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Evaluation of Tensile Properties and their Correlation with Microstructural Characteristics of a Closed Die Forging of Iso-symmetrical Aerospace Grade *Ti*-6*Al*-4*V* Alloy

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ABSTRACT

In the present technical paper an iso-symmetrical forging in titanium alloy, i.e., *Ti-6Al-4V* is chosen for cut-up evaluation and study of mechanical properties and their correlation with microstructural characteristics. Tensile test specimens were extracted from rim, web and bore regions of the forgings aligned in radial and tangential directions. Test specimens varying from various locations were extracted to conduct the tests (ASTM E8) at various temperatures from room temperature to 300 °C. Statistical analyses of the tested data were carried out to quantify the variation in tensile properties along rim, web, and bore regions at room temperature. Effects of radial and tangential alignments of specimens at room temperature was also studied. Among the different test specimens, the specimen that exhibited mechanical properties close to average values were further subjected to microstructural and fractographic investigations using optical and scanning electron microscopes. These studies revealed that there is a marginal inhomogenity in the microstructure of the forgings and this variation controls the mechanical properties and fracture characteristics of the material. Microstructure marginally varies from rim to bore region. Similarly, along the thickness of the forging, there is a small variation in the microstructure. The aforementioned correlations have established the fact that the microstructure variations from different locations and among different specimen orientations have resulted in mild variation in the tensile properties.

Keywords: α-β titanium alloy, primary α, prior β, closed die forging, tensile test, microstructure, fractrography

1. INTRODUCTION

Titanium is a low-density material having non-magnetic property and stands in the middle of aluminium and steel with good specific strength. Ti-alloy has disadvantage for high temperature applications compared to *Ni*-base superalloy where creep resistance is the primary requirement. Allowable temperature capability of this alloy if 0.4 T_m, whereas for *Ni*-base superalloy it is 0.9 $T_{m.}$ Density of titanium is 60 per cent of Steel and is considered as one of the work horse material for aerospace applications. Pure titanium has excellent resistance to corrosion by forming passive titanium oxide layer. Chemical plants using steel vessels are clad with titanium due to its corrosion resistance. *Ti*-alloy has wide applications in cold-end rotating and non-rotating components of gas turbine engines like fan disk, blades, casings, nozzle guide vanes, etc[1-3]. Usage of *Ti*-alloy is restricted to automobile industries due to its high processing cost. For structural applications, *Ti*-alloys are strengthened by suitable alloying additions[4-10]. Titanium shows allotropic property at high temperature. At room temperature, it exists as hexagonal close pack (HCP) crystal structure (α-phase), but at temperature beyond 883 °C, it transforms into body centre cubic (BCC) crystal structure and this BCC structure (β-phase) remains stable till it reaches meting temperature. For structural applications this material is further strengthen by suitable alloying addition by exploiting the urge of alloying with large number of elements. All elements within a range of atomic radius of 0.85-1.15 of Titanium, form substitutional solid solution. Elements with atomic radii less than 0.59 have the tendency to form interstitial solid solution. Tendency to form solid solution makes the *Ti*-alloy system difficult to form precipitation harden alloy. The alloying elements like *Al, Ga, O,* and *N* have the tendency to stabilise the α-phase at higher temperature by rising the β transus temperature. *Mo, V, W,* and *Ta* are β stabilisers and form solid solutions. Another set of β stabilisers like *Cu, Mn, Fe, Ni, Co, H* form eutectoid. Alloying elements like *Zn, Sn,* and *Si* play neutral role in *Ti*-alloy. Based upon the alloy content and the resultant crystal structure, the *Ti*-alloys are categorised into three groups; alpha (α)- alloy, β (beta)-alloy, and α-β (alpha-beta) alloy systems. The composition of α and β can be adjusted in such a way that optimum combination of creep, fatigue, and yield strength can be achieved based upon the component and its application. This can be achieved by applying suitable thermomechanical treatment to this alloy along with appropriate heat- treatment cycle. Till date, cold-end components of a gas turbine engine are dominated by *Ti*-alloys. *Ti-6Al-4V* is widely used α - β

