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Development Of Ring Forgings In Ti-6Al-4V Alloy For Aero-engine Applications

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ABSTRACT

Titanium base alloy-Ti-6Al-4V [Ti-64] is extensively used in aero gas turbine [Kaveri engine] for various applications. Majority of the wrought Ti-64 components in the engine are processed through ring rolling/ forging route. Indigenous development and productionisation of the ring forgings have been carried out using the ring rolling mill and allied forging facilities of M/s HAL (F&F), Bangalore / M/s Echjay Industries, Rajkot. Type certified indigenous Ti-64 forging stock [of size up to 250mm diameter] from M/s Mishra Dhatu Nigam Ltd. [MIDHANI], Hyderabad has been used for the development and subsequent productionisation. Satisfactory metallurgical and mechanical properties have been achieved in Ti-64 alloy ring forgings, as per the release specification. Total 79 batches of 29 varieties of the Ti-64 ring forgings for Kaveri engine have been indigenously produced and supplied. This paper presents details of the work done for the indigenous development of Ti64 ring forgings of various sizes for Kaveri engine.

1. INTRODUCTION

Kaveri engine is an advanced gas turbine engine being designed and developed by Gas Turbine Research Establishment, Bangalore, to power Light Combat Aircraft [LCA]. It is a turbo-fan and twin spool engine of 80kN thrust class, with low bypass ratio. One of the major tasks in the development of this engine is to establish indigenous capability for production of critical materials and components and type certification by air-worthiness agencies. Due to potential strength to weight ratio of Ti-6Al-4V material and its high temperature properties up to 300°C[1], significant number of rings in the Kaveri engine were designed with this material for various applications in the engine as follows :

(i) Sealing and locking rings in Fan module

(ii) Flange and actuator rings in Compressor module

(iii) Flange and stiffener rings in Jet pipe module and

(iv) Flange rings in By-pass duct.

Indigenous development and productionisation of the ring forgings have been carried out using the ring rolling mill and allied forging facilities of M/s Hindustan Aeronautics Limited, Foundry and Forge Division, [HAL (F&F)], Bangalore/M/s Echjay Industries, Rajkot. Type certified Ti-6Al-4V alloy forging stock from M/s Mishra Dhatu Nigam Ltd., (MIDHANI), Hyderabad, has been used for the manufacture of the ring forgings. Indigenous Ti-6Al-4V ring forgings meeting the specification [GTM-Ti-64/FORG (Rev.-4)] have been successfully developed and productionised. This paper provides the details related to material, development, processing, various sizes of Kaveri rings produced, structure and property evaluation of the indigenous Ti-64 ring forgings.

2. FORGING OF Ti-6Al-4V [Ti-64] MATERIAL

Ti-6Al-4V is a $\alpha + \beta$ titanium alloy[1,2]. The alloy is used in several forging types, including open die, closed die, rings and precision forgings and manufactured using appropriate forging equipments, such as hammers [standard and counter-blow], upsetters, mechanical presses, screw presses, HERF machines, hydraulic presses, ring mills etc. Among titanium alloys that are forged, Ti-64 is intermediate in forgeability. It is more difficult to forge, as measured by flow stress and crack sensitivity than most ferrous alloys [and all aluminium alloys], but is less difficult to forge than most nickel and cobalt-base superalloys.

Ti-64 may be forged using either conventional $\alpha+\beta$ [sub-beta transus] or β [supra-beta transus] forging techniques[1]. Both techniques are used in combination with annealing, and solution treating and annealing or ageing treatments. Other thermal treatments such as recrystallisation annealing and/or beta annealing or beta solution treatment and annealing may be combined with conventional forging to achieve tailored properties. Conventional $\alpha+\beta$ forging of Ti-6Al-4V predominate commercially because it achieves an equiaxed α in a transformed β matrix microstructure that is preferred for many of the aero-engine applications. β forging of Ti-64 creates an acicular alpha microstructure that is preferred for service conditions where fracture-related and/or creep properties are highly critical.

Resistance to deformation is reduced by increasing metal temperatures[3], however, in commercial practice, reheat furnace capabilities and maintenance of temperature uniformity [tolerance] of the furnace constrain the upper limit of metal temperature in conventional forging to ensure that the β transus is not exceeded to achieve the desired equiaxed α-β microstructure. Flow stresses of Ti-64 are significantly reduced in β forging[1,3] with metal temperatures above the β transus. However, this forging technique results in transformed, Widmanstatten α microstructures that may not be suitable for all applications.

