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Development and certification of Ti–8Al–1Mo–1V alloy for HP compressor blades for adour engine applications[†]

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Abstract. Titanium alloys, because of their excellent specific strength/density ratio result in significant weight reduction in airborne vehicles thus improving their performance and fuel efficiency. In addition, excellent corrosion resistance, high fracture toughness, creep strength up to ~ 600°C make them a wanted material for aeroengine applications. Though a number of alloys are in use, Ti-8Al–1Mo–1V alloy, due to its advantageous characteristics has been selected for HP compressor blades for Adour engine (JAGUAR Aircraft) applications. Optimization of chemical composition, forging technology and heat treatment were the main objectives to obtain best combination of properties for the end use. The alloy has been successfully evaluated in accordance with mandatory airworthiness requirements.

Keywords. Beta transus; near alpha alloy; HPC blades; type test schedule.

1. Introduction

Titanium has been recognized as an element for 200 years. However, it has gained strategic importance only in the last 40 years or so. Stimulus for the development of titanium alloys came initially from the aeronautical and aerospace industries because of their high specific strength and excellent corrosion resistance. With density about 55% that of steel, titanium alloys are widely used for highly loaded aerospace components that operate at low to moderately elevated temperatures, including both airframe and jet engine components. Though the melting point of titanium is considerably high i.e. 1668°C, the elevated temperature strength and creep resistance of titanium-base materials (along with the pickup of interstitial impurities due to the chemical reactivity of titanium) limits the elevated temperature application of wrought and cast products up to 600°C (Lampman 1990). Titanium's corrosion resistance is based on the formation of a stable, protective oxide layer. This makes the metal also useful in applications ranging from chemical processing equipments to surgical implants and prosthetic devices.

The physical metallurgy of titanium is dominated by the allotropic transformation from the high temperature BCC structure (β) to the HCP structure (α) at 882·5°C; that of its alloy is dominated by the influence of alloying elements on this reversible transformation (Flower 1990). By manipulating this allotropic transformation through alloying additions and thermomechanical processing, a wide range of titanium alloys with optimum combination of properties can be produced. Based on predominant microstructural phases present at room temperature, titanium alloys are classified viz. alpha alloys, near alpha alloys, alpha + beta alloys, near beta alloys and beta alloys. The composition ranges corresponding to these five classes of alloys are shown in figure 1.

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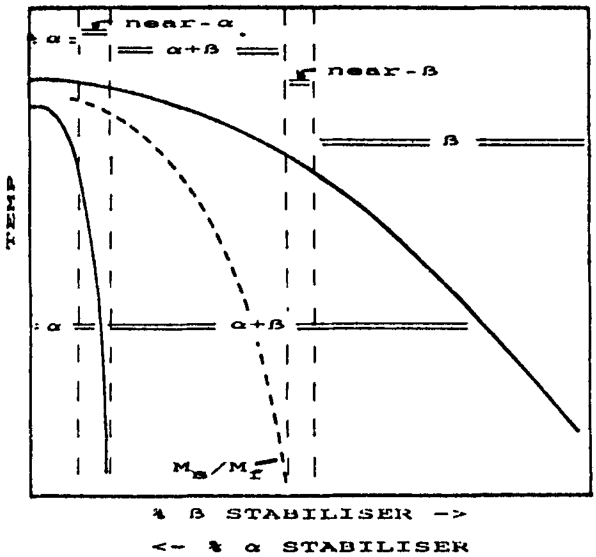

Figure 1. Schematic quasi-vertical section for ternary titanium alloys containing both alpha and beta stabilizing solute elements (Flower 1990).

The equilibrium proportions of alpha and beta phases are determined by relative concentrations of alpha-stabilizing elements (Al, C, O, N) or beta-stabilizing elements (Fe, V, Mo, Ni, Cu etc.). The dashed line, marked as M_s/M_f, indicates the martensitic start and finish lines, which are typically very close together. The alpha range is confined to compositions (alpha alloys) in which retention of beta, even in a metastable form, is not possible. For near-alpha alloys beta can be retained by alpha + beta treatment with a composition to the right of M_s/M_f line at room temperature. The alpha + beta composition range (alpha + beta alloy) extends to the compositions of the M_s/M_f line at room temperature; beyond this 100% beta retention is possible. The retained beta is highly metastable for composition just to the right of the M_s/M_f line and transform to martensite upon deformation (near-beta alloys). More strongly beta stabilized compositions can be transformed only by precipitation reactions within the equilibrium alpha + beta field, and termed as beta alloys.

