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SOME ASPECTS ON PRODUCTION OF WROUGHT γ(TiAl) BASED COMPONENTS FOR TRANSPORTATION

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Abstract

Within the last three years PLANSEE AG successfully extended its capabilities for wrought processing, machining and joining of conventional engineering γ(TiAl) base alloys to high Nb-containing γ(TiAl) alloys. In particular, large-scale extrusion of cast ingots, hot-rolling of sheets from extruded ingots as well as from gas-atomized powders and forging were successfully demonstrated on an industrial scale.

The present paper is focused on wrought processing of γ(TiAl) alloys with emphasis on the industrial production of valves for high performance automotive engines. Additionally the status of manufacturing technologies for sheet and sheet based components for future aerospace applications is presented.

Another objective is to address the current status of wrought-processing of high-Nb containing γ(TiAl) alloys as well as to report resulting mechanical properties in order to show the potential of this new class of structural high-temperature materials.

Introduction

It has been forecasted that for every 15 years of traffic growth a doubling of transport capacity will be needed [1]. This prediction underlines the importance of improving the environmental compatibility, economic performance and the safety of transport systems. Advanced engine concepts that incorporate new light-weight materials show potential for improvement in these fields.

Compared to other metallic materials used in automotive and aerospace industries today, titanium aluminides based on γ(TiAl) provide attractive properties like low density (≈3.9 - 4.1 g/cm^3), high specific yield strength (yield strength/density), high specific stiffness (modulus of elasticity/density), resistance against "titanium fire", and good creep properties up to high temperatures. Particularly, the high specific stiffness, which is retained even at elevated temperatures, is most advantageous for the design of light-weight structural parts in aerospace and automotive applications.

Titanium aluminides possessing long term oxidation resistance up to temperatures of about 750˚C are regarded to close the gap between high-temperature titanium alloys and nickel based super alloys [1]. The specific stiffness and yield strength of engineering γ(TiAl) based alloys at room-temperature (RT) and 750˚C in comparison with commercial Ni-base super-alloys and Ti-alloys are shown in Fig. 1. At temperatures between 600˚C and 800˚C γ(TiAl) based alloys are superior to Ti-alloys in terms of their specific stiffness. However, with regard to strength driven component designs it can also be seen that conventional γ(TiAl) based alloys are probably not optimal. In the last years high-strength γ(TiAl) based alloys characterised by a Nb-content ranging between 5 - 10 atomic percent have been developed. At room temperature yield strength levels > 1000 MPa can be achieved after proper thermo-mechanical processing. These alloys are particularly suitable for strength driven component design. It is important to note that also the high temperature properties, such as creep strength and oxidation resistance, are also remarkably increased by Nb additions, thus extending the application range of γ(TiAl) based alloys to higher temperatures[1].

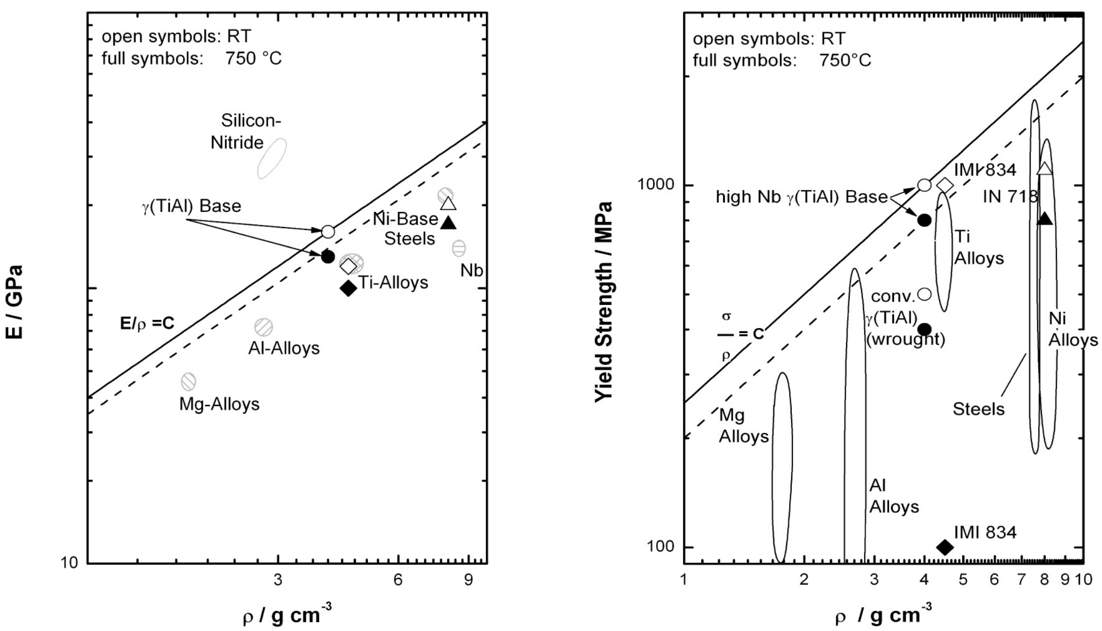

Figure 1: Left: Young´s modulus, E, vs. density , ϱ . The lines indicate constant E- ϱ ratios representative for γ(TiAl) -based alloys at RT (solid line) and at 750 °C , respectively. Right: Yield-strength,YS, vs. density ϱ . The lines indicate constant YS- ϱ ratios representative for γ(TiAl) -based alloys at (solid line) and at 750 °C , respectively.

In order to make use of these advantages and for a successfully implementation into aerospace and automotive applications it is necessary to provide suitable alloy compositions as well as industrial manufacturing and processing technologies which are adapted to this material class.

The present paper is focused on wrought processing of γ(TiAl) alloys with emphasis on the industrial production of valves for high performance automotive engines. Additionally the status of manufacturing technologies for sheet and sheet based components for future aerospace applications is presented.

