TiAl-BASED ALLOYS: PRESENT STATUS AND FUTURE PERSPECTIVES

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Abstract

Intermetallic TiAl-based alloys represent an important class of high temperature structural materials providing a unique set of physical and mechanical properties that can lead to substantial payoffs in aircraft engines, industrial gas turbines and automotive industry. The present status and future perspectives of TiAl-based alloys are reviewed from the point of view of alloy design, processing technologies, applications and prospects. Chemical composition, the typical microstructure and some mechanical properties of several generations of TiAl-based alloys are characterized. Several aspects of processing are discussed and the most promising cost-effective casting technology is described in details. Some current applications of TiAl components are summarised before considering some of the challenges still remaining for TiAl-based alloys.

Key words: titanium aluminides, TiAl, microstructure, casting, mechanical properties

1. INTRODUCTION

Titanium aluminides represent an important class of alloys providing a unique set of physical and mechanical properties that can lead to substantial payoffs in the automotive industry, power plant turbines and aircraft engines. It took more than 20 years of very intensive research to obtain maturity level of TiAl-based alloys that is sufficient to consider this class of materials for critical rotating components in commercial jet engines [1]. The outstanding thermo-physical properties of these alloys mainly result from strongly ordered structure, which involves: high melting point, low density of 3.9-4.2 g/cm³, high elastic modulus, low diffusion coefficient, good structural stability, good resistance against oxidation and corrosion and high ignition temperature when compared to conventional titanium alloys. Fig. 1 illustrates temperature dependence of specific strength of various groups of alloys [1]. TiAl-based alloys shows superior specific strength-temperature properties when compared to classical titanium alloys, steels and nickel based superalloys in the temperature range from 500 to 900 °C [2, 3]. Table 1 summarises qualitatively the properties of advanced high temperature alloys for applications in the aircraft industry. It is clear that the intermetallic TiAl-based alloys exhibit the highest potential for near term applications in future aircraft engines. Whilst their specific strength is higher than that of competing materials, the room-temperature ductility is poor and is typically about 1% for all TiAl-based alloys. Low ductility is the biggest problem in the application of these alloys as structural components since 1% ductility is generally accepted as the minimum acceptable level and cast samples in particular seldom reach even this value. The other major problem is the difficulty in processing to form a component. In spite of a large effort that has been made over the last two decades to introduce TiAl-based alloys into the market as engineering components, only few market applications in the automotive industry have been established. Although
Fig. 1. Temperature dependence of specific strength of various groups of alloys [1].

engine testing has been carried out by Rolls-Royce, P&W and GE, no component made from TiAl-based alloy is in use in any current aero engine.

The aim of the present work is to review chemical composition, microstructure and some properties of generic TiAl-based alloys, the factors governing alloy selection and current methods of manufacturing of components for automotive and turbine gas industry. The factors which at this stage are the most important in limiting the manufacture of mass market components will be discussed and possible ways forward will be outlined.

2. ALLOY DESIGN

Nowadays, the intermetallic TiAl alloys of great engineering interest follow the chemical compositions in the range Ti-(45-48)Al-(1-10)M (at.%), with M being at least one element from V, Cr, Mn, Nb, Ta, W, and Mo [4]. These alloys can be divided into single phase $\gamma$(TiAl) and two phase $\gamma$(TiAl) + $\alpha_2$(Ti$_3$Al) alloys. Single phase $\gamma$ alloys contain third alloying elements such as Nb or Ta that promote strengthening and additionally enhance oxidation resistance. The role of the third alloying elements in two phase alloys is to raise ductility (V, Cr, Mn), oxidation resistance (Nb, Ta) or combined properties. Additions such as B and Mg can markedly enhance hot

