ASTM 192). 100×

Fig. 33 Same as Fig. 32, but reduced 15% by upset forging while at 970 °C (1775 °F). The structure consists of slightly deformed acicular α (transformed β); boundaries of elongated prior-β grains. Kroll's reagent (ASTM 192). 100×

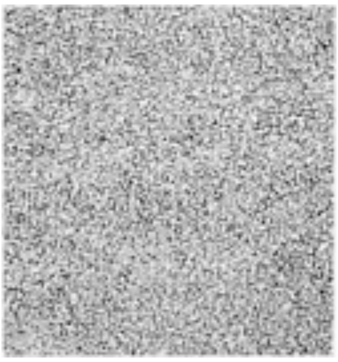

Fig. 34 Ti-5Al-6Sn-2Zr-1Mo-2.5Si, reduced 75% by upset forging starting at 980 °C (1800 °F), annealed 1 h at 980 °C (1800 °F), air cooled, and stabilized 2 h at 595 °C (1100 °F). Fine α grains (light); intergranular β. See also Fig. 35. HF, HNO_3, HCl, glycerol (ASTM 193). 100×

Fig. 35 Same as Fig. 34, except upset forged starting at 1150 °C (2100 °F), which is above the β-transus temperature. Distorted acicular α (light constituent); intergranular β; and boundaries of elongated prior-β grains. HF, HNO_3, HCl, glycerol (ASTM 193). 100×

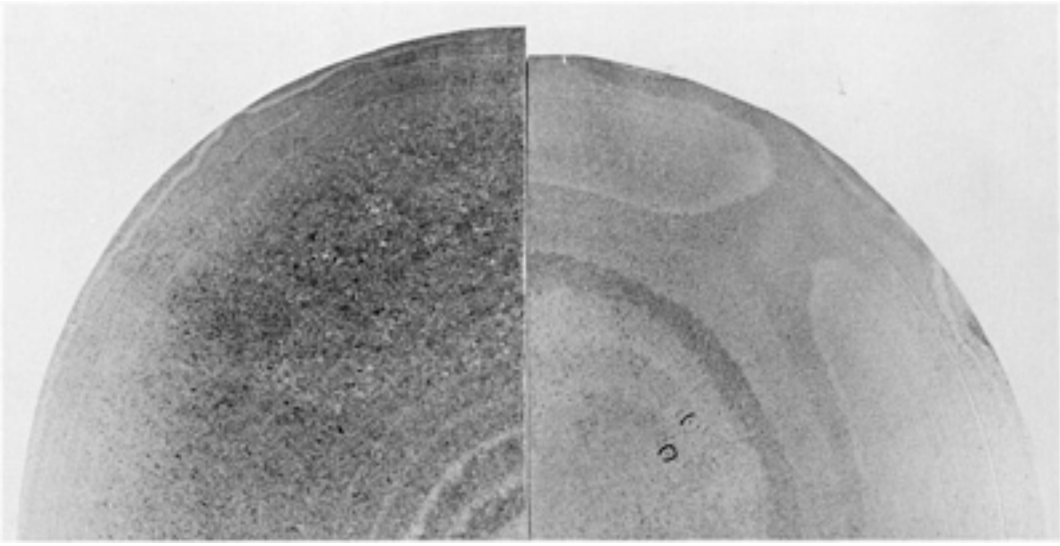

Fig. 36 Ti-6Al-2Sn-4Zr-2Mo α-β forged billet macroslice illustrating "tree rings," which represent minor compositional fluctuations. The slices are from two ingot locations. Etchant not known. 0.63×. (W. Reinsch)

[graphic]

Fig. 37 Held at 650 °C (1200 °F). A few small, equiaxed "primary" α grains in a matrix of acicular α (transformed β)

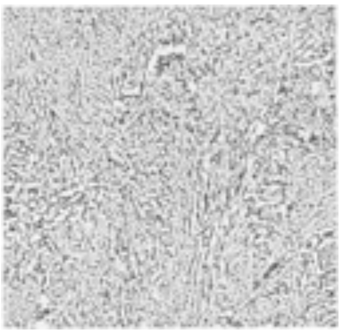

Fig. 38 Held at 925 °C (1700 °F). A few small, equiaxed "primary" α grains in a matrix of acicular α (transformed β)

[graphic]

Fig. 39 Held at 980 °C (1800 °F). A few small "primary" α grains (light) in a matrix of α' (martensite)

[graphic]

Fig. 40 Held at 995 °C (1825 °F), the β-transus temperature. The microstructure consists entirely of α'.

Ti-6Al-25n-4Zr-2Mo forgings, finish forged starting at 970 °C (775 °F), air cooled, machined to 13-mm (0.5-in.) diam test bars, reheated to the four temperatures indicated, held for 1 h, and air cooled. All etched with Kroll's reagent (ASTM 192). 100×

Fig. 41 Ti-7Al-2Mo-1V plate, solution treated at 995 °C (1825 °F), which is below the β transus. A replica electron micrograph. Structure: equiaxed α, acicular α and β (outlined). 2 mL HF, 8 mL HNO_3, 90 mL H_2O. 3000×

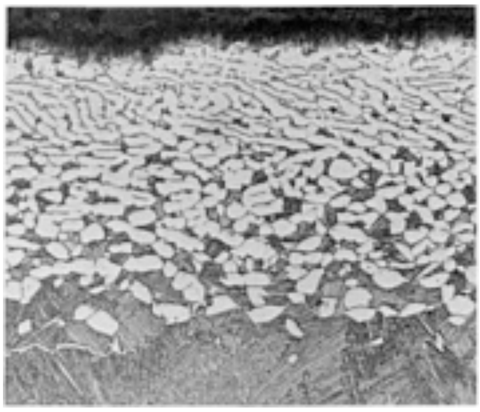

Fig. 42 Ti-7Al-2Mo-lV plate, heated to 1010 °C (1850 °F), which is above the β transus. Surface layer of white, oxygen-stabilized α (α case); the remainder of the structure is acicular α (transformed β). 2 mL HF, 8 mL HNO_3, 90 mL H_2O. 450×

Fig. 43 Ti-6Al-5Zr-4Mo-lCu-O.2Si, as-cast. Microstructure: transformed β containing acicular α (light platelets). A thin film of α phase (light) is evident at the prior-β grain boundaries. See Fig. 44 for effects of solution treating. 10 mL HF, 30 mL HNO_3, 50 mL H_2O (ASTM 187). 500×