Another objective is to address the current status of wrought-processing of high-Nb containing γ(TiAl) alloys as well as to report resulting mechanical properties in order to show the potential of this new class of structural high-temperature materials.

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[1]For further detailed information regarding the physical metallurgy of these alloys the reader is referred to [2]

Wrought processing of γ(TiAl) - some general aspects

The microstructure of γ(TiAl) alloys can be refined via hot-working. Proper thermomechanical processing results in a significant increase in strength when compared to cast material [3–5]. This effect is exemplified in Fig. 2 which shows yield-stress vs. temperature for a γ(TiAl)-alloy (Ti-46.5Al-4(Cr,Nb,Ta,B)) in the as-cast condition and after hot-extrusion to extrusion ratios (ER) between 10:1 to 268:1.

The observed increase in yield stress is related to a decrease in grain size. However, quantitative descriptions by means of a Hall-Petch relationship are often inaccurate due to the complexity of the microstructures [5]. It can also be seen from Fig. 2 that the increased tensile yield strength is retained up to temperatures of about 600˚C. However, at temperatures around the brittle-to-ductile-transition temperature (BDTT, in this case approx. 700˚C) the yield strength decreases. This effect is more pronounced for fine-grained microstructures, which might be explained by an increase of grain boundary sliding at the relatively low strain rates employed for the tests reported here. In fact it is known, that fine-grained γ(TiAl)-alloys can exhibit superplasticity at temperatures as low as 800˚C [6].

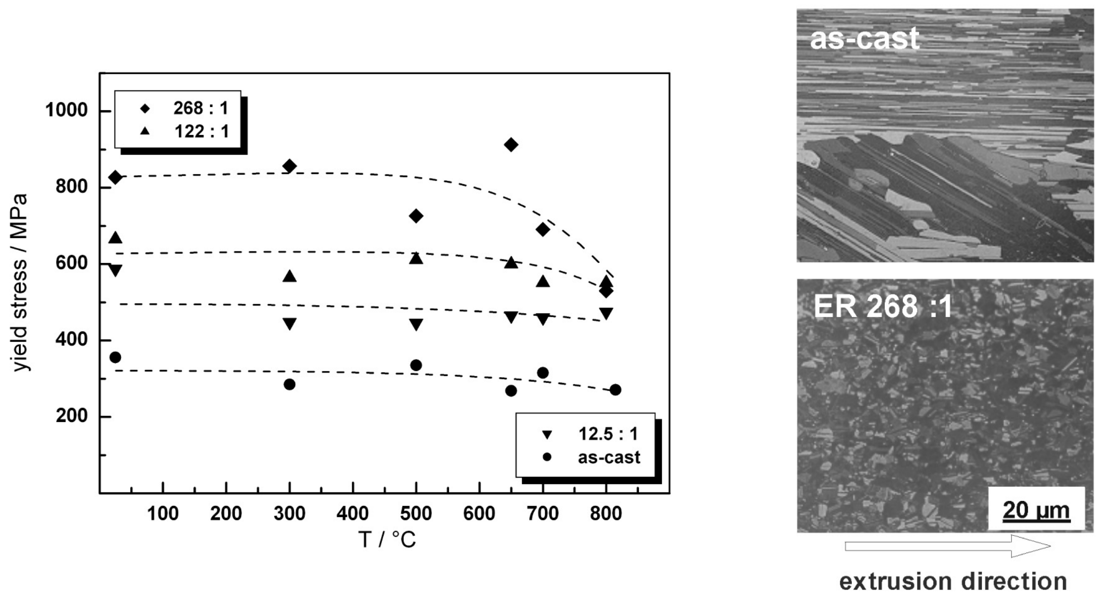

Figure 2: Temperature dependence of the tensile yield strength of a Ti-46.5Al-4(Cr,Nb,Ta,B) in differently hot-worked conditions. The micrographs represent microstructures of the as-cast condition and after extrusion with an ER of about 268:1. The tensile test were performed under constant crosshead displacement. Initial strain rate $1 \cdot 10^{-4}\, s^{-1}$; Tests at RT were performed in air; tests at T > RT in vacuum ($< 1 \cdot 10^{-5}$ mbar)

The general microstructure-property relations of γ(TiAl)-based alloys were summarized by Y.-W. Kim [3] as illustrated in Fig. 3.

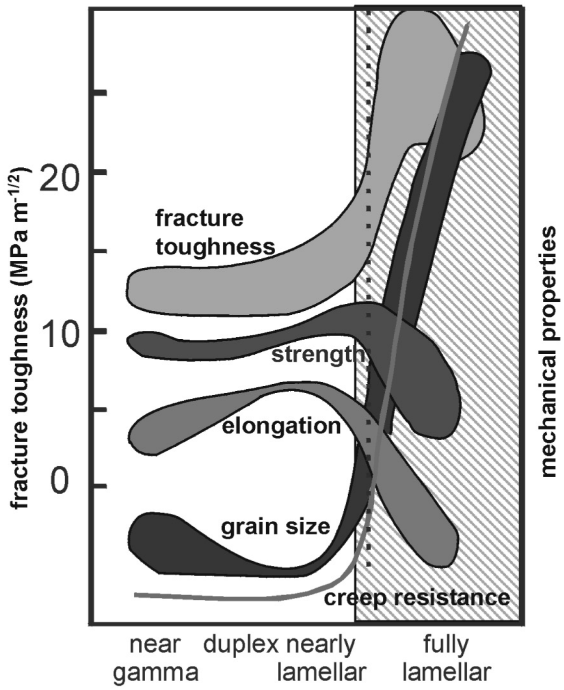

Figure 3: The microstructure-property relation of γ(TiAl) alloys after Y.-W. Kim [3].