Ti-64 is heated for forging using a variety of commercially available furnace[1] equipments including induction heating, resistance heating, electric [radiant], LPG, LDO and natural gas. Forging reheat furnaces include batch, rotary and continuous [walking beam] furnaces designed for the temperatures required. The alloy may be heated to required metal temperatures for forging at any convenient heating rate. However, Ti-64 has a low coefficient of thermal conductivity. Therefore, commercial forging preheat practices allow a hold of 20 to 30 min./inch of ruling section thickness [bar or forging] to ensure that the work-pieces reach the desired temperature throughout. Ti-64 is heated in oxidizing atmospheres to retard hydrogen pickup from furnace products of combustion. Heating of forgings in this type of atmosphere creates a surface layer, termed as α case, from diffusion of oxygen and nitrogen, that must be removed from finished forging by machining or pickling [or chemical milling] in appropriately constituted and controlled solutions of hydrofluoric and nitric acids.

3. RING ROLLING PROCESS

Ring rolling[4] is fundamentally a hot-rolling process for the manufacture of seamless ring shaped components using specialized equipments and forming processes. The process is well suited for manufacturing casings and rings for aero gas turbine engines, because it produces superior mechanical and high temperature properties similar to those achieved through forging. Seamless rolled rings require less input material, are produced faster, are more precise and due to the circumferential grain flow of the finished part, are stronger than those produced by alternative methods of ring production.

The process starts with a circular preform of metal that has been previously upset and pierced (using the open die forging process in a hydraulic press, mechanical press or forging hammer) to form a hollow/cylindrical ring. This preform is heated above the recrystallization temperature and is placed on the ring roller over an undriven mandrel, which will have lower diameter than the ID of the preform, and the mandrel is forced under pressure toward a driven main roll. When the blank comes in contact with the main roll, the friction between the main roll, blank and mandrel causes the blank and mandrel to rotate in the direction the main roll is turning. Centering arms are used to keep the blank centered during rolling to prevent defects from forming and to ensure concentricity on the ring. The gap between main roll and mandrel is progressively reduced, thereby reducing the wall thickness of the ring and simultaneously increasing its diameter due to the circumferential extrusion that occurs. Ring height is governed either by being contained by a groove of the main roll or by the use of axial rolls that simultaneously act on the top and bottom surfaces of the ring in a similar manner to the main roll and mandrel. The result is a uniform cross-section ring, disk or contour-shaped component that can be further processed into a finished part, usually by machining. The complete sequence of ring rolling process is schematically shown in Fig.1.

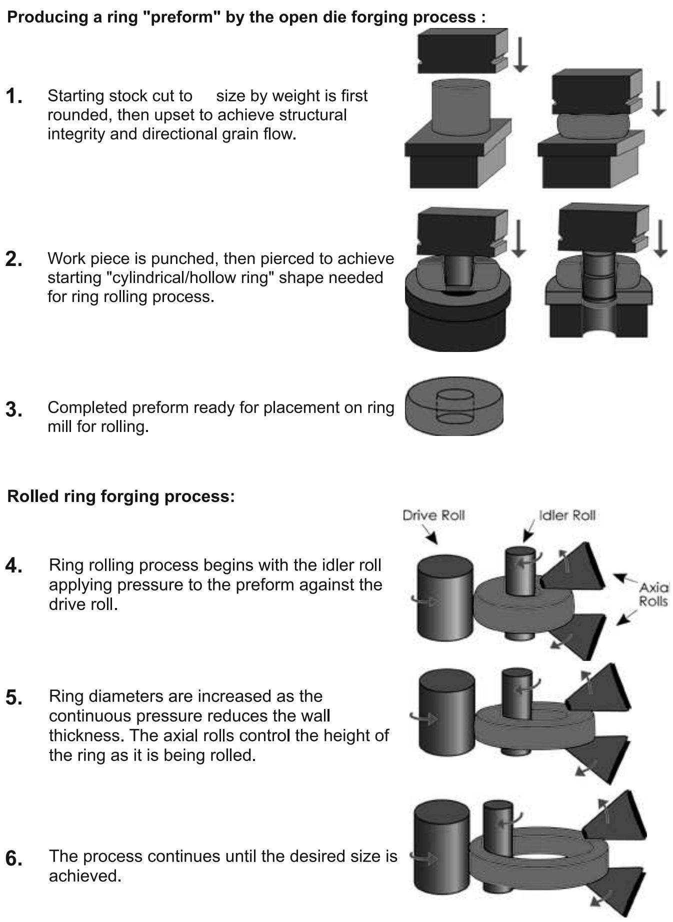

Fig. 1 : Seamless Rolled Ring Forging Process

4. MAJOR EQUIPMENTS

The following facilities were used for the development and subsequent productionisation of Ti-64 rings:

4.1 Forging equipments

(i) 2500 ton or 3000 ton hydraulic press for preforming operations [upset forging and piercing operations].

