

AN ABSTRACT OF THE THESIS OF

Utkarsh Kansal for the degree of Master of Science in Mechanical Engineering
presented on January 21, 1992.

Title: Microstructural Banding in Thermally and Mechanically Processed Titanium 6242.

Redacted for Privacy

Abstract approved:

Prof. M.E.Kassner

Ti-6Al-2Sn-4Zr-2Mo-0.1Si specimens 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 temperature. Macroscopic and microstructural banding is observed in some forged and solution annealed coupons, that consists of regions of elongated primary alpha. More significant banding is observed subsequent to annealing at lower temperatures (968 °C), whereas much less microstructural banding is present after annealing at higher temperatures (998 °C). About the same level of banding is observed in hammer forged and press forged coupons. The observation of these bands is significant since they may lead to inhomogeneous mechanical properties. Specifically, at least some types of banding are reported to affect the high temperature creep properties of this alloy. The origin of these bands was therefore researched. 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 composition inside the bands appears identical to that outside of the bands. The fraction of primary alpha is also found to be identical. The bands have higher microhardness. These results suggest that the bands are not related to composition gradients. The bands also do not appear to be a result of adiabatic shear or other localized deformation. The bands of this study appear to originate from the elongated primary alpha microstructure of the forged billet (from which test coupons were extracted). The deformation of the extracted coupon may be 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.

Microstructural Banding in
Thermally and Mechanically Processed Titanium 6242

by
Utkarsh Kansal

A THESIS
submitted to
Oregon State University

in partial fulfillment of
the requirements for the
degree of
Master of Science

Completed January 21, 1992

Commencement June 1992

APPROVED:

Redacted for Privacy

Professor of Mechanical Engineering in charge of major

Redacted for Privacy

Head of department of Mechanical Engineering

Redacted for Privacy

Dean of Graduate School

Date thesis is presented January 21, 1992

Typed by Utkarsh Kansal for Utkarsh Kansal

ACKNOWLEDGEMENTS

I would like to acknowledge financial support from U.S. Bureau of Mines, the Oregon Economic Development Department and OREMET Titanium, through the Oregon Metals Initiative for making this research possible. In addition, I am thankful to Dr. Roger Neilsen for the microprobe analysis and Mr. Al Soldner for SEM work . Discussions and help from Prof. Bill Warnes, Mr. Michael Tolle and Mr. Kurt Thiehsen are highly appreciated. Finally, I am extremely thankful to Prof.M.E. Kassner for his guidance, motivation and all help to me with which this thesis was made possible.

TABLE OF CONTENTS

INTRODUCTION	1
EXPERIMENTAL PROCEDURE	11
RESULTS	18
DISCUSSION	32
CONCLUSIONS	35
REFERENCES	36

LIST OF FIGURES

<u>Figure</u>	<u>Page</u>
1. Phase diagram showing α , β , $\alpha+\beta$ regions in titanium alloys.	2
2. Constant load 510 °C (950 °F) creep data for samples cut from α/β preform microstructure forgings in which (a) shear bands were present (b) there were no shear bands. [9]	3
3. Upset and sidepress forging of a cylindrical bar [3].	4
4. Shear band formation during forging(isothermal and non-isothermal) as reported by Semiatin [13].	7
5(a). Orientation of the coupons that were cut from the ingots.	13
5(b). Microstructure of the plane sections of 5(a).	14
6. Hammer and press forging on faces B and C of coupons.	16
7. Bands observed macroscopically on faces B and C in a set 1 hammer forged coupon (annealed at 968 °C ($T_\beta - 41$ °C)).	19
8(a). The final shape of the forged coupon and the plane-sections from which micrographs (shown in Figure 8(b) and Figure 8(c)) were extracted from two hammer forged coupons (from a set 1 coupon (annealed at 968 °C) and from a set 2 coupon (annealed at 998 °C ($T_\beta - 11$ °C))).	20
8(b). 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.	21
8(c). Micrograph from face B in a set 2 hammer forged coupon (annealed at 998 °C). Bands do not appear to be present.	21
9(a). Micrograph from face B in a set 3 press forged coupon (annealed at 968 °C). Some banding is evident.	22

9(b).	Microstructure from face B in a set 4 press forged coupon (annealed at 993 °C). Banding is not evident.	22
10.	Microstructure of face A in a set 1 hammer forged coupon (annealed at 968 °C).	24
11.	Schematic of the bands observed subsequent to forging on face B and face C in a set 1 hammer forged coupon (annealed at 968 °C).	25
12.	SEM micrograph of bands observed on face B in a set 1 hammer forged coupon (annealed at 968 °C). The band is surrounded by microhardness indentations.	26
13.	Microstructure of the coupon before hammer or press forging but subsequent to heating for 2 hours at 954 °C ($T_{\beta} - 55$ °C).	33

LIST OF TABLES

<u>Table</u>	<u>Page</u>
1. Processing conditions evaluated for development of shear bands [9].	8
2. Chemical composition of the tested Ti-6242-01.Si.	12
3. Forging and heat treatments summaries.	15
4 A. Results of electron microprobe analysis performed on a set 1 hammer forged coupon (annealed at 968 °C).	28
4B. Normalized values of electron microprobe results of a set 1 hammer forged coupon (annealed at 968 °C) described in Table 4 A.	29
5. The fraction of primary alpha inside and outside the banded structure in a set 1 hammer forged coupon (annealed at 968 °C).	30
6. Microhardness values inside and outside the bands of face B in a set 1 hammer forged coupon (annealed at 968 °C).	31

MICROSTRUCTURAL BANDING IN THERMALLY AND MECHANICALLY PROCESSED TITANIUM 6242

INTRODUCTION

Titanium alloys are widely used in different technical applications because of their light weight, high temperature strength and favorable corrosion properties. In gas turbine engines, compressor blades are made of Ti-6242-0.1Si and are capable of operating at temperatures up to 480-510 °C. Pure titanium undergoes a phase change from the α phase (hcp) to the β phase (bcc) when heated above 882.5 °C. This transition temperature is shifted with different alloying elements. The elements (e.g. Al, Ga etc.) which increase the transition temperature are known as α stabilizers. Titanium alloys containing these elements and have a hcp structure at ambient temperatures are known as α alloys. The elements (e.g. Mo, V, Nb etc.) which decrease the transition temperature are known as β stabilizers, and alloys that have a bcc structure at ambient temperature are known as β alloys. Titanium alloys containing both α and β stabilizers are known as α/β alloys. These alloys may consist of a mixture of α and β phases at ambient temperature. Usually α/β alloys contain 10 to 50% β phase at ambient temperature. In Ti - 6242, the 0.1Si and 6% Al are α stabilizers, 2% Mo acts as β stabilizer, 2% Sn and 4% Zr are added for solid solution strengthening. The 0.1% Si is principally added to improve the creep properties of the alloy. The phase change from α to β in Ti - 6242 - 0.1% Si occurs at approximately 990 °C [4].

Figure 1 shows the phase diagram with α , β and $\alpha+\beta$ regions in a general titanium alloy. As the alloy is cooled from above the transition temperature the transformed β structure varies from martensitic to Widmanstätten depending upon the cooling rate (varying from water quenching to air cooling). Slow cooling results in equiaxed α (plus

