Development of large-sized Titanium alloy Ti6Al4V and nickel-based superalloy Inconel-718 forgings for Reusable Launch Vehicle-Technology Demonstrator flight

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Ti6Al4V owing to its high specific strength and Inconel-718 due to its high strength and oxidation resistance at elevated temperatures, have been used in Reusable Launch Vehicle-Technology Demonstrator (RLV-TD). Achieving required properties in large cross-section aerospace quality forgings of these alloys is challenging and has not been reported earlier. Hence, thermo-mechanical processing cycles have been devised to realize forgings of ~1400 mm length in these alloys and successfully used in RLV-TD. Forgings of these alloys having desired microstructures and ultrasonic quality of Class-A1 as per AMS 2630 B standard have been realized. This article discusses the processing challenges and solutions thereof.

Keywords: Aerospace alloys, forging, microstructure, ultrasonic quality.

Introduction

THIS article discusses the aspects of realization of large cross-section forgings of two aerospace alloys, viz. titanium alloy Ti6Al4V and nickel-based superalloy Inconel-718. The processing challenges encountered during the various stages of materials realization such as melting, forging and heat treatment, and solutions thereof have been outlined. The components realized out of these alloys have been successfully used in India's maiden Reusable Launch Vehicle-Technology Demonstrator (RLV-TD) flight.

Titanium alloy Ti6Al4V

Ti6Al4V alloy is the workhorse aerospace alloy widely used in applications such as compressor blades, discs and rings for jet engines, airframe and space capsule components, pressure vessels, rocket engine cases and critical forgings requiring high strength-to-weight ratio. It is a two-phase ($\alpha + \beta$) titanium alloy, where aluminum is 'α' stabilizer and vanadium is 'β' stabilizer. It is used in annealed condition as well as in solution-treated and aged condition. Though Ti alloy forging process is well established, there are challenges in the realization of large-sized forgings conforming to stringent ultrasonic class requirements.

Vacuum melting processes are used to obtain desired quality of melt and cleanliness in the alloy since gas content beyond the specified limits can adversely affect its mechanical and physical properties. Use of pure raw materials is equally important since melt is processed under vacuum using a consumable compacted electrode, where significant refinement does not take place during melting and the raw material quality decides the melt quality. Further, maintaining uniform chemical composition/homogeneity, mechanical properties and microstructure becomes a challenge when size of the component (forging) is very large.

Downstream processing of the ingot, viz. preheating, forging, heat treatment, etc. governs the final properties, quality and microstructure of the material. Preheating under neutral/oxidizing atmosphere, forging with sufficient amount of reduction and heat treatment with uniform temperature control are essentially required[1,2]. The alloy has α to β transformation during heating to 995°C, known as β-transus temperature. Hot working of this alloy above this temperature is not desirable to achieve optimum mechanical properties, and hence it is hot-worked in the temperature range 950°C to 850°C avoiding transformation into single phase β-regime, which has its own associated problems. To derive the benefit of minimum flow stress, the forging window is selected as close to β-transus of the alloy but with sufficient care to ensure no adiabatic heating occurs during processing which may result in crossing the β-transus[2–4]. It has also been reported that a final reduction of 30–40% is recommended for achieving optimal properties. Finally, the finished product is subjected to various types of annealing operations depending on the end use of the component. For most applications, mill annealing at 705–790°C or