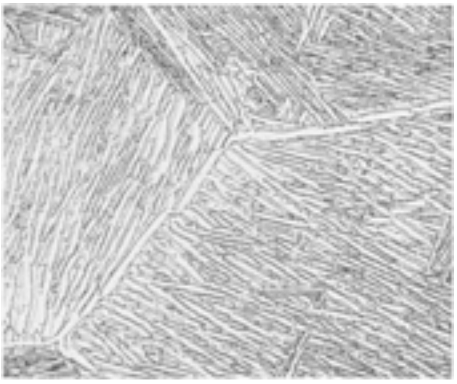

Fig. 44 Same as Fig. 43, but solution treated 1 h in argon at 845 °C (1550 °F), air cooled, and aged 24 h at 500 °C (930 °F). Acicular α (light) and aged β; α platelets at prior-β grain boundaries. 10 mL HF, 30 mL HNO_3, 50 mL H_2O (ASTM 187). 500 ×

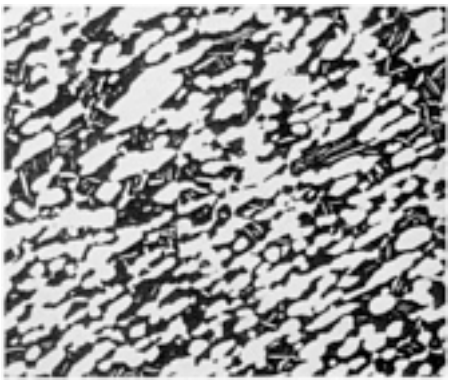

Fig. 45 Ti-6Al-5Zr-4Mo-1Cu-0.2Si forging, annealed 2 h at 705 °C (1300 °F), and air cooled. The structure consists of slightly elongated grains of α (light) and transformed β (dark) containing some acicular α. 10 mL HF, 30 mL HNO_3, 50 mL H_2O (ASTM 187). 500 ×

[graphic]

Fig. 46 Ti-6Al-4V, as-cast. The structure consists of transformed β containing acicular α; α is at prior-β grain boundaries. Keller's reagent. 100×

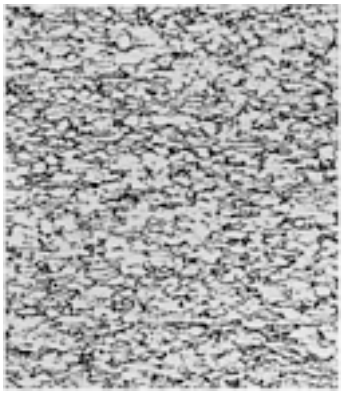

Fig. 47 Ti-6Al-4V sheet, rolled starting at 925 °C (1700 °F), annealed for 8 h at 730 °C (1350 °F), and furnace cooled. Structure consists of slightly elongated grains of α (light) and intergranular β (gray). See also Fig. 48. 2 mL HF, 10 mL HNO_3, 88 mL H_2O. 250×

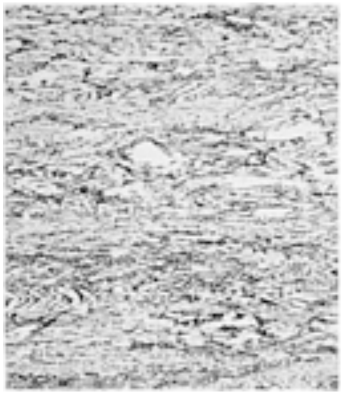

Fig. 48 Ti-6Al-4V plate, rolled starting at 900 °C (1650 °F), annealed for 1 h at 720 °C (1325 °F), and air cooled. The structure consists of elongated α grains (light) in a matrix of transformed β. See also Fig. 47 and 49. 2 mL HF, 10 mL HNO_3, 88 mL H_2O. 250×

Fig. 49 Same alloy and processing as in Fig. 48, but a specimen taken from an area of the plate that shows more banding of the structure, which consists of elongated grains of α (light) in a matrix of transformed β. 2 mL HF, 10 mL HNO_3, 88 mL H_2O. 250×

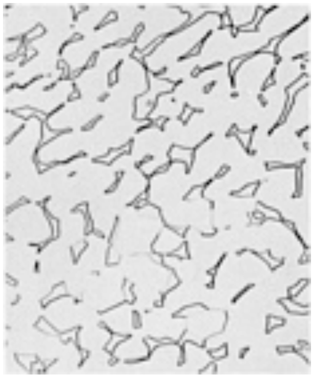

Fig. 50 Ti-6Al-4V plate, recrystallize-annealed at 925 °C (1700 °F) 1 h, cooled to 760 °C (1400 °F) at 50 to 55 °C/h (90 to 100 °F/h), then air cooled. Equiaxed α with intergranular β. The α-α boundaries are not defined. 50 mL oxalic acid in H_2O, 50 mL 1% HF in H_2O. 500×. (J.C. Chesnutt)

[graphic]

Fig. 51 Ti-6Al-4V plate diffusion-bonded joint (bonded at 925 °C, or 1700 °F) illustrating bond-line contamination. The white horizontal band is an area of O_2 and/or N_2 enrichment. An α case is also observable on the exterior surface. 50 mL H_2O, 50 mL 10% oxalic acid, 1 mL HF. 58×. (J.C. Chesnutt)

[graphic]

Fig. 52 Ti-6Al-4V extrusion, heated for 30 min at 1010 °C (1850 °F), air cooled, then heated for 1 h at 675 °C (1250 °F), and air cooled. Structure: acicular α (transformed β); α at prior-β grain boundaries. 2 mL HF, 8 mL HNO_3, 90 mL H_2O. 200×

[graphic]

Fig. 53 Ti-6Al-4V bar, 25 mm (1 in.) diam, annealed 2 h at 705 °C (1300 °F), and air cooled. Elongated grains of α (light) and intergranular β (mottled or outlined). See also Fig. 54, 55, 56, 57, 58, and 59. 2 mL HF, 8 mL HNO_3, 90 mL H_2O. 200×

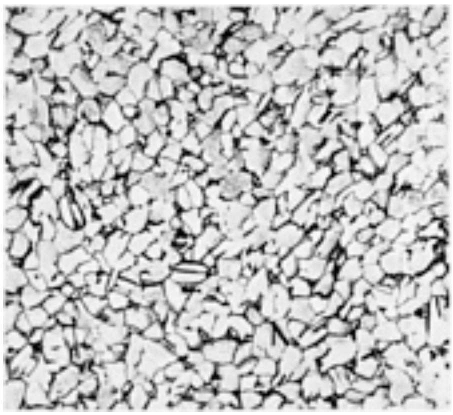

Fig. 54 Ti-6Al-4V bar, held for 1 h at 955 °C (1750 °F), below the β transus, and furnace cooled. Equiaxed α grains (light); intergranular β (dark). See also Fig. 55 and 56. 10 mL HF, 5 mL HNO_3, 85 mL H_2O. 250×

