THE ISOTHERMAL FORGING OF TITANIUM ALLOYS

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Abstract.

Isothermally forged titanium alloy components are characterised by a high degree of microstructure, property and shape control. The unique properties of titanium alloys have made them excellent materials for aerospace applications and the benefits of isothermal forging enable full advantage to be taken of these properties so that components may be manufactured which will withstand the extreme conditions found in service.

This paper briefly outlines the characteristics and benefits of isothermal forging, and describes the production equipment used in the manufacture of components. The isothermal forging of IMI834 is discussed in detail.

CHARACTERISTICS OF ISOTHERMAL FORGING

Isothermal forging may be characterised in the following way:-

1. The forging dies and material to be forged are maintained at the same temperature throughout the forging operation.

2. The forging operation is carried out at a low controlled strain rate.

3. Vacuum or inert atmosphere are used to prevent oxidation of the forging dies and material being forged.

Titanium alloys are generally forged at temperatures in the range 850 - 1050°C, depending on the particular alloy. In conventional forging the dies are relatively cold, being maintained typically at 100 - 200°C. To reduce the effects of die chilling of the workpiece the forging operation is carried out at relatively high strain rates (10^0 to 10^3/sec), and this usually means that the flow stress is also high, leading to high forging loads, adiabatic heating and inhomogeneous deformation.

In isothermal forging the dies are maintained at the same temperature as the workpiece and consequently there is no die chilling. The use of low strain rates means that adiabatic heating is eliminated and forging loads are greatly reduced (typically by a factor of 10).

It is obvious from the above that the forging dies require exceptional properties at high temperatures and these are achieved by the use of molybdenum alloy for the dies. To prevent oxidation the forging operation is carried out under vacuum or an inert atmosphere.

BENEFITS OF ISOTHERMAL FORGING

The characteristics of isothermal forging briefly outlined above lead to a number of benefits during the manufacture of titanium alloy components.

1. Increased control over structure and properties due to the absence of die chilling and adiabatic heating effects.

2. Close dimensional control results in forgings being produced which are closer to the final component shape than is possible by conventional means. Thus significant savings in input billet weight and post-forge machining operations can be made.

3. Fewer forging operations are required. Isothermal forgings can often be produced in a single forging operation from billet without the need to preform or the use of multi-blow/multi-heat procedures.

4. The size of isothermal forging plant is greatly reduced due to the relatively low forging loads.

5. The ability to exercise tight control over the forging parameters results in a high level of consistency of structure and properties from one forging to another.

With suitable equipment and process control most commercial titanium alloys are forgeable by conventional means. However, advanced titanium alloys, such as IMI 834, require tight structural control and have a high resistance to deformation which makes them less forgeable than other alloys. Consequently, the available "process window" is much narrower than normal titanium alloys and isothermal forging is particularly beneficial.

ISOTHERMAL FORGING FACILITY

Doncasters Monk Bridge Ltd. have recently installed a fully automated, computer controlled 3200 tonne hydraulic isothermal forging press. Fig.1. The press and its associated heating and handling system can operate under vacuum or inert atmosphere, thus enabling molybdenum dies to be utilised, which enable high temperature titanium alloys to be forged. Using the isothermal press critical components for most engines, eg. Tay, EJ200, RB199, CFM56, IAE 2500, and for airframes can be manufactured. Billets up to 200 kgs. in weight are manipulated by a robot which is enclosed in a circular chamber attached to the forging press. The ability to pre-programme the robot enables the billet to be transferred from the entry position, through the furnaces, which are placed around the periphery of the chamber, into the press automatically, precisely and at high speed; the transfer time from soaking furnace to dies being 15 seconds. Latest technology, high accuracy furnacing enables accurate temperature control to be maintained during the pre-heat cycle; and a temperature variation of only +/- 2°C has been achieved in the largest billet which the system is designed to handle. Once in the press the billet is isothermally forged and on completion of the forging operation the forged component is ejected from the dies and removed by the robot and is transferred to the exit position.