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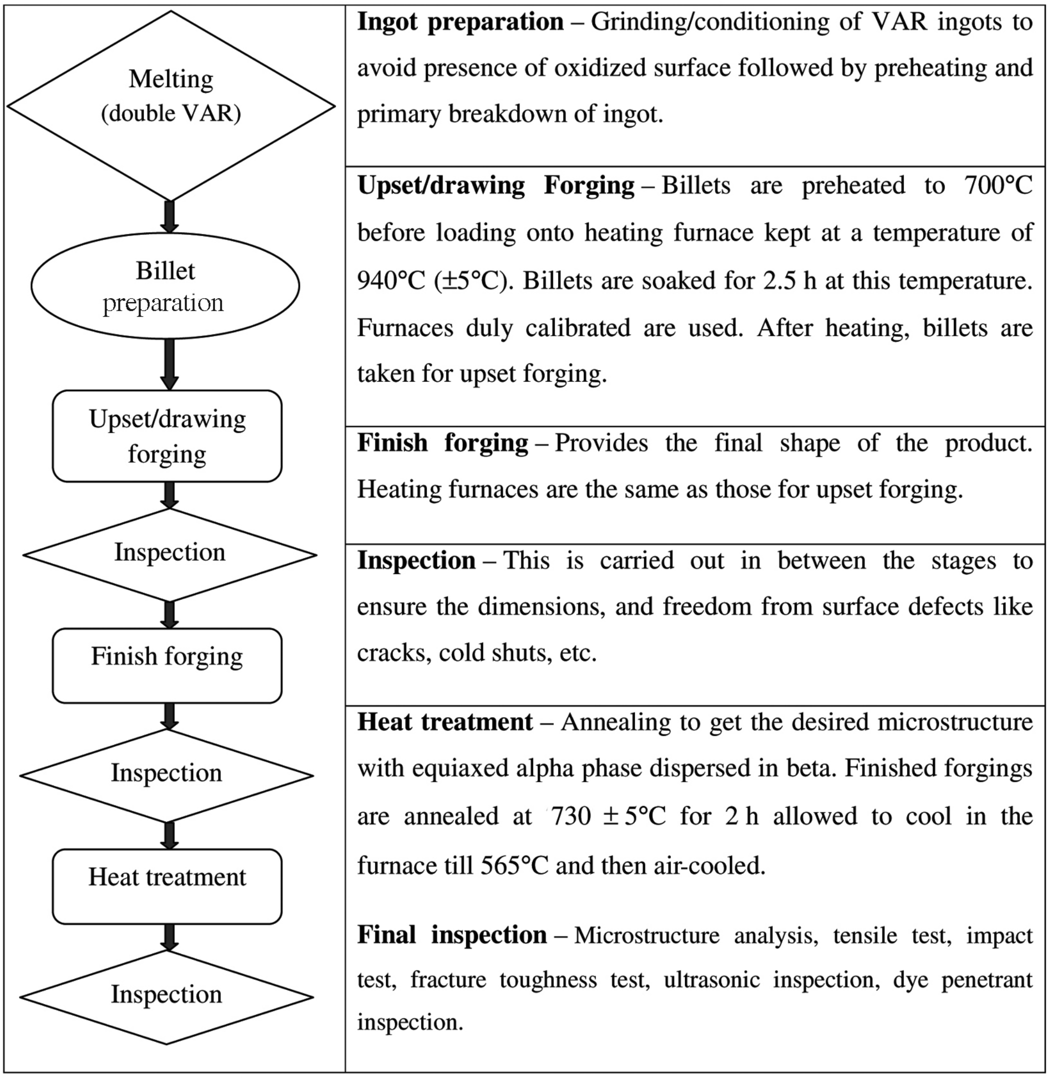

Figure 1. Process flow chart for realization of Ti6Al4V forgings.

recrystallization annealing at 905–930°C is the desired temperature regime[2,3].

Processing of Ti6Al4V alloy

In the present work, 830 mm diameter ingots were made through double vacuum arc remelting (VAR) process using pure raw materials (Ti sponge and Al–V master alloy). VAR ingot was first subjected to conditioning so as to remove the oxidized surface and preheated just above the β-transus temperature at a temperature range 1130–1000°C and forged to 650 mm diameter bars as an ingot breakdown operation to prepare the initial forged billet stock. Further, individual forge stock was forged in a 1500 tonne press below the β-transus temperature at a slow rate involving suitable upsetting and drawing operations. This stage of working is important in deciding the ultrasonic quality in the alloy with respect to amenability to inspection[1]. Hence sufficient working in all directions has been imparted. Figure 1 presents the process plan specifically made to meet the requirements of microstructure, mechanical properties and ultrasonic quality of large-sized forging ($80 \times 380 \times 1375$ mm^3). This scheme was evolved after realizing the difficulty in achieving the required ultrasonic inspection quality and microstructure in the final product.