[graphic]

Fig. 55 Same as Fig. 54, but air cooled instead of furnace cooled. Grains of "Primary" α (light) in a matrix of transformed β containing acicular α. See also Fig. 56. 10 mL HF, 5 mL HNO_3, 85 mL H_2O. 250×

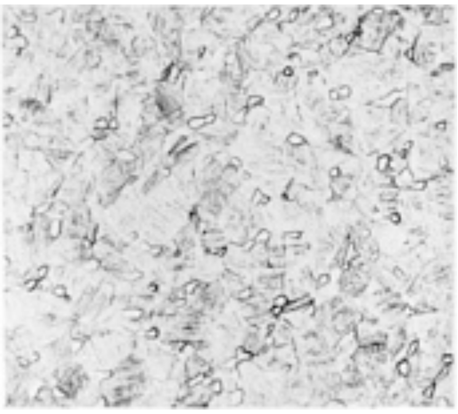

Fig. 56 Same as Fig. 54, but water quenched instead of furnace cooled. Equiaxed "Primary" α grains (light) in a matrix of α' (martensite). See also Fig. 57, 58, and 59. 10 mL HF, 5 mL HNO_3, 85 mL H_2O. 250×

[graphic]

Fig. 57 Ti-6Al-4V, thin foil transmission electron micrograph illustrating same microstructure as in Fig. 56, but at higher magnification. The large light grains are primary α; the darker region is acicular α' martensite in a β matrix. 5880×. (J.C. Williams)

[graphic]

Fig. 58 Ti-6Al-4V bar, held for 1 h at 1065 °C (1950 °F), above the β transus, and furnace cooled. Platelike α (light) and intergranular β (dark). See also Fig. 59. 10 mL HF, 5mL HNO_3, 85 mL H_2O. 250×

[graphic]

Fig. 59 Same as Fig. 58, but air cooled instead of furnace cooled. The structure consists of acicular α (transformed β); prior-β grain boundaries. 10 mL HF, 5 mL HNO_3, 85 mL H_2O. 250×

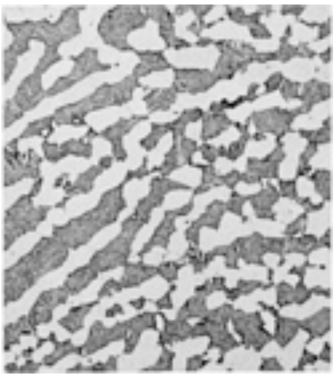

Fig. 60 Ti-6Al-4V, as-forged at 955 °C (1750 °F), below the β transus. Elongated α (light), caused by low reduction (20%) of a billet that had coarse, platelike α, in a matrix of transformed β containing acicular α. Kroll's reagent (ASTM 192). 250×

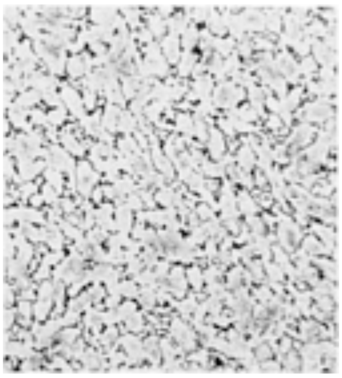

Fig. 61 Ti-6Al-4V forging, annealed for 2 h at 705 °C (1300 °F), and air cooled. The structure consists of equiaxed grains of α (light) and intergranular β (dark or outlined). See also Fig. 62 and 63. Keller's reagent. 250×

Fig. 62 Ti-6Al-4V, forged at 815 °C (1500 °F), annealed 2 h at 705 °C (1300 °F), and air cooled. Thin-foil transmission electron micrograph. Structure: equiaxed α containing dislocations; some intergranular β. See also Fig. 63. 23,000×

[graphic]

Fig. 63 Ti-6Al-4V, forged at 955 °C (1750 °F), annealed 2 h at 705 °C (1300 °F), and air cooled. A thin-foil electron micrograph, showing equiaxed α in matrix of alternate β (dark) and acicular α (light). See also Fig. 62. 4500×

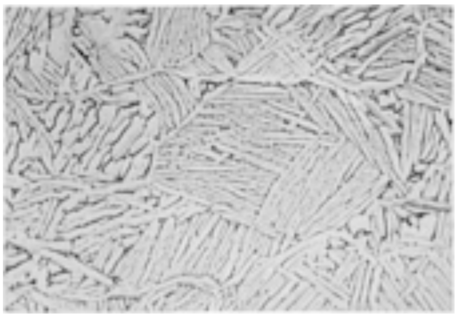

Fig. 64 Ti-6Al-4V press forging, reduced 50% at 1040 °C (1900 °F), above the β transus, then reduced 5% more at 970 °C (1775 °F), below the β transus, annealed 2 h at 705 °C (1300 °F), and air cooled. Slightly distorted, coarse, platelike α grains (light) and intergranular β phase (dark). See also Fig. 65 and 66. 2 mL HF, 8 mL HNO_3, 90 mL H_2O. 200×

Fig. 65 Same as Fig. 64, except reduced 21% at 970 °C (1775 °F). The structure is similar to Fig. 64, but the higher reduction below the β-transus temperature has resulted in some breakup of the coarse, platelike α grains that were still present after forging above the β transus. See also Fig. 66. 2 mL HF, 8 mL HNO_3, 90 mL H_2O. 200×

Fig. 66 Same as Fig. 64 and 65, except reduced 47% at 970 °C (1775 °F). The structure is similar to Fig. 65, but the still higher reduction below the β-transus temperature has resulted in elongated

grains of α (complete breakup of the coarse, platelike α grains that were present after forging above the β transus). 2 mL HF, 8 mL HNO_3, 90 mL H_2O. 200×

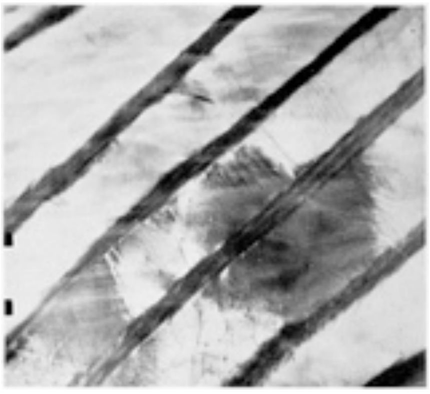

Fig. 67 Ti-6Al-4V, forged at 1040 °C (1900 °F), which is above the β transus, air cooled, annealed 2 h at 705 °C (1300 °F), and air cooled. Thin-foil transmission electron micrograph illustrates alternate layers of light, platelike α grains and dark intergranular β. 8500×