(ii) 80 ton Radial/63 ton Axial or 100 ton Radial/63 ton Axial Rolling mill for ring forging operations. The mill is shown in Fig. 2.

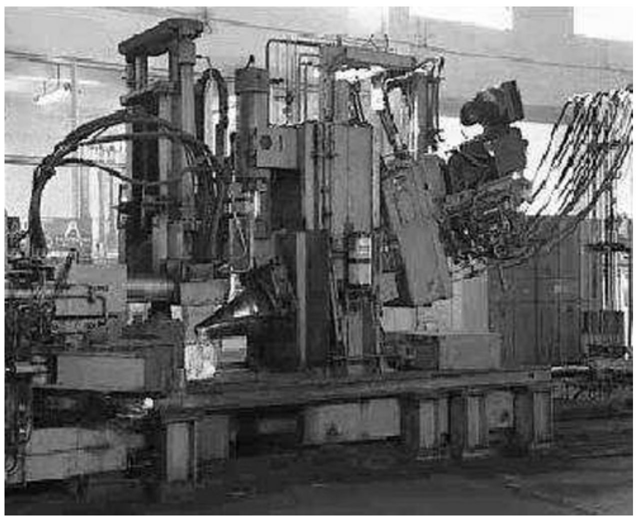

Fig. 2 : 100 ton Radial/63 ton Axial ring rolling mill

4.2 Forging furnaces

Electrically heated box type high temperature forging furnaces were used for the preforming and subsequent ring rolling forging operations. All these furnaces were calibrated to the temperature accuracy requirement of ±15°C at the forging temperature of around 1000°C.

4.3 Heat treatment furnace

Pit type electrically heated furnace having required accuracy [±10°C for solution heat treatment and ±5°C for ageing] and water quenching facility available at HAL(F&F) was used for carrying out the heat treatment of ring forgings. Details of the furnace are as follows:

(i) Power rating : 110 kW

Heating element : Kanthal

Operating temperature range : 780°C – 1180°C

Size of the furnace : 1.6m Dia. x 1.76m H

5. FORGING STOCK / BILLET FOR RING FORGINGS

Premium quality and triple/double vacuum arc [VAR] remelted grade - Ti-6Al-4V alloy forging stock were required for the Kaveri ring forgings. The required forging stock from indigenous approved source M/s Midhani was used for the development and productionisation of the ring forgings. Material was multiple vacuum arc melted [either Double melted or Triple melted grade] using a consumable electrode remelt process[5]. The original ingots of size 830 mm diameters were thermo-mechanically worked down to the billets of 180mm to 250mm diameters. Chemical composition, by weight per cent, required for Kaveri ring forgings as per GTM - specification is as follows:

Chemical Composition [in % weight] :			
Al : 6.20 – 6.75	V : 3.50 – 4.50	Fe : 0.30 (max.)	O : 0.16 – 0.20
C : 0.08 (max.)	N : 0.03 (max.)	H : *	Y : 0.001 (max.)
B : 10 ppm (max.)	Sn : 0.1 (max.)	Mo : 0.1 (max.)	Cu : 0.1 (max.)
Mn : 0.1 (max.)	Zr : 0.1 (max.)	Total Sn, Mo, Cu, Mn & Zr : 0.2 (max.)	
Other elements (each): 0.1(max.)	Total other elements: 0.2(max.)		Ti : Balance
* H for forging stock – 60 PPM (max.) and forgings – 100 PPM (max.)			

A photograph of the feedstock used for manufacture of ring forgings is shown in Fig. 3.

6. DEVELOPMENTAL TRIALS

A ring forging required for Fan seal application in the engine was identified for the first development trial. Selection of processing temperatures for both forging and subsequent solution heat treatment are very critical to achieve a desired equiaxed $\alpha + \beta$ structure[1,2,6] with the stipulated primary alpha content of 20% - 40% microstructure. The forging temperature of 950°C was chosen for the first development trial, based on the information provided in the literature[1,2].

