MICROSTRUCTURE AND MECHANICAL PROPERTY OPTIMIZATION THROUGH THERMOMECHANICAL PROCESSING IN Ti-6-4 AND Ti-6-2-4-6 ALLOYS

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Introduction

A good combination of mechanical properties such as tensile strength, ductility, fracture toughness, fatigue and fatigue crack growth resistance is required to enhance the performance of rotating components in gas turbine engines. In this study, efforts have been made to tailor the thermomechanical processing (TMP) conditions for Ti-6 Al-4 V and Ti-6 Al-2 Sn-4 Zr-6 Mo alloys to achieve a desirable combination of properties for dynamic applications in thick section size forgings.

Wide variations in mechanical properties are achieved through variation in thermomechanical processing history of the Ti-6 Al-4 V and Ti-6 Al-2 Sn-4 Zr-6 Mo alloys. Small equiaxed primary alpha (40-50 vol.%) in an aged beta matrix containing elongated secondary alpha (lamellar alpha) exhibits better low cycle fatigue life in Ti-6-4 alloy (1) for fatigue critical applications such as compressor impellers and turbine disks. It is, however, very important to have the average alpha grain size below 5-7 microns. The prior beta grain size also has second order effects on the low cycle fatigue life. The interrelations between the processing conditions, microstructures and related mechanical properties are presented in the following sections.

In Ti-6-2-4-6 alloy an equiaxed alpha (25-35 vol.%) in aged beta matrix type microstructure exhibits high tensile strength and good low cycle fatigue properties; however, the fracture toughness and fatigue crack growth resistance are low for this microstructure (2). An acicular to plate type transformed beta in an aged beta matrix microstructure exhibits low tensile strength and low LCF lives; however, excellent fracture toughness and fatigue crack growth resistance are observed in such microstructures. In our present studies, attempts have been made to tailor the microstructure in heavy section forgings (25.4 cm dia. x 6.35 cm thickness and 22.8 cm dia. x 13.7 cm thickness) to achieve a combination of good tensile properties, low cycle fatigue (LCF) lives, fracture toughness and fatigue crack growth resistance. It is observed that a 5-8% small equiaxed primary alpha in aged transformed beta matrix exhibits the best combination of desirable mechanical properties. Correlation of the microstructure with the observed mechanical properties, especially for the low cycle fatigue properties, has been outlined. As this paper deals with two separate titanium alloys, the experimental procedures, test results and the discussions are presented in two separate sections. Section I deals with Ti-6-4 alloy and Section II deals with Ti-6-2-4-6 alloy.

Section I: Ti-6 Al-4 V Alloy

Experimental Procedure

In order to achieve goal properties (Table I) in thick section size impeller forgings it was decided to use a Ti-6-4 bar stock with skewed composition (Table II) having oxygen and nitrogen at the higher end within the specification limits. A fine equiaxed primary alpha with spheroidal beta (3) or a fine primary alpha in aged beta matrix (1) exhibits excellent fatigue life. A bimodal microstructure having fine primary alpha and lamellar alpha also exhibits good fatigue properties. However, observations indicate that this type of microstructure (especially with higher oxygen and nitrogen) may be associated with lower fracture toughness (4). In order to meet high tensile and fatigue property goals with moderate fracture toughness thermomechanical processing (TMP) conditions were attempted to create a 40-60 vol.% primary alpha with minor amounts of plate-type secondary alpha (5-10%) in an aged beta matrix. Small equiaxed alpha and low aspect-ratio secondary alpha are supposed to provide lower mean free slip path and relatively lower interface areas with the matrix and, therefore, would increase fatigue life. Small amounts of plate-type secondary alpha may also improve fracture toughness by causing crack path deflection during the crack extension. A few TMP conditions, the related room temperature (25°C) tensile properties, generated through standard ASTM procedures, are shown in Table III. The room temperature fracture toughness and low cycle fatigue (LCF) properties are shown in Table IV. Smooth bar ($K_t = 1$) low cycle fatigue testing was conducted at a R-ratio = 0.05, using triangular waveform at a frequency of 20 cycles per minute. Processing conditions 1 and 3 met or exceeded the 15,000 cycle fatigue life goal property (Table IV). The elevated temperature tensile properties (at 300°C; not presented here) developed through these processing conditions met or exceeded the goal property requirements. The typical optical photomicrographs from these processing conditions are shown in Figure 1.