Evaluation of tensile strength and impact strength of the alloy was carried out using the prolongation provided in the forgings. The specimens for tensile test and Charpy impact test (2 mm V-notch) were prepared as per ASTM E8 and ASTM E23 standards respectively. Fracture toughness test was carried out on 25 mm thick specimens as per ASTM E399.

Results and discussion – Ti6Al4V

Mechanical properties are presented in Tables 1 and 2, which meet the specification requirements of the alloy in

Table 1. Tensile properties evaluated in forged blocks of Ti6Al4V – 80 × 380 × 1375 mm^3 size

Property	Specified (minimum) as per AMS 4928	Achieved values
Yield strength (MPa)	827	843–879 (*L*) 907–932 (*T*)
Ultimate tensile strength (MPa)	896	929–955 (*L*) 985–1014 (*T*)
% Elongation (GL = 4d)	10	14.0–16.0 (*L*) 13.0–17.0 (*T*)
% Reduction in area	25 – *L* direction 20 – *T* direction	38–41 (*L*) 30–45 (*T*)

Note: Unless specified, values are applicable for both *L* and *T* directions. Test sample dimensions: diameter = 6.25 mm, gauge length (GL) = 25 mm. Strain rate: Till yield = 0.005 s^{-1}, beyond yield = 0.02 s^{-1}, Directions: *L*, Longitudinal; *T*, Transverse.

Table 2. Impact strength and fracture toughness properties evaluated in forged blocks of Ti6Al4V – 80 × 380 × 1375 mm^3 size

Property	Specified (minimum)	Achieved values
Impact strength (kg-m cm^{-2})	2.5	3.3–3.6 (*L*) 2.9–3.5 (*T*)
Fracture toughness (MPa.$m^{1/2}$)	50	62–68 (*L–T*) 62–73 (*T–L*)

Note: Unless specified values are applicable for both *L* and *T* directions.

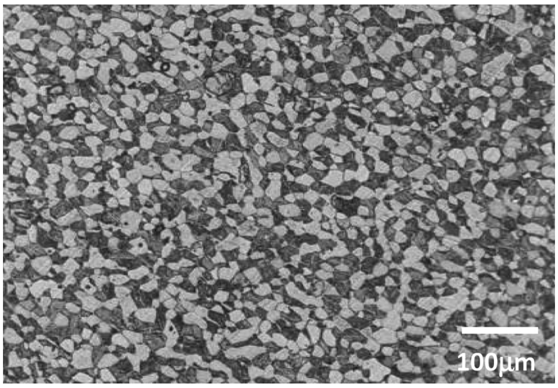

Figure 2. Microstructure of Ti6Al4V shows primary α phase in transformed β matrix.

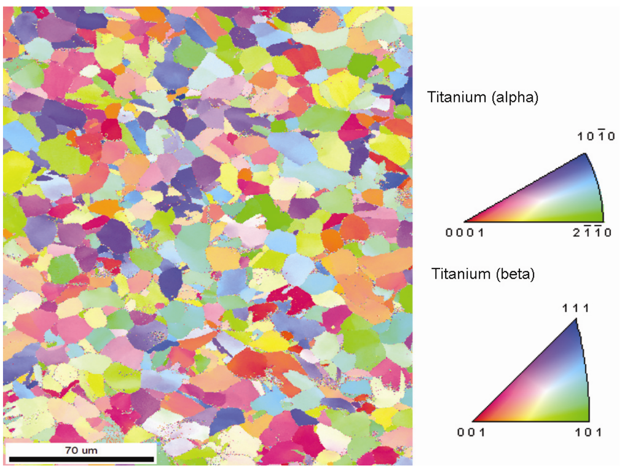

Figure 3. Electron back scattered diffraction image showing uniform fine $\alpha + \beta$ microstructure with random texture in Ti6Al4V.

annealed condition. It may be noted here that although the forgings have higher cross-sectional area, i.e. ~30,000 mm^2 (~1.5 times the maximum cross-sectional area, i.e. 23,225 mm^2 as per AMS 4928 for which guaranteed mechanical properties are specified according to Table 1), mechanical properties applicable to even lower-sized forgings are met. It is the result of sufficient mechanical working imparted during the processing of the large-sized forgings.