[graphic]

Fig. 68 Ti-6Al-4V forging solution treated 1 h at 955 °C (1750 °F), air cooled, and annealed 2 h at 705 °C (1300 °F). Equiaxed α grains (light) in transformed β matrix (dark) containing coarse, acicular α. See also Fig. 69. Kroll's reagent (ASTM 192). 500×

[graphic]

Fig. 69 Same as Fig. 68, except water quenched from the solution treatment (before the anneal) instead of air cooled. Structure is similar to Fig. 68, but the faster cooling resulted in finer acicular α in the transformed β. Kroll's reagent (ASTM 192). 500×

[graphic]

Fig. 70 Large oxide inclusion (gray band) in a Ti-6Al-4V forging that was annealed 2 h at 705 °C (1300 °F) and air cooled. Structure: grains of α (light) in a matrix of transformed β containing acicular α. Keller's reagent. 500×

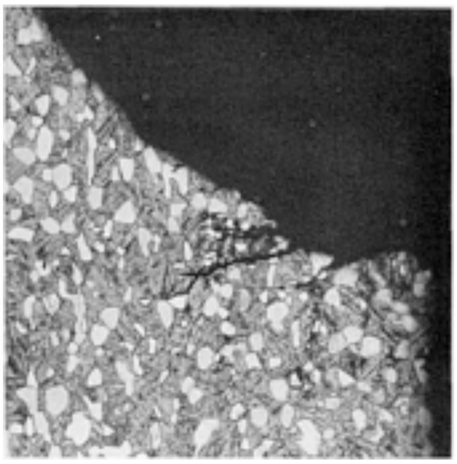

Fig. 71 Transgranular stress-corrosion cracks in a Ti-6Al-4V forging annealed same as Fig. 70. The cracks resulted from fingerprint contamination followed by bending and stress relieving for 1 h at 540 °C (1000 °F). Keller's reagent. 250×

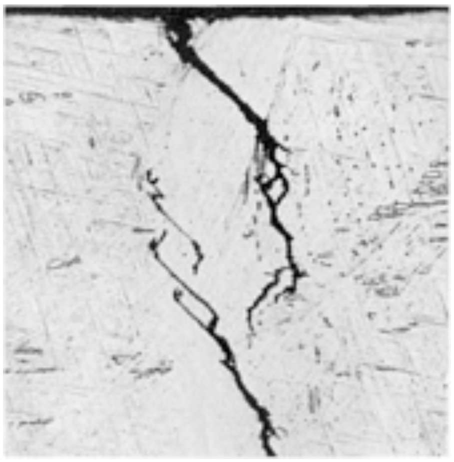

Fig. 72 Fusion zone of a gas tungsten arc weld in a Ti-6Al-4V forging showing transgranular stress-corrosion cracks caused by contamination with soap before the weld was stress relieved for 1 h at 540 °C (1000 °F). Keller's reagent. 500×

[graphic]

Fig. 73 Gas tungsten arc butt weld joining Ti-6Al-4V forgings that had been solution treated for 1 h at 955 °C (1750 °F), water quenched, aged 4 h at 540 °C (1000 °F), and air cooled. The forgings were welded using extra-low-interstitial unalloyed titanium filler metal, and the finished weldment was stress relieved for 1 h at 540 °C (1000 °F) and air cooled. See Fig. 74, 75, and 76 for details of the adjacent base metal, the weld bead, and the heat-affected zone. Keller's reagent. 8×

[graphic]

Fig. 74 Section of the base metal adjacent to the gas tungsten arc butt weld shown in Fig. 73. The structure consists of grains of "primary" α (light) in a matrix of transformed β containing acicular α . Keller's reagent. 250×

Fig. 75 Bead of the weld shown in Fig. 73. Structure: serrated α (outlined), acicular α (light), and a small amount of β (dark). See also Fig. 74 and 76. Keller's reagent. 250×

[graphic]

Fig. 76 Heat-affected zone of the weld shown in Fig. 73. Serrated α (outlined) and transformed β containing acicular α. See also Fig. 74 and 75. Keller's reagent. 250×

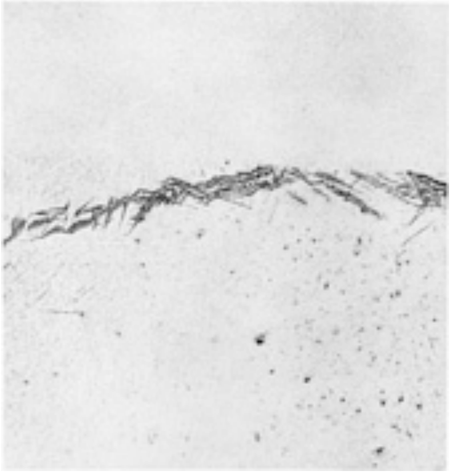

Fig. 77 Gas tungsten arc weld, which had been stress relieved 1 h at 540 °C (1000 °F), in a Ti-6Al-4V forging, showing needles of titanium hydride at the edge of the fusion zone. 10 mL HF, 30 mL HNO_3, 50 mL H_2O (ASTM 187), then light polish. 100×

[graphic]

Fig. 78 Ti-6Al-4V α-β processed billet illustrating macroscopic appearance of a high interstitial defect. See also Fig. 79. Actual size

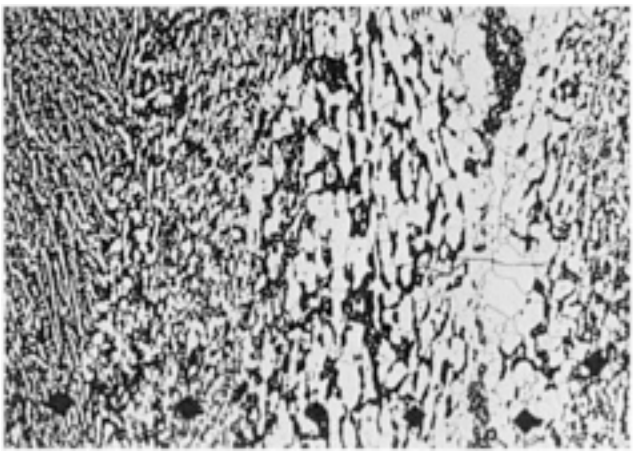

Fig. 79 Same as Fig. 78. The high oxygen content results in a region of coarser and more brittle oxygen-stabilized α than observed in the bulk material. 100×