Results and Discussion

The alloy composition used in this study meets the AMS (Aerospace Material Specification) 4920 and 4965D specifications; however the oxygen and nitrogen contents were skewed toward the higher limits intentionally to improve the strength level of this material. Processing conditions (1-3) known to refine alpha grain size and improve high cycle fatigue life were adapted in this study to improve the load controlled low cycle fatigue life. It was observed that an initial beta solution treatment followed by oil quenching prior to the "alpha-beta" fabrication processing helped to refine the grain size. Lower metal and die temperatures and higher amounts of deformation (at least 3:1 reduction ratio) were necessary to create a uniform and fine grained microstructure (Figure 1: Processing Condition 3). It was also observed that a randomly oriented coarse secondary alpha platelet phase (Figure 1: Process No. 3) improved the fracture toughness of the material. Fractographic observations indicate that the higher fracture toughness properties are associated with crack branching and crack-path tortuosity (Figure 2, Specimen No. 3), which might have resulted from crack deflection by the plate type secondary alpha colonies. SEM fractographic observations of the failed LCF specimens indicate that the crack initiations occurred at the surfaces of the specimens. Although the LCF lives were not affected adversely, a few specimens exhibited crack initiation from what might be recognized as prior beta grain boundaries (Figure 3).

Conclusions

A combination of very high strength, superior low cycle fatigue property and moderately high fracture toughness property was developed through suitable thermomechanical processing conditions in Ti-6-4 forgings. Higher oxygen and nitrogen (skewed composition) within the specification limits seem to have increased the tensile strength of the Ti-6-4 material. Such improvement in mechanical properties is expected to enhance the design life of Ti-6-4 rotating components.

Table I: Goal Properties for High Strength-High LCF Properties Ti-6-4 Impeller and Disk Forgings

Room Temperature Properties:		
I. Tensile:	YS	>900 MPa (131 ksi)
	UTS	$\geq$980 MPa (142 ksi)
	% El (in 5D)	$\geq$9%
II. Fracture Toughness:	K_{Ic}	$\geq$50 MPa $\sqrt{m}$ (45.5 ksi $\sqrt{in.}$)
III. Stress Controlled LCF:	LCF life of >15,000 cycles at a maximum stress of 880.0 MPa, R = 0.05, 20 cpm	
300°C Properties:		
Tensile	0.2% Offset YS	>580 MPa (84 ksi)
	UTS	$\geq$690 MPa (100 ksi)
	% El	$\geq$9%

Table II: Chemical Analysis of Ti-6 Al-4 V Forging Bar Stock

Billet No.	Dimensions	C	N	Fe	Al	V	O	H	Y
1	7.6 cm dia.	0.04	0.036	0.23	6.1	4.1	0.187	61 ppm	<50 ppm

Table III: Processing Conditions and Mechanical Properties of Ti-6-4 Pancake Forgings

Process No.	Prior Stock Treatment	Forging Condition (Soaking Condition)	Heat Treatments	Room Temp. Tensile Properties YS(MPa)	UTS(MPa)	% El	% RA
1	AR	T_β-100°C/1/2 hr. Press OQ	965°C/1/2, OQ + 705°C/2, AC	1038	1071	15	39
2	AR	T_β-100°C/1/2 hr. Press OQ	801°C/1, OQ + 500°C/24 hr., AC	1113	1126	14	31
3	Beta Soln. + OQ	T_β-165°C/1/2 hr. Press OQ	975°C/1/2, FAC, + 801°C/1, OQ + 500°C/24, AC	1087	1124	16	42

Table IV: Room Temperature Fracture Toughness and LCF Properties of Ti-6-4 Pancake Forgings

Process No.	Fracture Toughness MPa $\sqrt{m}$ (ksi $\sqrt{in.}$)	LCF Properties Maximum Stress (MPa)	R-Ratio	No. of Cycles to Failure	Remarks
1	40.5 (37.0)	127.7	0.05	22,325	FG
				18,808	FG
2	33.3 (30.3)	127.7	0.05	13,934	FG
				16,769	FG
3	52.8 (48.1)	127.7	0.05	32,581	R
				17,960	FI

NOTES: AR - as received stock ($\alpha\beta$), AC - air cool, OQ - oil quench.
FAC - fan air cool, FG - failed in gauge, R - run out, FI - failed at interface of radius and uniform section.