| Table 1. Property profiles of advanced high temperature alloys for jet engines [1] |
|---------------------------------|----------------|----------------|----------------|
| Density                         | Near-$\alpha$ Ti | Ni based | $\gamma$ TiAl |
| Specific tensile strength       | +               | -         | ++             |
| High-temperature Young’s modulus | +/-             | +         | ++             |
| Room-temperature ductility      | +               | +         | -              |
| Formability                     | +               | +         | -              |
| Creep                           | -               | ++        | ++             |
| Room-temperature fracture toughness | +               | ++         | -              |
| Specific fatigue strength       | +               | -         | +/-            |
| Oxidation                       | -               | ++        | ++             |
| High-temperature embrittlement  | -               | +         | +/-            |
workability, W and C increase creep resistance and reduction of O enhances room-
temperature tensile elongation. The phase diagram shown in Fig. 2 indicates the
sense of movement of the various phase boundaries caused by alloying additions
with the length of the arrows defining the relative magnitude of the shifts. Clearly if
alloys are to be heat treated the sense and magnitude of these shifts of phase
boundaries are important and this phase boundary shift is probably the most
important role of most alloying additions in TiAl-based alloys. Fig. 3 illustrates an
example of the shift of the phase boundaries by alloying of a binary system with
8 at.% of Nb.

Depending on chemical composition and heat treatments, TiAl-based alloys
exhibit four different types of microstructures: near-gamma, duplex, near lamellar and
fully lamellar microstructure [5, 6]. The fully lamellar or nearly lamellar microstructure,
consisting of the TiAl (γ-phase) and a small volume fraction of Ti₃Al (α₂-phase),
exhibits better creep resistance (apart from primary creep), higher fracture toughness
and crack propagation resistance than duplex microstructures [7-9]. On the other
hand, higher tensile strength, ductility and longer fatigue life are achieved for an alloy
with duplex microstructure [9]. Since, the largest proportion of usage of TiAl-based
alloys is assumed to be in gas turbine industry creep resistance of such components
is of primary importance and in this case the required Al-content is closer to 46 at.%. If
Ti-46Al alloy is cooled reasonably quickly from the α phase-field (see Fig. 2) a fully
lamellar structure is formed by precipitation of γ on the (0001) planes of the α. If the
cooling is slightly slower a near fully lamellar structure is formed, where some
γ lamellae coarsen, giving rise to lamellae with continuous γ grains in the colony
(grain) boundaries. Since there is only one family of (0001) planes in α, the γ/α
lamellae formed during cooling extend across the diameter of the α grains. This is
extremely significant because the α grain size formed during solidification is inherited
in cast products. If the sample is hot worked in the two phase α + γ region this
inherited structure is eliminated and a duplex structure consisting of γ grains and
lamellar γ + α grains is formed on subsequent cooling. For a fixed alloy composition
the ratio of γ to lamellar grains is determined by the hot working temperature and the
grain size is controlled by the extent of hot work and by the hot working temperature.

Large number of different alloy compositions has been patented because they are
described to have some particularly desirable combination of properties. The TiAl-based alloys of the 1st generation are mainly binary Ti-Al systems with various content of Al. In the nineties, large attention was paid to the TiAl-based alloys of the 2nd generation. The typical representatives of this group are Howmet, GE, ABB-2 and ABB-23 alloys with nominal chemical composition Ti-48Al-2Mn-2Nb [10], Ti-48Al-2Cr-2Nb [11], Ti-47Al-2W-0.5Si [12, 13] and Ti-45Al-2W-0.5Si-0.5B (at.%) [14, 15], respectively. Fig. 4a shows the typical microstructure of the ABB-2 alloy which exhibits pseudo-duplex microstructure after heat treatments [11]. Fig. 4b shows the typical microstructure of the ABB-23 alloy [14, 15]. The ABB-23 alloy was derived from its counterpart ABB-2 with the aim to refine the microstructure and improve creep properties by alloying with B. Addition of B was proved to be an effective and economic method to achieve grain refinement, reduce lamellar colony size and prevent uncontrolled grain growth during heat treatments performed within the single α-phase field.