[graphic]

Fig. 80 Ti-6Al-4V α-β processed billet illustrating the macroscopic appearance of a high aluminum defect. See also Fig. 81. 1.25×. (C. Scholl)

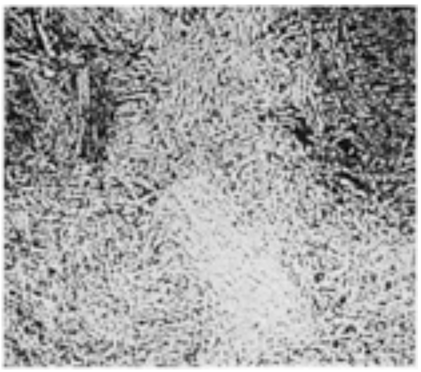

Fig. 81 Same as Fig. 80. There is a higher volume fraction of more elongated α in the area of high aluminum content. 50×. (C. Scholl)

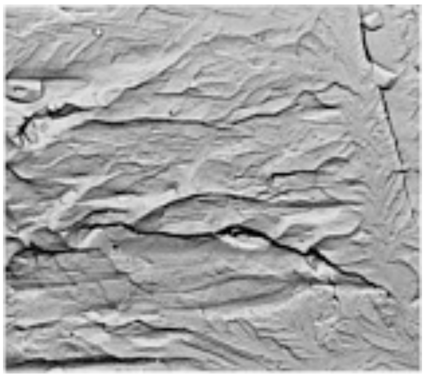

Fig. 82 Ti-6Al-4V alloy. A replica electron fractograph. Cleavage facets typical of salt-water stress-corrosion cracking. Cleavage occurs in the α phase. 6500×

[graphic]

Fig. 83 Ti-6Al-4V β-annealed fatigued plate specimen. Scanning electron micrograph at the polished and etched/unetched fracture topography interface showing microstructure/fracture topography correlation. Secondary cracks are a result of intense slip bands. Kroll's reagent. 2000×. (R. Boyer)

[graphic]

Fig. 84 Same as Fig. 83. This scanning electron micrograph illustrates that the "furrows" or "troughs" down which the striations propagate are defined by the lamellar α plates. These furrows link up as the crack progresses. Kroll's reagent. 2000×. (R. Boyer)

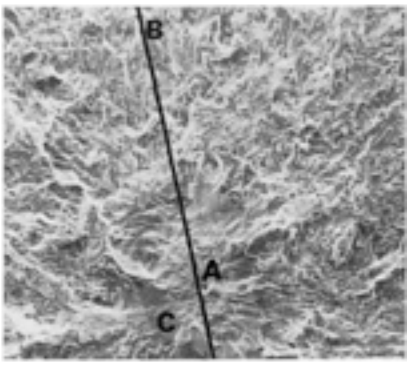

Fig. 85

[graphic]

Fig. 86

Ti-6Al-4V powder metallurgy compact, hot isostatically pressed at 925 °C (1700 °F), 103 MPa (15 ksi), for 2 h. This fatigue specimen had an internal origin at point A, which initiated at an iron inclusion, as determined in Fig. 86 by precision sectioning. The cleavage zone at point C in Fig. 85 is due to the $TiFe_2$ zone seen at point C in Fig. 86. Below the $TiFe_2$, the structure consists of transformed Widmanstätten α. The section (Fig. 86) was taken at line B in Fig. 85. Fig. 85: scanning electron micrograph. No etch. 80×. Fig. 86: optical micrograph. Kroll's reagent. 16×. (D. Eylon)

[graphic]

Fig. 87 Ti-6Al-2Sn-4Zr-6Mo, 100-mm (4-in.) thick forged billet, annealed 2 h at 730 °C (1350 °F). The microstructure consists of a matrix of transformed β (dark) containing various sizes of a grains (light), which are elongated in the direction of working. 2 mL HF, 8 mL HNO_3, 90 mL H_2O. 200×

[graphic]

Fig. 88 Ti-6Al-2Sn-4Zr-6Mo, forged at 870 °C (1600 °F), solution treated 2 h at 870 °C (1600 °F), water quenched, and aged 8 h at 595 °C (1100 °F), and air cooled. Elongated "primary" α grains (light) in aged transformed β matrix containing acicular α. See also Fig. 89, 90, 91, and 92. Kroll's reagent (ASTM 192). 500×

[graphic]

Fig. 89 Ti-6Al-2Sn-4Zr-6Mo bar, forged at 870 °C (1600 °F), solution treated 1 h at 870 °C (1600 °F), water quenched, and aged 8 h at 595 °C (1100 F). The structure is similar to that in Fig. 88, except that, as the result of water quenching, no acicular α is visible. 2 mL HF, 10 mL HNO_3, 88 mL H_2O. 250×

[graphic]

Fig. 90 Same as Fig. 88, except solution treated at 915 °C (1675 °F) instead of at 870 °C (1600 °F), which reduced the amount of "primary" α grains in the α + β matrix. See also Fig. 91 and 92. Kroll's reagent (ASTM 192). 500×

[graphic]

Fig. 91 Same as Fig. 90, except solution treated at 930 °C (1710 °F) instead of at 915 °C (1675 °F), which reduced the amount of α grains and coarsened the acicular α in the matrix. See also Fig. 92. Kroll's reagent (ASTM 192). 500×

Fig. 92 Same as Fig. 90 and 91, but solution treated at 955 °C (1750 °F), which is above the β transus. The resulting structure is coarse, acicular α (light) and aged transformed β (dark). Kroll's reagent (ASTM 192). 500×

[graphic]

Fig. 93 Ti-6Al-2Sn-AZr-6Mo forging, solution treated 2 h at 955 °C (1750 °F), above the β transus, and quenched in water. The structure consists entirely of α' (martensite). Kroll's reagent (ASTM 192). 500×

Fig. 94 Ti-6Al-6V-2Sn as-extruded, 8 mm ($\frac{5}{16}$-in.) thick. The microstructure consists of transformed β containing acicular α; light α is also evident at the prior-β grain boundaries. 2 mL HF, 8 mL HNO_3, 90 mL H_2O. 200×

[graphic]

Fig. 95 Ti-6Al-6V-2Sn billet, 100 mm (4 in.) thick, forged below the β transus of 945 °C (1730 °F), annealed 2 h at 705 °C (1300 °F), and air cooled. Light α in transformed β matrix containing acicular α. 2 mL HF, 8 mL HNO_3, 90 mL H_2O. 200×

[graphic]