Although preheating temperature is 940°C, forging was carried out between 920°C and 870°C due to loss of heat during transfer from furnace to forge press. However, this has resulted in uniform microstructure across the forging. Optical microstructures obtained from the forgings consist of fine $\alpha + \beta$ structure (Figure 2). Image obtained through electron back scattered diffraction (EBSD) also confirms uniformity of microstructure with random texture (Figure 3).

It may be noted that AMS 2631 is the applicable standard for ultrasonic inspection of titanium alloy forgings, which calls for inspection to single discontinuities only and not multiple and linear discontinuities. However, ultrasonic testing of the realized forgings was carried out with both normal beam and angle beam techniques as per AMS 2631/AMS 2630/AMS 2632 standards. The forgings were found to meet the acceptance criteria of 1.2 mm flat bottom hole (FBH) single and 0.8 mm FBH, or equivalent multiple/linear discontinuities as well. It is interesting to note that ultrasonic signal-to-noise ratio is more than 6 dB in the thickness direction for a forging of 80 mm thickness. This indicates good amount of reduction and correspondingly fine grain microstructure.

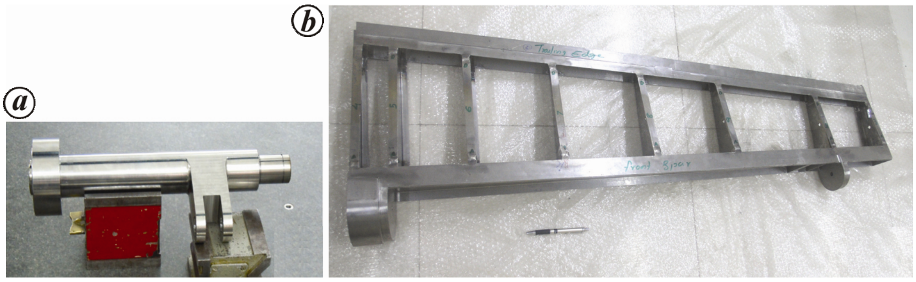

Figure 4. (***a***) Elevon shaft and (***b***) Elevon torsion box used in RLV-TD.