The purpose of this paper is to present an overview of technical and airworthiness aspects during development and certification activities of a 'near-alpha' titanium alloy, Ti–8Al–1Mo–1V which is intended to be used for high pressure compressor (HPC) blades for Adour engine (JAGUAR aircraft) applications.

1.1 *Near-alpha alloy*

This is a class of forging alloys developed to meet demands for higher operating temperatures in the compressor section of aircraft gas turbine engines for improving its performance and efficiency. These materials contain, like the alpha alloys, solutes which stabilize the alpha phase but also contain small concentrations of beta stabilizing elements which broaden the alpha + beta temperature range sufficiently for alpha + beta working to be possible. A small amount of beta phase can be retained on cooling (in metastable form) if solute enrichment can occur on passing through the alpha + beta field. Near-alpha alloys may be processed entirely within the beta-phase field (e.g. IMI 685) at temperatures of around 1100°C, or, with more recent alloys (e.g. IMI 834) at lower temperatures within the alpha + beta field. In the beta processed alloys the microstructure consists of alpha due to the transformation of the large grained beta and, in oil quenched or more slowly cooled condition, a small volume fraction of retained, metastable beta at the alpha plate boundaries. In the alpha + beta processed alloys the prior beta grain size is much smaller, and a low volume fraction of primary alpha is present after deformation high in the alpha + beta field, the balance of the structure being transformed beta (Flower 1990).

Keeping the above points in view, a development and certification programme has been taken up at M/s Mishra Dhatu Nigam Ltd., Hyderabad to indigenize import substitute for HPC blades of Adour engine (JAGUAR aircraft) applications. In this regard, Ti–8Al–1Mo–IV, a 'near alpha-alloy' having high specific strength and creep strength up to 550°C, best combination of LCF and HCF, and good fabricability has been chosen to meet the property requirements as listed in table 1 for HPC blades.

1.2 *Ti–8Al–1Mo–1 V alloy*

It is a near-alpha alloy and suitable for application at elevated temperature. It contains a relatively large amount of the alpha stabilizer, aluminium (Al). The presence of small amount of the beta-stabilizer (Mo and V) improve workability since these elements broaden the alpha + beta temperature range sufficiently for alpha + beta working and stabilizes only small amount of the beta phase.

Although the room temperature tensile strength of this alloy is about equal to Ti–6A1–4V alloy, the elevated temperature strength and creep resistance are superior to other commonly available alpha or alpha + beta alloys. It has the highest tensile modulus and lowest density (4·37 g/cc) among the titanium alloys. This alloy can be used in annealed condition and special duplex annealing can yield high fracture toughness in sheet at temperature as low as − 95°C (Aerospace Structural Metals Handbook 1980).

Fabrication and heat treatment schedules involving temperature above *beta-transus* are not recommended because of the possibility of surface embrittlement at

Table 1. Property requirements of HPC blades.

Operational condition	Property requirements
Centrifugal stresses at 10,000 rpm Forced excitation due to irregular airflow Self excitation due to blade flutter	High specific tensile strength HCF, LCF and fracture toughness
Rotational resonance	High '*E*' value, low density
High temperature of last stages of HP compressor	Elevated temperature properties
Rubbing against outer casing and adjoining stators	Low thermal conductivity
Foreign object damage (FOD) viz. sand, stones, birds etc.	Resistance to erosion, low notch sensitivity, high fracture toughness
Corrosive environment of coastal areas	High corrosion resistance

Table 2. Chemical composition of Ti–8Al–1Mo–1V alloy (wt%).

A.E.			Impurities (Max)										
Al	Mo	V	Fe	C	O	H	N	Ni	Ni + Cu	Mn + Cr	Yt	RE$^+$ Total	Ti
7·35 – 8·35	0·75 – 1·25	0·75 – 1·25	0·30	0·08	0·20	0·015	0·05	0·08	0·1	0·15	0·02	0·03	Bal.

*Alloying elements; $^+$rare earth element.

service temperature of about 450°C. If preferred, this alloy can nevertheless be beta-forged for the development of some particular property or as necessitated by some fabrication process. Working at temperature high in the alpha + beta field is the usual practice.

The composition of this alloy is given in table 2 (CRE(M)/33).

The effect of various alloying elements are summarized as follows (CRE(M)/33, Polmear 1981).

1.3 *Aluminium*

It is a principal alpha stabilizer in titanium alloys that increases tensile strength, creep strength, and the elastic modulus. The maximum solid solution strengthening that can be achieved by aluminium is limited because Al, when present above 8%, promotes ordering and results in formation of aluminides which cause embrittlement. Thus, aluminium equivalent of all titanium alloys is kept below 9%.

