Manufacture of Titanium Alloy Components for Aerospace and Military Applications

P.J. Bridges
Doncasters plc, 8 Richmond Road
Sutton Culdfield, B13 6BJ, UK

B. Magnus
SETTAS S.A. Doncasters plc Cy
Allee Central, Zone Industrielle
B-6040 Jumet, B, Belgium

Abstract

The advantages of titanium alloys in engineering applications are well known. They offer high strengths and good corrosion resistance, together with useful performance at temperatures up to about 600ºC with a density about 60% of engineering steels and almost half that of nickel alloys. Although there have been problems with its cost and supply, and the perception of it as an ‘exotic’ metal, the use of titanium in aerospace and military projects is increasing. The particular properties of titanium and its alloys mean that the cost-effective manufacture of components requires special techniques. DONCASTERS plc has considerable experience in the forming of titanium alloys by forging, sheet forming, casting and machining. Several hundred tonnes of such alloys are processed by the Group each year. This paper describes the forming methods used for titanium and discusses some of the factors affecting the costs associated with the products

----

Pure titanium melts at 1675C, somewhat higher than pure iron. In the solid state it exists in two crystalline forms. The low temperature one, known as α titanium, has a close- packed hexagonal crystal structure. Above 880C in the pure metal, this changes to a phase with a body-centred cubic structure known as β titanium. Alloying elements tend to show a chemical preference for one or other of these phases. For example, aluminium has much greater solubility in α titanium and tends to stabilise that phase, whereas vanadium stabilises the β phase. Adding both α-stabilising and β-stabilising elements leads to alloys in which the two phases co-exist over a wide temperature range, though in varying proportions. The composition Ti- 6%Al- 4%V gives the commonest titanium alloy. Most of the other titanium alloys important in aerospace are essentially of the same type, although many have a greater level of α stabilising elements and some are heavily β stabilised.

Cold forming of most alloys is not feasible, and hot working is required. Hot working also allows the generation of microstructures which cannot be produced by heat treatment alone. It is difficult to restrict grain growth at high temperatures where alloys comprise entirely of β phase, and cooling, at moderate rates, from temperatures in the beta range leads to the

Paper presented at the RTO AVT Specialists’ Meeting on “Cost Effective Application of Titanium Alloys in Military Platforms”, held in Loen, Norway, 7-11 May 2001, and published in RTO-MP-069(II).

precipitation of α phase in the form of plates. Hot working at temperatures where both phases are present 'breaks up' the α plates and leads to a fine and uniform microstructure. Such a structure is generally preferred, either as-worked or as a basis for further heat treatment.

In the context of manufacturing, perhaps the most important feature of titanium and its alloys is its chemical reactivity. In particular, titanium combines with oxygen and nitrogen to form thermodynamically stable compounds. At relatively low temperatures, say below 600ºC, these compounds occur as thin, self-healing surface films which lead to exceptional corrosion resistance. However, at higher temperatures titanium has the unfortunate property of dissolving or 'eating' its own oxides or nitrides. In this way it is different to, say, aluminium, where the protective oxide surface exists even in the liquid state. A piece of titanium alloy exposed to air at 400C will remain effectively inert indefinitely, but exposure at 1200C will result in a friable mass of oxide and nitride within a few hours. The fact that the reactions are exothermic is a further problem, and certainly could cause disaster if liquid titanium were exposed to air. The problem should not be overstated; it is possible to flame cut titanium for example, and argon shielded welding is straightforward but this fire risk cannot be ignored. Casting, forging and most sheet forming operations on titanium alloys require high temperatures and clearly the metal has to be protected from normal atmospheric elements in some way.

Although this reactivity causes problems in hot processing, it also creates an opportunity. As will be discussed below, the clean surface produced by dissolution of surface oxide and nitride layers allows diffusion bonding which, in combination with superplastic forming, means that complex sheet structures can be produced more easily in titanium alloys than in other engineering metals.

The reactivity of titanium at elevated temperatures is not restricted to atmospheric elements. It will readily dissolve, or at least bond with, most other metals and this means that machining operations have to be done in a way which is different to those for engineering steels.