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alloy in aerospace industry (50 per cent marketshare for various aero applications). Gas turbine disk is subjected to high centrifugal loading cycle to increase the compressibility of fan and compressor. Hence *Ti-6Al-4V* can be tailormade to impart optimum combination of yield strength and fatigue property[11-19]. As per the stringent airworthiness certification requirements any rotating component needs to be forged to improve the better properties and structural integrity of the components at critical operating conditions. Fan disk being a class 1 component[20], where failure is expected to cause structural collapse, personal injury or unacceptable malfunctioning[21-22]needs to have better centrifugal load-bearing capacity at higher speeds. Design of disks involves the evaluation of centrifugal and thermal stresses at different locations of the disk geometry. It again depends on the material behaviour at different temperatures. Under a given engine-operating condition, the disk should not burst and cause catastrophic failure and loss of aircraft and life[23]. Burst occurs when the mean hoop stress on a disk section becomes equal to the nominal tensile strength of the material, determined from a uniaxial tensile stress. Hence, ultimate tensile strength of the disk material is one of the critical design requirements. Normally, these forgings are made out of closed-die forging route to have enhanced property and more consistency in microstructures. Aero-engine fan disks are forged for *Ti-6Al-4V* alloys to obtain symmetric property throughout the contour of the forging. Main purpose of forging is to obtain desired shape and property, which is not achievable in bar or billets. As *Ti-6Al-4V* is strain rate-sensitive, forging processes (closed die, open die, rotary forging, and isothermal forging) are there to alter the microstructure of the alloy differently. Normally *Ti-6Al-4V* forging is carried out in α - β condition below β transus temperature. The final microstructure of the forging is dictated by the volume fraction of α and β, which decides the mechanical property of *Ti-6Al-4V*. Section size too plays a very important role in forging. The main disadvantage of α - β alloy is non-uniform hardenablity of sections with thickness more than 25 mm. Hence, it is observed that forgings with different thickness, shape, and sizes will have variation in hardenablity due to variation in the microstructure, and this will introduce metallurgical inhomogeneties and early failure of components.

This paper reports the cut-up evaluation of an aerospace grade *Ti-6Al-4V* disk forging and detailed evaluation of mechanical properties and the corresponding microstructural characteristics of these cut-up specimens from various locations. The observed anisotropy in mechanical properties is correlated with microstructural characteristics to establish the controlling microstructural features.

2. EXPERIMENTAL

2.1 Material

Triple-melted, close-die forging of *Ti-6Al-4V* was used for the present investigation. The nominal composition of the alloy is (*Al*: 6.5, *V*: 4, *Fe*: 0.3, *Sn:* 0.1, *Mo*: 0.1, *Cu*: 0.1, *Mn*: 0.1, *Zr*: 0.1, *O*: 0.14 -0.2, *C*: 0.08, *N*: 0.3, *B*: 0.005) as obtained from the supplier. Ingot for forging was obtained by triple-melted vacuum consumable remelt procedure (VAR). The forging was solution treated at 960 °C for 1 h, water quenched and annealed at 700 °C for 2 h and then air-cooled (AC). The forging was carried out below β transus temperature (~ 965 °C) to meet the forging specification of GTRE, DRDO. Typical aero engine and its disk forging drawing of the actual component is marked in phantom lines as shown in Fig. 1.

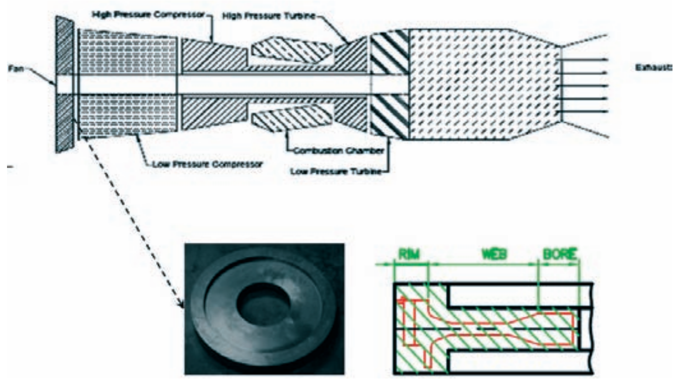


Figure 1. Sectional view of the aero engine and its machined forging (schematic drawing showing the final component in phantom line) for which the present cut-up evaluation is conducted in the present study.

The supplied forging against our Gas Turbine Materials specification was free from surface defects and contamination. Diameter of the forging was 530 mm. Thickness of the forging near the rim section was 75 mm, and near the bore section was 36 mm. Minimum achievable mechanical property of the forging as per the Gas Turbine Materials specification is given in Table 1.