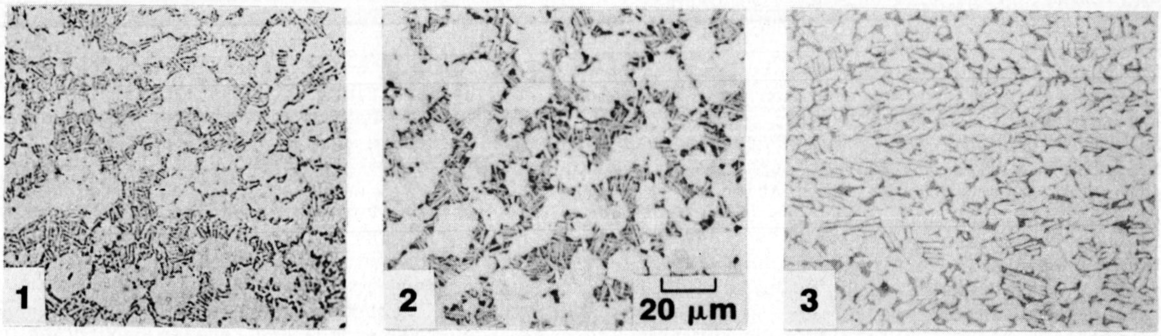
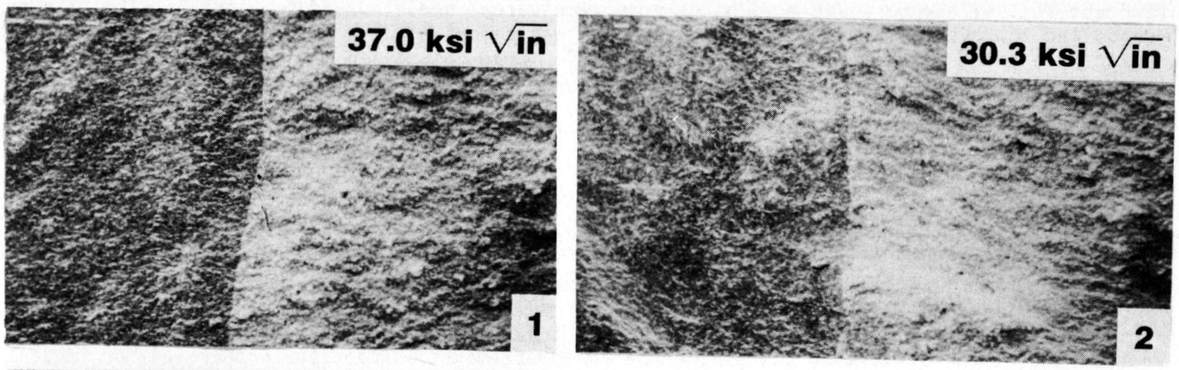


Figure 1. Optical Photomicrographs of Ti-64 Specimens Fabricated and Heat Treated Through Process Nos. 1, 2, and 3 Respectively



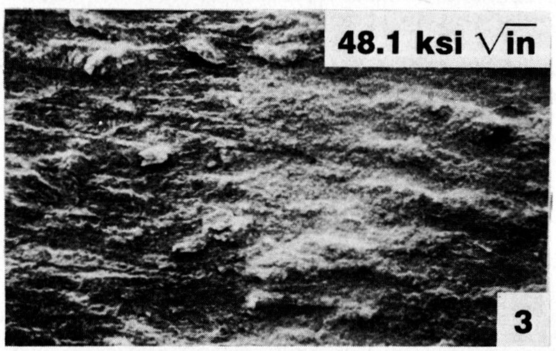


Figure 2. SEM Fractographs of the Fracture Toughness Tested Specimens No. 1, 2, and 3 Respectively Showing Fatigue Precrack and Fast Fracture Areas (All at 20X Magnification)