Forging is controlled by a computer which automatically controls the position and speed of the dies to produce the required deformation and strain rate. Thus the whole forging operation from billet entry to forged component removal is carried out automatically in a pre-programmed manner requiring only one operator in attendance. This system enables an extremely high level of process control and consistency from forging to forging to be achieved.

During forging the environmental conditions are continuously monitored to prevent oxidation of the molybdenum dies which are maintained at the forging temperature throughout the forging operation by the use of circumferential induction coils.

ISOTHERMAL FORGING OF IMI 834

The isothermal forging of IMI834 provides a good example of the ability to control structure, properties and shape in aerospace components IMI 834 is a recently developed - titanium alloy for use at the elevated temperatures to be found in the high pressure compressor stages of modern gas turbine aero engines. In general, in α - β titanium alloys as the proportion of β phase increases so does the creep properties but at the expense of fatigue properties, as illustrated schematically in Fig (2). Due to the slope of the β transus approach curve, it is possible to produce, in IMI 834, a structure with a relatively low α content (5 - 10%) and a fine β grain size (< 100pm) and this structure has both good creep and good fatigue properties. Disc forgings have been produced by isothermal forging and metallurgical examinations have been carried out as described below.

Fig (3) shows an example of a compressor disc isothermally forged in IMI 834. Forging was carried out high in the α - β region in one forging operation from a cylindrical billet. The ability to produce complex shapes by isothermal forging is clearly illustrated.

The as-forged discs were heat-treated in the following way:-

1. Solution treatment:- 1025°C for 2 hours, oil quench.

2. Ageing treatment:- 625°C for 2 hours, air cool.

The strain rate was chosen to prevent adiabatic heating yet enable a cost effective production rate to be achieved.

Examination of the fully heat-treated disc revealed a uniform α- β structure with the proportion of α phase indicated in Table 1.

As can be seen the volume fraction of the phase varies by only 2% throughout the whole forging and this obviously results in consistant properties throughout the disc. This illustrates the uniformity of temperature achieved in the forging. The other critical parameter is β grain size and table 1 also details β grain size measured at various locations throughout the forging. The β grain size is controlled within narrow limits throughout the forging thus illustrating both the close control of temperature and the homogeneity of deformation. The transformed β is extremely fine, with an average lath width of only 1μ and this does not vary throughout the disc forging.

Lack of control of forging parameters produces excessive variation in α phase throughout the forging and uncontrolled coarsening of the β grains.

Fig (4) illustrates a typical microstructure found in the fully heat-treated component. The microstructure consists of a uniform dispersion of primary alpha within a transformed β matrix. The transformed β grains are delineated by a grain boundary α film. The particles nucleate predominantly at the transformed β grain boundaries. The average particle size is 25 u. Little variation in proportion between the bore and the rim sections was observed.

Table (2) indicates the tensile properties determined in a fully heat-treated forging. To determine the effect of cooling rate from solution treatment on the structure and properties, one disc was isothermally forged and then air-cooled from the solution treatment temperature instead of oil quenching. The microstructure thus obtained differs from the oil quenched structure and a typical micrograph is illustrated in Fig (5) and consists of primary α in a coarse transformed β matrix. The volume fraction of α was again observed to be extremely consistant but slightly higher than for the oil quenched sample, probably due to the increased time spent in the $\alpha + \beta$ region for the air cooled disc and as a consequence the α particles have had more time to grow, resulting in larger particles of increased volume fraction. The phase can be seen to have nucleated at the β grain boundaries and subsequently grown to such an extent as to almost completely surround the transformed β grains with "flowery" particles which is considered to be deleterious to mechanical properties. The amount of grain boundary α present in the air cooled forging was significantly less than in the oil quenched forging due to the extra time in the α+ B region enabling the grain boundary film, initially formed, to grow into α particles. The β grain size was found to be similar to that of the oil quenched disc. However, the reduced cooling rate has produced a coarsening of the transformed β with an average lath width of 8μ. The mechanical properties measured in this disc are shown in Table (3) and a significant reduction in properties when compared with those of the oil quenched disc can be seen.