The generally accepted view [16] that all TiAl-based alloys are limited by low ductility and findings that a base composition of Ti-(45-46)Al-(4-8)Nb (at.%) with minor additions of C and B would offer the best properties, led to a development of the 3rd generation of TiAl-based alloys by GKSS [17]. This group of alloys was designed and optimized predominantly for hot mechanical forming. There is no doubt that Nb content of 4-8 at.% improves oxidation resistance which together with some solid solution strengthening provides a reasonable balance of properties. The room temperature strength is dominated by the Al-content where alloys with low Al being much stronger than those with high Al. Fig. 3 shows shifts of phase boundaries
caused by alloying by Nb in a quasi-binary phase diagram of a ternary Ti-46Al-8Nb (at.%) alloy [18] that have been studied as a potential material for turbine blades within the European integrated project IMPRESS [19]. Fig. 4c shows the typical microstructure of a cast Ti-46Al-8Nb (at.%) alloy. Grain refinement in this alloy is achieved through massive transformation of the α-phase to massive γ_M(TiAl) during heat treatments. However, the cooling rates to achieve massive γ_M are relatively high which can lead to distortion or even crack formation in complex shaped castings (blades, turbocharger wheels, etc.) [20]. Alternative material with chemical composition of Ti-45Al-8Nb-0.2B-0.2C (at.%) was designed with the aim to refine the microstructure by additions of B and to increase creep resistance by C [17]. The typical microstructure of this alloy is shown in Fig. 4d. However, the cast alloy has significantly lower ductility when compared to that of B and C free counterpart Ti-Al-Nb system.

The latest 4th generation of cast TiAl-based alloys with the chemical composition Ti-46Al-8Ta (at.%) is being developed in the frame of the IMPRESS project [19]. The design of these air-hardenable alloys is based on alloying with elements which reduce significantly diffusion to achieve massive transformations at low cooling rates [21, 22]. Fig. 5 shows comparison of variation of minimum creep rate with the applied stress and measured stress exponents \( n \) for four TiAl-based alloys developed for turbine blade applications at 750 °C. The minimum creep rates of a new Ti-46Al-8Ta (at.%) alloy are comparable with those of Ti-45Al-2W-0.6Si-0.7B (at.%) alloy [14]. However, the studied alloy shows significantly lower minimum creep rates when compared with those of Ti-46Al-8Nb (at.%) alloy [22] at all stresses or with those of Ti-46Al-2W-0.5Si (at.%) alloy [8] at higher stresses. Fig. 6 shows comparison of variation of applied stress with Larson-Miller parameter defined as \( \text{LMP} = T(C + \log t_{1\%}) \), where \( T \) is the absolute temperature, \( C \) is a constant (\( C = 20 \) in the present work) and \( t_{1\%} \) is the time to 1% creep deformation. The Ti-46Al-8Ta (at.%) alloy shows significantly increased time to 1% creep deformation when compared to that of ternary Ti-46Al-8Nb (at.%) alloy [22] at all applied stresses or Ti-46Al-2W-0.5Si (at.%) alloy [8] at higher applied stresses. Similar values of LMP are calculated for the studied and Ti-45Al-2W-0.6Si-0.7B (at.%) alloys [14] at low applied stresses.
3. PROCESSING

The biggest problem which is hindering the manufacture of engineering components from TiAl-based alloys is their processing. There are three approaches to component production: (i) extrusion and forging, (ii) casting and (iii) powder technology.

Extrusion and forging have been used to produce compressor blades for engine testing, but the processing costs are very high. The compressor blades shown in Fig. 7 have been produced by Thyssen, GfE, Leistritz and GKSS for Rolls-Royce using Ti-45Al-8Nb-0.5(B,C) (at.%) alloy which offers excellent high temperature strength [16]. These blades are only a few centimeters long and even for this size the production has been complicated by the heterogeneous microstructure. This problem, which is associated with compositional control of the ingots, will be difficult to overcome if larger ingots are required where segregation effects will be greater.

