

Microstructural Banding in Thermally and Mechanically Processed Titanium 6242

U. Kansal, M.E. Kassner, D.R. Hiatt, and B.M. Bristow

Ti-6Al-2Sn-4Zr-2Mo-0.1Si coupons were shaped by repeated cycles of heating (to 954 °C) and hammer or press forging followed by a solution anneal that varied from 968 to 998 °C. The coupons were originally extracted from billets forged below the beta transus (1009 °C) and slow cooled to ambient temperatures. Macroscopic and microstructural banding is observed in some forged and solution annealed coupons. The microstructure consists of elongated "platelets" of primary alpha. More significant banding is observed subsequent to annealing at lower temperatures (968 °C), whereas subsequent to higher annealing temperatures (998 °C) much less microstructural banding is present. About the same level of banding is observed in hammer forged coupons and press forged coupons. The observation of these bands is significant, because these may lead to inhomogeneous mechanical properties. Specifically, some types of banding are reported to affect the high-temperature creep properties of this alloy. Classically, banding in Ti-6242-0.1Si has been regarded as a result of adiabatic shear, chill zone formation, or compositional inhomogeneity. High- and low-magnification metallography, electron microprobe analysis, and microhardness tests were performed on forged and annealed specimens in this investigation. The bands of this study appear to originate from the microstructure that consists of the forged billet of elongated primary alpha. The deformation of the extracted coupon is neither fully homogeneous nor sufficiently substantial, and the coupon is only partly statically restored after a solution anneal. Areas not fully restored appear as "bands" with elongated primary alpha that are remnant of the starting billet microstructure. Therefore, a source of banding in Ti-6242-0.1Si alloy additional to the classic sources is evident. This type of banding is likely removed by relatively high solution treatment temperatures and perhaps greater plastic deformation during forging.

1. Introduction

Ti-6Al-2Sn-4Zr-2Mo-0.1Si is commonly used with two different microstructures.[1] The first (α/β) microstructure consists of equiaxed α phase in a matrix of transformed β phase. This can be obtained by forging and annealing the alloy at temperatures below the beta transus, T_β, followed by a relatively rapid cooling. The second microstructure is the β or basketweave (Widmanstätten) microstructure, which can be obtained by forging and annealing the alloy above T_β, followed by a relatively rapid cooling. This study emphasized the former microstructure. At relatively low annealing temperatures (*e.g.*, $T = 968$ °C or $T_\beta - 41$ °C), we observed some "banding" of the microstructure of our forged specimens. Such inhomogeneities would be considered undesirable because of an expected nonuniform mechanical behavior. Furthermore, Semiatin[2] reported that "shear" bands can degrade the creep properties of Ti-6242-0.1Si. He found that specimens with many shear bands showed poor high-temperature creep resistance in comparison to the specimens with fewer bands. Enhanced diffusion within these high dislocation density bands was suggested as the reason for enhanced creep. Therefore, in this work, research was performed to understand the origin of the bands in our α/β Ti-6242-0.1Si.

Semiatin[3-6] concluded that, in the case of the nonisothermally upset coupons, chill zones, resulting from the coupon coming into contact with the die, were formed because of the temperature difference between the forged coupon and the die. Bands of localized shear formed between the chill caps, which lead to bulge formation. Forging was performed using a strain rate ≈ 10/sec at a forge temperature of 913 °C ($T_\beta - 96$ °C) and die temperature of 191 °C. Therefore, in this case, shear bands are, at least partly, a result of flow localization due to a temperature gradient. In the nonisothermally sidepressed coupons, at high forging rates, bands were observed on face A forming an X, as the coupon was forged, on the face perpendicular to the dies. These bands initially form at an angle of roughly 45° to the forging direction. At high forging rates (strain rate ≈ 30/sec), the high rate of deformation within the bands may prevent the dissipation of the heat produced by plasticity. As a consequence, an instability may develop and flow localization can continue. No chill caps or bulging was observed in sidepressing of the coupon because the contact area between the die and the workpiece is small and the time of forging was too short for any significant heat exchange to occur between the die and the workpiece. Specimens forged (strain rate ≈ 30/sec) at 913 °C ($T_\beta - 96$ °C) showed intense shear banding, whereas no shear bands were observed when the coupons were forged at 982 °C ($T_\beta - 27$ °C) at the same strain rate. Furthermore, no shear bands were observed in coupons forged at 913 °C ($T_\beta - 96$ °C) as the solution anneal temperature was increased from 954 °C ($T_\beta - 55$ °C) to 979 °C ($T_\beta - 30$ °C). These bands were obvious on etched surfaces at low (<10×) magnification. The microstructural details of these bands were not investigated by Semiatin.