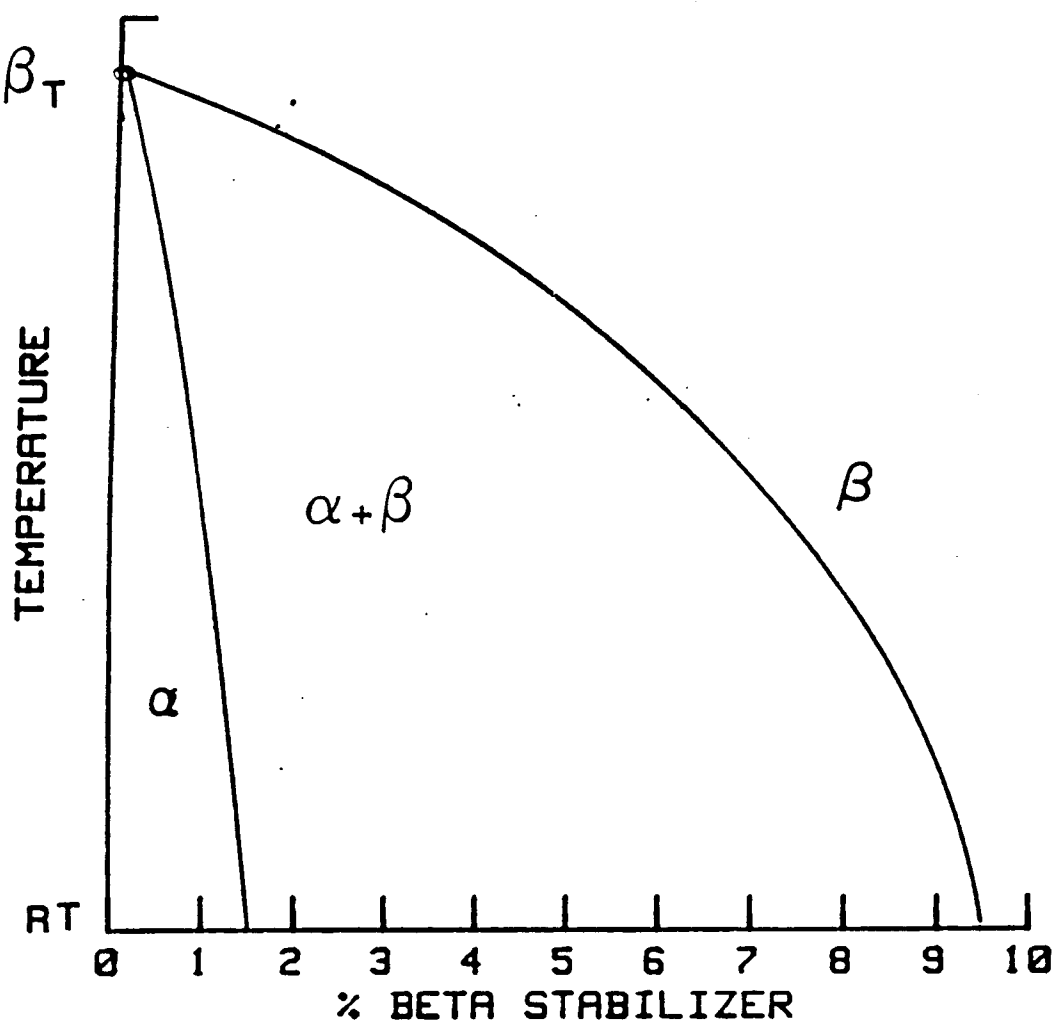


Figure1. Phase diagram showing α , β , $\alpha + \beta$ regions in titanium alloys[1].

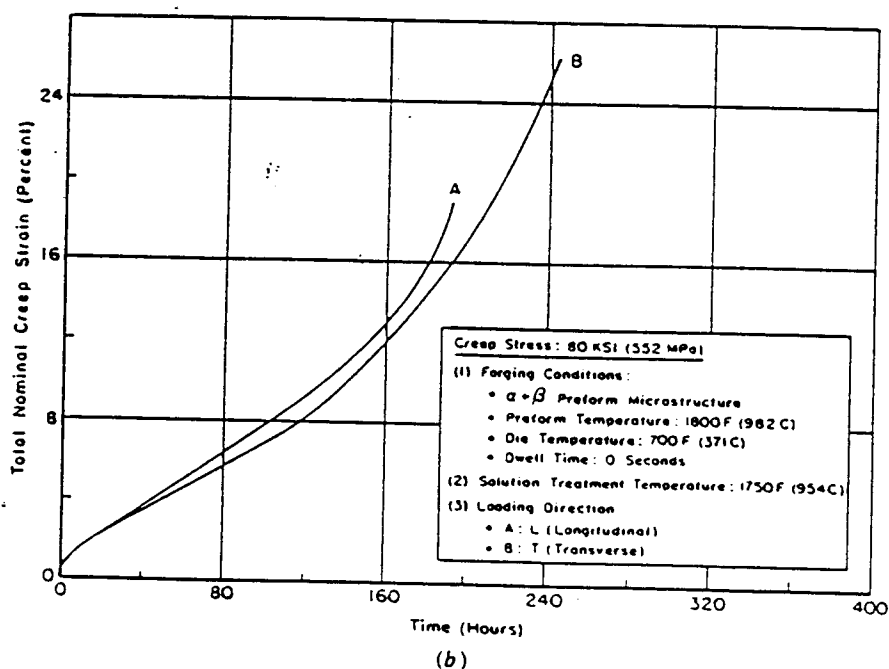
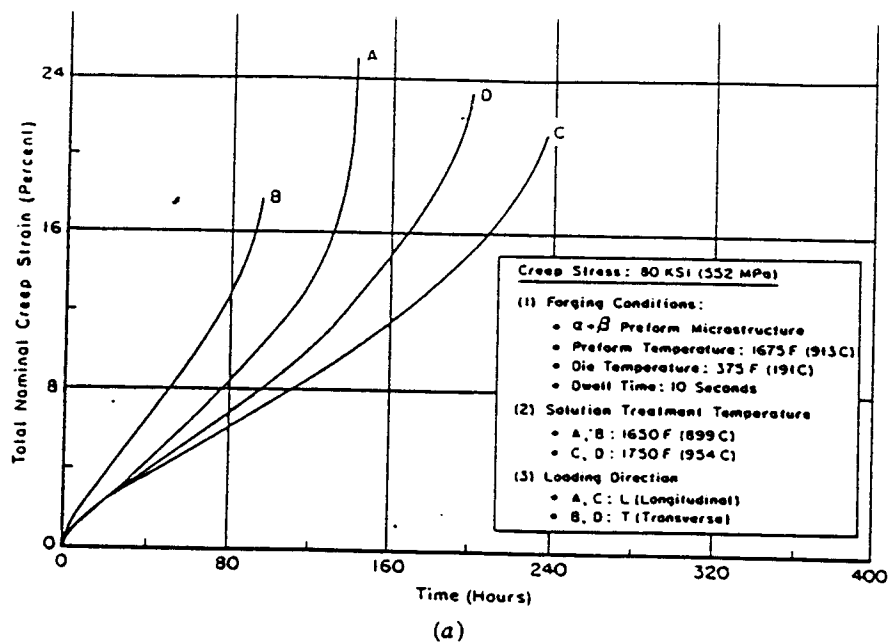
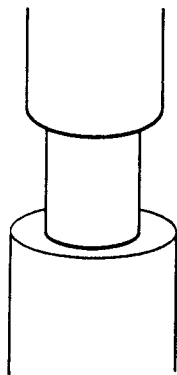
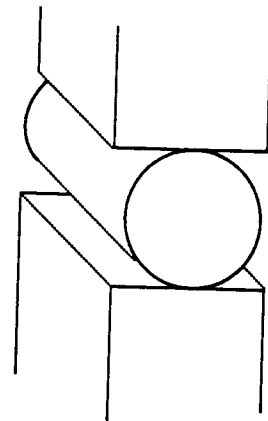


Figure 2. Constant load 510 °C (950 °F) creep data for samples cut from α/β preform microstructure forgings in which (a) shear bands were present (b) there were no shear bands. [9]



Upsetting



Sidepressing

Figure 3. Upset and sidepress forging of a cylindrical bar [3].

10% β for titanium 6242). A solution anneal below the β transus followed by relatively rapid cooling gives a microstructure of equiaxed α in the matrix of transformed β (usually Widmanstätten) microstructure. Ti-6%Al-2%Sn-4%Zr-2%Mo-0.1%Si is commonly used with two different microstructures [4]. The first 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. This is known as α/β microstructure. The second is a completely transformed 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.

The fabrication of α/β titanium alloys usually consists of a forging or forming operation at elevated temperature below T_β followed by a solution anneal (also below T_β) followed by a stabilization treatment at 593 °C for 8 hours. At relatively low annealing temperatures (e.g. $T = 968$ °C or $T_\beta - 41$ °C) we observed some "banding" in the microstructure of our forged specimens. Such inhomogeneities would usually be considered undesirable because of an expected non-uniform mechanical behavior. Furthermore, Semiatin 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. Creep rates of specimens with and without shear bands, as reported by Semiatin [9], are shown in Figure 2. Diffusion has been believed to be responsible for elevated temperature creep [5]. 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. Once the source had been identified, mitigative steps could be taken.