1.4 *Molybdenum*

It is a beta stabilizer that promotes the ability to harden and short time elevated temperature strength. Molybdenum makes welding more difficult and reduces long-term, elevated temperature strength.

1.5 *Vanadium*

It is also a beta stabilizer that is added primarily to improve thermomechanical working and better HCF.

Other elements are injurious impurities which present themselves with the raw materials. These elements are kept below specified limit.

2. Production of Ti–8Al–1Mo–1V alloy

The general process flow chart indicating major processing steps for manufacture of forged and hot rolled bars are shown in figure 2.

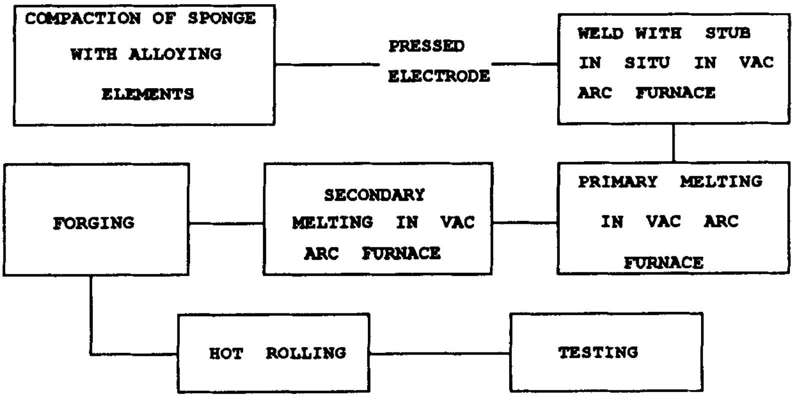

Figure 2. Process flow chart.

Salient steps involved during manufacture of wrought products are: (i) inspection of raw materials and preparation of electrode from titanium sponge and other raw materials, (ii) production of ingots (550 mm dia) by double melting in vacuum arc remelted (VAR) furnace, (iii) surface skin turning, ultrasonic testing to determine the depth of pipe at top and bottom ends, (iv) forging of ingots (to 120/100 mm square) above 960°C, followed by ultrasonic testing, (v) heating in $\alpha + \beta$ range and hot rolling to 30–60 mm diameter and (vi) testing and physical inspection.

The evaluation for forged and hot rolled bars was conducted in accordance with the type test schedule stipulating airworthiness requirements, issued by Directorate of Aeronautics, New Delhi. Following are the important results:

Heat treatment

(i) Solution treatment: 980°C–1010°C/1 h/AC.
(ii) Stabilization treatment: 565°C–595°C/8 h/AC.

Tensile properties

Temp °C	0·2% YS (MPa)		UTS (MPa)		% El		% RA	
	1	2	1	2	1	2	1	2
RT	980–985	827 min	1050–1085	896 min	15–18	10 min	30–36	20 min
200	730–780	—	830–875	—	17–19	—	40–47	—
425	573–569	483 min	689–695	621 min	18–21	10 min	52–63	25 min
530	514–536	—	595–640	—	19–24	—	42–56	—

Notch tensile strength

$\frac{\text{Notch UTS}}{\text{Smooth UTS}}$	
1	2
1·37	⩾1·30

Impact strength

Charpy 'V' Energy ft-lbs	
1	2
15–17	15 min

Notch stress rupture strength

Temp °C	Stress (MPa)	Life (h) 1	Life (h) 2
RT	1,034	32–97	5 min

Stress rupture strength

Temp °C	Stress (MPa)	Life (h) 1	Life (h) 2
530	105	> 236	150 min

Note: 1. Obtained value and 2 specified value.

Creep strength

Temp °C	Stress (MPa)	Duration (h)	% El 1	% El 2
530	90	150	0·07–0·20	0·2*

*Typical

Fatigue strength

Fatigue strength	Temp. °C	Specimen type	Stress range (MPa)	Cycles 1	Cycles 2
HCF	RT	Smooth	± 400	> 2·3 × 10^7	2 × 10^7 min
		Notch	± 270	> 2·1 × 10^7	> 2 × 10^7 min
LCF	RT	Smooth	85–850	> 1060	1 × 10^3 min

Note: 1. Obtained value and 2 specified value.

β-Transus temperature : 1040°C (Obtained)
: 1037°C (Specified)

Microstructure

Plate like α, β structure is observed: Typical photomicrographs are shown in figures 3 and 4.