6.1 Processing:

Ring Forging Size : 525mm OD x 425mm ID x 70mm thickness

Proof M/c Size : 510mm OD x 440mm ID x 35mm thickness

1. Feedstock size : 180mm diameter x 349mm length

Fig. 3 : Indigenous Ti-6Al-4V forging stock [180mm diameter]

2. Job lubrication : HAL glaze
3. Die lubrication : Mica used for upset forging operation.
4. Forging operations : The process parameters followed during forging operations are given in the table below:

Forging/Ring		S No.1			S No. 2			S No. 3	
Heating Cycle		1	2	3	1	2	3	1	2
Method of forging		Upset	Piercing	Ring Rolling	Upset	Piercing	Ring Rolling	Upset & Piercing	Ring Rolling
Soak Temp.		950°C	950°C	950°C	950°C	950°C	950°C	950°C	950°C
Soak Time		2hrs. 30min.	15min.	30min.	2hrs. 30min.	15min.	30min.	2hrs. 45min.	45min.
Press capacity		2500 T	2500 T	Rolling mill	2500 T	2500 T	Rolling mill	2500 T	Rolling mill
Mandrel Size		--	--	200mm	--	--	200mm	--	200mm
Main Roller Speed		--	--	1000 rpm	--	--	1000 rpm	--	1000 rpm
Force/Load	Axial	150 kg/cm^2	250 kg/cm^2	50 T	150 kg/cm^2	250 kg/cm^2	50 T	150 kg/cm^2	40 T
	Radial	--	--	40 T	--	--	40 T	--	40 T
	Guide Roller	--	--	5 T	--	--	5 T	--	5 T
Dimension	OD	--	--	530mm	--	--	530mm	--	530mm
	ID	--	--	400mm	--	--	400mm	--	400mm
	T	100mm	92mm	84mm	107mm	91mm	83mm	87mm	82mm

5. Visual inspection on forgings was carried out and they were found to have uniform surface without any defects, such as cracks, folds, etc.
6. The rings were solution heat treated - 965°C, soak for 1 hour and agitated WQ and then anneal - 700°C; soak for 2 hours and air cool.
7. Ti-64 ring forgings could be manufactured within limited number of heating cycles. It was observed that the flow characteristics of the material were quite satisfactory at the selected forging parameters. Therefore, the selected process parameters seemed to be compatible for ring roll forging of the material.

6.2 Testing

The forgings produced against the development batch were subjected to non-destructive testing [Ultrasonic inspection[7] (1.2mm FBH acceptance standard) and Fluorescent penetrant inspection[8]], metallurgical evaluations [macro and microstructure] and mechanical testings [RT Tensile, HT Tensile at 300°C and NSR at RT]. The products met all the requirements as per the specifications.

7. PRODUCTIONISATION OF KAVERI RINGS

Based on the experience gained during development work, process sheets/method sketches have been evolved for all the Kaveri ring forgings for productionisation. Total 79 batches of different sizes of ring forgings required in Ti-64 alloy for Kaveri engine have been indigenously produced and supplied meeting all the technical requirements as per Test sheets/schedules of the respective components. Details of weight of the forgings and number of batches processed are as follows:

Forging Weight	Number of Batches Processed
Up to 10 kg	3 Batches
11 kg – 20 kg	3 Batches
21 kg – 30 kg	28 Batches
31kg – 40 kg	17 Batches
41 kg – 50 kg	13 Batches
51 kg – 75 kg	8 Batches
76 kg – 99 kg	4 Batches
100 kg – 124 kg	3 Batches

The rings were of different sizes and varied in diameter from as low as 300mm to as large as 950mm and thickness from as low as 20 mm to as large as 200mm as shown below:

Description of Ti-64 ring forgings	Size of the component (OD x ID x T in mm) [Weight]	Feedstock size [Forging weight]
Smallest in terms size and forging weight	304 x 283 x 20 [1 kg.]	180mm dia. x 83 L [9 kg.]
Largest in terms of size	947 x 830 x 71 [52kg.]	250mm dia. x 440 L [96 kg.]
Largest in terms of weight	812 x 727 x 195 [89 kg.]	250mm dia. x 570 L [124 kg.]

Photographs of ring rolling operation at HAL (F&F) and rolled ring in hot condition are shown in Figs. 4 and 5 respectively.

The ring rolled forgings have been machined to semi-machined or sonic shape, to the forging drawing requirements, using conventional lathe process. A ring forging in sonic-machined condition is shown in Fig. 6.