The formation of shear or deformation bands during high strain rate forging has been reported by Semiatin [10,11,12,13] in Ti-6242-0.1Si. He found that as the coupons

are forged at elevated temperatures, thin regions of localized deformation crossing many grains were observed for 50% or higher reduction in non-isothermal upsetting and sidepressing of the coupons (see Figure 3 for the description of two processes). These bands were increasingly "diffused" as the coupons were solution annealed above 954 °C (T_{β} - 55 °C). Semiatin explained the formation of shear bands in different forging conditions as follows.

Semiatin concluded that in the case of the non-isothermally upset coupons (forging during which the workpiece cools because of the contact with the cooler dies), chill zones, resulting from the coupon coming into contact with die, were formed because of the temperature difference between the forged coupon and the die. Bands of localized shear formed between the chill caps led to bulge formation. Forging was performed using a strain rate $\approx 10 \text{ s}^{-1}$ at a forge temperature = 913 °C (T_{β} - 96 °C) and die temperature = 191 °C. Therefore, in this case, shear bands are, at least partly, a result of flow localization due to a temperature gradient. In the "non-isothermally" sidepressed coupons, at high forging rates, bands were observed on face A (see Figure 4) forming an 'X', as the coupon was forged on face B. These bands initially form at an angle of roughly 45° to the forging direction. With larger deformation, some of these bands form a larger angle with the forging direction. If the forging is performed at low strain rates, any heat developed from deformation is dissipated. At high strain rates, there is local heating of the metal due to plastic work (because of short deformation times). The heat locally raises the temperature and causes thermal softening. The heat from deformation exceeds the strain hardening rate of the material. Thus, flow localization occurs in the material. At high forging rates (strain rate $\approx 30 \text{ s}^{-1}$), the high rate of deformation within the bands may prevent the dissipation of the heat that is 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 since the contact area between die and the workpiece is small and time of forging was too short for any significant heat exchange to occur between the die and the

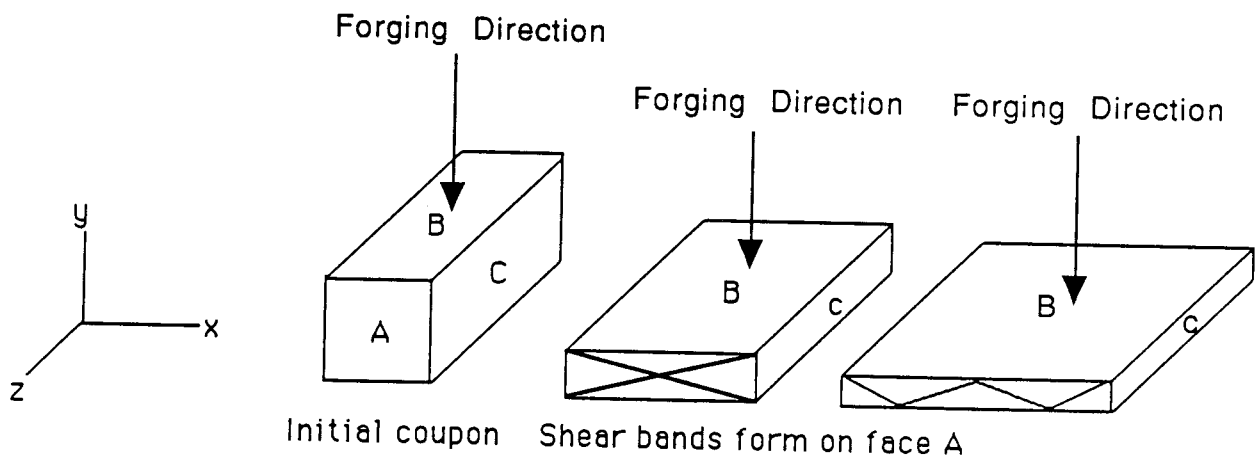


Figure 4. Shear band formation during forging(isothermal and non-isothermal) as reported by Semiatin [13].

TABLE 1. Processing conditions evaluated for development of shear bands [9].

Preform Micro- structure	Forging Temp.	Die Temp.	Shear Band Rating after Heat Treatment				
			F	A	B	C	D
$\alpha+\beta$	913 °C	191 °C	1	1.5	2	3	3
$\alpha+\beta$	913 °C	371 °C	1	1	2	2.75	3
$\alpha+\beta$	982 °C	191 °C	3	3	3	3	3
$\alpha+\beta$	982 °C	371 °C	3	3	3	3	3

Strain rate $\approx 30 \text{ s}^{-1}$

Qualitative shear band rating:

1 - Intense shear bands; 2 - Weak shear bands; 3 - No shear bands

Heat Treatments code:

F - As forged (no heat treatment)

A - 898 °C/ 1 hour + 593 °C/ 8 hours; B - 954 °C/ 1 hour + 593 °C/ 8 hours; C - 979 °C/ 1 hour + 593 °C/ 8 hours; D - 1010 °C/ 1 hour + 593 °C/ 8 hours

workpiece.

In sidepressed coupons, the effects of forging temperature, strain rate and the solution anneal temperature on band formation/presence have been reported by Semiati. Table 1 shows which processing conditions are associated with shear bands [9]. Specimens forged (strain rate $\approx 30 \text{ s}^{-1}$) at 913°C ($T_\beta - 96^\circ\text{C}$) showed intense shear banding whereas no shear bands were observed when the coupons were forged at 982°C ($T_\beta - 27^\circ\text{C}$) at the same strain rate. Further, no shear bands were observed in coupons forged at 913°C ($T_\beta - 96^\circ\text{C}$) as the solution anneal temperature was increased from 954°C ($T_\beta - 55^\circ\text{C}$) to 979°C ($T_\beta - 30^\circ\text{C}$). These bands were obvious on etched surfaces at low ($<10 \times$) magnification. The microstructural details of these bands were not investigated by Semiati.

Macroscopic banding was reported by Woodward [16] and Me Bar et al. [7] in Ti-6Al-4V (also of a α/β microstructure). 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 because the high rate of deformation prevents the dissipation of the heat produced by the plastic flow. Here, again, a negative strain hardening phenomenon (i.e. thermal softening exceeding the rate of strain hardening of the material) is observed. The thin deformation bands were described as "adiabatic shear bands". Elongated cavities as wide as the shear bands were observed and were believed to result from liquification. Me Bar et. al. [7] 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 Semiati. Woodward [16] reported microstructural banding in Ti-6Al-4V that was suggested not to be a result of adiabatic shear. Segregation of α -phase stabilizers in banded areas was observed and these regions were associated with a higher volume-fraction of α 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-6242-0.1 Si 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 explanation may be valid.

EXPERIMENTAL PROCEDURE

Ti-6242-0.1Si, coupons were supplied by OREMET and the composition is listed in Table 2 [8]. The beta transus (T_β) of the material used was found to be 1009 °C using differential thermal analysis (DTA). Ti-6242-0.1Si ingots were cast as 0.762 m (30 inches) diameter cylinders at OREMET. These ingots were press forged at 971 °C to 0.2032 m (8 inches) diameter cylinders and air cooled to ambient temperature. Figure 5(a) describes the orientation of the coupons cut from the ingot. Figure 5(b) shows the microstructure of the forged ingot in the plane sections delineated in Figure 5(a). Elongated primary alpha phase is the dominating feature due to relatively slow cooling and the plastic deformation of the ingot.

Coupons of dimensions listed in Table 3 were cut from a forged ingot along the z-axis of the ingot (as in figure 5) and heated at 954 ± 15 °C for 2 hours. The coupons were then either hammer or press forged. Hammer forging (using a Chambersburg Series 2 type forging machine with a reported strain rate between 63 and 252 s⁻¹[5]) was performed at OREMET. Press forging (using a 500 ton capacity HPM hydraulic forging press (approximate strain rate between 16 and 63 s⁻¹[15]) was performed at the US Bureau of Mines, Albany Research Center, Albany, OR. 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 °C 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" (Figure 6).

