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Novel Processing Techniques for γ-TiAl Alloys

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Abstract The processing of large or near-net shaped parts from γ-TiAl alloys is extremely challenging. The forging of large-scale TiAl-parts is hampered by the unavailability of high-quality, chemical homogenous pre-material. However, using an innovative combination of forging and joining large discs of TiAl with excellent mechanical properties can be produced. Metal Injection Moulding (MIM) facilitates the production of near-net shaped parts of high-strength TiAl-alloys with strength comparable to the cast condition.

Introduction

Due to their higher specific strength compared to nickel-base superalloys γ-TiAl alloys have the potential to supplement them in structural applications at temperatures as high as 800 °C. Therefore γ-TiAl alloys are an attractive material for turbine blades in aero engines or turbocharger wheels in automotive engines. But while the low density of about 4 g/cm³ is a property of all technical γ-TiAl alloys only modern high-strength alloys with low Al- and high Nb-content (TNB-alloys) are superior to nickel-base superalloys with respect to specific strength [1]. However, microstructural and chemical homogeneity of these high-strength alloys must be strictly controlled during processing to avoid embrittlement and preserve the good mechanical properties. This poses special problems if large parts should be produced or if near-net shape processing is desired. An aero-engine turbine disc is a prime example for a large part where security and damage tolerance is of special concern. Accordingly the ductility should be as high as possible. This is the reason why such parts are usually forged. Unfortunately for forging itself pre-material with good chemical homogeneity is necessary. This is not achieved by conventional casting of large TiAl-ingots. Utilizing powder metallurgy compacts with excellent chemical and structural homogeneity can be produced. However, for TiAl alloys the technique is demanding due to the high susceptibility of TiAl-alloys to pick up gaseous interstitial elements [2]. Similar problems hamper the production of near-net shaped parts from high strength TiAl-alloys. The cast route produces material with inferior chemical homogeneity and low ductility while near-net shape forging of parts is very ambitious as the dies have to endure high stresses as well as high temperatures [3]. The two processing methods presented here address the problems mentioned above and can produce large forged parts or near-net shape parts from the high strength γ-TiAl alloy TNB-V5 (Ti-45Al-5Nb-0.2C-0.2B, all in atomic percent) with excellent microstructure homogeneity.

Large scale TiAl parts

The problems with large ingots as pre-material for the forging of pancakes from high-strength TiAl-alloys are two-fold. Firstly, compared to smaller ingots it is more difficult to produce large cast ingots with good chemical homogeneity. Secondly, it is difficult, if not impossible to monitor large ingots for defects like pores or inclusions with non-destructive evaluation methods. To overcome these problems a novel technique was developed which combines the joining of smaller parts to a large pre-shape with a subsequent forging process to produce a pancake.

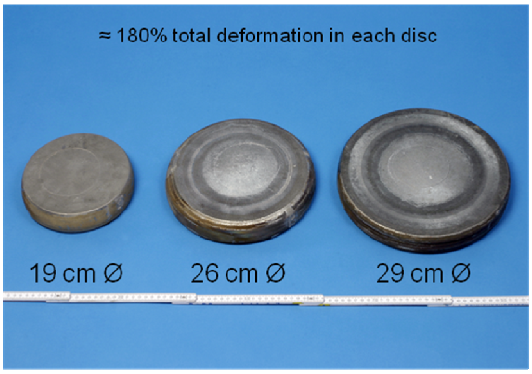

Fig. 1: Three examples of large scale TiAl-pancakes of alloy TNB-V5 produced by the novel forging process

This pancake is a first step in the process of for example producing a turbine disc. In a test run three pancakes were successfully forged until now. These pancakes with different diameters are shown in Fig. 1. The process has some inherent advantages. In addition to the fact that it is easier to produce smaller parts with good chemical homogeneity (either directly by casting or by additional processing steps) it is also possible to test these parts by current day non-destructive evaluation methods. Accordingly, parts which are outside the specifications with respect to composition or contain defects can be rejected. If some of these smaller parts do not fulfill the specifications also the financial damage is reduced as only these have to be rejected and not an expensive large casting. Joining was done by diffusion bonding which is able to produce high-quality joints in TiAl-alloys [4]. While in this showcase study the largest pancake had a diameter of 29 cm it should be mentioned that the process is easy to upscale. In the pancakes processed during this work no signs of the former joint areas were visible after the forging. After forging two different heat treatments were performed: a stress annealing treatment of 4h@1030 °C with subsequent furnace cooling (called SF (=stress free) from now on) and stress annealing followed by a near $\alpha_{\mathrm{Transus}}$ heat treatment (30min.@1280 °C), subsequent air cooling and a final annealing of 6h@800 °C (called SF+α_T from now on). While after the former heat treatment slight microstructural inhomogeneities could be observed a homogenous microstructure was achieved with the latter heat treatment as shown in Fig. 2 a) and b).