The value of titanium swarf ,off-cuts and grindings is considerably less than that of the input material and these residues cannot be easily re-cycled without expensive recovery treatments. Therefor there is considerable economic incentive in the primary manufacturing stage to minimise material input and make as near as possible to the required form. This is graphically illustrated in the evolution of methods used to make titanium blades for gas turbines. These were originally machined from solid bar, with the associated waste of material. There was then a move to using oversize forgings from which the final shape is machined. More recent developments in preform design using mathematical modelling, lubrication technology, tool heating and process modelling and control have enabled precision airfoils which need very little treatment after forging

Forging and Ring Rolling

The majority of airfoils in the compressor stages of gas turbines for aeroengines are made from titanium alloys. As noted above, it is desirable to make these components near to net shape, i.e. precision forged (fig.1). Prior to that stage, the cast ingot material is forged to produce bar with not only the required geometric form but also to modify the microstructure. A certain amount of deformation is required to give the structural breakdown described above, and final shape forming operation may not achieve this in regions such as the root block of an airfoil.

To minimise reaction with normal atmosphere, a glass coating is used. This is only necessary in the later stages when section sizes become small. The glass coating also acts as a lubricant during the forging process Material affected by pick-up of atmospheric elements form a so called hard 'alpha case' on the surface. This needs to be removed by mechanical or chemical means otherwise it can act as an initiator of cracks.

Conventional forging operations involve a large initial temperature difference between the dies, usually tool steel, and the workpiece. The dies are typically at about 200C with the workpiece being pre-heated to between 900C to 1000C. The forging operation needs to be quick, otherwise the workpiece cools too much. That would not only increase forging load and possibly lead to damage to the dies, but could also lead to cracking or other damage to the workpiece. In terms of size range covered we make gas turbine blades from 2 to 75 cm long with chord widths from1 to 25 cm. These would be done on screw presses with capacity up to 15,000 tonnef and could be either precision forgings or oversize forgings. The latter would go for final shaping by machining or electrochemical machining. The larger titanium blades would be for the fan at the front of the engine whilst the smaller ones would generally be for the compressor stages.

Hot forging is also used to make titanium rings and engine casings. The method used in manufacture of these parts depends on their geometry. Large section rings and casings would be formed from a pierced or punched billet on a press using a series of support tools. Smaller sections would be ring rolled from a preform and the end product could be either rectilinear in section or have some shape; examples are shown in fig.2. Using a combination of these methods it is possible to make titanium alloy rings out to a diameter of 2.5metres, a section size of 125mm, and a weight of 1200Kgs . These components have the advantage of containing the optimum mechanical properties because they have been forged. Their disadvantage is that there is often a lot of machining needed to reach the final required shape.

Under certain circumstances, it is necessary to form material at a slower rate than occurs in conventional forging operations. To do this, the temperature difference between dies and workpiece needs to be reduced by heating the dies to the same (isothermal forging) or a somewhat lower (hot die forging) temperature. One case where isothermal forging has been used is in the manufacture of poppet valve blanks in titanium aluminide intermetallic alloy, where the limited ductility of the material at temperatures below about 700C means that chilling has be avoided. In that case molybdenum alloy tooling and a vacuum were used.

Airframe parts in high strength titanium alloys can be forged isothermally using nickel alloy dies, using the 3200 tonnef isothermal press at DONCASTERS Sheffield Precision forge. There is greater microstructural control with isothermal forging than with conventional operations as well as lower tool and press loads, though the operation is, of course, slower.

Sheet forming

As with other forming operations, sheet forming often needs to be carried out at elevated temperatures. Some β, and very lean, alloys can be formed cold, but Ti-6%Al-4%V and others require hot forming. Clearly the geometry means that such processes have to essentially isothermal, and a large proportion of sheet forming with titanium is carried out at temperatures from 800C to 950C using gas pressure to effect the operation. At these temperatures, the flow stress of the alloys is low and so the pressures are moderate. The low flow stress also means that residual stresses and springback are low, and this type of process gives good shape definition. Hot gas-pressure forming of large aircraft exhaust components in titanium alloys is carried out at DONCASTERS Bramah, with excellent dimensional control.

With many alloys, slow forming at temperatures of about 900C-950C gives extremely high ductility which is known as ‘superplasticity’. In many cases forming can be carried out quicker and at lower temperatures, but superplastic forming (SPF) allows very complex shapes to be formed. This is particularly true when it is combined with diffusion bonding (DB).

The ability of titanium to dissolve surface oxide and nitride layers at elevated temperatures means that clean metal surfaces can be produced simply by heating in inert atmospheres. At these temperatures the plasticity of material is high and quite modest loads can give intimate contact between two alloy surfaces, which then bond. These diffusion bonds are essentially perfect: they cannot be microscopically detected. The fact that bonding can be prevented through the use of ‘stop-off’ mixtures of ytrria and hexagonal boron nitride allows the manufacture of multilayer forms which can then be inflated in hot gas-pressure forming to form complex shapes. It is also possible to allow surfaces to come into contact during SPF which then bond.