7.1 Method of manufacture

The first development batch of forging in Ti-64 alloy was heat treated after completion of forging and as well as proof-machining. Certain rings processed at the same time exhibited

Fig. 4 : Ring rolling operation at HAL(F&F)

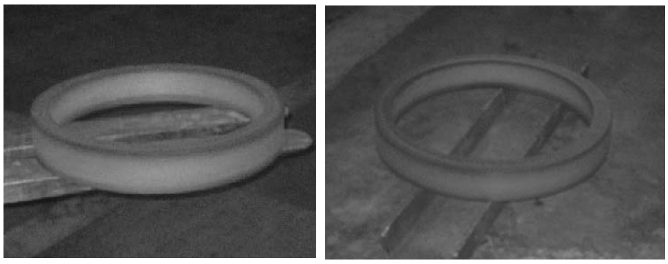

Fig. 5 : Kaveri ring forging in hot condition.

Fig. 6 : Kaveri ring forging in machined condition

ovality and warpage [bowness] to the extent of 2.2mm to 6.53mm on diameter. In view of this problem, the method of manufacture for all the ring forgings was reviewed and it was decided to heat treat the rings in as-rolled condition. Machining is carried out subsequently. In the event of warpage in as-rolled condition or due to heat treatment, the same can be corrected by subsequent machining making use of adequate machining allowance in as-rolled rings. All the subsequent batches of the ring forgings have been processed following this methodology and no ovality and/or warpage problems have been encountered till date, which could not be corrected by machining.

7.2 Solution heat treatment temperature

As per the GTM-Ti-64/FORG specification, the solution heat treatment cycle requirement is to heat the products to 950 – 975 ± 10°C, hold for 1 – 2 hours and follow by quenching in agitated water. In order to meet the desired primary α content [within the specified level of 20% - 40%] in the microstructure, selection of this temperature is very important. In the early days of development, the temperature chosen for this heat treatment was 965°C. One of the forging, solution heat treated at 965°C exhibited an unacceptable microstructure with very low primary alpha content. The cause for this problem was identified as selection of relatively higher solution heat treatment temperature [965°C] with respect to the β transus temperature of the billet material used for the manufacture [990°C]. In view of this, the solution heat treatment cycle followed has been reviewed and finalized as "955°C or β-transus temperature minus 30°C, whichever is lower, hold for 1 – 2 hours and follow by quenching in agitated water". Based on the experience during indigenous development of disc forgings, the maximum permissible quench delay of 30 seconds has been followed during solution heat treatment of the Ti-64 ring forgings. Subsequent to implementation of this revised solution heat treatment cycle, no microstructural deviations have been observed.

7.3 Mechanical properties

As stated earlier, all the rings produced met the mechanical properties requirement as per the material specifications. Scatter diagrams of RT tensile, HT tensile and hydrogen content of the Ti-64 Kaveri ring forgings with respect to radial (forging) thickness, which are controlling section sizes during heat treatment, are provided at Figs. 7-9.