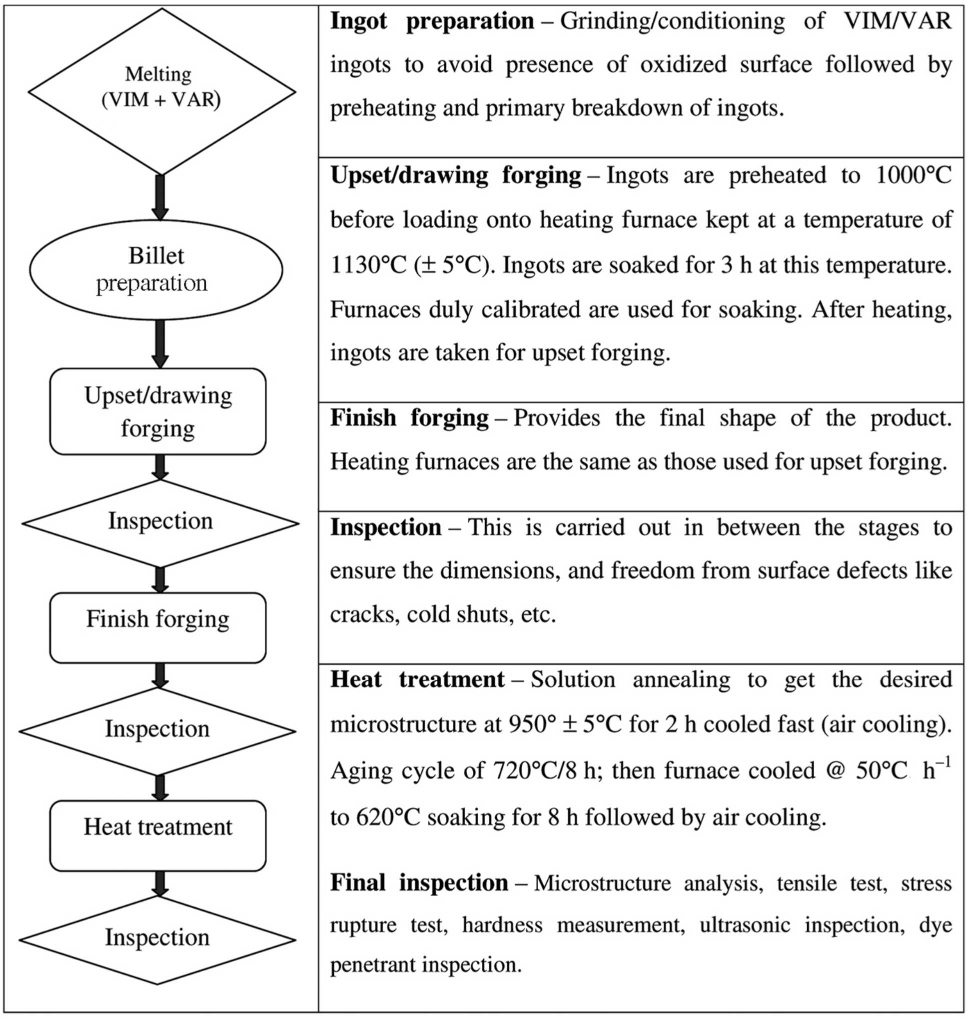

Figure 5. Process flow chart for realization of Inconel-718 forgings.

Dye penetrant testing was carried out as per ASTM E165 standard on 100% surface area of forgings, which were found to be free of any surface defects. Achieved properties, ultrasonic quality and microstructure confirm that the devised scheme of thermo-mechanical working for realizing the large-sized forgings is adequate to achieve the desired quality in them.

The realized forgings were used to realize elevon-shaft, elevon torsion box, front spar and leading edges of RLV-TD airframe. Figure 4 shows the photographs of some of these component.

Nickel-based superalloy Inconel-718

The Ni-based superalloy Inconel-718 has been widely used in age-hardened condition for moderate to elevated temperature applications. It is age-hardened by the

Table 3. Room temperature tensile properties in annealed and aged conditions evaluated on Inconel-718 forgings of size 60 × 120 × 1420 mm^3

	Annealed		Aged	
Property	Specified (minimum)	Achieved	Specified (minimum)	Achieved
Yield strength (MPa)	550	610	1034	1217–1225 (*L*) 1183–1217 (*T*)
Ultimate tensile strength (MPa)	965	1025	1240	1407–1427 (*L*) 1385–1420 (*T*)
% Elongation (GL = 4d)	30	36	12	20–22 (*L*) 16–19 (*T*)
% Reduction in area	25	31	15	35–44 (*L*) 26–41 (*T*)

Note: Unless specified, values are applicable for both *L* and *T* directions. Test sample dimensions: Diameter = 6.25 mm, GL = 25 mm. Strain rate: Till yield = 0.005 s^{-1}, beyond yield = 0.02 s^{-1}.

Table 4. Elevated temperature (650°C) tensile properties in aged condition evaluated on Inconel-718 forgings of size 60 × 120 × 1420 mm^3

	Aged (*T* direction)	
Property	Specified (minimum)	Achieved
Yield strength (MPa)	862	1025
Ultimate tensile strength (MPa)	965	1188
% Elongation (GL = 4d)	10	12
% Reduction in area	12	32

Table 5. Stress rupture properties in aged condition evaluated on Inconel-718 forgings of size 60 × 120 × 1420 mm^3

Temperature: 650°C Stress: 690 MPa	Specified (minimum)	Achieved
Life (h)	23	75.2
% Elongation	4	8.0

combined precipitation of fine γ' and γ'' phases in an austenitic (γ) matrix[5–7]. It has been found that the major hardening phase is the metastable γ''-phase, which transforms to orthorhombic δ-phase under equilibrium conditions. The amount of precipitation phases, together with their shape and distribution, has influence on the mechanical properties, which are governed by thermo-mechanical processing. Considerable research has been carried out on the strengthening effects of the γ' and γ'' phases and the toughening effects of δ-phase in order to improve the overall mechanical properties[5–7]. It is widely accepted that the δ-phase has an important influence on the microstructure and mechanical properties of Inconel-718. With the aim to improve the mechanical properties further, heavy-duty components are often forged. In the aircraft industry, great emphasis is put on lightweight construction as well as on operational reliability, and hence obtaining the desired mechanical properties has been always essential. It becomes challenging, especially when component size is large.