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 ($T_\beta - 41$ °C) and 998 °C ($T_\beta - 11$ °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 ($T_\beta - 41$ °C)

TABLE 2. Chemical composition of the tested Ti-6242-01.Si [8]

(weight %)											
Ti	Al	Mo	Sn	Zr	Si	Fe	Cr	Ni	N	O	Others
85.69	5.97	2.0	2.02	3.99	0.08	0.08	0.01	0.004	0.011	0.119	0.03

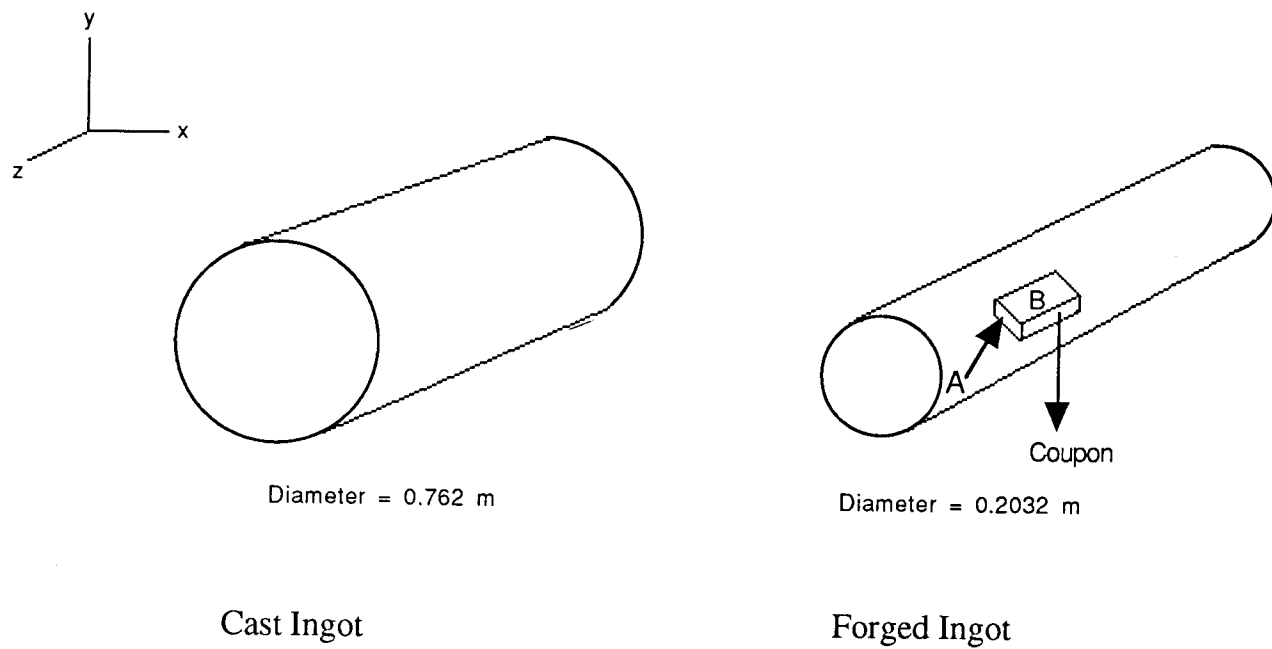
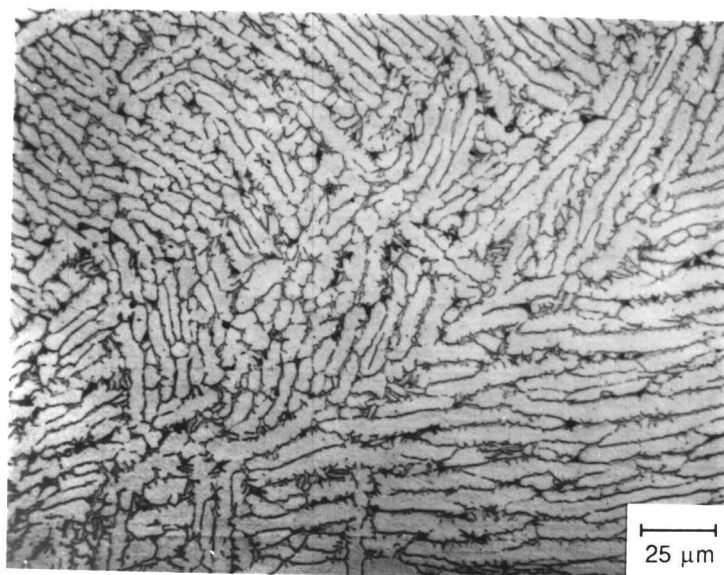
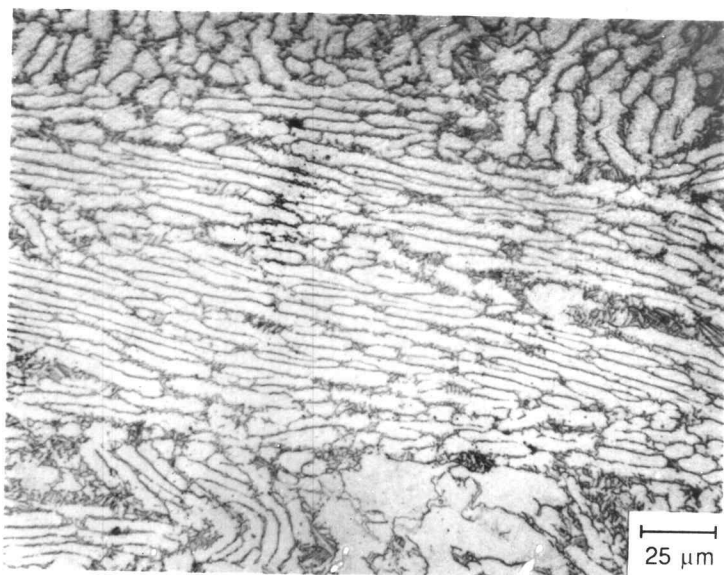


Figure5(a). Orientation of the coupons that were cut from the ingots.



Face A



Face B

Figure 5(b). Microstructure of the plane sections of 5(a).

TABLE 3. Forging and heat treatment summaries

Type	Initial Size	Final Size	Anneal Temp	Passes	Bands	Strain	
						ϵ	ϵ
Set 1 HF	0.0635 m x 0.0635 m x 0.038 m	0.041275 m x 0.015875 m x 0.228 m	968 °C	3	1.5	5.0	1.79
Set 2 HF	0.0635 m x 0.0635 m x 0.095 m	0.041275 m x 0.015875 m x 0.5842 m	998 °C	6	2.75	5.1	1.81
Set 3 PF	0.0635 m x 0.0635 m x 0.038 m	0.041275 m x 0.015875 m x 0.228 m	968 °C	3	1.5	5.0	1.79
Set 4 PF	0.0635 m x 0.0635 m x 0.038 m	0.041275 m x 0.015875 m x 0.228 m	993 °C	3	3	5.0	1.79

Bands: 1 - Many, 2 - few, 3 - None

Pass: Deformation sequence between reheating

HF: Hammer forged

PF: Press forged

ϵ : Engineering strain

ϵ : True strain

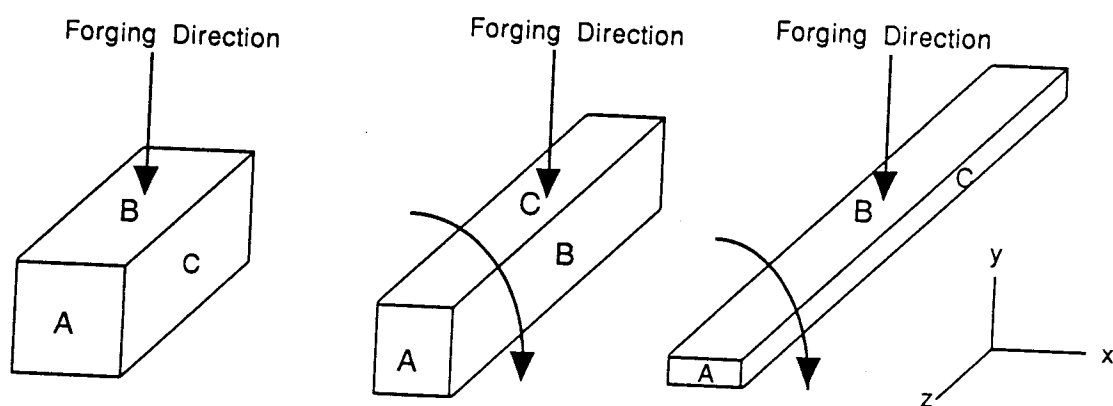


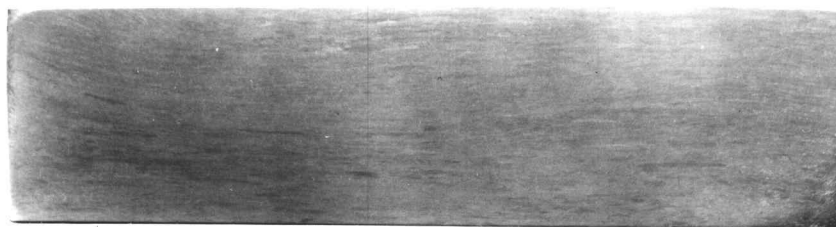
Figure 6. Hammer and press forging on faces B and C of coupons.

and the other at 993 °C ($T_{\beta} - 16$ °C) for 1 hr and air cooled to the ambient temperature. Finally, all the coupons were aged at 593 °C for 8 hours ("stabilization" treatment) 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 10 ml HF, 15 ml HNO_3 and 75 ml of water. The microcomposition of banded and unbanded regions 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).