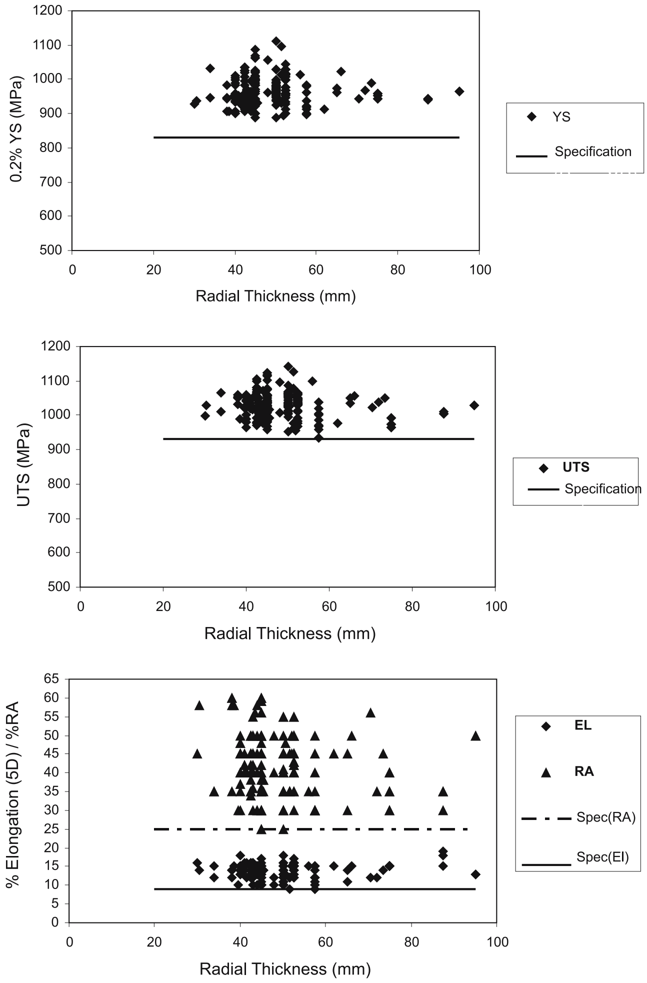

Fig. 7 : 0.2% YS, UTS, %El. & %RA at Room temperature achieved in various rings

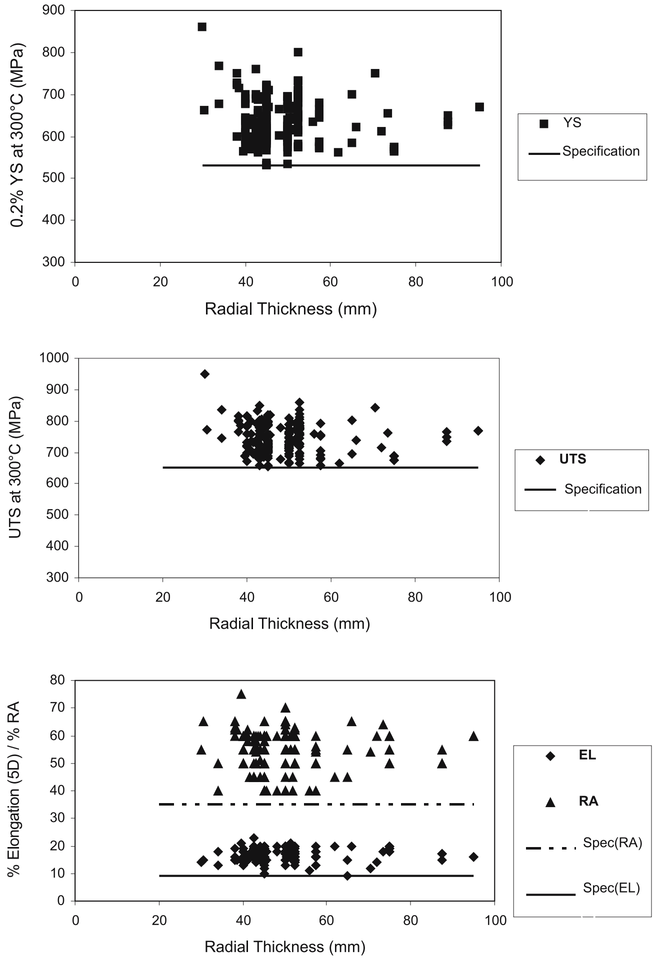

Fig. 8 : 0.2% YS, UTS, %El. & %RA at 300°C achieved in various rings

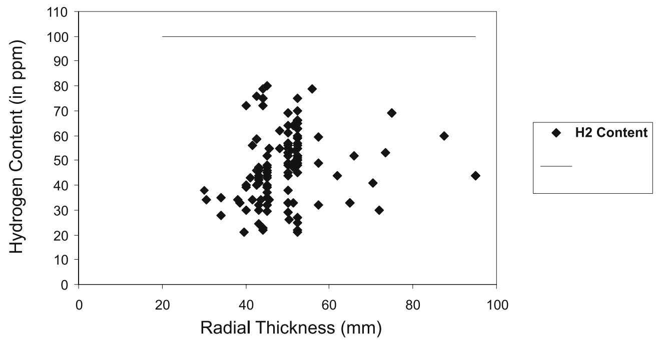

Fig. 9 : Hydrogen content in the Ring forgings

7.4 Metallurgical properties

As stated earlier, all the rings produced met the macrostructure and microstructure as per the material specifications. Typical macrostructure and microstructure of recently supplied Kaveri ring forging in Ti-64 alloy are shown in Fig.10 and Fig.11 respectively. Primary alpha content should be within the range of 20% to 40% as per the specification. This is clearly seen in the microstructure of the rings (Fig. 12).

7.5 Ultrasonic inspection

Earlier the ring forgings were ultrasonically inspected to the defect standard of 1.2mm FBH and reported as "Satisfactory".