Macroscopic banding in Ti-6Al-4V (also of α/β microstructure) was also reported by Woodward[7] and Me Bar et al.[8] In Woodward's work, high-velocity projectiles impacted Ti-6Al-4V targets, and thin bands were observed with metallographic examination. Again, it was suggested that banding occurs be-

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Table 1 Chemical Composition of Ti-6242-0.1Si[9]

Composition, wt%									
Al	Mo	Sn	Zr	Si	Fe	Cr	Ni	N	O
6.00	2.0	2.02	3.98	0.08	0.088	0.008	0.005	0.011	0.119

Note: Heat No. T 90487

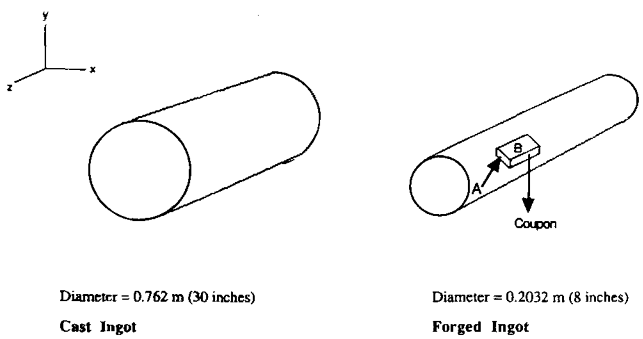

Fig. 1(a) Orientation of the coupons that were cut from the ingots.

cause the high rate of deformation prevents the dissipation of the heat produced by the plastic flow. A negative strain-hardening phenomenon (*i.e.*, thermal softening exceeding the rate of strain hardening of the material) was observed. The thin deformation bands were described as "adiabatic shear bands." Elongation cavities as wide as the shear band were observed and were believed to result from liquification. Me Bar *et al.*[8] also reported the formation of bands in Ti-6Al-4V, resulting from the impact of high-velocity projectiles. Elliptical cavities were also found in these bands. It is not clear whether these bands are an extreme case of the bands in sidepressed specimens observed by Semiatin.

Woodward[7] reported microstructural banding in Ti-6Al-4V that was suggested not to be a result of adiabatic shear. Segregation of alpha phase stabilizers in banded areas was observed, and these regions were associated with a higher volume fraction of alpha phase. Microstructural banding was observed in the plane of rolling in the deformed coupons.

The purpose of the present study was to determine the source of banding in our forged Ti-6242-0.1Si alloy. This included a determination as to whether the above "classic" (*e.g.*, chill caps, adiabatic shear, compositional inhomogeneity) explanations are appropriate. Alternatively, a different kind of explanation may be valid.