RESULTS

As stated earlier, large billets were forged below the beta transus and (slow) cooled to ambient temperature leaving a microstructure that consists of elongated primary alpha (about 10% beta phase is probably present between the elongated alpha). Coupons were cut from the ingot, heated and then press or hammer forged. This is followed by a solution anneal below the beta transus, T_{β} . Metallographic examination of our specimens frequently revealed thin bands, that could be observed macroscopically ($< 10\times$) subsequent to prolonged etching. Obvious banding was observed in set 1 (hammer forged) and set 3 (press forged) coupons annealed at the relatively low temperatures of 968 °C ($T_{\beta} - 41\text{ °C}$). The coupons from set 2 and set 4, forged and then annealed at higher temperatures of 993 °C ($T_{\beta} - 16\text{ °C}$) and 998 °C ($T_{\beta} - 11\text{ °C}$) showed little or no banding. Figure 7 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. Our 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 observed on both faces B and C and were primarily aligned in the z-direction. Set 2 coupons (hammer forged at the standard temperature and annealed at 998 °C) showed very little banding whereas no banding was observed in the set 4 coupons (press forged and annealed at 993 °C). Figure 8(a) shows the final shape of hammer forged coupons of Ti-6242-0.1Si and the plane sections from which the micrographs shown in Figure 8(b) and Figure 8(c) were extracted from a set 1 (annealed at 968 °C) and from a set 2 (annealed at 998 °C) coupon. Figures 9 (a) and 9 (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 forged coupons. The banding is, perhaps, best described as regions or bundles of elongated



0.75 cm

FACE B



0.75 cm

FACE C

Figure 7. Bands observed macroscopically on faces B and C in a set 1 hammer forged coupon (annealed at 968 °C (T_{β} - 41 °C)).

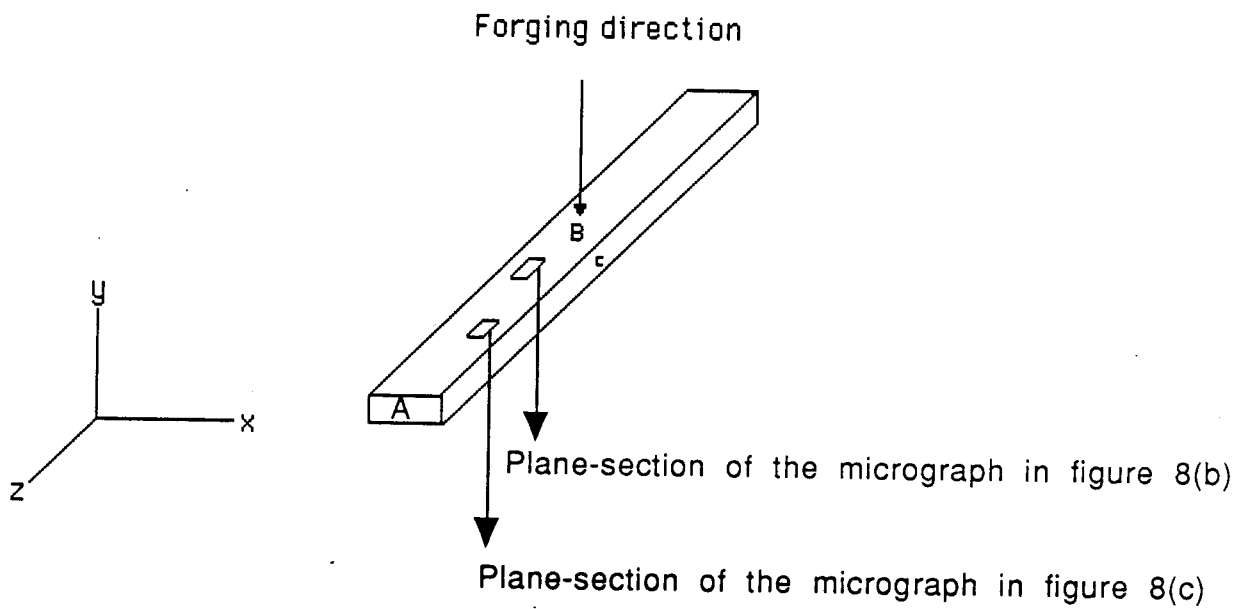


Figure 8(a). The final shape of the forged coupon and the plane-sections from which micrographs (shown in Figure 8(b) and Figure 8(c)) were extracted from two hammer forged coupons (from a set 1 coupon (annealed at 968°C ($T_{\beta}-41^{\circ}\text{C}$)) and from a set 2 coupon (annealed at 998°C ($T_{\beta} - 11^{\circ}\text{C}$))).

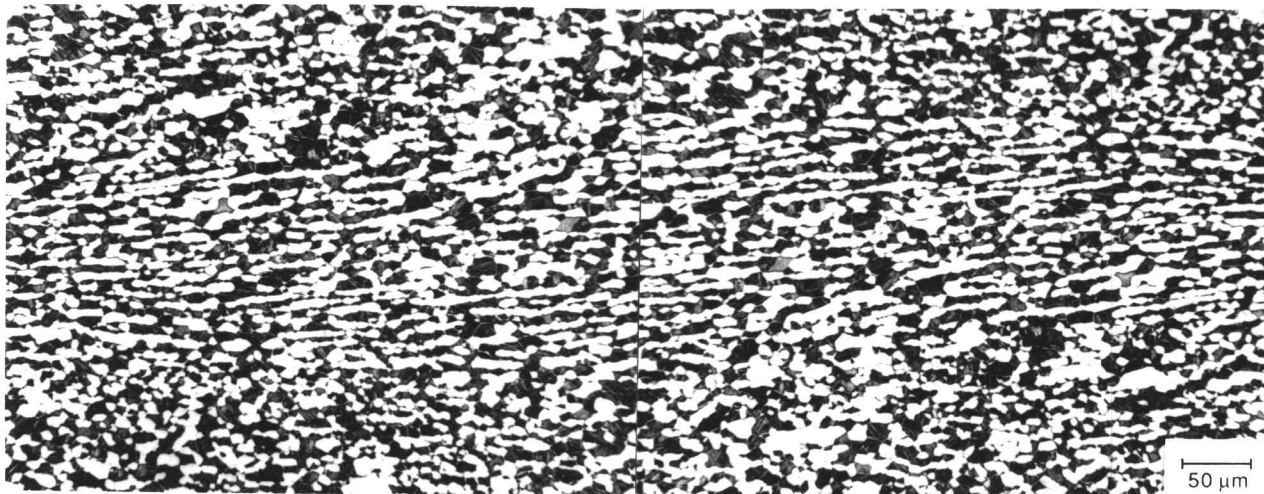


Figure 8(b). Microstructural banding observed in a set 1 hammer forged coupon (annealed at 968 °C). Banded structures observed here on face B are parallel to the z-direction.