(1) 40.7 MPa $\sqrt{m}$ (37.0 ksi $\sqrt{in}$)
(2) 33.3 MPa $\sqrt{m}$ (30.3 ksi $\sqrt{in}$)
(3) 52.9 MPa $\sqrt{m}$ (48.1 ksi $\sqrt{in}$)

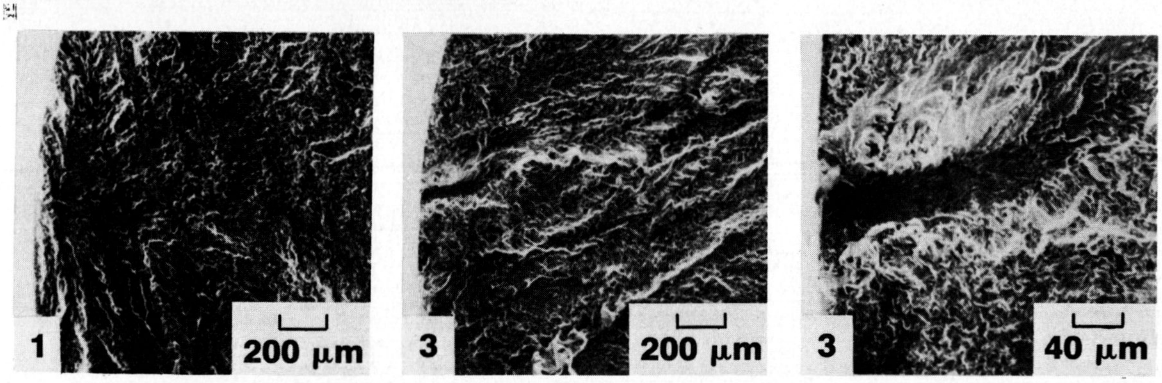


Figure 3. SEM Fractographs of the LCF Tested Ti-64 Specimens (Nos. 1 and 3) Showing Fatigue Crack Initiation from the Surface of the Specimens

Section II: Ti-6 Al-2 Sn-4 Zr-6 Mo Alloy

Experimental Procedure

The objective of this study was to develop an excellent combination of mechanical properties in Ti-6-2-4-6 forgings for the rotating application. Considering information available in the literature, ten thermomechanical processing (TMP) conditions were adapted in an earlier study (2) to investigate the effect of TMP conditions on the microstructure and mechanical properties in Ti-6-2-4-6 alloy. Based on this study, TMP conditions with or without some modifications were selected to simulate the fabrication of full size impeller (22.5 cm dia. x 13.7 cm thick) or disk forgings (25.4 cm dia. x 6.35 cm thick) and are listed in Table V. The composition of the Ti-6-2-4-6 bar stock used in this study is shown in Table VI. The goal properties for these impeller and disk forgings are shown in Table VII. The typical microstructure of the αβ-forged plus αβ heat treated and β-forged plus αβ heat treated forgings are shown in Figure 4. Room temperature tensile properties for tangential specimens and fracture toughness properties for T-R orientation for all 5 forgings are shown in Table V. Elevated temperature tensile properties at 200, 300, 425 and 500°C were generated only for the forging numbers 4 and 5, and are presented in Figures 5, 6 and 7. Effect of strain rate on the tensile properties was studied at 425, 500 and 550°C and the effect of prolonged exposure at 500°C was investigated for both αβ and β forgings (Process Nos. 4I and 5I - Table V). The room temperature and elevated temperature (425°C) strain controlled low cycle fatigue property evaluation was conducted at a R_{ε} ($\varepsilon_{min.}/\varepsilon_{max.}$) = 0. The results are shown graphically in Figures 9 and 10. Load controlled fatigue testing at R-ratio ($\sigma_{min.}/\sigma_{max.}$) = 0.05 was conducted at room temperature and 425°C. The results are not presented here. The limited amount of creep data generated so far for the beta processed material (Process No. 5I) is shown in Figure 10.

Results and Discussion

Microstructural observations indicate that the alpha-beta processed with alpha-beta solution treated materials (Process Nos. 1D and 4I) exhibit a duplex microstructure consisting of fine equiaxed primary alpha with fine platelets of secondary alpha in an aged beta matrix. The β-finished material (2D, 5I) and the "αβ"-finished plus β-solution treated material (Process No. 3D) exhibit Widmenstatten-type transformed beta in aged beta-matrix (Figure 4).