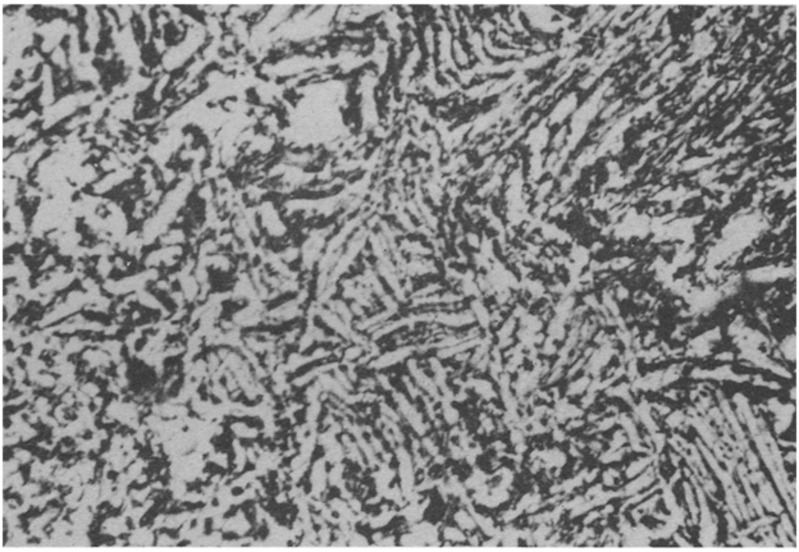

Figure 3. Microstructure of Ti–8Al–Mo–1V alloy (×400). Product: 40 mm dia.

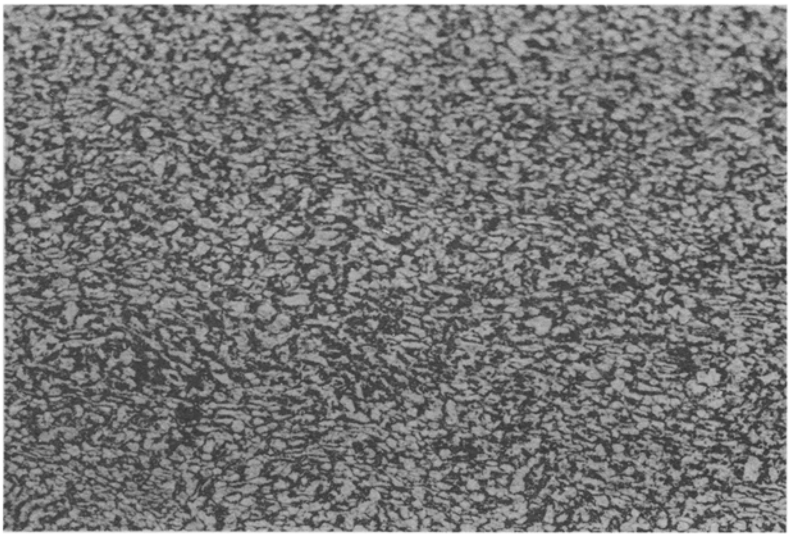

Figure 4. Microstructure of Ti–8Al–1Mo–1V alloy (× 100). Product: 60 mm dia.

3. Conclusions

Process and properties evaluated on forged and hot rolled bars of Ti–8Al–1Mo–1V alloy, developed at M/s Mishra Dhatu Nigam Ltd. (MIDHANI), Hyderabad have been successfully completed as the first step in airworthiness certification. Optimization of chemical composition, forging technology and heat treatment parameters were the main objectives to meet airworthiness requirements so as to obtain best combination of properties. These developed F & HR bars of Ti–8Al–1Mo–1V alloy are intended to be used as the feed stock for forgings of HPC blades for Adour engine (JAGUAR Aircraft) applications.

Glossary of Terms

AE—Alloying element;
FOD—Foreign object damage;
F&HR—Forged and hot rolled;
HPC—High pressure compressor;
M_f—Temperature at the finish of spontaneous martensitic transformation and
M_s—Temperature at the start of spontaneous martensitic transformation.

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References

Aerospace Structural Metals Handbook 1980 *Titanium alloy* (*Ti-3709*) Vol. 4
Flower H M 1990 *Mater. Sci. & Technol.* **6** 1082
Lampman S 1990 in *Metals handbook* (Metals Park, Ohio: ASM International) 10th edition., p. 593
Polmear I J 1981 Light alloys, in *Metallurgy of light metals* (ed.) E Arnold (London: Edward Arnold (Pub.) Ltd.) pp 162–204