Table 1. Mechanical property of forging specification

S. No.	Properties	GTM Specification values, min
1	Ultimate Tensile Strength(MPa)	930
2	Yield Strength(MPa)	830
3	Elongation in 4D (%)	10
4	Reduction in Area (%)	25

2.2 Testing and Evaluation

The disk forging was divided into three zones. Zone near to the disk centre was addressed as bore. Peripheral region of the disk was addressed as disk rim, and the middle portion of the forging was called as web. Specimens were aligned either along the radial direction of the forging disk or along the tangential direction. Specimens obtained from this cut-up plan were tested at various temperatures as per the ASTM E8 standard at a strain rate of 10^{-3} per s. All tensile tests were performed by loading the test specimens till fracture. One half portion of the fractured specimens was examined under scanning electron microscope and the other half was fine polished and etched (using Kroll's reagent) to carry out the microstructural investigation using optical microscope.

3. RESULTS AND DISCUSSION

3.1 Tensile Properties

Nomenclature: Rim region is called as *X*; web portion of the forging is called as *Y*, and bore region is called as *Z*. Radial direction of the forging disk will be called as *R* and tangential direction of the forging named as *T*. For example, XRT stands for rim region radial direction tensile sample, XTT stands for rim region tangential direction tensile sample].

Figure 2 shows in the wide-ranging test values of yield and ultimate tensile strength wrt temperature which includes all combinations of direction and region of the forging. The yield and ultimate tensile strength values show a decreasing linear trend with increase in temperature, as expected. The test specimens were then segregated as per each test condition, which was selected from the extracted cut up specimens for further analysis.

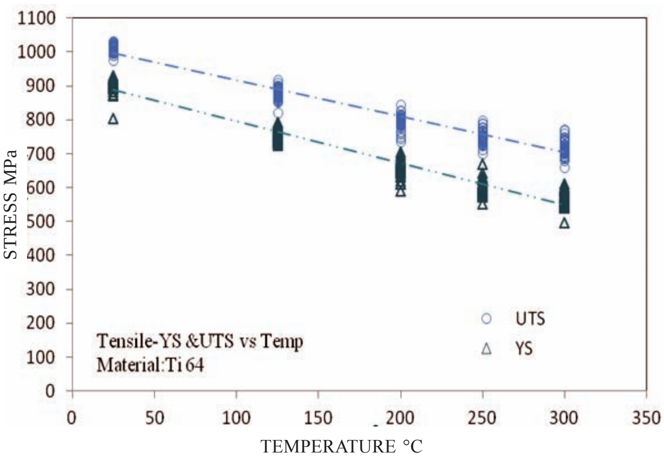


Figure 2. Variation of yield stress and UTS with test temperature.

From Table 2, it is observed that the average yield strength is found to be less in bore region as compared to the rim and web regions. Similarly Table 3 gives the UTS data and its average values. It is found that the average UTS of bore region is found to be less, both along radial and tangential directions. Such variations are found to be due to the differences in the optical microstructure discussed in Section 3.3. Figure 3 shows engineering stress-strain data for the specimens extracted from various locations along radial and tangential directions. From Fig. 3, the average yield strength and UTS values along the transverse direction show higher values than in the radial direction in the cases of rim and bore locations. It is observed that variation of average yield strength between radial and transverse direction sin three locations - rim, web, and bore region is 0.7 per cent, 0.9 per cent, and 1.2 per cent, respectively; whereas the variation of average UTS between radial and transverse directions in three locations; rim, web and bore locations of the forgings is 2.6 per cent, 1.2 per cent, and 1.9 per cent, respectively. It is observed that strain hardening is active till 13-15 per cent of the plastic strain for all test specimens, beyond which the damage accumulation overtakes the deformation process and results in necking.

The above tensile engineering stress-strain curves are further analysed using different empirical deformation laws in the strain-hardening regime for all the combinations of the rim, web, and bore regions along radial and transverse directions of the forgings. The true stress-strain curve is the flow curve which represents the plastic flow of the material in the strain-

Table 2. Variation of 0.2% yield strength wrt orientation and location at room temperature

Specimen Type	Yield strength values (MPa)		
	Min value	Max value	Average Value
XTT	804	929	903
XRT	892	922	910
YTT	896	925	910
YRT	875	914	899
ZTT	872	903	888
ZRT	883	898	890

Table 3. Variation of UTS as a function of orientation and location at room temperature

Specimen Type	UTS (ultimate tensile strength) values (MPa)		
	Min value	Max value	Average Value
XTT	910	1032	1008
XRT	999	1024	1011
YTT	990	1028	1010
YRT	1000	1020	1007
ZTT	975	1004	989
ZRT	990	999	994