Fig. 96 Ti-6Al-6V-2Sn hand forging, forged at 925 °C (1700 °F), solution treated for 2 h at 870 °C (1600 °F), water quenched, aged 4 h at 595 °C (1100 °F), and air cooled. Structure: "primary" α grains (light) in a matrix of transformed β containing acicular α. Kroll's reagent (ASTM 192). 150×

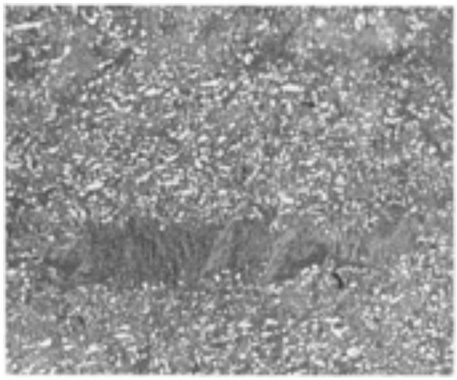

Fig. 97 Ti-6Al-6V-2Sn forging, solution treated, quenched, and aged same as in Fig. 96. The structure is the same as in Fig. 96, except that alloy segregation has resulted in a dark "β fleck" (center of micrograph) that shows no light "primary" α. See also Fig. 98 and 102. Kroll's reagent (ASTM 192). 75×

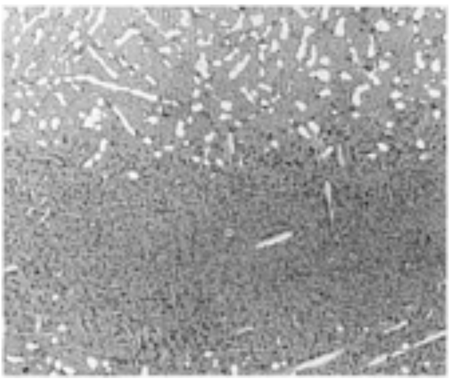

Fig. 98 Ti-6Al-6V-2Sn forging, solution treated for $1\frac{1}{4}$ h at 870 °C (1600 °F), water quenched, and aged 4 h at 575 °C (1070 °F). Structure: same as in Fig. 97, but higher magnification shows a small amount of light, acicular α in the dark "β fleck." See also Fig. 102. 2 mL HF, 8 mL HNO_3, 90 mL H_2O. 200×

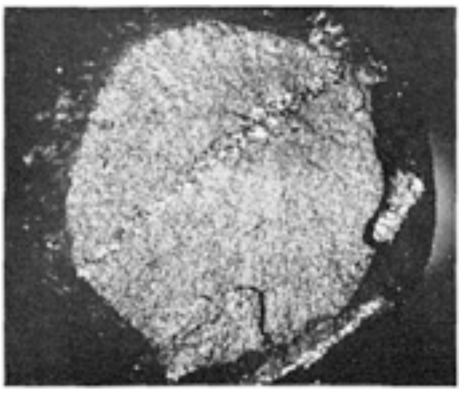

Fig. 99 Ti-6Al-4V-2Sn alloy; fracture surface of a tension-test bar showing a shiny area of alloy segregation that caused low ductility. See also Fig. 100 and 101. Not polished, Kroll's reagent (ASTM 192). 10×

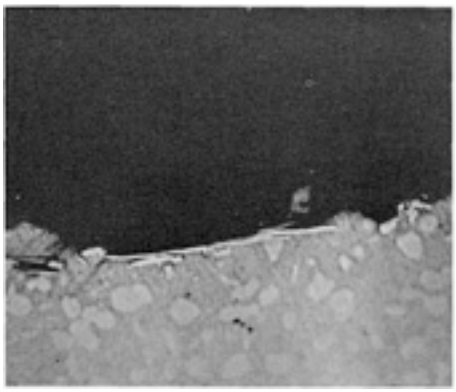

Fig. 100 Same as Fig. 99, except a section normal to the fracture surface, polished down to a stringer of boride compound (light needle) in the area of segregation. See also Fig. 101. Polished, Kroll's reagent (ASTM 192). 400×

[graphic]

Fig. 101 Same as Fig. 99, except a replica transmission electron fractograph of the etched surface, which shows the stringer of boride compound as parallel platelets. Not polished, Kroll's reagent (ASTM 192). 1500×

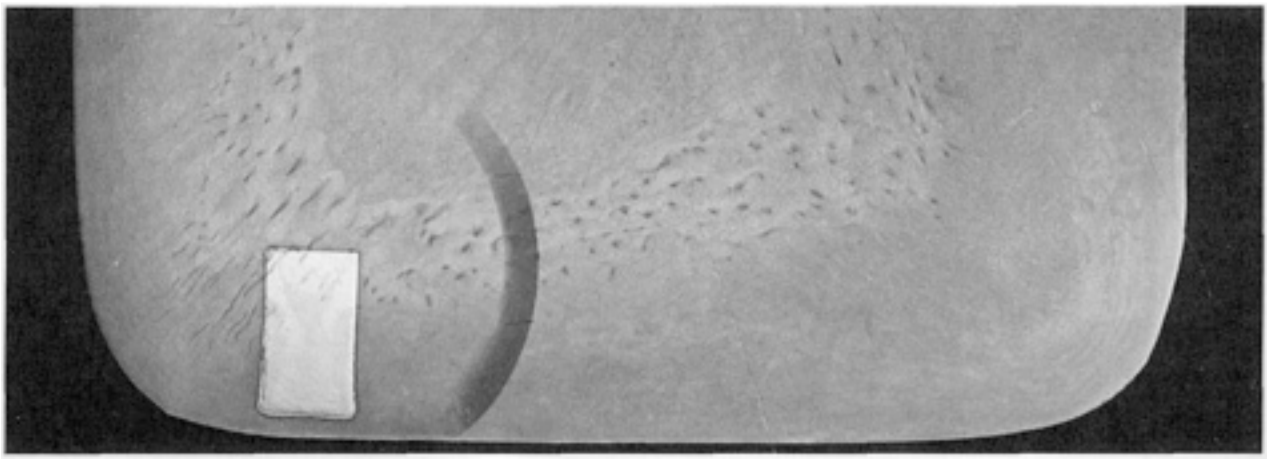

Fig. 102 Ti-6Al-6V-2Sn α + β forged billet illustrating macroscopic appearance of β flecks that appear as dark spots. See also Fig. 97 and 98. 8 mL HF, 10 mL HF, 82 mL H_2O, then 18 g/L (2.4 oz/gal) of NH_4HF_2 in H_2O. Less than 1×. (C. Scholl)