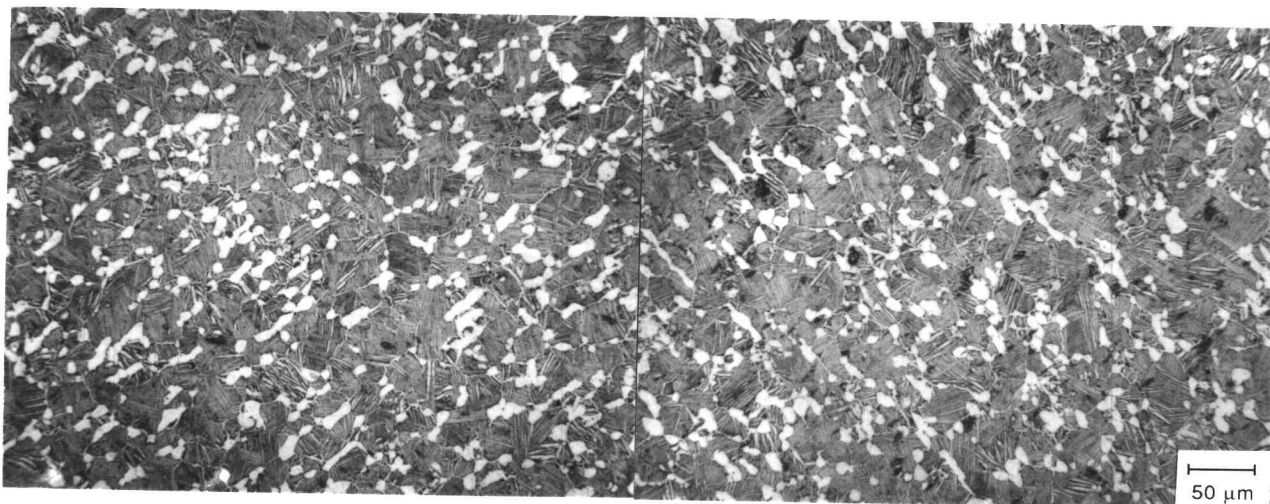


Figure 8(c). Micrograph from face B in a set 2 hammer forged coupon (annealed at 998 °C). Bands do not appear to be present.

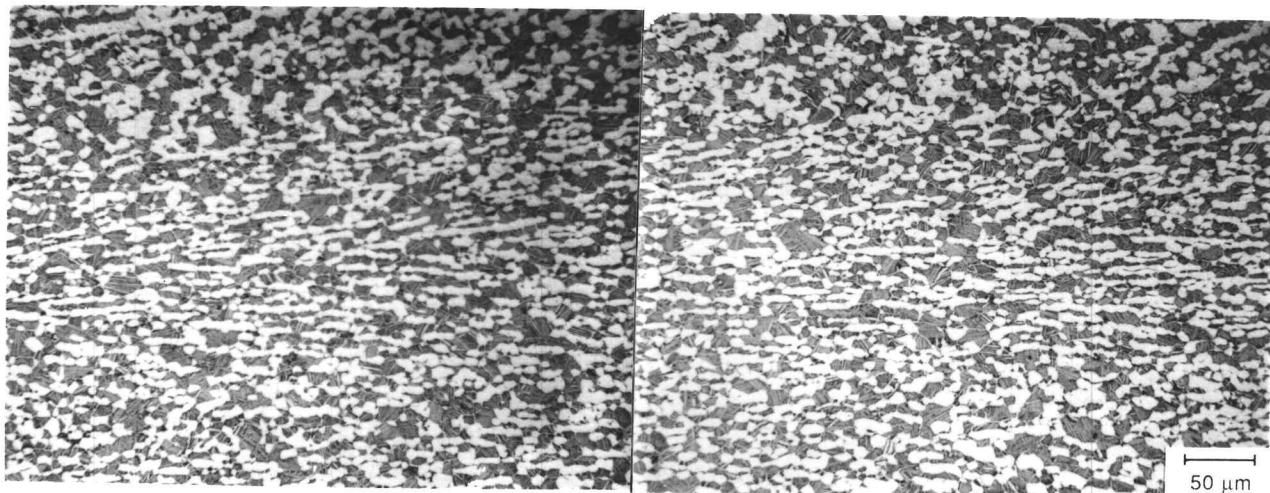


Figure 9(a). Micrograph from face B in a set 3 press forged coupon (annealed at 968 °C).
Some banding is evident.

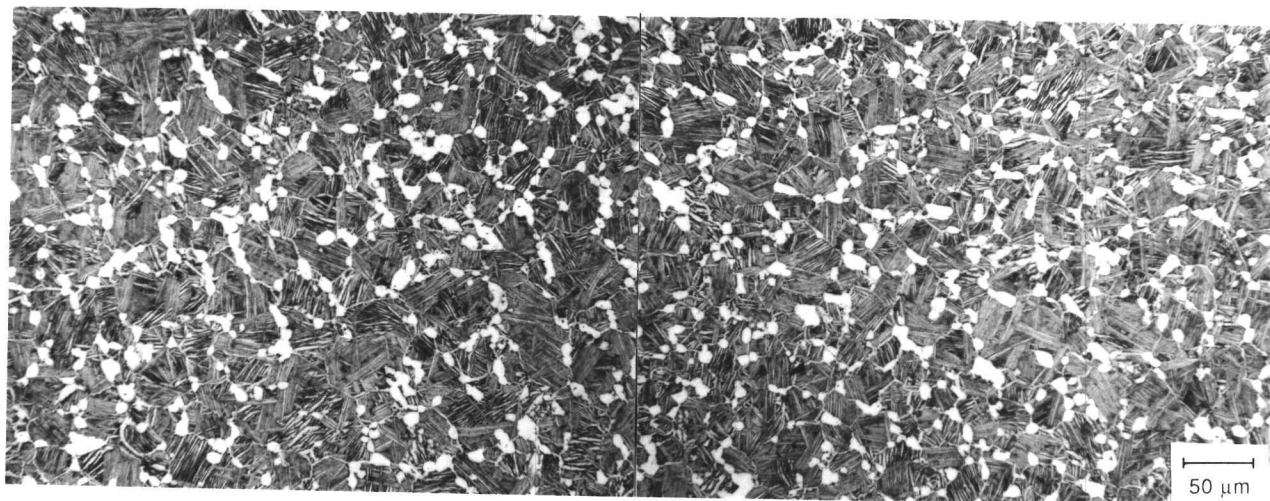


Figure 9(b). Microstructure from face B in a set 4 press forged coupon (annealed at 993 °C). Banding is not evident.

primary alpha surrounded by areas of more equiaxed alpha. No bands were revealed on face A (perpendicular to the axis of the coupon or ingot) of the coupon. Figure 10 shows the microstructure of face A in a set 1 hammer forged coupon (annealed at 968 °C).

Based on the literature [7,10-13,16], and as discussed in the introduction, there appears to be several possible "classic" explanations for the formation of the observed banded structures. One possibility is localized deformation (sometimes "adiabatic") as a result of a temperature gradient (chill zones) in the specimen or due to high strain rates. Compositional variation leading the inhomogeneties is another possible explanation.

Figure 11 shows a schematic of the bands observed subsequent to forging on face B and face C in a set 1 hammer forged coupon (annealed at 968 °C). These findings may be significant because the shear bands observed by Semiatin often form angles near 45° to the forging direction. Therefore, there was some suspicion as to whether the bands of our study were the result of the same shearing process observed by Semiatin. Our 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 and Me Bar et al. No microvoid formation was observed in our specimens, consistent with the proposition that the bands are not a result of an adiabatic shear process. Figure 12 shows an SEM micrograph of bands observed in a set 1 hammer forged coupon (annealed at 968 °C). Again, microscopically, these bands consist of elongated primary alpha, observable only at relatively high magnifications.

Electron microprobe analysis was performed by Woodward [16] to understand the formation of microstructural banding observed in Ti-6Al-4V which was not believed to be a 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 while 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.