Inconel-718 is a difficult-to-forge alloy, especially when the section size is large. Therefore, forging operations are performed at temperatures up to 1030–1130°C without affecting its mechanical properties. A reduction of 30–40% in the cross-section is recommended for achieving optimal properties.

Processing of Inconel-718

The raw material for the forging is made through vacuum induction melting (VIM) followed by the VAR process. Figure 5 presents a process plan specifically made to meet the requirements of microstructure, mechanical properties and ultrasonic quality of large-sized forgings (60 × 120 × 1420 mm^3). This has been especially designed to meet the properties through working and subsequently through uniform precipitation during aging. Alloy was realized in annealed condition and was followed by aging treatment. Room-temperature properties were evaluated at both conditions to confirm the response of alloy to heat treatment.

Tensile test was performed as per ASTM E8 standard on specimens taken from the prolongation of the forgings to ascertain tensile properties. High-temperature tensile properties were evaluated at 650°C. Stress rupture test was also conducted on samples in aged condition as per ASTM E292 standard.

Results and discussion – Inconel-718

Room-temperature tensile properties in annealed as well as aged condition are presented in Table 3, while Table 4 presents the high temperature (650°C) tensile properties. Stress rupture testing in aged condition (Table 5) is found to meet the requirements specified in AMS 5662 standard.

Figure 6. Microstructure showing fine austenitic grain matrix in sample representative of large-sized Inconel-718 forgings.

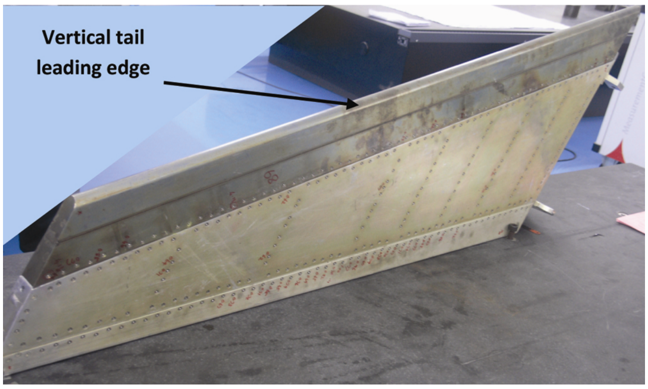

Figure 7. A vertical tail leading edge fabricated from Inconel-718 forged block of size 60 × 120 × 1420 mm^3 used in RLV-TD.

It has been noted that lower finishing temperature results in fine-grained microstructure, and similar philosophy has been followed. This confirms that the amount of working is adequate, which has resulted in meeting the specified properties through its response to heat treatment. Optical microstructures obtained from the forgings consist of fine-grained austenitic structure (Figure 6). Absence of necklace-type structure confirms proper heat treatment of the alloy.

Ultrasonic testing of forging was carried out with normal beam and angle beam techniques as per AMS 2630 standard. The forgings were found to meet the acceptance criteria of 1.2 mm FBH for single discontinuity and 0.8 mm FBH or equivalent for multiple/linear discontinuities. This also indirectly indicates that the material is not only defect-free, but also homogenous with uniform microstructure throughout. Dye penetrant testing as per ASTM E165 standard on 100% surface area of forgings did not reveal any defects.

The realized forgings were used for realizing the vertical tail leading edges of RLV-TD, which experiences elevated temperatures during the entire duration of the atmospheric re-entry flight (Figure 7).

Summary

Development of forging process was carried out in stages, viz. upset, draw-down and finish forging. Heat treatment cycles for Ti6Al4V and Inconel-718 were fine-tuned to achieve the desired mechanical properties in these large-sized forgings. Microstructure revealed primary alpha in a matrix of transformed beta in Ti6Al4V and fine-grained austenitic structure in Inconel-718 forgings. Ultrasonic acceptance criteria of 1.2 mm FBH single and 0.8 mm FBH or equivalent multiple/linear discontinuities, and desired properties with a uniform microstructure in the large-sized forgings have been achieved by optimization of thermo-mechanical processing parameters. These forgings have been used successfully in India's first RLV-TD flight.

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