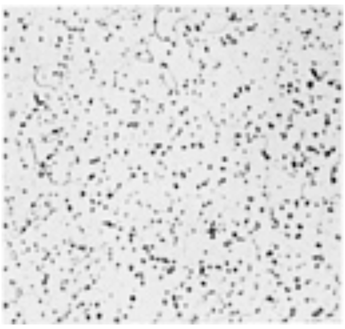

Fig. 103 Ti-3Al-2.5V tube, vacuum annealed for 2 h at 760 °C (1400 °F). Structure is equiaxed grains of α (light) and small, spheroidal grains of β (outlined). See also Fig. 104. 10 mL HF, 5 mL HNO_3, 85 mL H_2O. 500×

[graphic]

Fig. 104 Ti-3Al-2.5V tube that was cold drawn, then stress relieved for 1 h at 425 °C (800 °F). Yield strength, 724 MPa (105 ksi); elongation, 15%. Elongated α grains; intergranular β. Kroll's reagent (ASTM 192). 500×

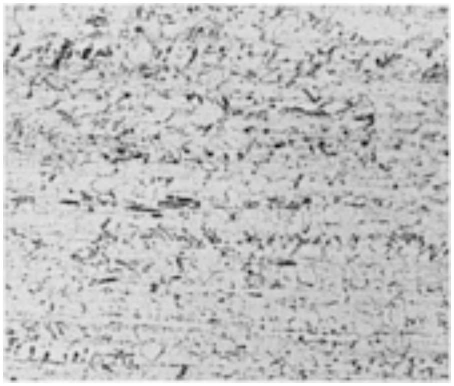

Fig. 105 Ti-11.5Mo-6Zr-4.5Sn sheet, 2 mm (0.080 in.) thick, solution treated 2 h at 760 °C (1400 °F), and water quenched. Elongated grains of β (light) containing some α (outlined or dark). See also Fig. 106. Kroll's reagent. 150×

[graphic]

Fig. 106 Same as Fig. 105, except aged for 8 h at 565 °C (1050 °F) after the water quench following solution treating. Most of the β shown in Fig. 105 has changed to dark α; some β phase (light) has been retained. Kroll's reagent. 150×

[graphic]

Fig. 107 Ti-5Al-2Sn-2Zr-4Cr-4Mo (Ti-17) β-processed forging with heat treatment at 800 °C (1475 °F), 4 h, water quench, + 620 °C (1150 °F). Consists of lamellar α structure in a β matrix with some grain-boundary α. 95 mL H_2O, 4 mL HNO_3, 1 mL HF. 100×. (T. Redden)

[graphic]

Fig. 108 Same as Fig. 107, but a higher magnification better illustrating lamellar α structure in an aged β matrix. Acicular secondary α due to aging not resolvable at this magnification. 95 mL H_2O, 4 mL HNO_3, 1 mL HF. 500×. (T. Redden)

[graphic]

Fig. 109 Ti-3Al-8V-6Cr-4Zr-4Mo rod, solution treated 15 min at 815 °C (1500 °F), air cooled, and aged 6 h at 565 °C (1050 °F). Precipitated α (dark) in β grains. 30 mL H_2O_2, 3 drops HF. 250×.

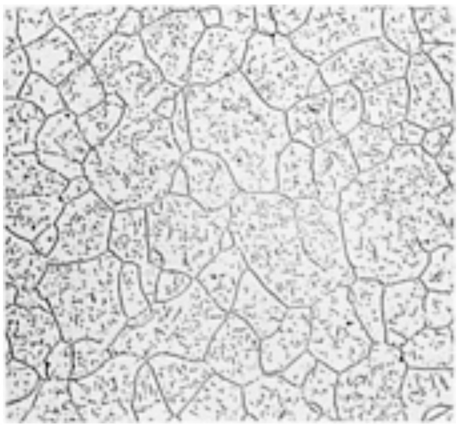

Fig. 110 Ti-3Al-8V-6Cr-4Zr-4Mo rod, cold drawn, solution treated 30 min at 815 °C (1500 °F), and aged 6 h at 675 °C (1250 °F). Precipitated α (dark) in grains of β. Kroll's reagent (ASTM 192). 250×

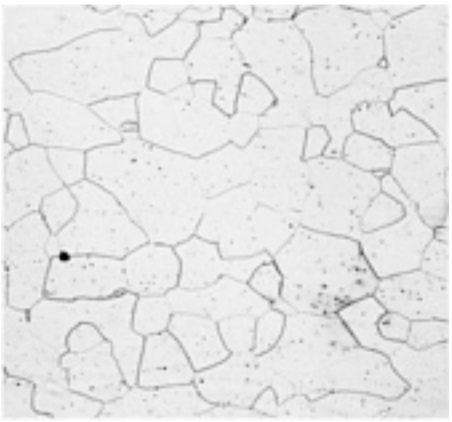

Fig. 111 Ti-13V-11Cr-3Al sheet, rolled starting at 790 °C (1450 °F), solution treated 10 min at 790 °C (1450 °F), air cooled. Equiaxed grains of metastable β. See also Fig. 112. 2 mL HF, 10 mL HNO_3, 88 mL H_2O. 250×.

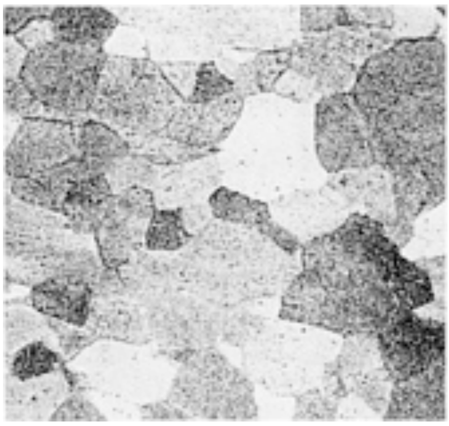

Fig. 112 Same as Fig. 111, except aged for 48 h at 480 °C (900 °F) after solution treating and air cooling. Structure: dark particles of precipitated α in β grains. 2 mL HF, 10 mL HNO_3, 88 mL H_2O. 250×.