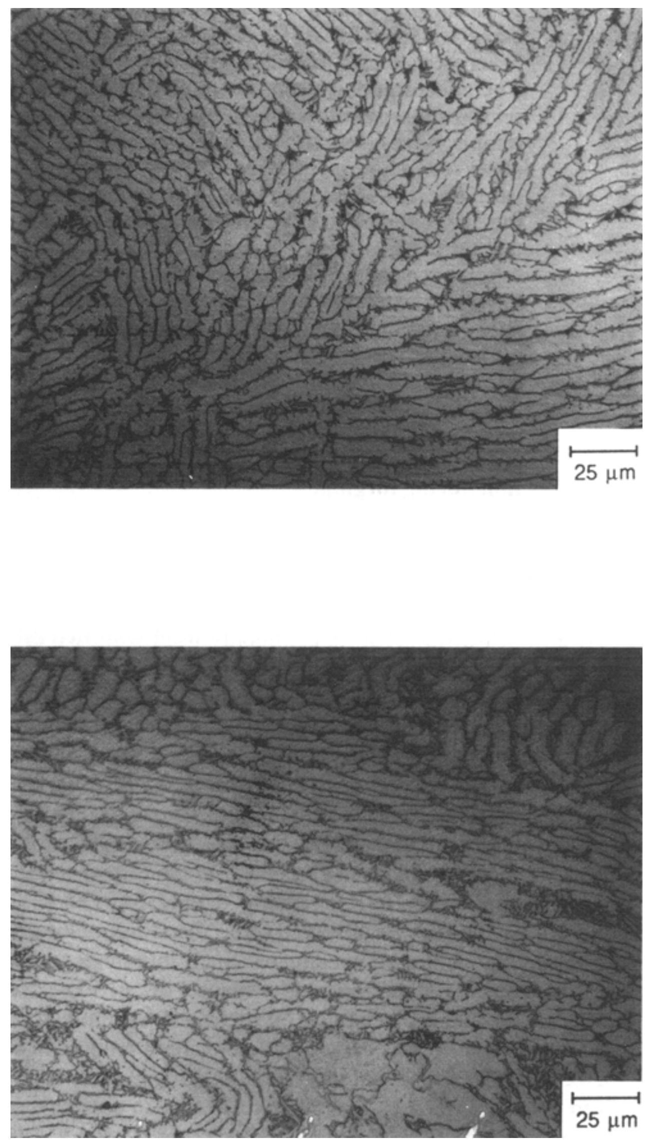

Fig. 1(b) Microstructure of the plane sections of Fig. 1(a).

2. Experimental Procedure

Ti-6242-0.1Si coupons were supplied by OREMET. The specimen composition is listed in Table 1.[9] The beta transus of the material used was found to be 1004 °C using differential temperature analysis (DTA). Ti-6242-0.1Si ingots were cast as 0.7652-m (30-in.) diameter cylinders at OREMET. The billet was fabricated by forging a vacuum arc melted 914-mm-diameter ingot to 152-mm-diameter billet in a two-stage process. The initial breakdown was in the beta temperature range of 1065 to 1149 °C where the ingot was forged down to a 254-mm octagon. The final forging step down to 152 mm was at T_β − 36 °C, resulting in a microstructure of principally equiaxed primary alpha in a transformed beta matrix. Figure 1(a) describes the orientation of the coupons cut from the ingot. Figure 1(b) shows the microstructure of the forged ingot in the

Table 2 Forging and Heat Treatment Summaries

Type	Initial size	Final size	Annealing temperature, °C	Passes(a)	Bands(b)	Strain Engineering	Strain True
Set 1, hammer forged	0.0635 × 0.0635 × 0.038 m	0.041275 × 0.015875 × 0.228 m	968	3	1.5	5.15	1.82
Set 2, hammer forged	0.0635 × 0.0635 × 0.095 m	0.041275 × 0.015875 × 0.5842 m	998	6	2.75	5.16	1.82
Set 3, press forged	0.0635 × 0.0635 × 0.038 m	0.041275 × 0.015875 × 0.228 m	968	3	1.5	5.15	1.82
Set 4, press forged	0.0635 × 0.0635 × 0.038 m	0.041275 × 0.015875 × 0.228 m	993	3	3	5.15	1.82

(a) Pass ≡ deformation sequence between reheating. (b) Bands: 1 ≡ many, 2 ≡ few, 3 ≡ none.