Machining

Despite its reactivity and tendency to bond, titanium alloys can be machined by all the standard processes used for engineering steels. It is imperative to keep the temperature low during cutting operations, and this is not helped by the relatively low thermal conductivity of titanium alloys. Cutting speeds need to relatively low, and a suitable halogen-free lubricant used. Carbide tools are preferred and ceramic coated carbides are even better. Because titanium has a lower modulus than steels there is a greater tendency for “chatter” during machining. This is minimised by ensuring adequate support or jigging for the workpiece.

Grinding and surface dressing can be carried out, again with adequate lubrication and relatively low speeds. Both silicon carbide and alumina wheels are suitable. It is particularly important in grinding to prevent fire in grinding fines, and precautions should also be taken with machining swarf.

Alloys can be electro-discharge machined and chemically- or electrochemically- milled. The latter process is useful for generating high- precision forms on airfoils. Chemical milling, using solutions of hydrofluoric and nitric acids is used for removing alpha case, and in conjunction with masking compounds, for selectively reducing the thickness of sheet.

Casting

Castings for aerospace/military applications are generally made using the lost wax/ investment shell moulding route. This can give a net shape component of complex geometry directly from the casting process. Utilisation of material is relatively high but, in terms of the ratio of metal in to useful product out, is unlikely to exceed 50%. This is because there is redundant metal tied up in the risers, feeders and ingates of the casting. This metal can be recycled but it needs a cleaning and grading process. There is also a need, in some cases, for the customer to approve the use of recycled material which will give a cost advantage

The problems caused by the reactivity of titanium become most acute in casting. Not only does the process needs to be carried out in vacuum, or an inert atmosphere, it also needs special melting facilities. Very few refractories are suitable for containing molten titanium, and those are either extremely expensive or very difficult to deal with in practice. The usual solution is to effectively use a titanium crucible in a method known as skull melting. At DONCASTERS titanium foundry, SETTAS SA, deep pool electric arc melting is used, as shown in fig.3. The relatively low thermal conductivity of the solid titanium means that a large liquid mass can be produced with quite a thin solid 'skull', maintained by heat conduction into the water-cooled copper crucible.

This melting technique means that the liquid metal temperature cannot be much greater than the melting point i.e. the superheat possible is very low. Because of this, it is imperative to fill moulds as quickly as possible. The technique adopted at SETTAS is centrifugal casting. This employs casting tables of diameter up to 3 metres rotated to give peripheral speeds sufficient to generate accelerations of about 90G. The furnace charge can be up to 1Tonne of metal. Moulds- either sand, ceramic shell (investment casting) or metal- are usually filled from runners returning inwards which are supplied with metal *via* 'legs' radiating from a central sprue. Casting is rapid- a full charge would be poured in about 5 s. The rapidity of casting minimises time for metal- mould reactions. The centrifugal system helps to consolidate the castings while they are solidifying and thereby enhance their integrity

The centrifugal casting arrangement is ideal for making near-axisymmetric shapes such as engine casings. An example is shown if fig.4, which was cast into a ceramic shell mould. This type of component is conventionally fabricated from rings and extensively machined, and a great cost saving results from using casting.

Casting defects such as shrinkage porosity can be eliminated by hot isotatic pressing (HIPing), and no included oxide contamination occurs in titanium casting because the molten metal is contained by solid metal. However, the thermomechanical refinement of microstructure is not easily done in a casting and there is a trade-off in terms of reduced mechanical properties, particularly toughness and fatigue resistance.

Summary

The paper has reviewed the range of capabilities within the DONCASTERS Group for making titanium components for aerospace applications. The methods can be complementary or competitive. The design of a component has a considerable bearing on the choice of manufacturing route and associated costs. To make the most of the opportunities for titanium it is essential that design, engineering and manufacturing are considered together at the concept stage

Acknowledgements

The authors acknowledge the permission given by DONCASTERS plc to publish this paper.

