Niobium for High Temperature Applications
Edited by Young-Won Kim and Tadeu Carneiro
TMS (The Minerals, Metals & Materials Society), 2004

POTENTIAL OF HIGH-Nb-TiAl ALLOYS FOR AERO-ENGINE APPLICATION

Dan Roth-Fagaraseanu

Rolls-Royce Deutschland; Dahlewitz, D-15827, Germany

Keywords: titanium aluminide, TNB, compressor blades

Abstract

Intensive efforts in TiAl technology over recent years has promoted TiAl as having a high potential for entering the production phase in automotive and aero engines applications. The application spectrum investigated for TiAl ranges from high loaded components like compressor and turbine blades, casings and structural components to fabricated parts in the exhaust area. The introduction of TiAl into service is mainly determined by the two principal factors of alloy and process development to achieve competitive properties/quality with developed manufacturing technologies. Additionally a proper component selection is required in order to maximise the benefits of implementing the new technology. This paper is concentrated on the development and implementation of TiAl compressor blades for aero engines with the focus on the improved benefits associated with the development of the new high Nb containing TiAl alloy family. A property review together with critical manufacturing aspects associated with the new alloy family will be addressed. Additional requirements for successful implementation of the technology will also be discussed.

Introduction

The overall benefits using TiAl alloys for components in aero engines have been broadly discussed in the literature for a variety of applications like blades and vanes in the high pressure compressor or turbine [1,2].
The general characteristics of the gamma titanium aluminides a

- Low density of 4g/cm^3 compared to 8-8.5 g/cm^3 for Ni-base super alloys.
- High stiffness E=175 GPa at 20^{o}C (120GPa for Ti- and 200GPa for Ni-base alloys)
- High burn resistance (no Ti-fire)
- High temperature strength and oxidation resistance to 750^{o}C.
- Low thermal expansion coefficient and high thermal conductivity.

However the introduction of a new material into service includes more aspects than the material availability. Additional significant aspect is the establishment of supply chains, able to produce a competitive product with regard to costs and quality compared to current technology. In the following section the current status regarding development and availability of industrial production routes for TiAl technology in aerospace focusing on hot working routes for compressor blade application will be addressed.

Prior to implementation a number of technical and manufacturing issues have to be addressed to optimise the process and determine the effects of each parameter on the mechanical properties.

Additionally to the process availability the introduction of new technologies, like γ-TiAl into service needs to satisfy also the business case requirements for a certain product. Therefore the cost aspects need to be addressed early in the development programmes of the new technologies

to increase the commercialisation potential. The Ti- or Ni-base alloys to be replaced by titanium aluminides have already accumulated a large manufacturing and tooling experience and competitive mass production methods for these alloys are already established.

Rolls-Royce Development

Worldwide research and manufacturing process development has focused on both: cast and hot working processes. Rolls-Royce was involved in the development of gamma titanium aluminides since the 1980s. Early efforts were aimed at improving oxidation resistance in this material system over the original P&W developed alloy, Ti-48Al-1V [3]. The result of this work led to the invention of a lightweight superior alloy Ti-46Al-5Nb-1W [4] for application on turbine and compressor rotating airfoils for high performance engine designs.

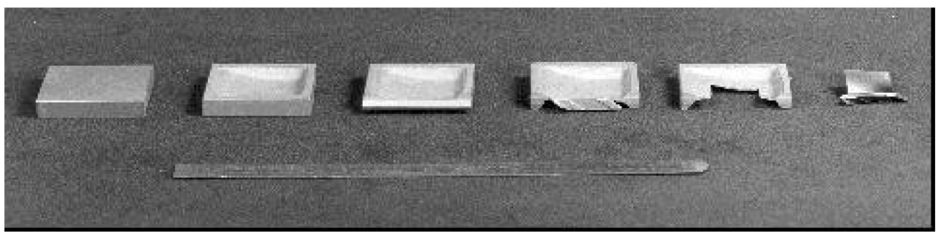

Figure 1: Early efforts to produce small compressor vanes in TiAl. The picture is showing AE3007 14th stage compressor blades manufactured by ECM using production tooling

On the casting side Rolls-Royce activities have been concentrated mainly on the process development for low pressure turbine blades and vanes. The effort resulted in successful manufacturing of components in small batches, however an industrial production route for large component quantities still needs to be established. Figure 2 shows the result of a casting trial for low pressure turbine blades in γ-TiAl.