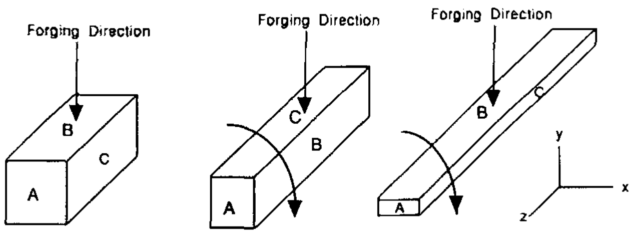

Fig. 2 Hammer and press forging on faces B and C of coupons.

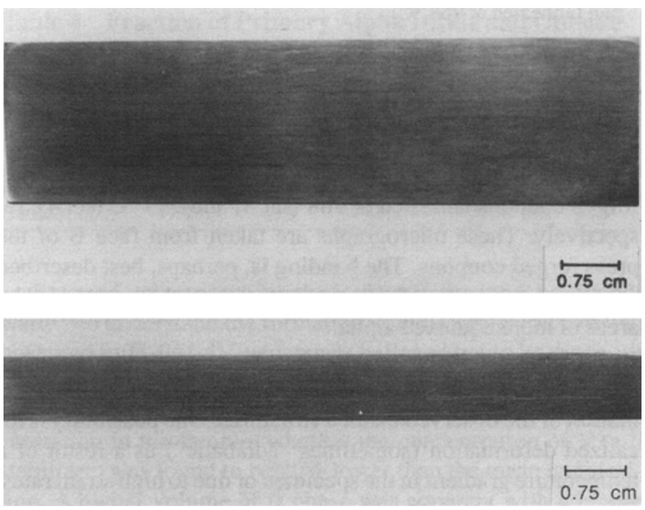

Fig. 3 Bands observed macroscopically on faces B and C (see Fig. 4) in a set 1 hammer-forged coupon annealed at 968 °C (T_β - 41 °C).

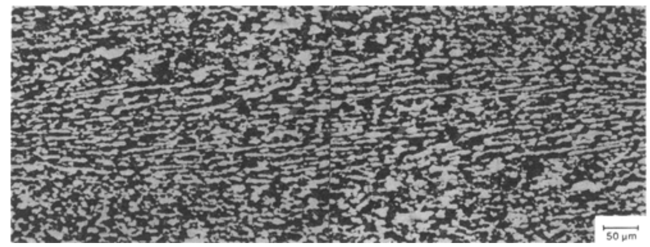

Fig. 4(a) Microstructural banding observed in a set 1 hammer-forged coupon (annealed at 968 °C). Banded structures observed here on face B are parallel to the *z*-direction.

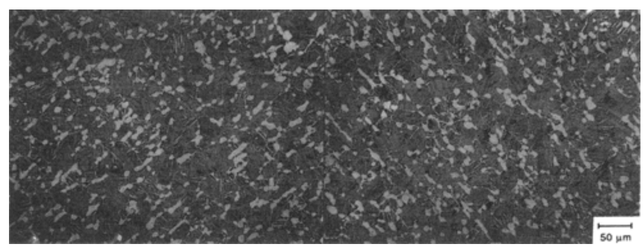

Fig. 4(b) Micrograph from face B in a set 2 hammer-forged coupon (annealed at 998 °C).

plane sections delineated in Fig. 1(a). Elongated primary alpha phase is the dominating feature.