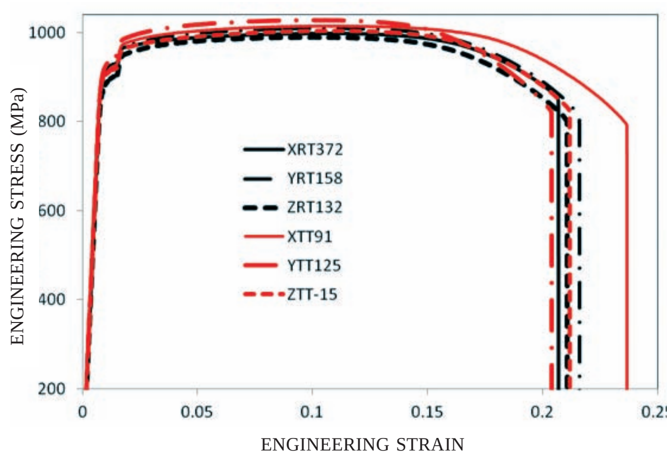


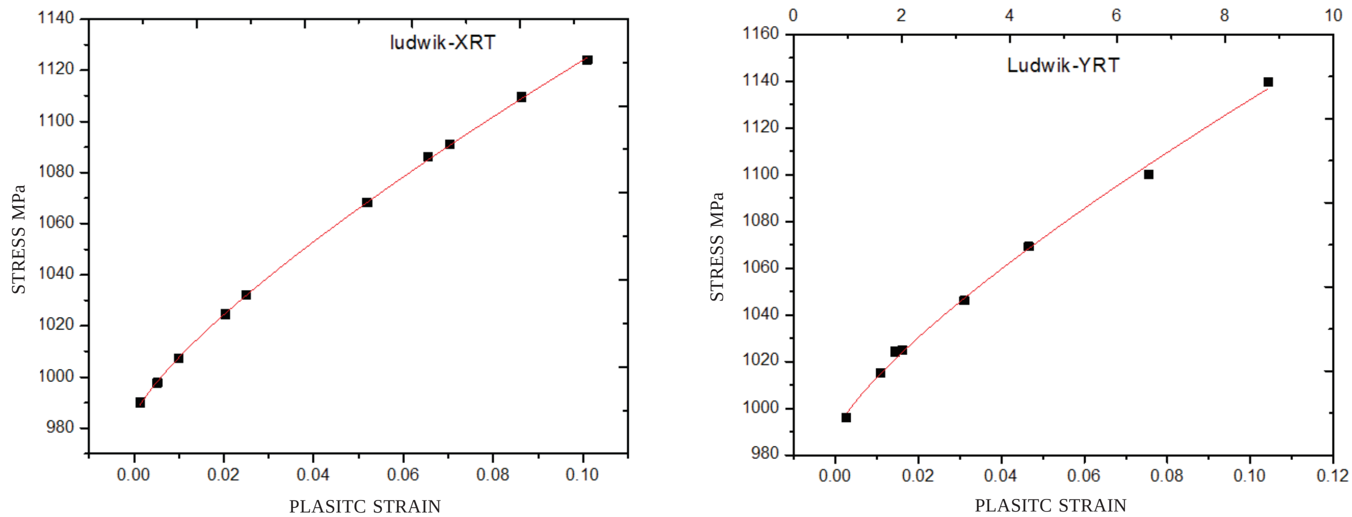
Figure 3. Engineering stress-strain diagram of tested specimens extracted from various locations along different directions.

hardening regime. The flow behaviour for all combinations of test specimens extracted from the forging shows similar trends in strain-hardening behaviour and the Ludwik eqn. was found to represent the strain-hardening regime in the most appropriate manner[24]. The typical curve for rim radial and web radial specimens is shown in Fig. 4. At GTRE, stress analysis using FEM was carried out and LS Dyna software also supports material model. Hence, an attempt has been made here to analyse strain-hardening data of cut up forging.