Figure 2: Cast trial of low pressure turbine blades in γ-TiAl at Birgmingham University. Material used for this trials is the 45-2-2 alloy.

Material Selection

A large variety of material compositions have been extensively used in the development work at Rolls-Royce over the past years including the widely used 45-2-2XD or 47-2-2XD alloys for the casting routes or the Ti-46Al-5Nb-1W known as alloy 7 developed at Rolls-Royce in Indianapolis. Additionally several alloy compositions have been investigated together with the development work for wrought products like the γ-TAB from GKSS in Germany. All this alloys are part of a "second alloy generation" described by the equation 1 below and are characterized by moderate strength of about 600MPa and reasonable oxidation levels up to 600°C.

$$\textbf{Ti} - \textbf{Al}_{45\text{-}48} - (\textbf{Cr, Mn, V})_{1\text{-}3} - (\textbf{Nb, Ta, W, Mo})_{2\text{-}4} - (\textbf{Si, B, C})_{<1}\ \textbf{at\%} \qquad (1)$$

When compared to the Ni- or Ti-based alloys to be replaced by the γ–TiAl this class of materials are inferior in the mechanical properties where the strength levels achieved by the conventional technology are in the above 1GPa tensile strength at room temperature. Therefore the application potential for this alloys can only target low stressed components or the lack in properties needs to be balanced by robust design which in turn lower the weight reduction potential.

More recently high Nb containing alloys have been developed at GKSS in Germany and show superior properties over all other compositions investigated in terms of flow stresses, creep resistance and oxidation behaviour. This alloy class with the composition Ti-45Al-(5-10)Nb with additions of Bor or Carbon is also known as the TNB family [5-7]. Based on the superior properties, Rolls-Royce selected the TNB alloy for further evaluation on both casting and hot working products.

Casting γ-TiAl

Development and characterisation of casting processes for blades and vanes application is still a prime target in Rolls-Royce materials strategy, however at the moment there is no industrial supplier chain capable of producing components with a satisfactory quality and acceptable process yield. Figure 3 is showing a low pressure turbine blade for the BR715 engine (from Rolls-Royce Deutschland) casted by Howmet with conventional investment casting methods in the 45-2-2XD alloy.

Figure 3: Low pressure turbine blade for the BR715

engine investment cast by Howmet in 45-2-2XD alloy

A promising development in this area is coming from the research institute ACCESS in Germany. The process investigated here is based on centrifugal casting in both: permanent and precision casting mould and has been demonstrated so far for automotive components such as exhaust valves (centrifugal permanent mould) or turbocharger wheels (centrifugal precision casting). The first investigation into the process for small static components such as vanes in the compressor are showing positive results: compared to the conventional precision casting the components casted with the ACCESS process reduces significantly the problems related to line porosity and component distortions. Additionally, due to the high cooling rates specific for the process, the resulting microstructure is very fine even with non-boron contained alloys like the high Nb TNB alloys. However this development is still on a pre-production level and a industry partner needs to be involved in the development and optimise it for robust serial production.

Figure 4: Casting trials for vane application in TNB a) centrifugal precision casting b) centrifugal casting in permanent mould

As conclusion for the casting activities within Rolls-Royce a industrial supplier chain for cast structural components is still missing at the moment with the conventional investment casting failed to achieve a robust production levels wit acceptable yield. Actual development work is concentrated on the centrifugal processes using both: a permanent an a investment mould technique. For small components like cantilever compressor vanes a technology demonstration in a core engine being targeted within the next two years.

Hot Working Routes

Intensive activities over the last years within Rolls-Royce and especially within Germany were focused on developing and characterising hot working routes for compressor blades and vanes. These activities represent the most advanced processing routes with the highest potential for aerospace applications to date. To achieve this target a highly competitive team including experts from the industry (GfE, Thyssen, Leitritz and Rolls-Royce Deutschland), supported by the research institute GKSS and contributions from the Universities of Dresden and Cottbus have collaborated to develop and demonstrate the manufacture of compressor blades in TiAl on a production scale.

The processes routes investigated include raw material production by ingot metallurgy and powder production, primary forming processes by canned extrusion or pancake forging, near net shape forming by isothermal forging, heat treatments, NDT techniques and machining / ECM operations to the final geometry. In the following the processes steps investigated are addressed together with a analysis towards a commercialisation for high pressure compressor blades.