It can be concluded from Fig. 3 that hot-working of γ(TiAl)-alloys extends the range of achievable microstructures when compared to cast microstructures which are mainly restricted to lamellar or nearly-lamellar morphologies (hatched region in Fig. 3). The main advantage of wrought processing is the controlled modification of the resulting microstructures and mechanical properties. In duplex materials a finer overall grain size, irrespective of the volume fraction of grains and lamellar colonies, generally leads to an improved ductility and increased strength [5].

One key concept here is grain refinement via dynamic recrystallization, which characterizes the deformation behaviour of γ(TiAl) alloys at high temperatures and medium strain rates. However, even under these conditions dynamic recrystallization is often incomplete. A more homogeneous refinement of the cast microstructures can be achieved by multi-step hot-working, which involves static recrystallization due to an intermediate heat-treatment [5].

Some additional insight in the high-temperature deformation behaviour of γ(TiAl) alloys and the influence of temperature and strain-rate on the resulting microstructures might be gained from Fig. 4. In the diagram on the left of Fig. 4 the peak flow stress is given as function of deformation temperature for two deformation rates. The data of the high-Nb containing γ(TiAl) alloy is compared to a more complex “low-Nb” containing γ(TiAl) alloy as well as to Ti64 and IN718LC. It is obvious, that for both γ(TiAl) alloys much higher stresses have to be overcome during hot-working than for the Ti- and Ni-based alloys. Additionally, it can be estimated that both, the strain-rate sensitivity as well as temperature dependence of the flow stresses of the γ(TiAl)-alloys are much more pronounced when compared to Ti64 and IN718LC. The high-Nb containing γ(TiAl) alloy exhibits the highest resistance to deformation up to temperatures of about 1300˚C.

From an engineering point of view these findings may shed some light on the challenges that have to be faced during practical hot- working of γ(TiAl) alloys. Usually, hot-working of γ(TiAl) alloys is carried out at high temperatures (i.e. > 1100˚C) which also demands high strength and wear resistant tooling materials. The pronounced temperature and strain-rate sensitivity of the flow-stress leads to a narrow processing window and demands a stringent control of the hot-working parameters. Under isothermal hot-working conditions the latter requirements can be fulfilled as was shown for example by Appel et al. [2]. On the other hand, the availability of facilities for isothermal hot-working of γ(TiAl) alloys is limited and for some important hot-working operations like extrusion and rolling not existing. A suitable workaround is thermal insulation of the workpiece by canning order to make conventional hot-working techniques feasible, as will be shown in the following sections. To the right of Fig. 4 the response of the microstructure on the deformation parameters temperature and strain rate in terms of grain size and the Zener-Holomon parameter (Z) is shown.

The microstructural parameters for the high-Nb containing alloy were obtained from compression tests after a true compression to 0.6. The data for the Ti 47Al 2Cr 0.2Si alloy was obtained after tensile tests performed on sheet samples (details on the test conditions and the thermo-mechanical history of the sheet specimens can be found in [7]). The observed grain

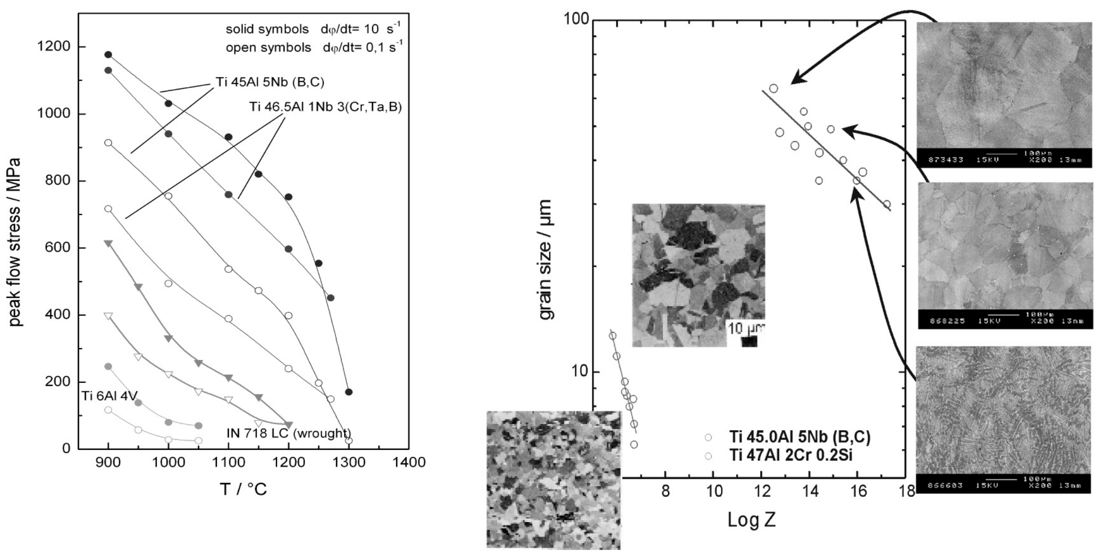

Figure 4: Left: Peak flow-stress vs. deformation temperature of wrought γ(TiAl) alloys at strain rates of about $10\mathrm{s}^{-1}$ and $0.1s^{-1}$ obtained from laboratory compression tests. For comparison, peak flow-stress data of Ti64 and IN718 LC are also given (source: ASM Hot Working Guide). Right: Response of microstructure on the deformation parameters in terms of the Zener-Holomon-Parameter, Z, for a high Nb containing γ(TiAl) alloy and Ti 47Al 2Cr 0.2Si.

refinement with increasing Z (i.e. higher strain rates and decreasing temperature) in the Ti 47Al 2Cr 0.2Si alloy was related to dynamic recrystallization [7]. The situation is not so clear for the high-Nb containing alloy and needs further investigation. However, on an empirical basis, the increasingly refined morphology with increasing Z is also obvious. Although in the above consideration many important features of the physical metallurgy regarding hot-working of γ(TiAl) alloys, as well as the role of texture formation and the impact of the homogeneity of the prematerial were not addressed we may conclude that thermo-mechanical processing of γ(TiAl) alloys provides a suitable way for the control of microstructures. The mechanical properties can be optimized by means of primary hot-working of cast pre-materials and during secondary forming operations.