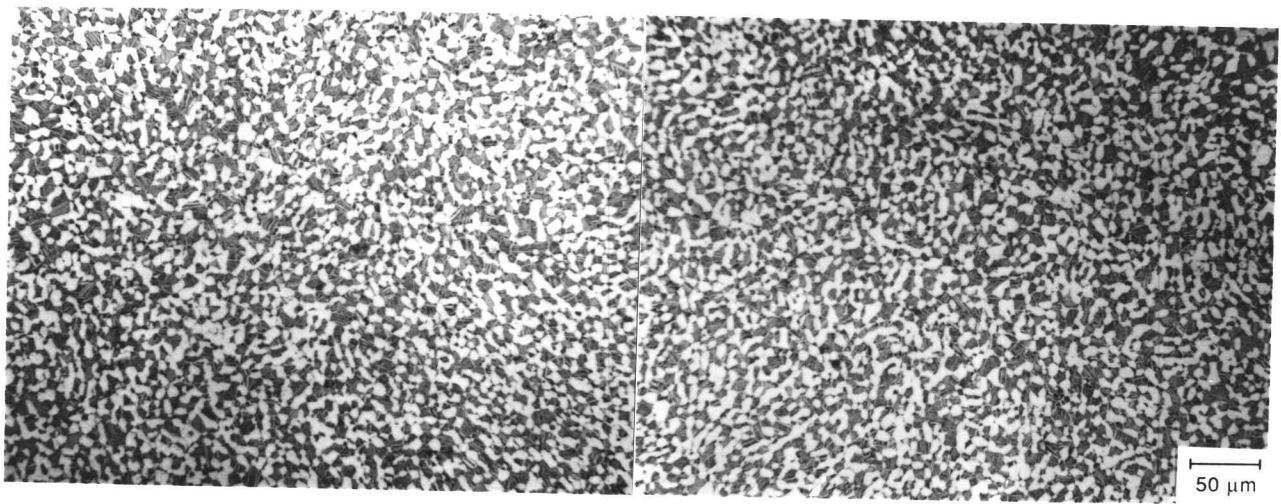


Figure 10. Microstructure of face A in a set 1 hammer forged coupon (annealed at 968 °C).

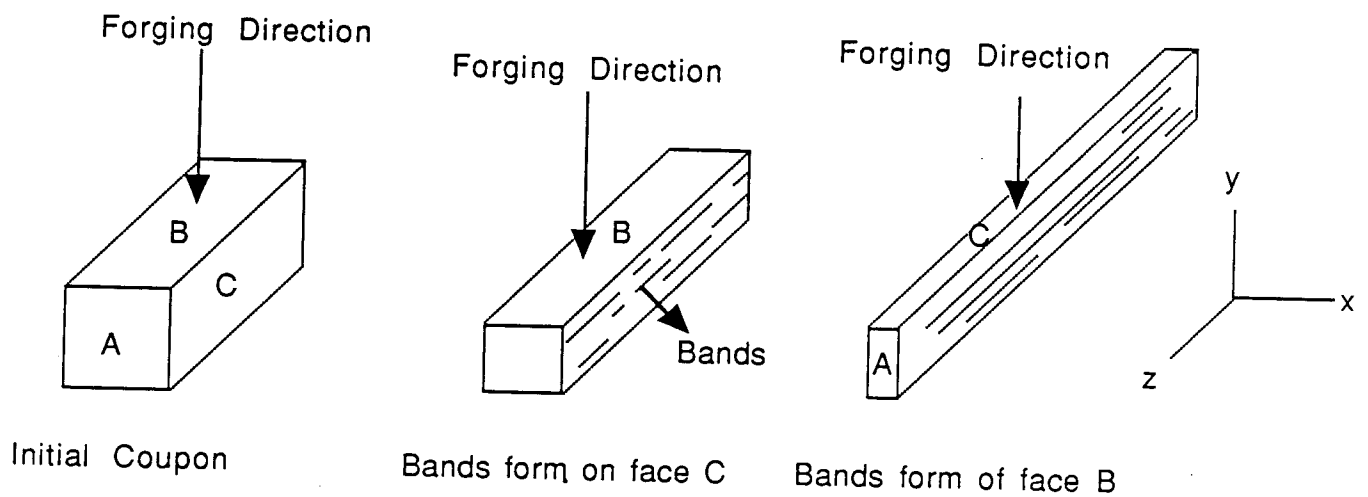


Figure 11. Schematic of the bands observed subsequent to forging on face B and face C in a set 1 hammer forged coupon (annealed at 968 °C).

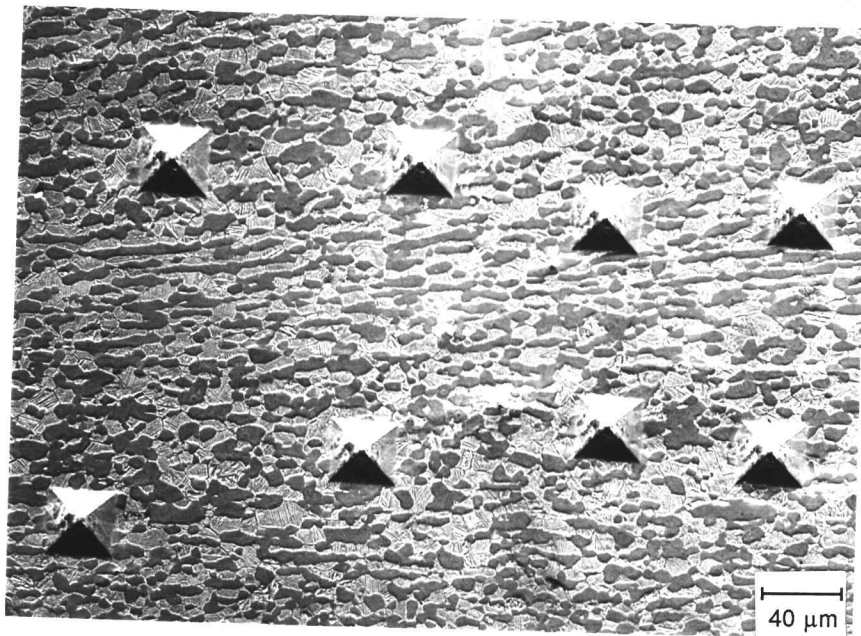


Figure 12. SEM micrograph of a band observed on face B in a set 1 hammer forged coupon (annealed at 968 °C). The band is surrounded by microhardness indentations.

Electron microprobe analysis was performed across the microstructural bands in our samples. Table 4A reports the electron microprobe composition results inside (I) and outside (O) the banded areas in a hammer forged coupon (annealed at 968 °C). These results were normalized in IVB because of the scattering (due to pitting, fine scratches etc.) during the microprobe analysis. The percent error for counting statistics (due to back scattering) in the analysis is $\pm 0.19\%$ for Ti, $\pm 0.04\%$ for Al, $\pm 0.004\%$ for Si, $\pm 0.15\%$ for Zr, $\pm 0.013\%$ for Fe, $\pm 0.08\%$ for Mo and $\pm 0.056\%$ for Sn. We conclude, from Table 4B, that there is not a significant compositional difference between banded and unbanded regions.

Image analysis was used to calculate the volume fraction of α present inside and outside the bands. Table 5 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, further, we do not believe that the bands are a result of any compositional variation.

In other investigations of Ti-6242-0.1Si and Ti-6Al-4V [9,16], the bands, when observed, were found to be harder than the material outside these bands. Semiatin suggests that the "finer microstructure" of these bands causes the higher hardness [9]. We discovered that the banded structures observed in the set 1 hammer forged coupon (annealed at 968 °C), were harder than the surrounding areas of the bands. These results are reported in Table 6. Hardness values with a load of 500 g for 30 seconds (ASTM standard) gives the best result. The disparity in hardness may be yet greater than indicated in Table 6 since some hardening of the polished surface may have occurred during mechanical polishing. This could both increase the "true" hardness somewhat and reduce the difference between the banded and unbanded regions.

TABLE 4 A: Results of electron microprobe analysis performed on a set 1 hammer forged coupon (annealed at 968 °C)

		(In wt %)						
		Ti	Al	Si	Zr	Fe	Mo	Sn
Band 1	I	82.8	5.39	0.09	3.8	0.09	1.9	2.0
	O	83.0	5.38	0.08	3.8	0.09	1.8	2.0
Band 2	I	83.4	5.41	0.1	4.2	0.09	1.9	2.1
	O	82.5	5.37	0.1	4.1	0.1	2.0	2.1
Band 3	I	83.0	5.34	0.09	3.9	0.08	1.9	2.1
	O	82.9	5.52	0.1	4.7	0.09	1.7	2.1
Band 4	I	82.6	5.52	0.1	4.0	0.09	1.9	2.1
	O	83.5	5.54	0.09	4.1	0.1	2.0	2.1
Band 5	I	79.2	5.39	0.1	4.2	0.07	1.8	2.1
	O	80.4	5.44	0.09	4.0	0.09	2.0	2.1
Band 6	I	82.7	5.31	0.07	4.0	0.08	2.0	2.1
	O	82.9	5.31	0.09	4.1	0.09	1.9	2.0
Av (Overall)	I	82.3	5.39	0.07	4.0	0.08	1.9	2.09
Av (Overall)	O	82.8	5.31	0.08	4.1	0.08	1.9	2.0