Room temperature tensile properties and fracture toughness of all the forgings fabricated via Process Nos. 1 through 5 meet the goal property requirements; except the properties for Process No. 4I which exhibit slightly lower yield and ultimate tensile strength and slightly lower fracture toughness (Table V). The ultimate tensile strength vs. test temperature relations for the beta and alpha-beta processed materials (Process Nos. 4I and 5I) are shown in Figures 5, 6 and 7. It is observed (Figures 5 and 6) that there is a difference in strength between the radial, tangential and axial directions and the tensile strength decreases continuously as the test temperature increases. It is also observed that the beta processed material (Process No. 5I) exhibits slightly higher strength compared to that of "alpha-beta" processed material (Process No. 4I) in the tangential direction over the entire temperature range (Figure 7). The effect of strain rate on the yield strength for the αβ and β-processed materials (Process Nos. 4I and 5I) at 500 and 550°C are shown graphically in Figure 8. It is observed (Figure 8) that the effect of strain rate on the ultimate strength is negligible at 500°C; however, at 550°C the UTS increases with the increasing strain rate. No dynamic instabilities were observed in the tensile data plots. The effect of prolonged exposure at 500°C on the room temperature tensile properties of

Table V: Thermomechanical Processing Conditions for the Ti-6-2-4-6 Impeller and Disk Forgings

Forging No. (Process No.)	Forging History	Heat Treatments	Room Temperature/Mechanical Properties: Tensile YS (MPa)	Tensile UTS (MPa)	% El	% RA	Fracture Toughness MPa √m
1D	αβ-Preform αβ-Finish	Tβ-8°C/1, OQ+Tβ-97°C/2, AC+593°C/8, AC	1055	1262	7.0	10.3	51.1
2D	αβ-Preform β-Finish	Tβ-42°C/1, AC+ 593°C/8, AC	1072	1183	11.5	16.0	73.8
3D	αβ-Preform αβ-Finish	Tβ+22°C/1, OQ+ Tβ-97°C/2, AC+ 593°C/8, AC	1037	1126	8.0	9.6	57.4
4I	αβ-Preform αβ-Finish	Tβ-10°C/1, OQ+ Tβ-40°C/2, Fan Cool + 593°C/8, AC	1021	1086	13.9	-	47.5
5I	αβ-Preform β-Finish	Tβ-40°C/2, Fan Cool + 593°C/8, AC	1042	1117	9.7	-	71.0
Goal Properties			1034	1103	7	15	49.0

NOTES: D - Disk Forging (25.4 cm. dia. x 6.35 cm. thick); Tβ - Beta Transus Temperature;
I - Impeller Forging (22.8 cm. dia. x 13.7 cm. thick).

the αβ and β-processed impeller forgings (Process Nos. 4I and 5I) are shown in Table VIII. No appreciable changes in tensile properties were observed in these specimens indicating excellent thermal (microstructural) stabilities of the Ti-6-2-4-6 material at up to 500°C. The room and elevated temperature strain controlled low cycle fatigue properties of some of these forgings are shown in Figures 9 and 10. It is observed (Figures 9 and 10) that the αβ-processed materials exhibit better low cycle fatigue properties both at the room and elevated temperatures. The fatigue crack propagation is found to be progressing through the equiaxed alpha phase in the αβ-processed material and through the transformed-beta platelets in the β-processed material. Whether the crack initiation occurs by slip localization (strain localization) within the alpha phase or at the αβ interface is not revealed in our studies; however the crack propagation to a large extent occurred through the transformed beta platelets-aged beta matrix interfaces (Figure 11). An initial cyclic softening followed by a cyclic hardening until the appearance of crack initiation was observed in αβ and beta specimens. The limited amount of creep data (Figure 12) generated thus far (at 450 and 500°C) indicates an excellent creep resistance for the β-processed material (Process No. 5I). The room temperature fatigue crack propagation data generated on the disk forgings (Process Nos. 1 through 3D) indicate that the beta-processed disk forging (Process No. 3D) has the best fatigue crack propagation resistance (not shown here).