In the following sections we will show how some of these concepts were exploited on an industrial base using the example of wrought processed automotive valves. Furthermore some practical examples displaying our current status in the hot-working of high-Nb containing alloys.

Wrought processing of γ(TiAl) automotive valves

Automotive engine valves appear to be an ideal application for γ(TiAl) based alloys. Generally, there are three major benefits which could be exploited by the use of light-weight engine valves: (a) higher fuel economy, (b) better performance and (c) reduced noise and vibration. For exhaust valve application in series automotive engines, the requirements are as follows [8]: High cycle fatigue strength (10^7 cycles) of ≥ 250 MPa at 800°C; thermo-shock resistance; oxidation resistance; wear resistance. So far, near-net shape casting is the mostly investigated processing method [9–13] and the reported mechanical properties are likely to meet the requirements mentioned above [14].

However, the demands on valves for high-performance racing engines are more challenging.

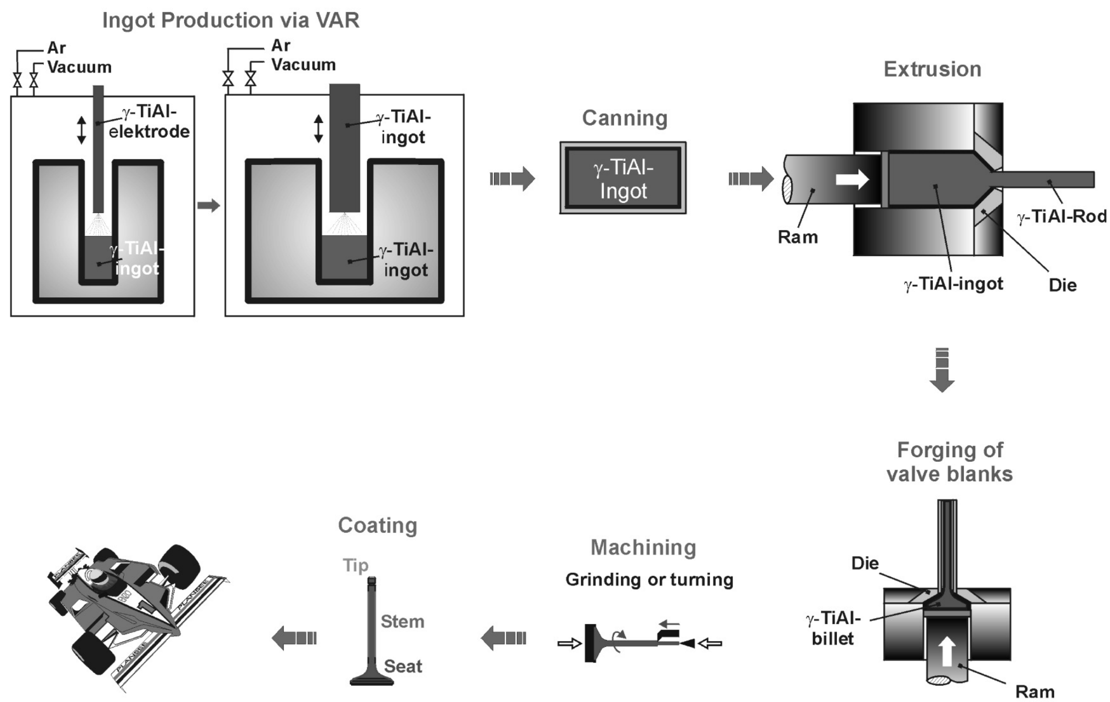

Figure 5: Schematic representation of the production steps of high-performance γ(TiAl) car valves at PLANSEE AG.

Especially high tensile and fatigue strength as well as a reproducible minimum ductility at medium temperatures are required for the valve stems. On the other hand, sufficient high temperature strength and thermal shock resistance has to be provided in the valve head and the seat area, respectively.

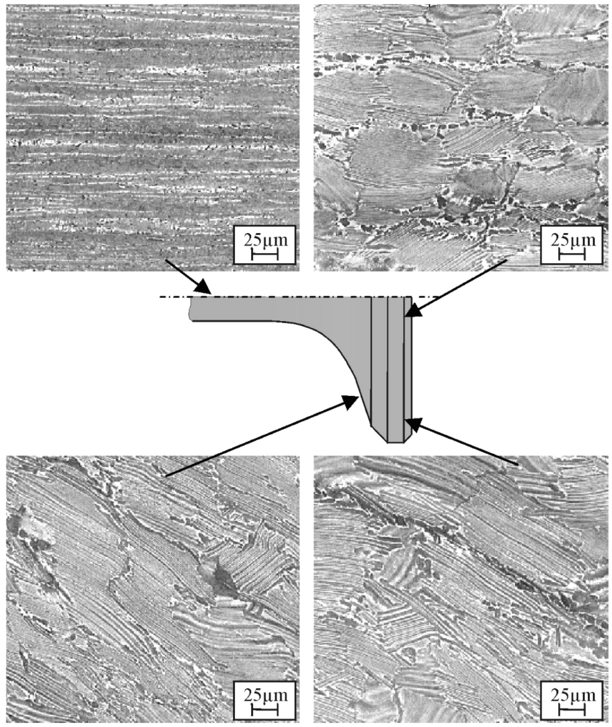

Figure 6: Controlled microstructures of γ(TiAl) high-performance car valves (PLANSEE AG)

From the above consideration of the microstructure-property relation this combination of properties is hardly to be met by a single morphology so that a fine grained microstructure in the stem and coarser (lamellar) microstructure in the valve head is desirable. It might also be deduced from the above that via wrought processing such microstructures can be readily obtained.