Coupons of dimensions given in Table 2 were cut from a forged ingot along the z-axis of the ingot (as in Fig. 1) and heated at 954 ± 15 °C for 2 hr. The coupons were then either hammer or press forged. Hammer forging (using a Chambersburg Series 2 type forging machine, reported strain rate[10] between 63 and 252 sec^{-1}) was performed at OREMET. Press forging using a 500-ton capacity HPM hydraulic forging press (approximate strain rate between 16 and 63 sec^{-1}) was performed at the U.S. Bureau of Mines, Albany Research Center, Albany, Oregon. Forging proceeded until the flow resistance was excessive. At this point, the temperature of the coupons, determined using an optical pyrometer, dropped to between 901 and 814 °C. The coupons were then returned to the furnace and reheated to 954 ± 15 °C. Coupons were rotated during forging on faces B and C (see Fig. 2). The coupon face with the larger width is denoted "B." Four sets of coupons were forged and annealed. The first two sets of coupons were hammer forged, one in three passes and the second in six passes, then annealed at 968 °C (T_β - 41 °C) and 998 °C (T_β - 11 °C), respectively, for 1 hr and air cooled to ambient temperature. The third and fourth sets of coupons were press forged in three passes and annealed, one at 968 °C (T_β - 41 °C) and the other at 993 °C (T_β - 16 °C) for 1 hr and air cooled to the ambient temperature. Finally, all the coupons were aged at 593 °C for 8 hr and air cooled to ambient temperature.

Metallographic samples were prepared from these coupons. Grinding was performed using 240-, 320-, 400-, and 600-grit silicon carbide grinding papers. The specimens were then polished using 5-, 0.3-, and 0.05-µm alumina powder slurries. The samples were etched using a solution of 1 ml HF, 15 ml HNO_3, and 75 ml of water. The microcomposition of banded regions

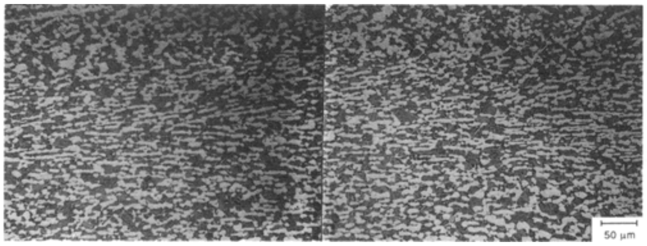

Fig. 5(a) Microstructure of face B observed in a set 3 press-forged coupon (annealed at 968 °C).

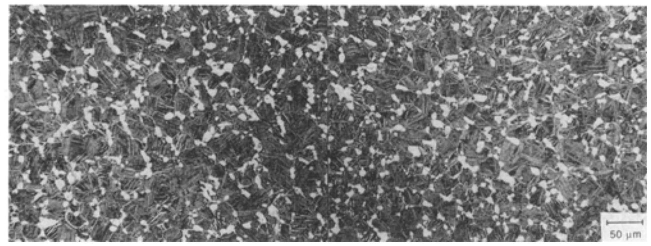

Fig. 5(b) Microstructure of face B observed in a set 4 press-forged coupon (annealed at 993 °C).

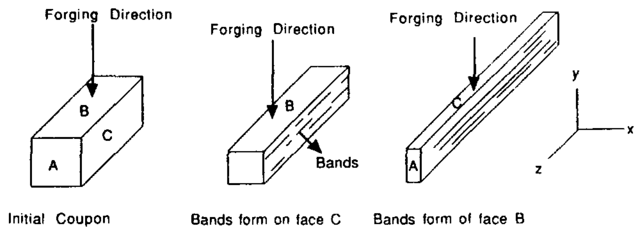

Fig. 6 Bands observed subsequent to forging on face B and face C in a set 1 hammer-forged coupon (annealed at 968 °C).

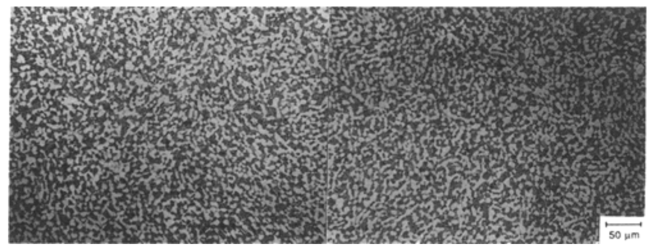

Fig. 7 Microstructure of face A in a set 1 hammer-forged coupon (annealed at 968 °C).

was determined using a Cameca SX 50 electron microprobe. Microhardness studies inside and outside the banded regions were performed using a Leco M-400 A microhardness testing machine. The fraction of primary alpha inside and outside the banded structures was calculated using an optical microscope equipped with an Automatix Inc.version 7.2 image analyzer. Higher magnification metallography was performed using an AmRAY 1000A scanning electron microscope (SEM).