Conclusions

Excellent combination of tensile, fracture toughness, low cycle fatigue, creep and fatigue crack propagation resistance has been achieved in heavy section size forgings (22.5 cm dia. x 13.7 cm thick and 25.4 cm dia. x 6.35 cm thick) through αβ and β-processing. The αβ materials (Process Nos. 1D and 4I) exhibit better LCF properties and the overall best combination of mechanical properties whereas the β-processed material exhibits higher toughness, greater crack growth resistance and creep resistance properties (Process Nos. 2D and 5I). A 10-15% increase in design properties up to temperatures of 450°C (850°F) seems very promising.

References

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Table VI: Chemical Analysis of Ti-6-2-4-6 Alloy

Elements	Wt.% in Bar Stock (1)	Wt.% in Bar Stock (2)
C	0.01	0.02
N	0.010	0.012
Fe	0.06	0.09
Al	6.0	5.9
Sn	2.0	2.1
Zr	3.8	4.0
Mo	5.8	6.0
O	0.09	0.10
H	35 ppm	50 ppm
Ti	bal.	bal.

Table VII: Goal Properties for Ti-6246 Disk and Impeller Forgings

Tensile:

YS (0.2% offset)	>1034 MPa
UTS	>1102 MPa
% El	>7%
% RA	>15%

Fracture Toughness: $K_{Ic} > 49$ MPa$\sqrt{m}$

Low Cycle Fatigue: 70% or better of the currently processed (αβ) material. (Number of cycles to failure at a strain range, in a strain controlled room temperature test at 1.4% and 1.0% strains, should be greater than or equal to 5,200 and 22,000 cycles, respectively.)

Fatigue Crack Growth Rate: Room temperature fatigue crack growth rate at R = 0.05 and at ΔK range of 11-16.5 MPa$\sqrt{m}$ should be less than or equal to 1.27-2.54 x 10^{-8} m/cycle.

Table VIII: Effect of Prolonged Exposure at 500°C on the Tensile Properties of αβ and β -Processed Impeller Forgings

Process No./ Process Type	Exposure Time at 500°C	Specimen Type	Room Temperature Tensile UTS (MPa)	YS (MPa)	% El
4I	100 hrs.	Radial	1101	1035	13.4
αβ		Tangential	1109	1029	1[illegible].6
5I	377 hrs.	Tangential	1143	1070	8.4
β		Tangential	1116	1047	6.5

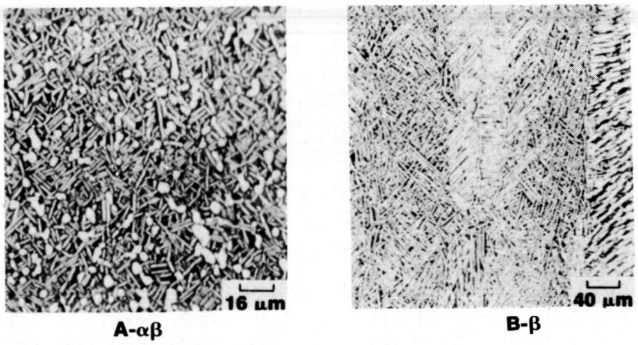

Figure 4. Typical Microstructure of Ti-6246 Forgings. A-alpha-beta Processed and alpha-beta Heat Treated (Process - 4I) B-, Beta Forged Plus alpha-beta Heat Treated (Process - 5I)

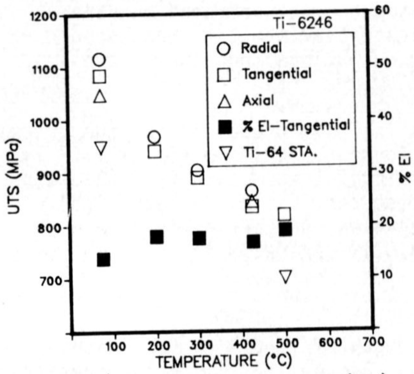

Figure 5. Ultimate tensile strength (MPa) vs. temperature relation for the αβ forging

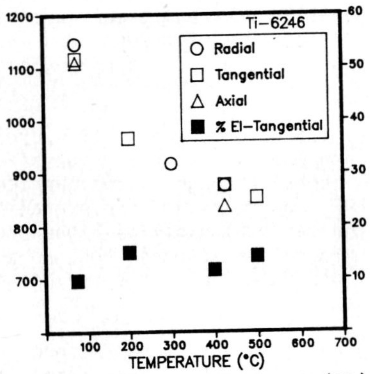

Figure 6. Ultimate tensile strength (MPa) vs. temperature relation in the β–forging