The processing route is a variant of a multi-step hot-working process. The main production steps are depicted in Fig. 5. In early 2002 PLANSEE AG transferred the commercial production of wrought processed high-performance γ(TiAl) valves to its affiliate Sinterstahl GmbH, Germany. The important feature of this processing route is the distinct hot-working parameters to which the valve head-section and the stem are subjected. The morphology of the valve head is determined by the primary extrusion of the γ(TiAl) ingot, where Z is chosen such that a coarse grained nearly-lamellar microstructure is resulting. The stem is subsequently forged at a much higher Z, thus promoting a fine grain size but leaving the valve head microstructure unchanged. The result is a single part with controlled and gradually changing microstructures as shown in Fig. 6 which are tailored to the described requirements in mechanical properties.

Tensile data at RT and 800˚C obtained from 150 independent production lots of Ti-46.5Al-4(Cr,Nb,Ta,B) valves are shown in Fig. 7 in terms of box and whisker plots. Specimens representing the valve head were prepared from primary extruded material, which was additionally heat-treated in order to simulate the intermediate re-heating during valve production.

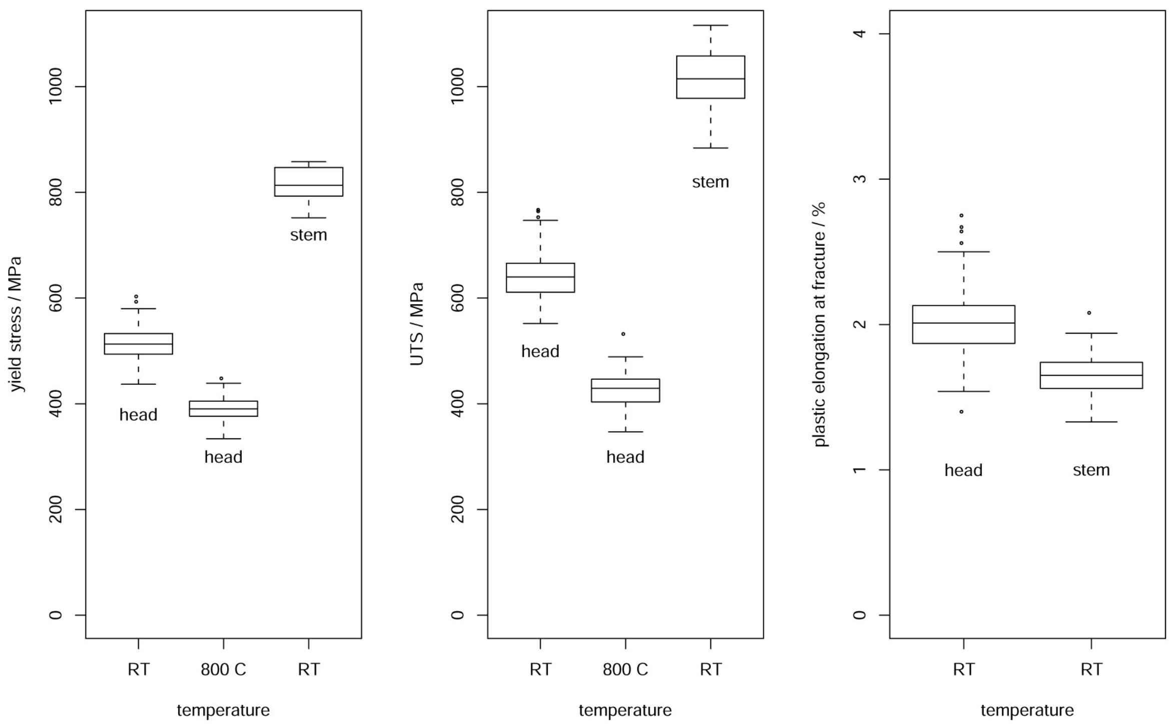

Figure 7: Tensile properties of Ti-46.5Al-4(Cr,Nb,Ta,B) valves at RT and 800°C. The box and whisker plots represent data from 150 industrial production lots.

Specimens representing the valve stem were machined directly from valve blanks. The following conclusions might be drawn from the statistical data shown in Fig. 7: (i) the distinct Z parameters employed for hot-working of valve head and stem lead to a drastic increase in the RT-tensile yield strength and UTS of the valve stem; (ii) at 800˚C the tensile yield strength and UTS of the head material are decreased by 100 MPa and 200 MPa, respectively when compared to the RT data. However, the yield strength of the valve head material is about 100 MPa above that of the as-cast material at 800˚C (see Fig. 2); (iii) the plastic elongation to fracture is consistently above 1 %, which underlines the reliability of the hot-worked γ(TiAl) valves. Since the year 2000 high performance γ(TiAl) valves are being routinely produced at PLANSEE AG, Austria, and Sinterstahl GmbH, Germany and successfully applied in high performance car and motorcycle engines.

Potential for high-Nb containing alloys in aerospace applications

The major pay-off areas for γ(TiAl) based alloys in advanced jet turbine engines might be summarized as follows [9, 15–17]: (a) Generally, the high specific stiffness is valuable whenever clearances are concerned, such as frames, seal supports, cases, and linings (e.g. consisting of honeycomb structures). The higher specific stiffness (E/ρ) also shifts acoustically excited vibrations towards higher frequencies, which is usually beneficial for structural components, e.g. turbine blades, disks and parts within the exhaust nozzle area. (b) The high burn resistance of γ(TiAl) based alloys can enable the substitution of heavy fire resistant designed Ni- and Ti based alloy components. (c) γ(TiAl) based alloys with good creep resistance in the temperature regime of 600˚C to 700˚C could substitute Ni based alloys possessing twice the density as γ(TiAl) alloys for certain applications.