Ingot Production and Ingot Qualities

Ingot production was found to be a critical processing step, especially if ingots of large diameters are necessary. Good quality ingots are available up to 200mm diameter with smaller ingots being more homogeneous compared the larger ones. One problem is macroscopic pores, which could not be completely closed by hot working and can even lead to cracking of the material during the following forming processes. For this reason the ingots were subjected to hot isostatic pressing at 1200°C, 200 MPa for 4 hours. Existing pores in the ingots persist during the following process steps and are difficult to close during the forming processes. The most severe problem connected with ingot production is, however, macro and micro segregation of Al, because the mechanical properties depend on the Al content. As opposed to defects like pores, the variation in element concentration due to segregation mechanisms can be completely removed by subsequent forming processes. However the non-uniform ingot microstructure and the poor failure resistance of TiAl alloys make hot working of ingot material difficult. Research in this field has made significant progress in the last few years and the problems associated with large-scale wrought processing are now being overcome. This has been the subject of a number of excellent reviews [7,8].

Hot Forming Using Extrusion and Isothermal Forging

Apparently, the most critical step is to convert the coarse grained, textured and segregated microstructure into a more homogeneous and workable structure that is suitable for secondary processing. Primary ingot breakdown was accomplished by extrusion at a temperature of 1250°C, which is about 90° below the α-transus temperature. Under these conditions severe oxidation and corrosion occurs, thus, the work piece was encapsulated in austenitic steel.

Extrusion below T_α led to duplex microstructures with coarse and fine grained banded regions. Nevertheless, the microstructural refinement obtained in the primary wrought material reduced the susceptibility to cracking in secondary hot working steps and allowed the material to be worked by closed-die forging.

Figure 5: Extruded bars using stainless steel capsule technique in TNB alloy.

Figure 5 is showing extrude bars in rectangular shape using capsule of stainless steel. The bars have been extruded on a industrial press to dimensions up to nine meters and can be delivered in different shapes depending on the application needs. Extruded material can also be used directly for the manufacturing of the blades by ECM / machining operations without any further forming steps (Figure 6).

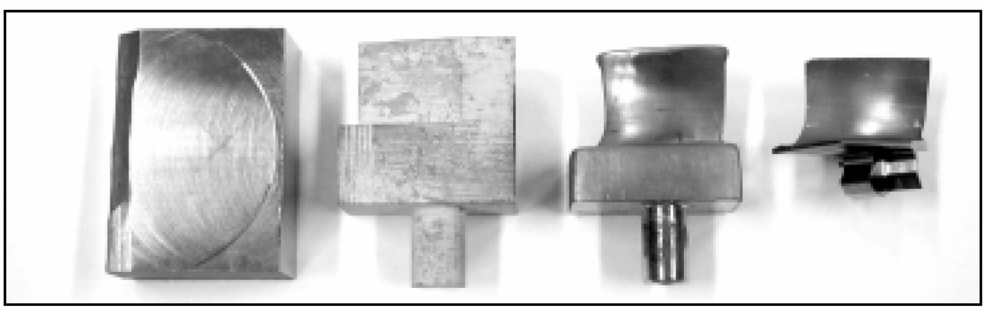

Figure 6: Overview over the manufacturing steps of a high pressure compressor blade out of extruded bar

Compared to the manufacturing of the blades by isothermal forging, the material in this case has been extruded to a higher extrusion ratio in order to achieve a fine fully recrystallised microstructure. To minimise raw material usage, rectangular tooling was used, which had been previously optimised for the blade geometry.

In a secondary working step the blade geometry was produced by forging in a temperature range between 1000°C and 1150°C utilizing two sets of impression dies. Using optimal secondary forging conditions, more than 200 blades were successfully produced with the forging steps shown in Figure 7. After forging a substantial improvement of the microstructural homogeneity was observed both in the blade aerofoil and the root compared to the as-extruded material.

Figure 7: Process steps required to forge a near net shape blade from extruded bar

Optimisation of the forging route can be also achieved when using multiple-form pre-forging operation. Due to the nature of the isothermal forging in a protective environment (nitrogen) each single piece needs to be separately handled within the equipment so that a multiple preforge optimisation reduce significantly both the handling time within the camber and the forging time. Examples of forged pre-shapes with different number of pre-shapes are shown in Figure 8.