3.2 Fractrography

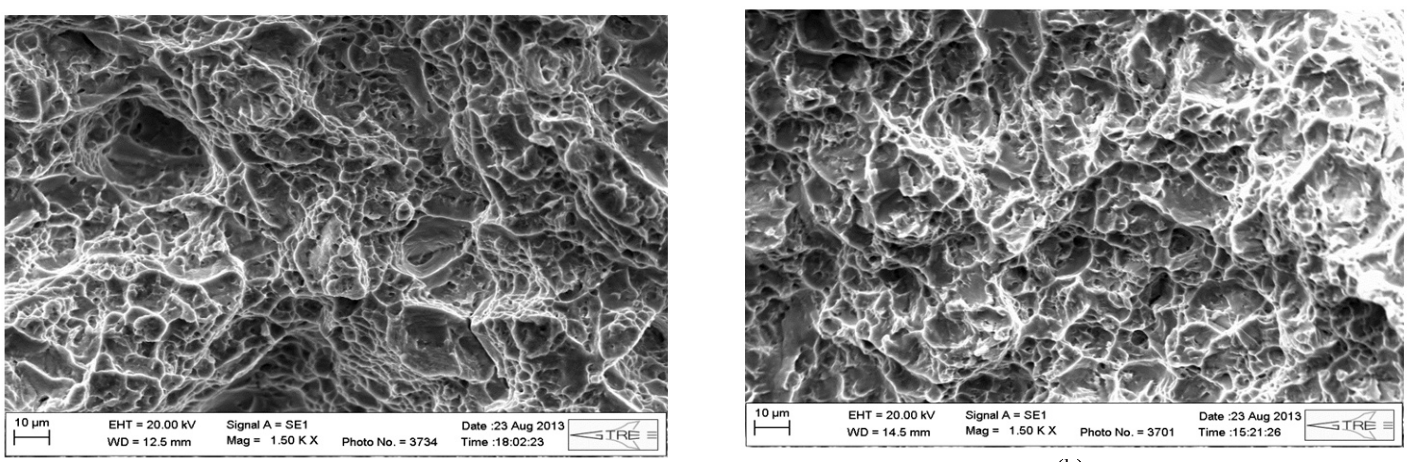
Figures 5(a), and 5(b) show fractographic images of tangential specimens from rim and bore locations, respectively. On the other hand, Figs 6(a) and 6(b) show the fractographic images of radial specimens from rim and bore locations, respectively. From these fractographic images, it is clear that tensile specimens, irrespective of forged location and test direction, fail by mixed fracture mode comprising ductile, dimple fracture and transgranular shear fracture.

Higher dimple sizes were observed in the specimens oriented in tangential directions which means higher extend of deformation, and it was reflected in higher ductility values. Further, dimple density in rim-tangential direction specimens was higher than rim-radial direction specimens. Dimple sizes



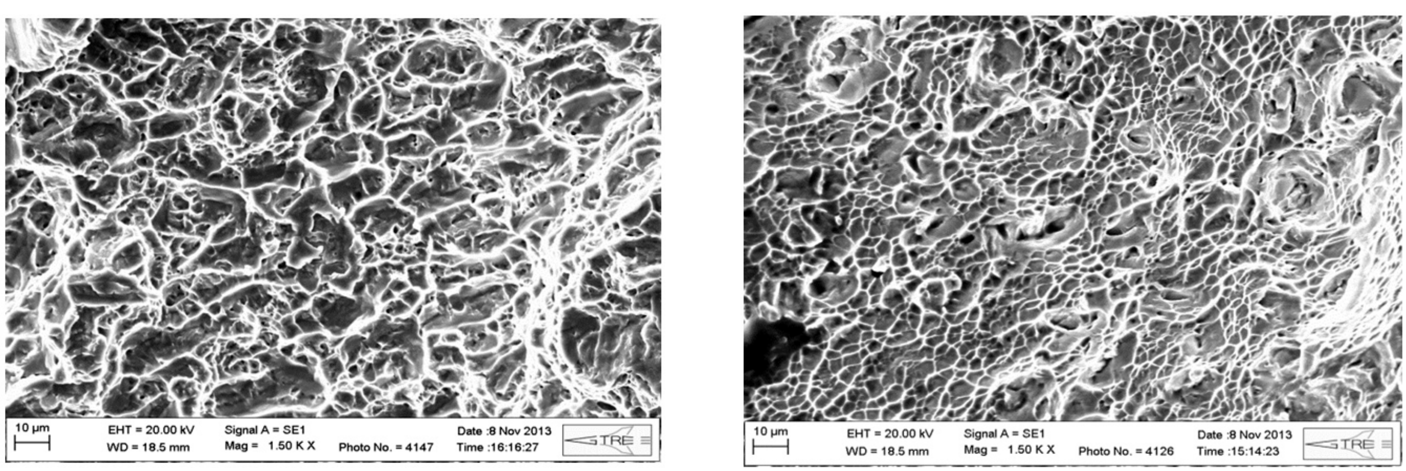
(a) (b)

Figure 4. Ludwik fit of rim radial and web radial specimens.



(a) (b)

Figure 5. Fractographic images of tangential specimens from: (a) rim, and (b) bore locations.