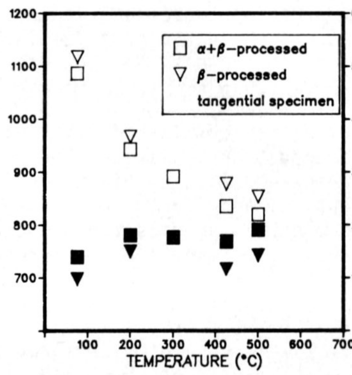

Figure 7. Tensile Property Comparison for αβ-Processed and β-Processed (4I,5I) Forgings

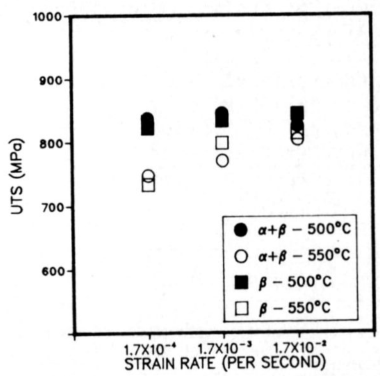

Figure 8. Effect of Strain Rate on the Ultimate Tensile Strength of αβ and β Processed Material (Processed -4I,5I) at 500 and 550°C

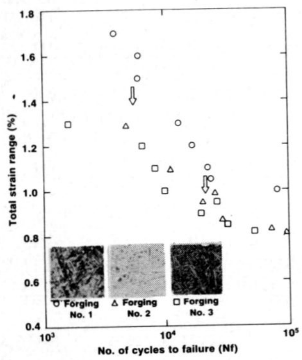

Figure 9. Total Strain Range Versus Number of Cycles to Failure Relation for the three 25.4 cm Diameter × 6.35 cm Thick Ti-6-2-4-6 Pancake Forgings

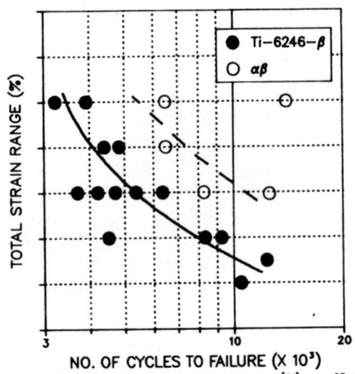

Figure 10. Total strain range (%) vs. No. of cycles to failure relation for Ti–6246 material at 425°C

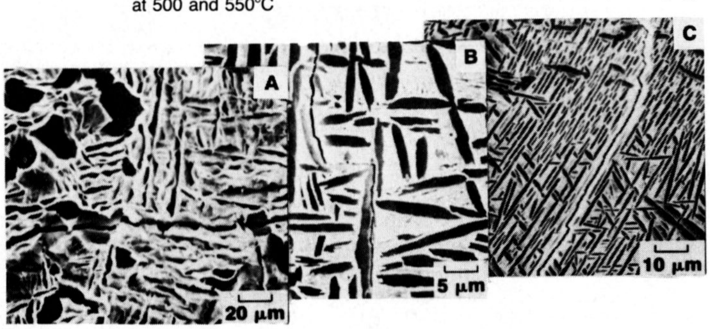

Figure 11. Fatigue Crack Propagation Through Ti-6246 LCF Specimens. A-alpha-beta Processed (Forging-4I),B,C - Beta Processed (Forging-5I)

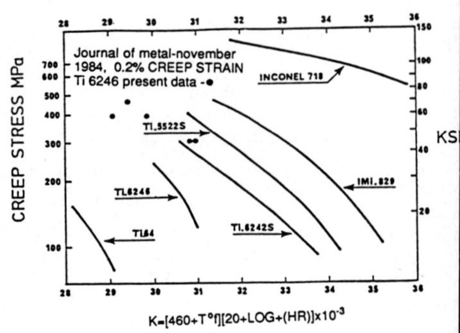

Figure 12. Larson-Miller plot for 0.2% creep for several materials.