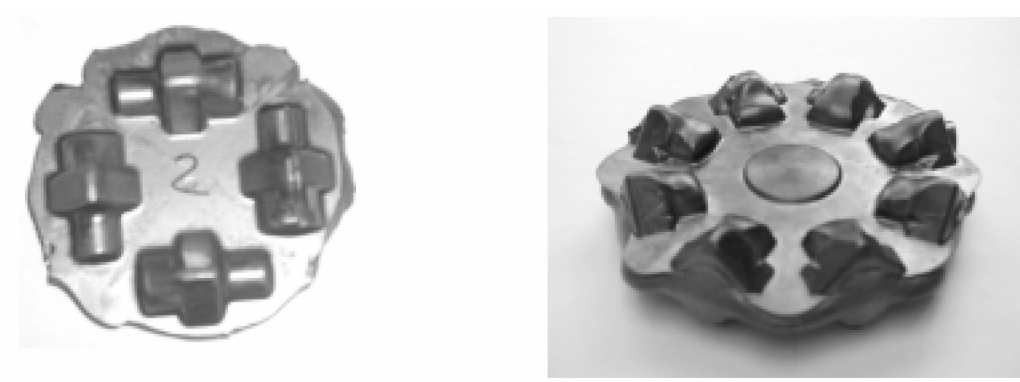

Figure 8: Examples of multiple pre-forged shapes including four respectively eight pieces to reduce the forging and handling time

Extrusion / Isothermal Forging

A direct comparison between the extrusion route (extrusion + final machining) and the forging route (extrusion + isothermal forging + final machining) must include cost aspects. While the extrusion route uses more raw material and therefore includes more machining time, the forging is associated with better material homogeneity and material properties but is the more time and energy consuming route. From the cost point of view this assumption is true only for conventional materials. For the gamma alloys there are two aspects in the processing route, which need to be considered when selecting the proper production route:

- γ alloys are still a niche product with relatively low production volumes compared to conventional alloys. As a result γ-TiAl are still expensive materials compared to conventional alloys.
- For conventional materials the high ductility exceeding 20% at room temperature is reflected in a high flexibility in the selection of machining operations. This results in the a ability to select cost effective machining steps with high material removal rates. For γ alloys the material brittleness restricts the machining operations to "material friendly steps" with relative low removal rates per pass. This problem demands pre-shaping operations to minimise the material volume to be machined out. In the case of machining out of the extruded bar the material yield is about five times lower than the near net shape process. Additionally the removal of the capsule material necessary for the extrusion operation leads to further time consuming steps.

An analysis of the two production routes including these two aspects above indicates the manufacture of the blades by isothermal forging to be the most attractive route not only from the microstructure quality point of view but also in terms of production costs.

<u>Near Net Shape / Precision Forging</u>

The two processes described above have been assessed in parallel by manufacturing small serial production batches and comparing the sequential operations in each route including also the cost aspects. Because of the highly competitive market in aerospace, only a cost competitive route enhances the introduction potential of the new technology and motivates the design community to take advantage of the new product. A comparison between the actual component price in IN718 design and a γ component manufacture by near net shape process reflect a 2 to 2.5 times higher cost for the γ technology. This is far too much to be balanced by the benefits associated with use of γ titanium aluminides. Starting from the near net shape technology and taking into account the high raw material costs and limited flexibility in the machining operations the logical step forward is the manufacturing of the blades by precision forging. The only way to achieve this target is a higher temperature during the forging operations. With the technology available for conventional materials this step is not possible due to the following two problems:

- The high flow stresses of the γ-alloys require a higher temperature to achieve a processing window for precision forging. This temperature cannot be achieved with the actual die material (Mo-dies)
- At the forging temperature the die material is to soft and due to the plastic deformation only a limited number of components can be produced within the required component tolerances.

For a precision forging of the γ-alloy the demand is towards higher temperature dies, which can allow a process window close to the α-transus or above. The development within the described program focuses at the development and test of high temperature dies as a key technology for the precision forging of γ-TiAl alloys.

Outlook

Beside the process development described in the previous sections, new technologies like γ-titanium aluminide alloys need to be validated and demonstrated in an engine environment prior to introduction in service. Demonstrators of latest technologies like the German funded program “Engine 3E” and the European program ANTLE are very useful to test new materials and technologies in an engine environment and minimise the risk of component failure in service due to unexpected mechanisms. The success of the program described in this paper motivated Rolls-Royce to select the γ-technology to be tested in the last stages of the high pressure compressor of both ANTLE and “Engine 3E” demonstrators.