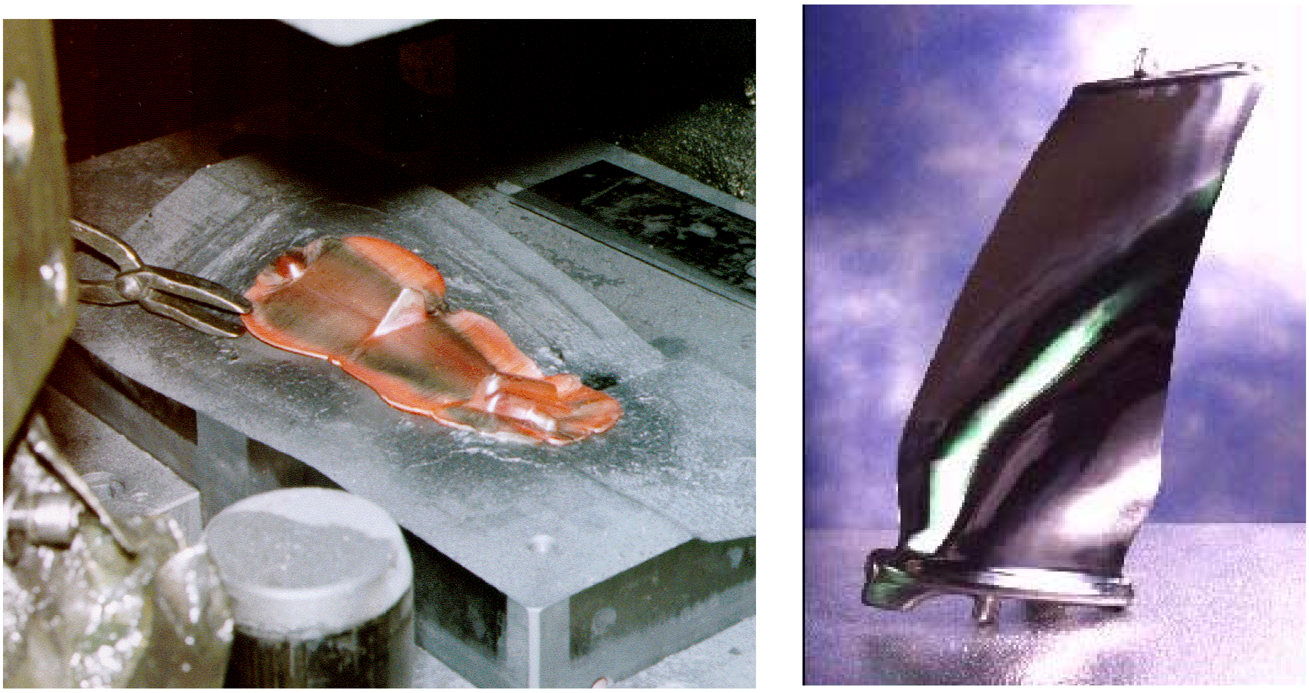

Figure 1. (a) An airfoil being removed from the die and (b) a large compressor blade made by precision forging.