(a) (b)

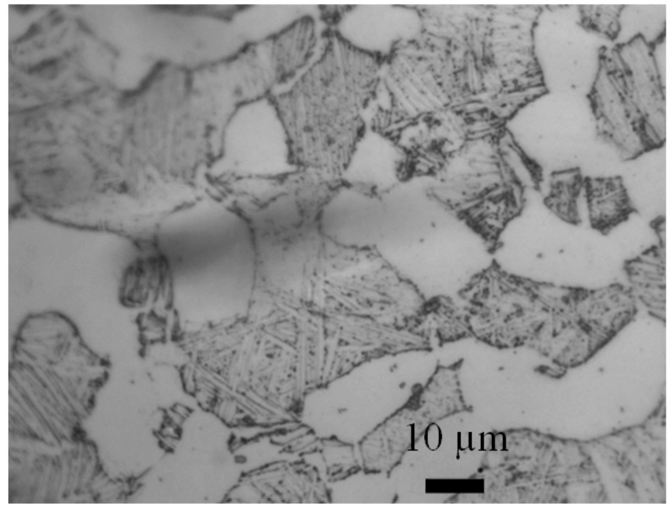
Figure 6. Fractographic images of radial specimens from: (a) rim, (b) bore locations.

and density observed were also greater**.** Dimple depth was also shallow in radial specimens compared to tangential specimen. It gives the impression that the rim-tangential specimens is more ductile compared to the rim radial direction specimens. The same is correlated with the tensile test data which shows the fracture strain in transverse specimens is higher (15 per cent more) than in the radial direction. It is quite evident that the mode of fracture is different in web radial than that of web tangential. Both the web direction locations show high density of micro-dimples but the extent of low energy transgranular faceted fracture is higher in tangential direction. Even the dimple distribution tangential specimens showed higher dimple density as compared to radial direction. Depth of the dimples in tangential specimens was also higher. Dimple orientation shapes and sizes are not uniform in transverse specimens. This could be linked with the occurrence of high values of UTS compared to radial specimens. The typical fractographic images of tangential specimens are shown in Figs 5(a) and 5(b) for rim and bore locations, respectively. Similarly fractographic images of radial specimens are shown in Figs 6(a) and 6(b) for rim and bore locations, respectively.

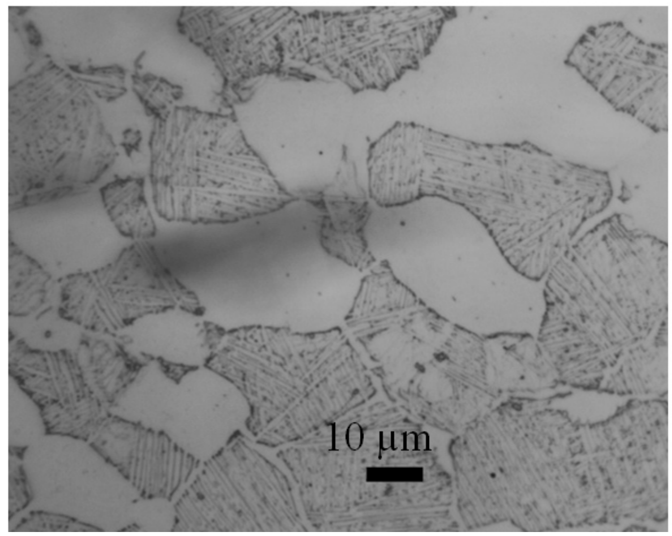
3.3 Micro Structural Correlations

The average size of primary α grains is higher in XTT specimens compared to XRT specimens. In both XTT and XRT specimens, the primary α grains are equiaxed and do not show any preferential orientation along any particular direction. But the size of prior β grain size in rim radial specimen (19.8 µm) is marginally higher than rim transverse specimens (17.9 µm). The microstructural features of the other two regions- the web and bore, are similar with only variation in size and volume fractions of the constitutive phases. The web radial and transverse test specimens reveal equiaxed primary α on transformed β matrix. Primary α grain size in transverse specimens is higher than in the radial specimens. Higher magnification optical images of web specimens along radial and transverse directions reveal that the volume fraction of primary α is also higher in transverse specimens compared to radial specimens. Primary α (*P*α) in radial specimens is showing tendency to elongate along a specific direction, but the distribution of primary α in transverse specimens does not show any such tendency. Network of fine α has been observed along prior β grain boundary of web radial specimen, but the morphology is not similar to that observed in XRT. Network of fine α is not much observed in transverse specimens in web region. Optical micrographsrim and bore regions are shown in Fig. 7.