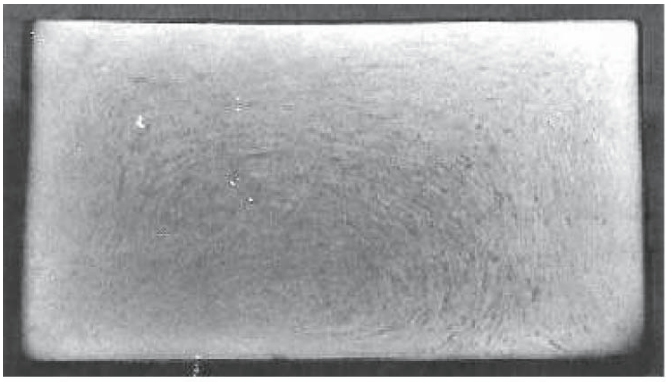

Fig. 10 : Macrostructure and grain flow pattern of Kaveri ring in Ti-64 alloy

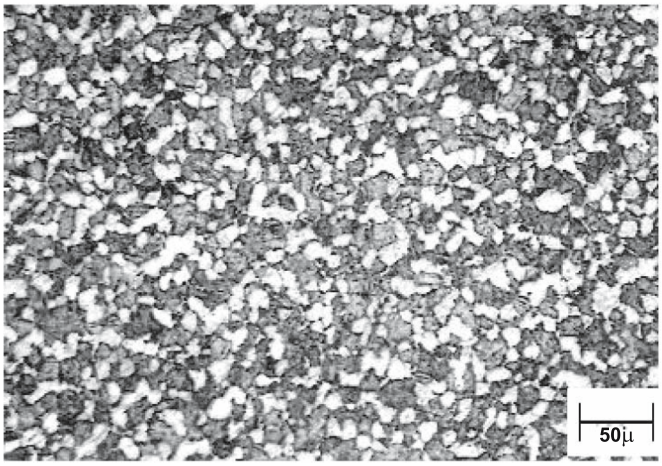

Fig. 11 : Microstructure of Kaveri ring in Ti-64 alloy

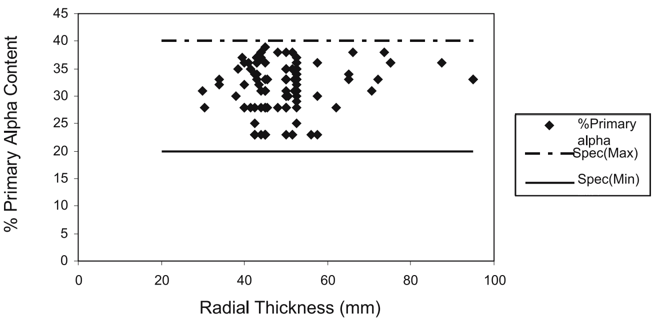

Fig. 12 : % Primary alpha content in the microstructure for various rings

Noise level and attenuation characteristics of the products were not reported. Ultrasonic inspection requirements have been revised and incorporated in specification and testing practice in addition to stipulating the test procedure as per AMS-2631[7].

(i) Noise level shall not exceed 50% of DAC.

(ii) Attenuation check [% Loss of BWE] shall be carried out on the product with the first back-wall echo reflection below the vertical limit and variation in back-wall reflection from one location to the other within the same product shall not exceed 50% [6 dB].

All the ring forgings are evaluated to these requirements and the results are furnished in a detailed inspection report. Noise level information reported would be very useful, not only for acceptance of forging, but also in understanding its sonic integrity and review of the FBH defect level, if needed in future. Attenuation data provides useful information on uniformity and consistency of the ring forgings being supplied.

8.0 IMPORTANT OBSERVATIONS DURING PRODUCTIONISATION

8.1 Yield during processing

An assessment of production rings at HAL (F&F) shows that yield achieved by the indigenous source [24% - 47%] is lower compared to the yield [40% - 76%] achieved by the foreign firms for the similar products. Scatter diagrams of yield data of indigenous Kaveri ring forgings with respect to radial and forging (axial) thickness are shown at Fig. 13.