I - Inside band, O - Outside band

TABLE 4 B. Normalized values of electron microprobe results of a set 1 hammer forged coupon (annealed at 968 °C) described in Table 4 A

Average Inside Bands (In wt %)

	Ti	Al	Si	Zr	Fe	Mo	Sn
Band1 I	86.5	5.63	0.09	4.0	0.09	1.9	2.1
Band2 I	85.9	5.60	0.09	4.3	0.09	2.0	2.2
Band3 I	86.0	5.54	0.09	4.1	0.09	1.9	2.1
Band4 I	86.0	5.75	0.09	4.1	0.09	1.9	2.2
Band5 I	84.7	5.77	0.10	4.5	0.08	1.9	2.2
Band6 I	86.1	5.53	0.07	4.2	0.08	2.0	2.2
Av	85.9	5.64	0.09	4.2	0.09	2.0	2.2
Sd Dv	0.61	0.10	0.01	0.1	0.00	0.03	0.04

Average Outside Bands (In wt%)

	Ti	Al	Si	Zr	Fe	Mo	Sn
Band1 O	86.4	5.60	0.09	4.0	0.09	1.9	2.0
Band2 O	85.4	5.56	0.1	4.3	0.1	2.0	2.1
Band3 O	85.4	5.68	0.1	4.8	0.09	1.8	2.1
Band4 O	85.2	5.68	0.09	4.2	0.09	2.0	2.2
Band5 O	85.0	5.76	0.09	4.3	0.09	2.0	2.2
Band6 O	86.3	5.53	0.09	4.3	0.09	1.9	2.1
Av	85.6	5.63	0.10	4.3	0.09	1.9	2.1
Sd Dv	0.60	0.08	0.03	0.28	0.004	0.1	0.07

I - Inside band, O - Outside band

TABLE 5. The fraction of primary alpha inside and outside the banded structure in a set 1 hammer forged coupon (annealed at 968 °C)

	(Percentage primary alpha) (α)			
	Band 1	Band 2	Band 3	Band 4
Inside	50.1%	49.9%	49.9%	49.7%
Outside	49.9%	49.9%	49.8%	49.8%

TABLE 6. Microhardness values inside and outside the bands of face B in a set 1 hammer forged coupon (annealed at 968 °C)

Position		Vicker's Hardness (average)
Setting: 300 g, 15 sec		
Inside	3 Indents	415.5
Outside	3 Indents	360.0
Setting: 500 g, 30 sec		
Inside	3 Indents	435.0
Outside	3 Indents	416.0
Setting: 1000g, 30 sec		
Inside	3 Indents	396.0
Outside	3 Indents	368.0

DISCUSSION

From the above results, the bands observed in our work may be explained as follows. Based on Figure 5(b), the forged 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 hours (before the coupons were forged), as shown in Figure 13. Transformed β is seen as darker areas in the micrograph, which is not observed in Figure 5 (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 coupon forging would tend to elongate the primary α in a direction coincident with the ingot forging step. The unrecrystallized elongated primary α would have a higher dislocation density and, therefore, higher hardness, as observed. When annealing 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 that is similar to the starting ingot microstructure. The final microstructure consists of elongated α surrounded by equiaxed α 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 vs. hammer forged) suggests that these may not be a result of a shear banding phenomena. 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 and as discussed earlier, the composition in banded and unbanded areas is essentially identical.

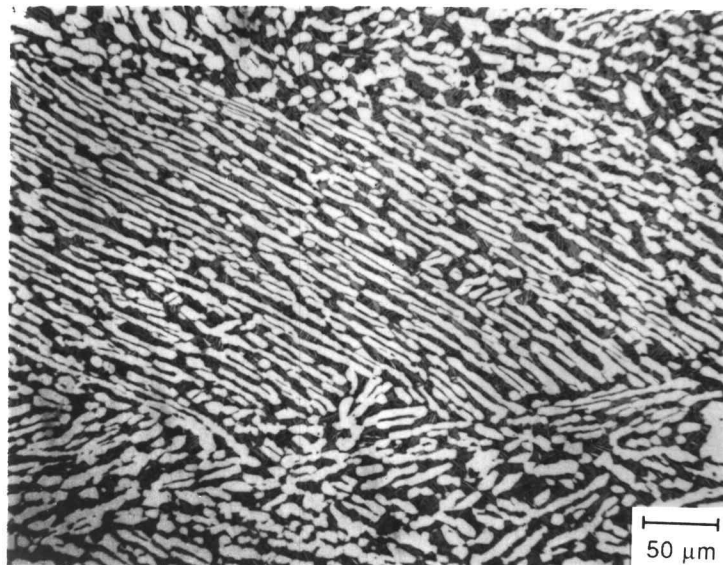


Figure 13. Microstructure of the coupon before hammer or press forging but subsequent to heating for 2 hours at 954 °C (T_{β} - 55 °C).

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 [2] have observed that our utilized strain levels during forging (see Table 3) 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 the banding. Higher annealing temperatures would also encourage the restoration. As presented earlier, higher annealing temperatures ($T_{\beta-14}^{\circ}\text{C}$) appears to eliminate the bands. The effect of these particular bands on the creep properties has not been established [14]. 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.

CONCLUSIONS

1. Banding was observed in Ti-6242-0.1Si coupons that were forged (using hammer and press forges) and annealed at low annealing temperatures (954 °C (T_{β} - 55 °C) and 968 °C (T_{β} - 41 °C)). Microscopically these bands are "bundles" of elongated primary α and transformed β grains. Substantially fewer bands are observed at higher annealing temperatures (998 °C (T_{β} - 11 °C)).
2. The observed bands are not believed to be classic "shear bands", as the bands did not become more pronounced at 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.
3. No compositional change is found to occur in the microstructural bands. Hence, the phenomenon of deformation banding due to compositional variation is not observed as reported in some other α/β titanium alloy investigations.
4. It appears that the observed bands have ancestry to the starting ingot microstructure that consists of elongated primary alpha resulting from forging and slow cooling. Subsequent heating and forging sequences restores (recrystallizes and/or recovers) most, but not all, of the substructure. The remnant alpha is elongated and relatively hard.
5. Larger strain deformation and/or higher annealing temperatures would probably restore nearly all of the substructure, and the inhomogeneities of bands should disappear.

REFERENCES

1. Bania P.J., Metallurgy of Advanced Titanium alloys, Short course, ASM International Materials Park, OH, 10-11 Oct 1990 Detroit, MI.
2. Bania P. J., Private communication, Sept. 1991.
3. Byrer T.G., Semiatin S.L. and Vollmer D.C., *Forging Handbook*, p. 95 & p. 156, ASM, Metals Park, OH, 1985.
4. Collings E.W., *The Physical Metallurgy of Titanium alloys*, p. 2, ASM, Metals Park, OH, 1984.
5. Lurthy H., Miller A.K. and Sherby O.D., *Acta Metallurgica*, Vol 18, 1979, pp 169-178.
6. Manufacturer's Specification, Chamberburg Engineering Company, Chamberburg, PA.
7. Me Bar Y. and Shechtman D., *Materials Science & Engineering*, Vol 58, 1983, pp. 181 - 188.
8. OREMET Titanium Company, Albany, Oregon, 9 June 1989.
9. Semiatin S.L. and Lahoti G.D., *Metallurgical Transactions*, Vol 14 A, 1983, pp. 743 - 750.
10. Semiatin S.L. and Lahoti G.D., *Metallurgical Transactions*, Vol 14 A, 1983, pp. 105 - 115.
11. Semiatin S.L. and Lahoti G.D., *Metallurgical Transactions*, Vol 12 A, 1981, pp. 1705 - 1717.
12. Semiatin S.L., Thomas Jr. J.F. and Dadras P., *Metallurgical Transactions*, Vol 14 A, 1983, pp. 2363 - 2374.
13. Semiatin S.L. and Jonas J.J., *Formability and workability of Metals*, ASM, Metals Park, OH, 1984.
14. Thiehsen K.E., Kassner M.E., Hiatt D. and Bristow B., to be published.
15. US Bureau of Mines, Albany Research Center, Albany, OR.
16. Woodward R.L., *Metallurgical Transactions*, Vol. 10 A, 1979, pp. 569 - 573.