However, conventional engineering γ(TiAl) based alloys often exhibit insufficient creep resistance [18]. Therefore the creep resistance of these alloys has to be optimized by means of controlled microstructures. It is well known that fully lamellar microstructures with a fine lamellae spacing show superior creep properties. However, the adjustment of such microstructures involves heat-treatments above the α -transus temperature and a precisely controlled cooling through the (α + γ) phase field [19]. From a practical point of view heat treatments of that kind are undesirable because the complexity of any production process is significantly increased. Moreover, lamellar microstructures have to be regarded as metastable and are prone to instability leading to degradation of the mechanical properties upon long term exposure at temperatures above 700˚C [20, 21].

So far, the improvement of the "high-temperature properties" of γ(TiAl) alloys seems to be an important prerequisite for aerospace applications amongst additional requirements, which might be summarized as damage tolerance from low to the maximum service temperatures [8, 16, 22–24].

In order to increase the high-temperature capabilities of γ(TiAl) based alloys, current alloy development programs are focused on high Nb-containing alloys [2]. As mentioned in the introduction, this class of alloys exhibits improved strength properties and oxidation resistance when compared with conventional γ(TiAl) based alloys [25, 26]. This might be rationalized by the tensile and creep data shown in Fig. 8. As can be seen from Fig. 8 a room temperature tensile yield strength of more than 1100 MPa was obtained from a hot-extruded Ti-45at%Al-(5-10)at%Nb-X(B,C) alloy which will be further referred to as γ-MET PX[2]. It should also be noted that the yield strength is well retained up to 700˚C and exceeds the Ti-base alloy as well as the more conventional engineering γ(TiAl) alloy. The data plotted for γ-MET PX after hot-extrusion to an ER of about 200:1 also indicate, that under certain conditions the yield strength of γ- MET PX can even exceed Ni-base alloys up to temperatures of about 800˚C.[2]

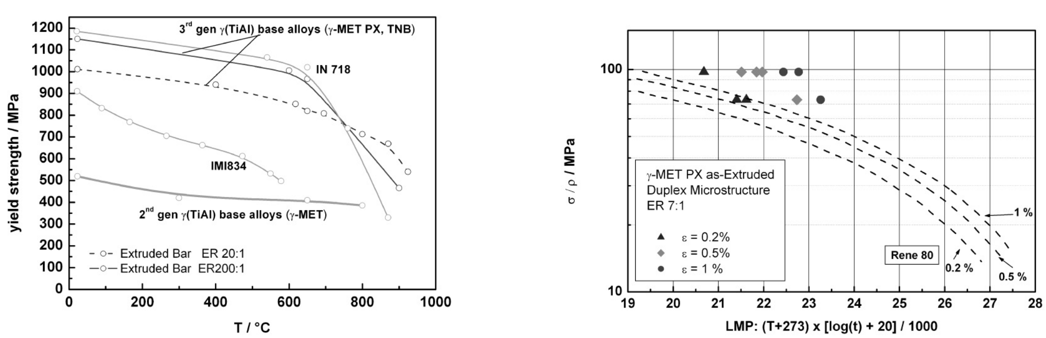

Figure 8: Left: Tensile yield-strength vs. temperature of hot-extruded high-Nb and conventional γ(TiAl) -based alloys. For comparison, tensile data of a near-(α) Ti- and a Ni-base alloy are also plotted. For γ(TiAl) , all tests at T $>$ RT were performed in vacuum at an engineering strain rate of $1 \cdot 10^{-4}\,\mathrm{s}^{-1}$. Right: Larson-Miller-Plot representing the creep-resistance of an extruded high Nb-containing alloy in comparison to Rene 80 in air

[2]The composition of this particular alloy is based on the so-called TNB alloy class developed by GKSS Research Centre, Germany

At RT relatively high plastic elongations at fracture of > 2% were reported. The relatively high fracture strain has been attributed to the high Nb content which decreases the stacking fault energy in γ(TiAl) alloys and thus mechanical twinning is facilitated and contributes to the RT ductility [2]. However, scatter in the strength and ductility of these alloys must not be neglected and under industrial processing conditions a careful analysis of the relationship between processing parameters, resulting microstructures and mechanical properties is mandatory.

Large Nb additions also reduce the diffusibility of Al in γ(TiAl) [27] which is beneficial for creep resistance [28]. Improvements in creep strength of conventional γ(TiAl) based alloys have also been achieved by carbon additions in the range of 0.2 - 0.4 at% [9, 29]. This might readily be seen from the Larson-Miller-Plot given in Fig. 8 where the creep resistance of hot-extruded γ- MET PX is compared to Rene80.

To this end, precipitation-hardened γ(TiAl) based alloys appear to be promising for high temperature service. However, the thermal stability of the Ti_3AlC precipitates against coarsening, for example under long-term creep conditions, has to be proved. Besides perovskite phases, silicide or Laves phases may be attractive to increase the creep strength of γ(TiAl) alloys [9, 21, 30]. In order to compete with super-alloys in aerospace applications within a wider temperature range, future γ(TiAl) based alloys must exhibit increased high temperature capabilities (creep, oxidation) along with an appreciable room temperature ductility and fracture toughness. From the current status of research it is believed that high Nb containing γ(TiAl) alloys with precipitation hardening are most promising candidates to fulfill these demands.