The radial specimens of the bore show irregularly distributed smaller primary α along a certain direction. Primary α in tangential specimens is distributed uniformly on transformed β matrix. The optical micrographs of bore radial and tangential test specimens revealed that primary α in tangential specimens is higher compared to radial specimens. Primary α is little elongated and aligned at an angle approximately 45°. Trace of fine network of α has been found in micrographs of both the radial and transverse specimen. But the thickness of grain boundary network α is quite thick in transverse specimens compared to those in radial specimens.



(a)



(b)

Figure 7. Optical micrographs of rim region and bore region, respectively.

Optical micrographs of bore-radial specimens is shown in Fig. 8. Prior β grain size in bore-radial specimens is approximately 22.4 µm and it is observed around 18.1 µm in bore-transverse specimens. It is found in the literature that transformed beta (T_β) structure and α/β (alpha/beta) interface will not act as a barrier to the slip but the prior β grain size may alter and control the slip and yield strength. Higher is the size of prior β, lesser is the obstacle to the dislocation (obeying the Hall-Petch relation) and less is the yield strength and UTS.

Thus, the present study provides the following understanding based on microstructure-property correlations (similar to discussions made above):

1. ZTT and XTT specimens have been extracted from the bottom portion of the S1 segment of the disk. Microstructural observation along transverse direction reveals only a minor change in the prior β and Pα volume fraction (see data in Table 4). Morphology of widmanstatten structure is more fine and compact in XTT specimens compared to ZTT specimens and this has an impact on the overall mechanical properties of the specimens. As

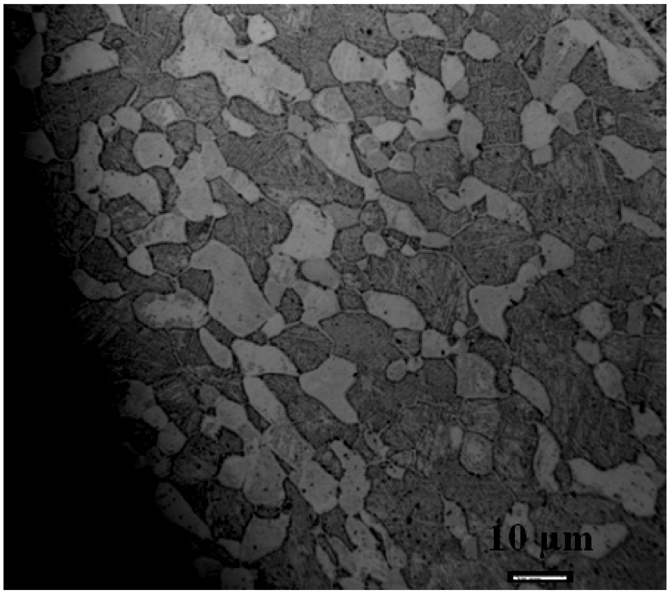


Figure 8. Bore-radial specimen.

T_β also controls the fracture-toughness of this alloy, XTT exhibits superior strength and very higher fracture strain compared to ZTT specimens and is expected to possess higher fracture toughness.

2. XRT and ZRT specimens, extracted from middle portion of the forging, show higher volume fraction of Pα in XRT as compared to ZRT. On the other hand, prior β grain size is bigger in ZRT specimens compared to XRT specimens. This results into higher strength and higher fracture strain in rim-radial specimens compared to bore-radial specimens.
3. The higher α flakes content and flake size are found to result in higher extent of quasi cleavage faceted fracture, and hence, lower strain to fracture.
4. The microstructure-fracture strain (and/or fracture mode) correlations are to be treated at this stage as a preliminary analysis and subjective. Detailed quantitative analysis has been attempted but such quantitative correlation could not establish anything different as the variations in the total strain to fracture is very small, if not negligible (18.3-21.2%) as shown in Fig. 9.

Table 4. Variation of prior β grain size across the forging

S. No	Location and direction of test specimen	Specimen type	Prior β (µm)
1	Rim-Radial	XRT	19.844
2	Rim-Transverse	XTT	17.912
3	Web-Radial	YRT	19.255
4	Web-Transverse	YTT	18.79
5	Bore-Radial	ZRT	22.39
6	Bore-Transverse	ZTT	18.06