3. Results

Metallographic examination of the specimens frequently revealed thin bands that could be observed macroscopically (<10×) after prolonged etching. Obvious banding was reported in set 1 (hammer forged) and set 3 (press forged) coupons annealed at the relatively low temperatures of 968 °C ($T_\beta - 41$ °C). The coupons from set 2 and set 4, forged and annealed at higher temperatures of 993 °C ($T_\beta - 16$ °C) and 998 °C ($T_\beta - 11$ °C), showed little or no banding. Figure 3 shows the macrographs of these bands on faces B and C of a hammer forged specimen subsequently annealed at 968 °C. Microstructural examination of these coupons was consistent with the macroscopic analysis. The specimens revealed banding of primary alpha in set 1 coupons (hammer forged at the standard temperature and annealed at 968 °C) and set 3 coupons (press forged at the standard temperature and annealed at 968 °C). The banding was observed on both faces B and C and was primarily aligned in the z-direction. Set 2 coupons (hammer forged at the standard temperature and annealed 998 °C) showed very little banding, whereas no banding was observed in the set 4 coupons (press forged and annealed at 993 °C). The plane sections shown in Fig. 4(a) and Fig. 4(b) were extracted from a set 1 (annealed at 968 °C) and from a set 2 coupon (annealed at 998 °C). Some banding was also observed in press forged coupons (set 3) annealed at 968 °C. Figures 5(a) and 5(b) show the microstructure of press forged coupons annealed at 968 (set 3) and 993 °C (set 4), respectively. These micrographs are taken from face B of the press forged coupons. The banding is, perhaps, best described as regions or bundles of elongated primary alpha surrounded by areas of more equiaxed alpha.

As discussed in the introduction, based on the literature[3-8], there appears to be several "classic" explanations for the formation of the observed banded structures. One possibility is localized deformation (sometimes "adiabatic") as a result of a temperature gradient in the specimen or due to high strain rates. Compositional variation leading to heterogeneous plastic flow is another possible explanation. Figure 6 shows bands observed subsequent to forging on face B and face C in a set 1 hammer forged coupon (annealed at 968 °C). No bands were revealed on face A of the coupon. Figure 7 shows the microstructure of face A in a set 1 hammer forged coupon (annealed at 968 °C). These findings are significant because the shear bands observed by Semiatin often form at angles near 45° to the forging direction. Therefore, there was some doubt as to whether the bands of our study were the result of the same shearing process observed by Semiatin.

The bands were also examined using a scanning electron microscope (SEM). The SEM was used to reveal whether cavities had formed in the bands, as observed by Woodward[7] and Me Bar and Shechtman.[8] No microvoid formation was observed in our specimens, consistent with the proposition that the bands are not the result of an adiabatic shear process. Microscopically, these bands consisted of elongated primary alpha, observable only at relatively high magnifications.

Table 3 Normalized Values of Electron Microprobe Chemical Analysis Within and Outside the Banded Regions of a Set 1 Hammer-Forged Coupon Annealed at 968 °C