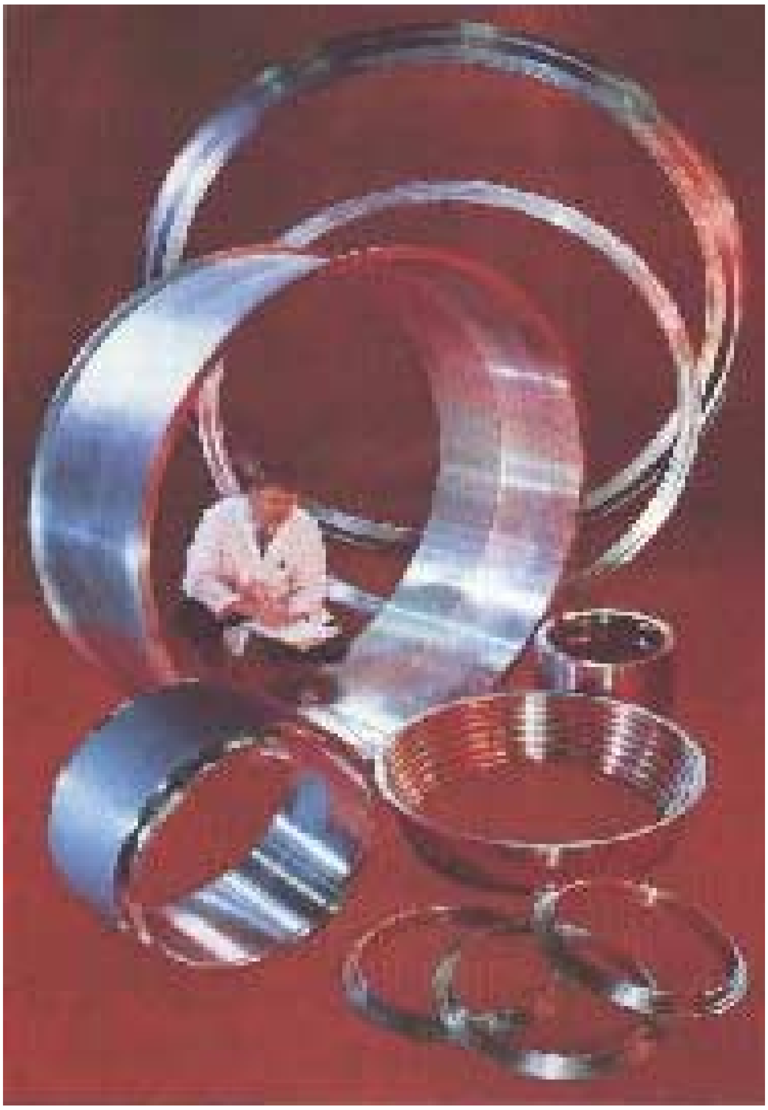

Figure 2. A selection of ring sections made by forging, ring rolling and machining.

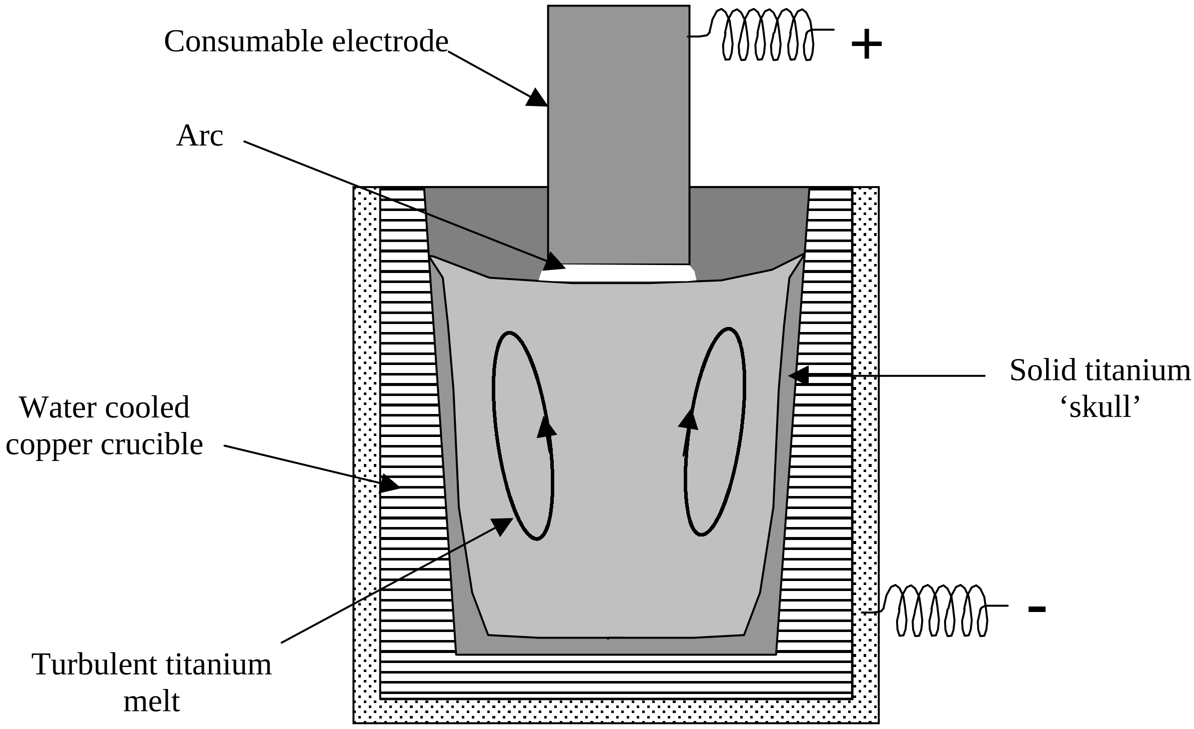

Figure 3. A schematic of the vacuum arc melting arrangement used for titanium casting. The arc is pulsed DC, this causes vigorous stirring and gives very good homogeneity.

Figure 4. Titanium engine casing centrifugally cast into shell ceramic mould.

Paper #2 by P. Bridges

Q by J.P. Immarigeon – “What is the material used for tooling in super plastic forming of titanium alloys?”
A by Mr. Bridges – “Typically, nickel-base super-alloys in cast form, and finished machined in a variety of ways, including EDM.”

Q by K. L. Cheung – “Are the cast titanium blades that you showed, production castings?”
A by Mr. Bridges – “Yes.”

This page has been deliberately left blank

Page intentionnellement blanche