Precise casting of TiAl-based alloys represents very promising technology for production of complex shaped components with a competitive price when compared to those of nickel-based superalloys [23]. Despite of enormous efforts over the last 15 years no cast components have been produced which meet aerospace requirements of reliability and cost. The difficulties arise mainly from the high reactivity of molten TiAl-based alloys with ceramic crucible, which has resulted in the
necessity of using cold wall crucibles. However, cold wall crucibles are thermally inefficient and enable superheating of only about 60 °C [23]. This leads to the requirement of pre-heated moulds in order to improve filling. The resulting slow cooling rates lead to the production of components with coarse grains. Large cast porosity results in formation of surface dimples after HIP-ing which can lead to rejection rate as high as 80% and thus to very high cost of cast components. At this stage casting technology is thus inadequate to produce aero engine components from TiAl-based alloys. Fig. 8 shows an example of successfully cast and heat treated large turbine blade from the ABB-2 alloy. There is a further problem which is illustrated in Fig. 9 where the large (fully lamellar) columnar grains grow from the surface towards the central region of the blade containing equiaxed grains. Large columnar grains with lamellar γ+α₂ microstructure shown in Fig. 10 give rise to low ductility, high creep resistance and to a large anisotropy in mechanical properties. On the other hand, pseudoduplex equiaxed microstructure shown in Fig. 11 leads to higher ductility at the expense of the creep resistance [8, 24].

The poor properties of coarse-grained lamellar samples are a major problem and a great deal of work has been done to refine the microstructure of cast products. The addition of boron was shown to refine the grain size of cast TiAl-based alloys and there is no doubt that this is an effective technique. There are however limitations of this approach. During slow cooling large borides are formed which act as failure initiation sites. If the boron concentration is reduced, the refining effect is progressively reduced and a minimum B-content of about 0.5 at.% is required [25]. It should be noted that in thermo-mechanically processed samples the borides provide valuable grain refinement in the original ingot and since the borides are broken up during processing and these smaller borides provide pinning points on grain boundaries during recrystallisation. Alternative approaches to microstructural refinement in cast products use the fact that rapid cooling from the α phase-field gives rise to massively transformed γₘ [26]. Subsequent ageing in the two phase region α + γ leads to α precipitation on all four {111} planes in the γ. This treatment thus produces a more isotropic microstructure than the original large lamellar grains and the as-cast α grain size is no longer significant.

Powder processing is potentially important, especially for larger products where as noted above, segregation limits the homogeneity of products. High dimensional
precision can be obtained through ISOPREC, minimizing the need for machining. Powder metallurgy is also appropriate to increase the deformability (it is used by Plansee to produce thin laminated ribbons). However, the powders and the process itself are highly expensive.

Snecma and Turbomeca made several demonstrations of feasibility using various processes (foundry, extrusion, forging, powder metallurgy) as illustrated in Figs. 12 and 13 [27]. Several demonstrations were technically successful, or proved that remaining problems could be solved if necessary. However, none of these applications are expected to enter in production at medium term.

The above discussion makes it clear that processing of TiAl-based alloys requires further development before components can be produced with quality acceptable to aero engine applications at an acceptable cost. The thermo-mechanically processed samples are extremely expensive and at present ingot heterogeneity imposes a size limit on components. Casting technology needs to be improved and the microstructural control, aimed at refining the microstructure requires further development.

4. APPLICATIONS

TiAl-based products are currently used in automotive applications. The most successful of applications of TiAl-based alloys has been developed in Japan for turbochargers which were fitted in relatively small numbers (about 1000) in 1998 to top of the range Lancer cars. Success over the intervening years has led to more than 20 000 cars being equipped with second generation of turbochargers in 2003. These turbochargers shown in Fig. 14 are now manufactured from Ti-46Al-6.5Nb (at.%) alloy with other minor additions [16, 28]. The alloy is melted using a cold wall furnace and the turbochargers are cast using counter gravity casting [16, 29]. Several other companies are now manufacturing TiAl-based turbochargers and it appears that the successful application of TiAl in this relatively undemanding component (where very low ductility was acceptable to the design engineers) will allow experience in casting technology to be built up so that eventually safety-critical
components can be manufactured using this route. Thermo-mechanically processed valves have been used for many years in formula one cars (where cost was not the main issue) but formula one regulations no longer allow their use [16]. Attempts to develop cast TiAl-based valves (Fig. 15) have been successful in terms of performance but are still far too expensive because the amount of scrap is too large and the cost of raw materials is an increasing cause of concern [30]. A major 5-year European programme (IMPRESS) which was started in 2005 aims at the production of 40 cm long turbine blades for aero engines by improving casting technology and by producing fine grained cast products which have acceptable properties with much reduced scatter. This is a very ambitious project but it is being driven by the end-users who see a major need for light weight turbine blades. In addition work is underway to produce the compressor blades illustrated in Fig. 7 using casting rather than extrusion and forging.