Within the last three years PLANSEE AG successfully extended its capabilities for wrought processing, machining and joining of conventional engineering γ(TiAl) base alloys to high Nb-containing γ(TiAl) alloys. In particular, large scale extrusion of cast ingots, hot-rolling of sheets from extruded ingots as well as from gas atomized powders and forging were successfully demonstrated on an industrial scale.

In the following we will demonstrate potential applications of wrought processed γ(TiAl) alloys in future aerospace applications. Although the sheet based components shown below were manufactured from a conventional γ(TiAl) alloy, we want to emphasize that most of these components are currently being demonstrated using the high Nb-containing γ-MET PX alloy.

Already in the mid-nineties, within the framework of a German Hypersonic Technology Program the feasibility of γ(TiAl) sheet components has been investigated. At the end of 1995, a panel structure was fabricated based on rolled γ(TiAl) sheet. The results of a structural stability test conducted on the γ(TiAl) panel are summarized in [31]. This early demonstration of feasibility of a γ(TiAl) sheet based component was followed by a number of programs aiming to explore applications for γ(TiAl) sheets.

Since the past decade sheet γ(TiAl) has been considered as a material candidate in current major aerospace programs which include:1) Reusable Launch Vehicles; 2) the NASA Future X Plane; 3) the Joint Strike Fighter; 4) the X-38 Crew Rescue Vehicle; 5) Military Hypersonic Vehicles 6) the Space Manoeuvrable Vehicle; and 7) supersonic transport type aircrafts [32]. For example, within the framework of the High Speed Research (HSR) program γ(TiAl) sheet material was selected as divergent flap material [33]. The flap construction consists of two super-alloy box beams supporting a series of subelements made of γ(TiAl) sheet as shown in Fig. 9.

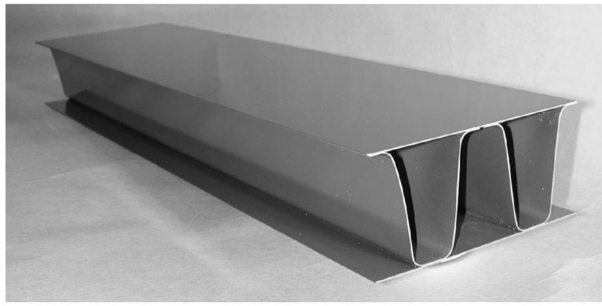

Figure 9: Sheet TiAl subelements of the divergent flap concept [33, 34]. The parts are made from Ti-46.5 at.%Al-4 at.%(Cr,Nb,Ta,B) sheet and the overall dimensions are approx. 66 mm (height) x 146 mm (width) x 610 mm (length). Sheet thickness: 0.025" (0.635 mm). Courtesy of NASA/NASA Glenn research Centre.

Another field of application for γ(TiAl) sheet based components are thermal-protection systems (TPS) for future reusable launch vehicles (RLV). Here, the aim is to provide light-weight, stiff, durable as well as easy to assemble components for the RLV´s outer skin in areas where during reentry the temperatures reach up to 850˚C [32]. A prototype honeycomb-TPS panel, fabricated entirely from γ(TiAl) sheet and foil is shown in Fig. 10. The face sheets (thickness 125 µm) were hot-rolled using a conventional hot-rolling mill as described in [35] and finished by mechanical grinding. The core foils (thickness 75µm) were manufactured from γ(TiAl) sheet via a combination of hot-rolling and advanced milling techniques. The joining techniques employed were laser-spot welding in order to assemble the honeycomb core and high-temperature brazing of core and face sheets. It should be mentioned, that the honeycomb sandwich panel also represents a demonstrator of future noise suppression components substituting Ni-base acoustic honeycombs used in aero-engines.

Furthermore, in advanced gas turbine engine concepts γ(TiAl) sheet material is under consideration for fabrication of stationary components such as nozzle components, acoustic honeycombs and static substructures [9, 15, 16, 30, 32, 36].

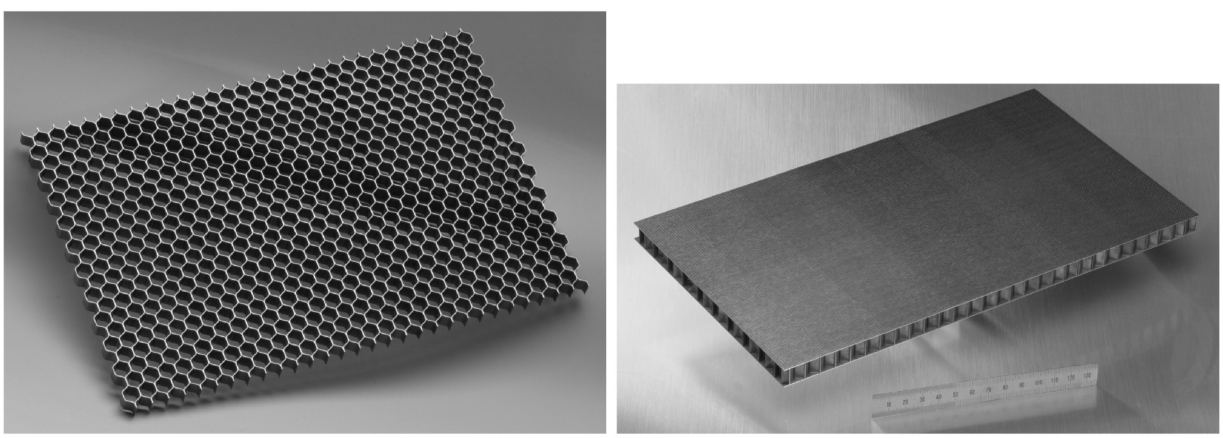

Figure 10: Stiff, light-weight γ(TiAl) honeycomb core and sandwich panel.