	Composition, wt%						
Specimen	Ti	Al	Si	Zr	Fe	Mo	Sn
Average inside bands							
Band 1	86.5	5.63	0.09	4.0	0.09	1.9	2.1
Band 2	85.9	5.60	0.09	4.3	0.09	2.0	2.2
Band 3	86.0	5.54	0.09	4.1	0.09	1.9	2.1
Band 4	86.0	5.75	0.09	4.1	0.09	1.9	2.2
Band 5	84.7	5.77	0.10	4.5	0.08	1.9	2.2
Band 6	86.1	5.53	0.07	4.2	0.08	2.0	2.2
Average	85.9	5.64	0.09	4.2	0.09	2.0	2.2
Standard deviation	0.61	0.10	0.01	0.1	0.00	0.03	0.04
Average outside bands							
Band 1	86.4	5.60	0.09	4.0	0.09	1.9	2.0
Band 2	85.4	5.56	0.1	4.3	0.1	2.0	2.1
Band 3	85.4	5.68	0.1	4.8	0.09	1.8	2.1
Band 4	85.2	5.68	0.09	4.2	0.09	2.0	2.2
Band 5	85.0	5.76	0.09	4.3	0.09	2.0	2.2
Band 6	86.3	5.53	0.09	4.3	0.09	1.9	2.1
Average	85.6	5.63	0.10	4.3	0.09	1.9	2.1
Standard deviation	0.60	0.08	0.03	0.28	0.004	0.1	0.07

Table 4 Fraction of Primary Alpha Inside and Outside a Banded Region in a Set 1 Hammer Forged Coupon Annealed at 968 °C

	Primary alpha, %				
	Band 1	Band 2	Band 3	Band 4	Average
Inside	50.1	49.9	49.9	49.7	49.9
Outside	49.9	49.9	49.8	49.8	49.9

Electron microprobe analysis was performed by Woodward[7] to understand the formation of microstructural banding observed in Ti-6Al-4V, which was believed not to be the result of adiabatic shear. The concentration of Al (an α stabilizer) within the band was found to be 5% higher than the mean concentration in the sample, whereas the concentration of V (a β stabilizer) was found to be 20% lower than the mean composition. A higher volume of α phase was apparent with a higher concentration of α stabilizer within the bands.

Electron microprobe analysis was performed across the microstructural bands in our samples. Table 3 reports the electron microprobe composition results inside and outside the banded areas in a hammer forged coupon (annealed at 968 °C). These results were normalized because of the scattering (due to pitting, fine scratches, etc.) during the microprobe analysis. The percent error for counting statistics (due to backscattering) in the analysis is ±0.19% for Ti, ±0.04% for Al, ±0.004% for Si, ±0.15% for Zr, ±0.013% for Fe, ±0.08% for Mo, and ±0.056% for Sn. From Table 3, it is evident that there is not a significant compositional difference between banded and unbanded regions. Image analysis was used to calculate the volume fraction of α percent inside and outside the bands. Table 4 reports the results from four different bands in a set 1 hammer forged coupon (annealed at 968 °C). As expected from microprobe analysis, the fraction of primary alpha phase is found to be essentially the same inside and outside the bands. Therefore, we do not believe that the bands are the result of any compositional variation.

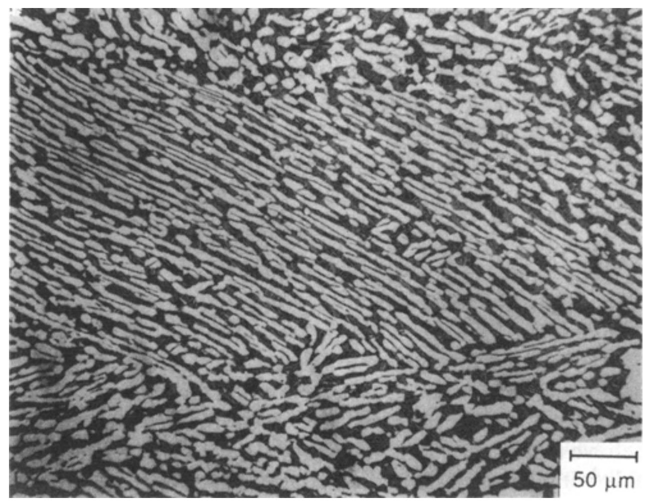

Fig. 8 Microstructure of the coupon before hammer or press forging but subsequent to heating for 2 hr at 954 °C (T_β –55 °C).