ISOTHERMAL FORGING OF OTHER TITANIUM ALLOYS

Several other Ti alloys have been successfully isothermally forged including Ti6-4 and Ti 829. Fig 6 illustrates a section taken through a titanium 6-4 impeller. This particular impeller is in the as-forged condition and is a good example of the complexity of shape which is possible from the isothermal press. This forging is produced directly from a cylindrical billet in one forging operation and requires only minimal machining before assembly.

Ti 829 is a β heat-treated, high temperature titanium alloy and this has been successfully isothermally forged producing a uniform β microstructure of constant grain size again in a complex compressor disc shape.

Due to the ability to accurately control the major forging parameters, (temperature, strain and strain rate) isothermal forging of titanium alloys offers the aero engine manufacturer increased control over microstructure, properties and forging shape. It is possible to achieve microstructures in these advanced titanium alloys which can only be achieved in part by conventional forging techniques. As more alloys are developed the necessity to accurately control the manufacturing processes at all stages of production becomes even more important and the development of isothermal forging is a major step forward.

Isothermal forging lends itself to mathematical modelling of the forging process and extensive use of an analysis technique, known as Finite Element Analysis (F.E.A) is made. Using this technique temperature distribution, material flow, strain and strain rate distribution and variation of die stresses may all be accurately predicted before forging takes place. In terms of structural control the F.E.A. technique is a powerful tool in predicting the microstructure to be obtained in the final forging and changes in forging parameters, die or billet design may be made in order to influence the microstructural response in the forging without the need to carry out expensive forging trials.

The paper has been confined to the isothermal forging of titanium alloy components in a single operation from a cylindrical billet in order to achieve the required uniform structure throughout the forging. However, this is only one way in which isothermal forging can be used successfully. In addition, isothermal forging may be used as part of a forging sequence which includes conventional forging so as to achieve the optimum process route in terms of structure, properties and cost effectiveness. Also there is an increasing demand to produce forgings with a controlled but variable structure throughout the section so as to produce a range of properties in the component which more closely fits the requirements of the component in service. By maintaining close control over temperature, strain and strain rate throughout the forging operation, isothermal forging may provide a means of achieving this objective and further development work in this area will be required.

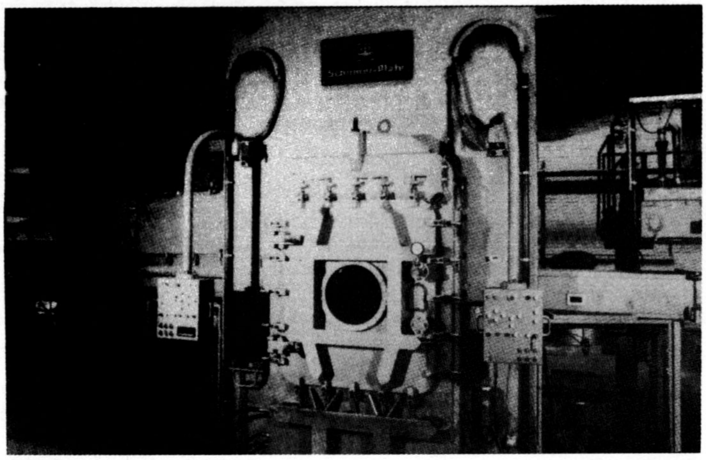


Fig. 1. 3200 tonne Isothermal Forging Press

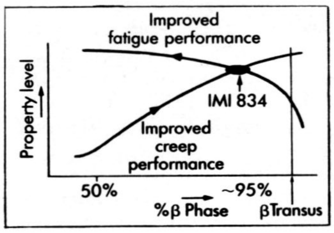


Fig.2. Effect of Microstructure on the Properties of α/β Titanium alloys.