An example for the application of γ(TiAl) sheet based material in aero-engines is the exhaust nozzle cone shown in Fig. 11. This component was developed and fabricated as a technology demonstrator in a recent European framework program (DOLSIG) under the leadership of Rolls-Royce Derby (GB). It is important to note that manufacturing techniques established for Ti- and Ni-base alloys were adopted successfully for this component.

In particular, super-plastic- and hot-forming of the cone-cap and the wall segments, high temperature brazing of the γ(TiAl) cone-cap and wall segments as well as dissimilar joining of the γ(TiAl) body to a Ni-base support ring. As the weight-reduction potential is highest in the low-pressure turbine (LPT), γ(TiAl) seems to have a realistic chance to be introduced for the turbines rear-end rotor blades in the near future. Already in 1992 the first spin test of investment-cast γ(TiAl) blades in a rotor of a low-pressure turbine at 700˚C and 16000 rpm was performed by MTU Motoren- und Turbinen-Union München GmbH (Germany)[15]. In 1993, General Electric (USA) conducted their first engine test [16] with full set of 98 low-pressure turbine blades were installed in a CF6-80C2. The engine test included over 1000 simulated flight cycles as part of a normal endurance test.

Casting of γ(TiAl) LPT´s was envisaged as the production route of highest cost efficiency. However, the technological and economical breakthrough towards application of cast aeroengine components could not be achieved, but some information can be found in [37].

The manufacturing of γ(TiAl) LPT-blades by hot-isothermal forging was also investigated in the past [38] while conventional forging was expected to be impractical because of too high strain-rates and too cold tools [39, 40].

Recently PLANSEE AG started the investigation of hot-die forging of γ(TiAl) aiming to demonstrate the feasibility of the production of LPT-blades from high-Nb containing γ(TiAl) alloys. The fabrication process includes ingot metallurgy, thermo-mechanical processing of ingot material, conventional hot-forging as well as final machining. Encouraging results have been obtained so far as might be demonstrated by the prototype LPT-blade shown in Fig. 12.

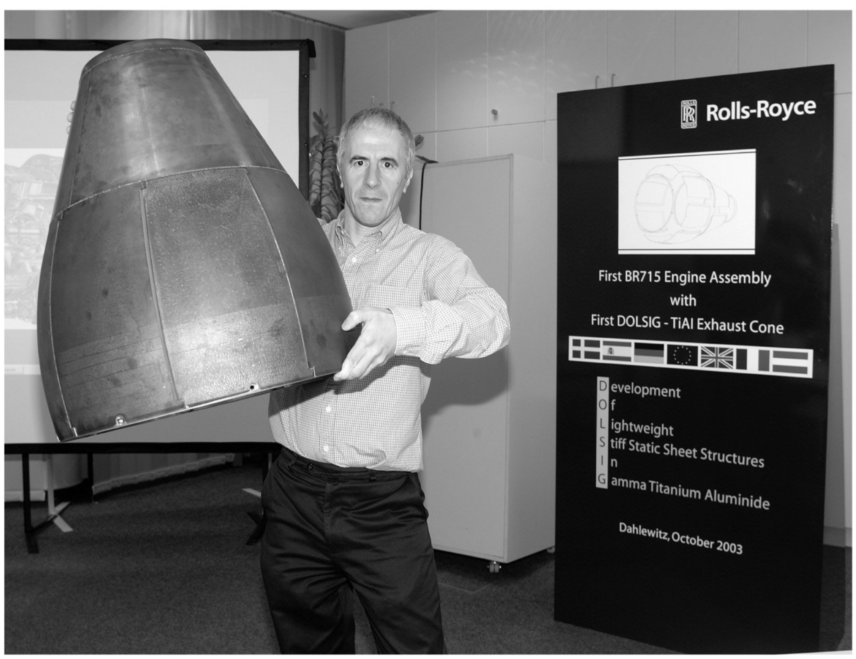

Figure 11: Sheet based γ(TiAl) exhaust nozzle cone developed and fabricated in the European framework program DOLSIG.

Concluding remarks

Intermetallic γ(TiAl) based alloys are considered as most important candidate materials for advanced applications in aerospace, automotive and related industries. Research and development on γ(TiAl) alloys have progressed significantly over the last 10 years. This research has led to a better understanding of the fundamental influence of alloy composition and microstructure on mechanical properties and processing behaviour.

Industry appears to be on the threshold of significant use of this new class of materials. In particular, all major aircraft and automotive engine manufacturers are advancing the qualification and introduction of γ(TiAl) components. γ(TiAl) based alloys can be processed using conventional metallurgical methods - a factor, which is necessary for these materials to be economically competitive with other state-of-the-art materials. The processing of γ(TiAl) alloys via ingot- and powder metallurgical routes on industrial scale has been successfully demonstrated. Also the feasibility of sheet forming by means of superplastic forming and other thermo-mechanical processing techniques has been successfully transferred from laboratory to industrial facilities.

For widespread application of γ(TiAl) alloys it must be shown, that semi-finished products as well as components with specified mechanical properties can be manufactured in large quantities at reasonable cost. From today´s point of view it is expected that cost issues will be solved as soon as γ(TiAl) based alloys are produced in industrial-relevant quantities.

Appropriate joining methods for the manufacturing of structural components under development must be made available in order to guarantee reliable joints exhibiting good mechanical properties especially at temperatures below the brittle-to-ductile transition temperature.

Engineering γ(TiAl) based alloys should exhibit a more improved balance between room temperature ductility, fracture toughness, high-temperature strength, creep and oxidation resistance. The currently established high Nb-containing γ(TiAl) based alloys are seen very promising to provide these improved properties.

Figure 12: Prototype LPT-blade hot-forged and precision machined from a high Nb-containing γ(TiAl) alloy.

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