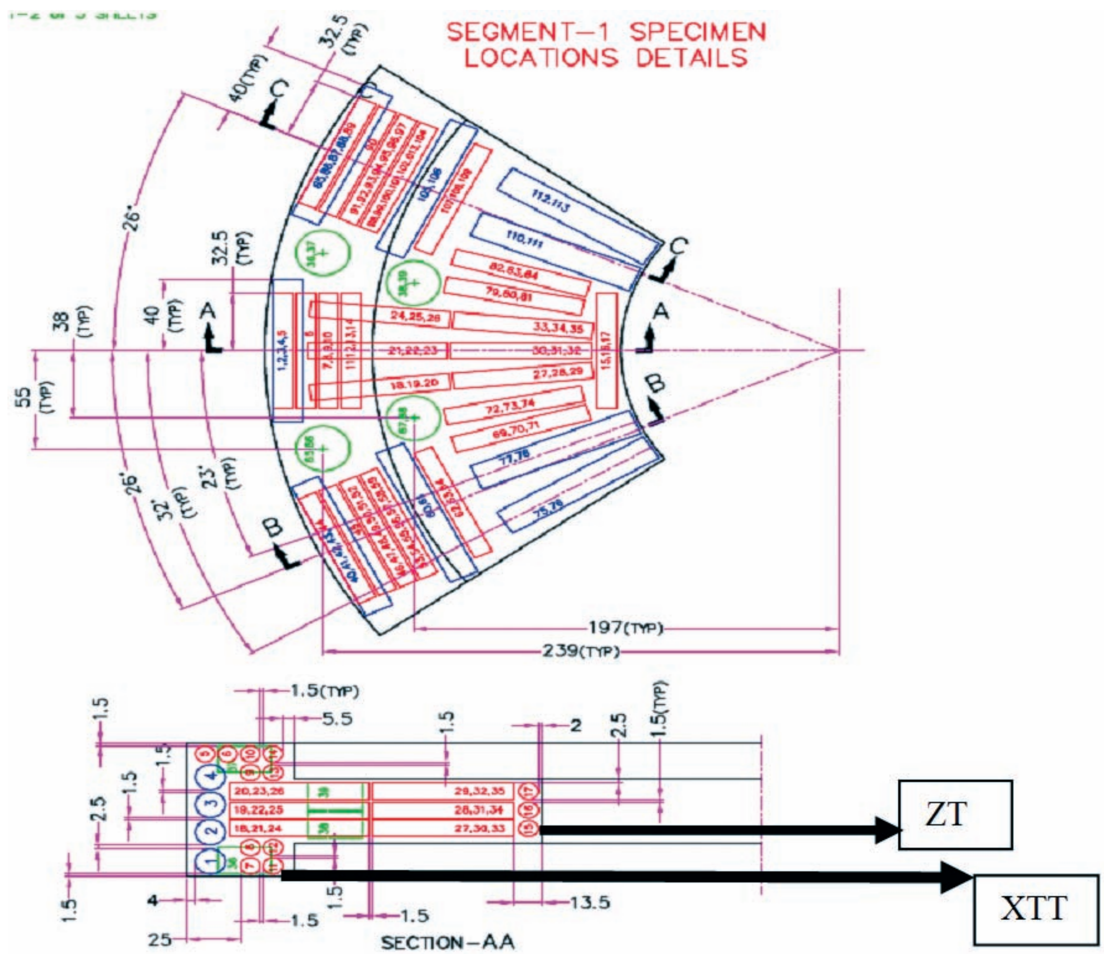


Figure 9. Segment 1 of the forging disk and its cross-sectional view locating rim and bore tangential specimens.

4. CONCLUSIONS

A fairly elaborate forging cut-up evaluation study of *Ti-6Al-4V* has been carried out to access the homogeneity of the close die forging product. Cut-up evaluation test plan has been prepared to extract test specimens from various locations (rim, web, and bore regions) of the forgings, both along radial and transverse directions. Tensile tests were performed using those extracted specimens at room temperature and statistical analyses were carried out to derive a suitable unified value to evaluate the forging. It is found that the average distribution of the test data lies beyond the limit of the acceptable range as mentioned in the forging specifications. The key findings of the study are given below:

- The average mechanical properties of the forging are better than the specification property, and hence the forging is sound.
- There is a mild variation in the microstructure along the radial direction of the forging, i.e., rim, web, and bore show variations in microstructure and that reflects into the tensile property and in fracture strength of the forging.
- Bore region of the forging is showing poor mechanical properties both in terms of yield strength and UTS along radial and transverse directions.
- Variations in the mechanical properties have been observed along the height of the forging.
- Transverse specimens exhibit better performance compared to radial specimens in rim and bore regions.
- Volume fraction of primary α and prior β grains size controls the strength of the forging.
- More the primary α volume fraction and less the prior β grains size, higher is the mechanical strength of the alloy.
- Morphology of the transformed beta (T_β) controls the fracture strain and fractrography features of the alloy.

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