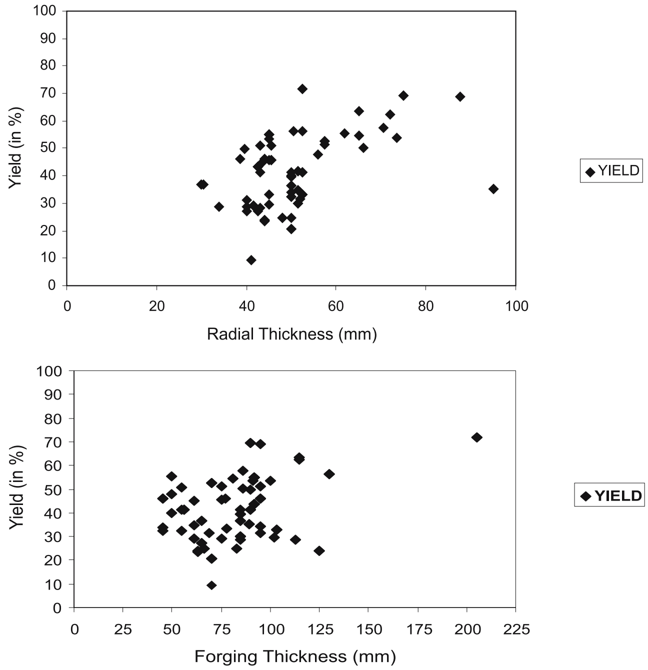

Fig. 13 : Scatter diagram of process yield vs. Radial/Axial Thickness

It was noticed that the process loss occurred at the following two manufacturing stages:

1. Piercing/making center hole to accommodate mandrel for ring rolling.
2. Final machining of the rolled ring to the semi-machined/ sonic shape.

The following modifications in forging/rolling practice were recommended and are under consideration by HAL (F&F) to improve upon the yield by reducing the losses during above processing stages:

- The upset pancakes are to be made to final thickness (height) of the ring forging. Therefore, material removed from the center of the upset pancake during piercing operation becomes minimal. If needed, the smaller center hole [70 to 110mm] can be made initially on the upset pancake and the same is subsequently enlarged by conventional mandrel forging to the size of mandrel (around 200mm) required for the ring rolling operation. These steps would lead to reduced material loss as compared to present practice of directly piercing hole of size 150mm to accommodate the mandrel of the rolling mill.

- The indigenous rings are manufactured with the machining allowance of 10mm to 20mm, as compared to the international practice of 6mm to 8mm on diameter/ thickness. Higher machining allowances are provided in the indigenous rings to accommodate surface defects, warpage and non-concentricity, if any, occurring during the processing. Following practices are suggested for reducing the machining allowances:

- Billet preparation: Billets should be prepared [by machining / facing operation] so that both faces are exactly parallel. This helps in producing the upset forging, with round shape, of uniform size. Further, the sharp corners of the as-cut billets are rounded off by machining [typical corner radius followed for 250mm diameter billet is around 25mm R]. This practice helps in preventing the formation of lap/fold defect on the surfaces. The above billet preparation may also help in avoiding the forging cracks originating at the corners. Thus, effectively the ring forgings may be designed with less machining allowances, as this billet preparation methodology helps in reducing the anticipated surface defects.

- The rings should be finished in the ring rolling mill with 1% to 1.5% lower diameter with respect to the final dimensions required. Immediately after the ring rolling, the rings are subjected to limited axial load in low capacity hydraulic press [~ 600 tons] to flatten the ring forging and then stretching operation is carried out to enlarge the ring by 1 to 1.5% to achieve the final dimension required. These operations are carried out either at lower temperature [~700°C] or at forging temperature. The axial flattening in hydraulic press and the stretching operations, mentioned above, are carried out to correct the axiality and ovality of the ring forgings and help to manufacture the ring forgings with very low machining allowance of 2 – 3mm per side. By means of manufacturing the rings with small machining allowances, the size of forging stock material and consequently the cost for the ring forging can be reduced to an extent of 30%.

- All the above improvised processing practices for economical manufacturing of the rings are under implementation at HAL (F&F) except the radial stretching operation, for which the required infrastructure is not available.

9. CONCLUSIONS

(i) Satisfactory metallurgical and mechanical properties have been achieved during development and subsequent production batches of Ti-64 ring forgings, as per the release specification [GTM-Ti-64/FORG (Rev.-4)], which have validated processing technique and parameters.

(ii) Total 79 batches of ring forgings required in Ti-64 alloy for Kaveri engine have been indigenously produced meeting all the technical requirements as per test sheets/ schedules for the respective component and supplied for the further use.

(iii) Test sheets/schedules have been evolved for all the ring forgings with due co-ordination of designer and air-worthiness agencies. Ring forgings developed at HAL (F&F) for Kaveri engine programme are now being supplied with clearance of air-worthiness agencies.

(iv) Ultrasonic procedure for inspection and reporting format for the ring forgings to the acceptance standard of 1.2mm FBH have been evolved and implemented. All the ring forgings were reported to be meeting this requirement.

(v) However, process improvisation and efforts to manufacture the ring forgings to the near net shape with low machining allowance need to be attempted on continual basis to improve the yield and economics of the ring manufacturing process.

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