In other investigations of Ti-6242-0.1Si and Ti-6Al-4V,[6-7] the bands, when observed subsequent to deformation, were found to be harder than the material surrounding these bands. Semiatin suggests that the "finer microstructure of these bands causes the higher hardness."[4] We found that the hardness inside and outside the banded structures observed in the set 1 hammer forged coupon (annealed at 968 °C) were 435 and 416 DPH, respectively.

4. Discussion

From the above results, the bands observed in our work may be explained as follows. Based on Fig. 1(b), the ingot initially consists principally of primary α grains elongated along the *z*-direction (axes) of the forged ingot. Interestingly, the banded structures were still observed in these coupons after heating at 954 °C for 2 hr (before the coupons were forged), as shown in Fig. 8. Transformed β is observed as darker areas in the micrograph, which is not observed in Fig. 1(a) due to slower cooling of the ingot.

Apparently, the regions with elongated α microstructure of our forged coupons did not completely recrystallize to equiaxed primary α (in a transformed β matrix) after repeated forging and reheating to 968 °C. The unrecrystallized elongated primary α would have a higher dislocation density and, therefore, higher hardness, as observed. When annealed at 968 °C, the more heavily deformed regions undergo restoration (*i.e.*, recovery and recrystallization), and this structure becomes relatively equiaxed. The remaining structure consists of elongated primary α grains, which is similar to the starting ingot microstructure. The final microstructure consists of elongated α surrounded by equiaxed and transformed β grains. These deformed α grains that did not restore etch differently than the rest of the microstructure and can be seen macroscopically. No microvoid formation was seen in our work, as confirmed by SEM. The fact that there is not a pronounced dependence of banding on strain rate (press forged versus hammer forged) suggests that these may not be the result of a shear banding phenomenon. On annealing at 998 °C, most of the microstructure restores to an equiaxed shape, and little microstructural banding is observed. With these higher annealing temperatures, the banding that is present is at least partially obscured by a low volume fraction of primary alpha. Also, fewer bands are seen macroscopically.

Therefore, with the analysis of the above results, we believe that the bands observed in this study are not a consequence of compositional variation or shear bands, but rather areas of incomplete static restoration together with a starting microstructure of elongated primary alpha grains. Although others[11] have observed that our strain levels during forging (see Table 2) might preclude the proposed type of banding, we nonetheless believe that "remnant" bands are evident in our work. Presumably with greater forging (higher plastic strains), the elongated alpha is increasingly "broken up" and there would be a higher "driving force" for the restoration mechanisms that would mitigate banding. Higher annealing temperatures would also encourage restoration. The effect of these particular bands on creep properties has not been established.[12] As these bands may lead to inhomogeneous mechanical properties, the above steps may be recommended. Therefore, an additional source of banding is documented and should be considered in thermal and mechanical processing.

5. Conclusions

Banding is observed in Ti-6242-0.1Si coupons that were forged (using hammer and press forging) and annealed at low annealing temperatures (954 °C and $T_\beta - 55$ °C and 968 °C and $T_\beta - 41$ °C). Microscopically, these bands are "bundles" of elongated primary α and transformed β grains. Very few bands are observed after annealing at higher temperatures (998 °C and $T_\beta - 11$ °C).

The observed bands are not believed to be classic "shear bands," because they did not become more pronounced at a higher strain rate. Furthermore, the bands never appeared at expected angles (*e.g.*, 45°) to the forging direction. Also, microvoids, often associated with adiabatic shear bands, were not observed.

No compositional change was found to occur in the microstructural bands. Hence, the phenomenon of deformation banding due to compositional variation was not observed, as reported in some other α/β titanium alloy investigations. It appears that the observed bands have ancestry to the starting ingot microstructure, which consists of elongated primary alpha resulting from forging and slow cooling. Subsequent heating and forging sequences restore (recrystallize and/or recover) most, but not all, of the substructure. The remnant alpha is elongated and relatively hard. Large strain deformation and/or higher annealing temperatures restore nearly all of the substructures, and the inhomogeneities of bands appear to disappear.

Acknowledgments

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