5. PROSPECTS

There are two types of reasons to explain the difficulty in applying intermetallic technology to engines: technical reasons (intrinsic properties of intermetallics and manufacturing difficulties) and economical reasons, both being closely related.

The prospects for increased applications of TiAl-based alloys depend essentially on several factors. The first is the development of low cost processing of components with reproducible and acceptable properties. The second is the establishment of a supply chain so that homogeneous ingots or clean powder is available to meet the increased demand. One of the biggest problems in the use of TiAl-based alloys for casting or for thermo-mechanical processing is the fact that the ingots can be heterogeneous, with variations in Al-content of at least 1 at.% between top and bottom and across the diameter. It appears that plasma melting is able to produce homogeneous alloys routinely and since there is no preferential loss of volatile elements (such as Al), these ingots have compositions very close to that of the feedstock [16]. The final factor, which has not been covered here is the low temperature embrittlement which can occur at times as short as 2 h at 700 °C [19]. This embrittlement has been shown to be a surface effect which is removed when the thin oxide (typically tens of nanometer thick) is removed [22, 31]. Table 1 summarizes average room-temperature 0.2% offset tensile yield strength (YS), ultimate tensile strength (UTS) and measured range of plastic elongation to fracture [22]. The specimens prepared from the as-received bars show relatively high reproducible
Table 1. Effect of ageing on RT 0.2 % offset tensile yield strength (YS), ultimate tensile strength (UTS) and plastic elongation to fracture

<table>
<thead>
<tr>
<th>Heat treatment</th>
<th>YS (MPa)</th>
<th>UTS (MPa)</th>
<th>Elongation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>As-received</td>
<td>625</td>
<td>724</td>
<td>0.94 – 1.02</td>
</tr>
<tr>
<td>Machined and aged at 700 °C/2 h in air</td>
<td>-</td>
<td>637</td>
<td>0.11 – 0.18</td>
</tr>
<tr>
<td>Machined, aged at 700 °C/2 h in air and re-</td>
<td>623</td>
<td>726</td>
<td>0.92 – 1.11</td>
</tr>
<tr>
<td>machined</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aged 700 °C/2000 h and machined</td>
<td>498</td>
<td>564</td>
<td>0.68 – 0.84</td>
</tr>
</tbody>
</table>

plastic elongation to fracture close to 1%. However, when such specimens are subjected to short-term ageing at 700 °C for 2 h in air, large drop in RT ductility characterized by a decrease of plastic elongation to fracture by about 82% is observed. On the other hand, removing of oxygen-rich surface layer formed during ageing at 700 °C fully restores YS, UTS and ductility. Hence, surface absorption of oxygen is responsible for the observed embrittlement of the short-term aged samples.

For most applications the required properties of alloys will be able to be met by alloys with compositions based on Ti-(45-46)Al-(5-8)Nb but cost considerations in some cases (e.g. automotive exhaust valves) may drive the Nb content down. Finally, it appears that the two major companies which produce large engines for civil aircraft are committed to use TiAl based alloys in the next generation of engines which is a very encouraging decision for those who have been working on developing the alloys and their processing over the years.

6. CONCLUSIONS
The overview of the present status and future perspectives of TiAl-based alloys can be summarized as follows:

1. Three generations of TiAl-based alloys that have been developed over the last 20 years were briefly characterized and basic concept of the latest 4th generation was described.
2. Several processing technologies such as powder metallurgy, hot extrusion, forging and precise casting were described and related to microstructure and properties of produced components.
3. Current applications in automotive industry such as turbocharger wheels and automotive valves are described and the typical examples of components are given. In spite of several engine tests, there are no commercial aircraft engine applications for TiAl-based alloys until now.
4. The factors affecting the prospects for increased applications of TiAl-based alloys are defined from the point of view of cost, properties, processing technology and alloy composition.

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REFERENCES