A successful validation of the technology in E3E and ANTLE will release the γ-titanium aluminide technology for service application.

For the ANTLE program the blades have already been manufactured and delivered for engine assembly (Figure 9).

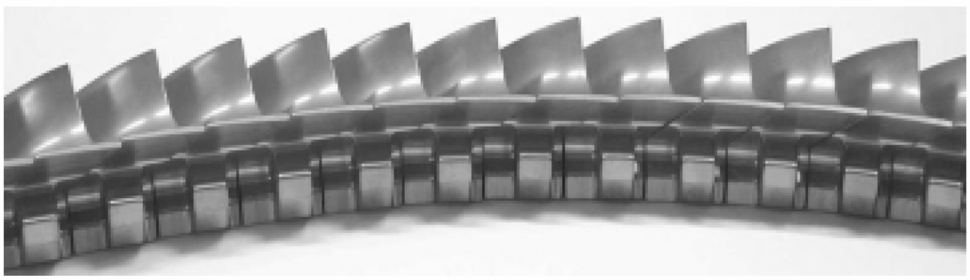

Figure 9: Gamma TNB blades to be tested in engine demonstrator

However before serial production can be started some further work is needed to achieve a competitive cost compared to the current products. The necessary steps to achieve this target have been identified to be a precision forging operation and the related changes in the process route. Additionally, to achieve a maturity level comparable to Ti- or Ni-base technologies, a broad application spectrum is necessary for γ-TiAl alloys. This target is only possible with a continuous long-term activity including development and implementation of new innovative γ-TiAl specific processes.

Conclusions

The drive to reduce engine and operating / life cycle costs, assisted by materials technology is and will continue to be very significant.

Gamma TiAl has, at the moment, the highest potential for entry into production for components like blades and vanes in the high pressure compressor of aero engines.

The newly developed alloy family TNB shows superior properties over all other titanium aluminide alloys investigated and has the highest potential for production.

A hot working route for γ titanium aluminide compressor blades in a production scale has been successfully demonstrated including ingot production, primary forming step by canned extrusion, isothermal forging and final machining by conventional milling and electro chemical machining.

The successful manufacture of γ-TiAl blades in an production environment has lead to the selection of this material to enter the validation phase for engine application. The technology developed in this program is part of the engine demonstration packages “Engine 3E” and ANTLE, which will qualify the γ-TiAl technology for realistic service introduction.

Before a serial production can be started further work is necessary to reduce the manufacturing and material cost in order to increase the commercialisation potential of the γ-technology.

The manufacturing knowledge gained and the materials data generated in this programme make TiAl technology a realistic prospect for future applications significantly enhancing the competitiveness of actual products.

Acknowledgements

The authors are grateful to all project partners from GKSS, GfE, Thyssen, Universities of Cottbus and Dresden for their contribution to the success of the program and for the many valuable discussions and support. Financial support by the German Federal Ministry for Education and Research is gratefully acknowledged.

References

1. Y-W. Kim and D.M. Dimiduk, in *Structural Intermetallics* (Eds: M.V. Nathal, R Darolia, C.T. Liu, P.L. Martin, D.B. Miracle, R. Wagner, M. Yamaguchi), TMS, Warrendale, PA, 1997, 531.
2. Y-W. Kim, in *Gamma Titanium Aluminides* (Eds: Y-W. Kim, R. Wagner, M. Yamaguchi), TMS Warrendale, PA, 1995, 637.
3. M.J. Blackburn and M.P. Smith, AFML-TR-79-4056, May 1979
4. S.K. Jain et.al., US Patent No. 5,296,056,1994
5. Paul JDH, Appel F, Wagner R. Acta Mater 1998;46:1075
6. Appel F, Oehring M, Wagner R, Intermetallics 2000;8:1283.
7. Appel F, Oehring M, Paul JDH, Lorenz U. In: Hemker KJ, Dimiduk DM Clemens H, Darolia R, Inui H, Larsen JM, Sikka VK, Thomas M, Whittenberger JD, editors. Structural intermetallics. Warrendale (PA): TMS; 2001. p. 63.
8. Semiatin, S.L. (1995). Gamma Titanium Aluminides (Eds: Y-W. Kim, R. Wagner, M. Yamaguchi). TMS, Warrendale, PA, p. 509.