[graphic]

Fig. 113 Ti-8.5Mo-0.5Si water quenched from 1000 °C (1830 °F), Thin-foil transmission electron micrograph illustrating heavily twinned athermal α'' martensite. 5000× . (J.C. Williams)

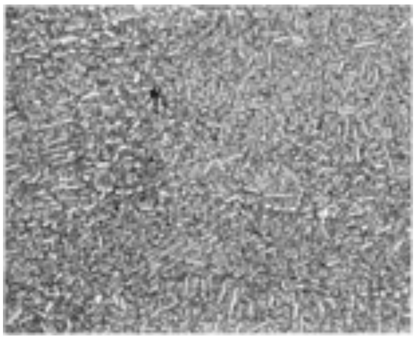

Fig. 114 Ti-10V-2Fe-3Al pancake forging, β forged about 50% + α-β finish forged about 5%, with heat treatment at 750 °C (1385 °F), 1 h, water quench, + 540 °C (1000 °F), 8 h. Lamellor α with a small amount of equiaxed α in an aged β matrix. 10 s with Kroll's reagent, then 50 mL of 10% oxalic acid, 50 mL of 0.5% HF. 400×. (R. Boyer)

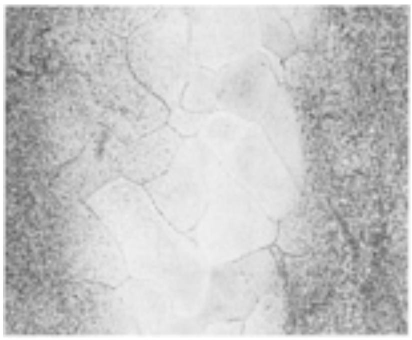

Fig. 115 Same as Fig. 114, but amount of α + β finish forging is 2%. Micrograph illustrates darkened aged β surrounding a lighter etched β fleck. See also Fig. 116. Same etch as Fig. 114. 50×. (T. Long)

[graphic]

Fig. 116 Same as Fig. 115, but at higher magnification to demonstrate the reduced amount of α in the β fleck. The α observed (light) is primary α; the α that forms upon aging is too fine to resolve. Same etch as Fig. 114. 200×. (T. Long)

[graphic]

Fig. 117 A titanium-iron binary alloy, β solution treated, water quenched, and aged to form ω. The ω is the light precipitate in this thin-foil transmission electron micrograph. In alloys where the ω

has a high lattice misfit, the ω is cuboidal to minimize elastic strain in the matrix. 320,000×. (J.C. Williams)

[graphic]

Fig. 118

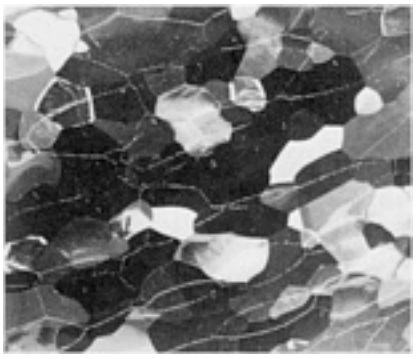

Fig. 119

Ti-10V-2Fe-3Al deformed at 1150 °C (2100 °F). Fig. 118 demonstrates the as-deformed structure that has been heavily etched. The specimen was recrystallized at 925 °C (1700 °F) for 1 h in a vacuum of 10^{-6} torr. Recrystallization in vacuum caused thermal etching of the recrystallized grains (Fig. 119 shows recrystallized structure). The prior unrecrystallized structure can still be observed as ghost boundaries remnant from the initial overetching. Fig. 118: 60 mL H_2O, 40 mL HNO_3, 10 mL HF for 30 min. Fig. 119: 60 mL H_2O, 40 mL HNO_3, 10 mL HF for 30 min + thermally etched at 925 °C (1700 °F) for 1 h in vacuum (10^{-6} torr). Magnification not known. (D. Eylon)

[graphic]

Fig. 120

[graphic]

Fig. 121

[graphic]

Fig. 122

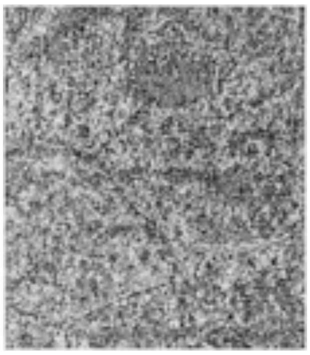

Fig. 123

Ti-15V-3Cr-3Al-3Sn cold-rolled strip that has been annealed at 790 °C (1450 °F) for 10 min and aged at various times to illustrate the progression of aging and what is termed "decorative aging," a technique used to determine the extent of recrystallization. Equiaxed β grains are observed in Fig. 120, which was not aged. Fig. 121 has been aged 2 h at 540 °C (1000 °F) and shows dark aciculor α that forms upon aging. Grains in center are completely aged (uniform α precipitation throughout the grains), which means they were not recrystallized (had more stored energy), resulting in rapid aging. Fig. 122 and 123 carry the progression further with 4- and 8-h aging, respectively. An 8-h age results in a fully aged structure. All etched with Kroll's reagent. All 200×. (P. Bania)

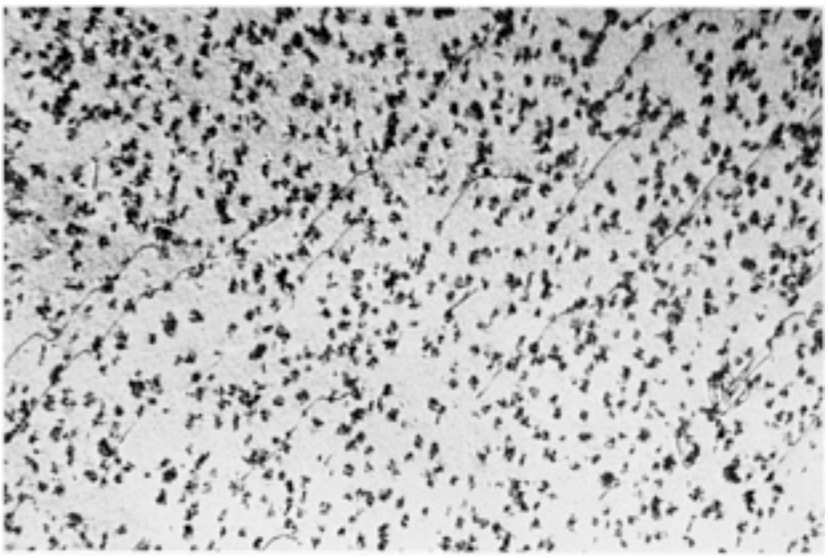

Fig. 124 Ti-40 at.% Nb, β solution heat treated at 900 °C (1650 °F), water quenched, then aged at 400 °C (750 °F) for 24 h. The dark precipitate is β' (solute-lean β phase) in a solute-enriched β matrix. Thin-foil transmission electron micrograph. 31,000×. (J.C. Williams)

[graphic]

Fig. 125 Ti-10V-2Fe-3Al, β solution treated, water quenched, and strained 5% at room temperature. This Nomarski interference micrograph illustrates deformation-induced α'' martensite in a β matrix. No etch. 500×. (J.E. Costa)

<Previous section in this article