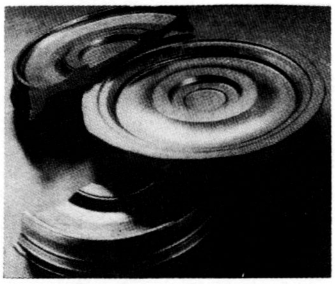
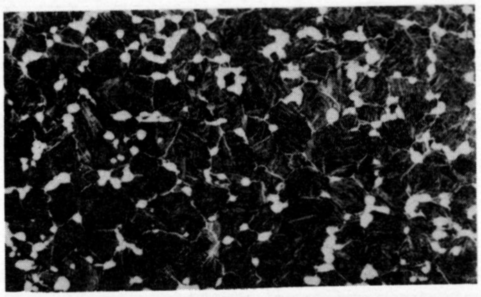
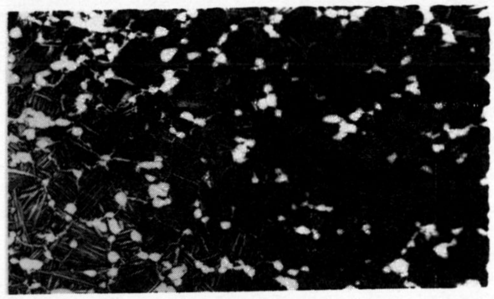


Fig.3. Isothermally Forged Compressor Discs





Typical Microstructure in Isothermally Forged IMI 834

Fig. 4. Oil Quenched

Fig. 5. Air Cooled

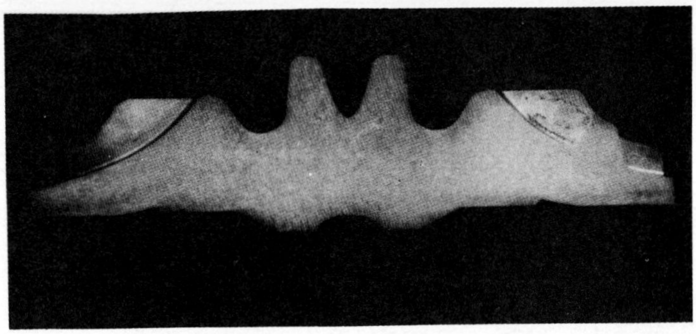


Fig.6. Section through an Isothermally Forged Ti6-4 Impeller

Location	Volume fraction α (%)	β grain size (μm)
1	9.5	75
2	7.6	60
3	8.5	60
4	9.0	72
5	7.8	75
6	9.1	70
7	7.4	62

Table.1. Variation in α% and β grain size in IMI834 Compressor Disc.

	Room temperature tensile			Elevated temperature tensile (650°C)		
	Radial	Tangential	Aim (min)	Radial	Tangential	Aim (min)
0.2% PS (MNm^{-2})	943	979	910	548	549	480
UTS (MNm^{-2})	1053	1096	1030	711	735	585
El (%)	16.1	10.7	6	17.9	18.8	9
R of A (%)	29.1	25.5	15	59.0	59.2	20

Tablè 2. Tensile Properties in IMI834 Compressor Disc, Oil Quenched

	Room temperature tensile			Elevated temperature tensile (650°C)		
	Radial	Tangential	Aim (min)	Radial	Tangential	Aim (min)
0.2% PS (MNm^{-2})	892	914	910	453	437	480
UTS (MNm^{-2})	984	1016	1030	616	616	585
El (%)	14.3	14.3	6	19.6	19.6	9
R of A (%)	29.9	26.1	15	46.1	38.2	20

Table. 3. Tensile Properties in IMI834 Compressor Disc, Air Cooled.