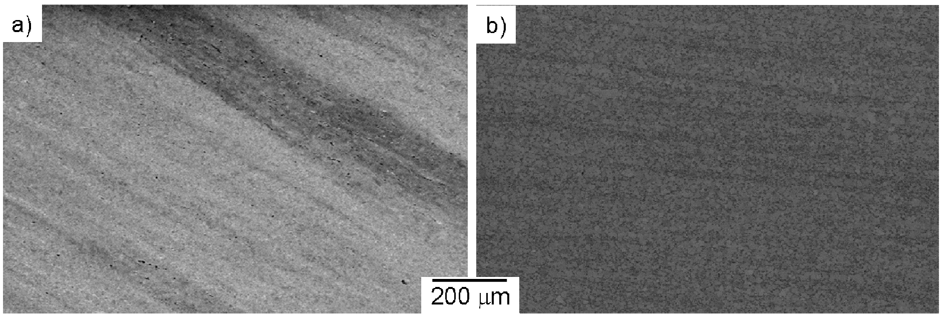

Fig. 2: Microstructure of large part forging after SF heat treatment (a) and after SF+α_T heat treatment (b)

Tensile tests for both heat treatment conditions were performed at room temperature. Two types of specimens were machined with their specimen axis perpendicular to the forging direction: one parallel to the radius (termed *parallel to material flow*) and the other parallel to the circumference of the pancake (termed *perpendicular to material flow*), respectively. Additionally specimens with their axes parallel to the forging direction were machined. One set was taken from positions near the center of the pancake (termed *through thickness central region*) and the second from positions near the rim of the pancake (termed *through thickness outer rim*).

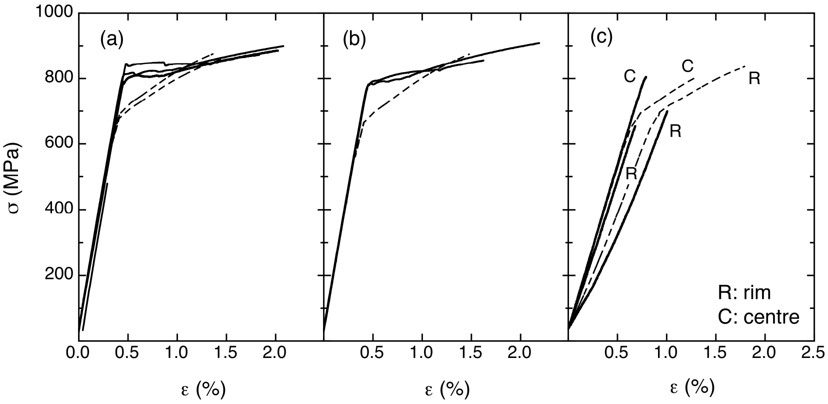

Fig. 3: Tensile test curves at room temperature of specimens from different positions of the pancake: (a) Parallel and (b) perpendicular to material flow, (c) through thickness direction central region and outer rim; solid curves for specimens with SF treatment and dashed curves for specimens with SF+α_T treatment

The results of the tensile tests are shown in Fig. 3. The *parallel/perpendicular to material flow* specimens showed high strength and good ductility in the SF state (solid curves in Fig. 3 a and b). while no ductility is found for the *through thickness* specimens (Fig. 3 c). In the SF+α_T state (dashed curves in Fig. 3) the strength with respect to the yield point is slightly reduced but significant ductility is achieved for all specimen orientations including the *through thickness* specimens. It is also interesting to note that the yield stress seems relatively insensitive to specimen orientation.

Metal injection moulding of TiAl

The problems associated with chemical homogeneity of cast ingots can be avoided if a powder metallurgical processing route is chosen. This was tested to produce small to medium scale near-net shape parts by metal injection moulding (MIM). MIM is well established for stainless steels [5]. Here MIM was applied to produce parts from the same high-strength TiAl-alloy TNB-V5 which was also used to investigate the forging of large parts described above. As a test part the standardized MIM-tensile test specimen was used. MIM consists of mixing of metallic powder with an organic binder, injection moulding of this material and subsequent de-binding and sintering to a compact part. The MIM-process is described in more detail elsewhere [6]. This work will concentrate on the properties of the produced parts and some special peculiarities concerning the MIM-processing of TiAl-alloys.

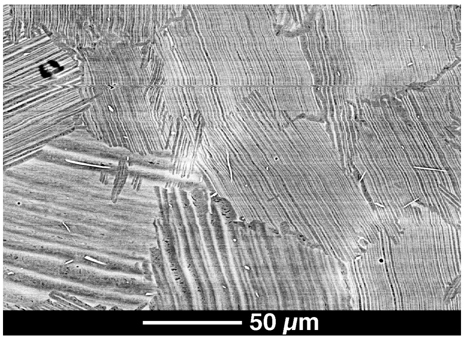

Fig. 4: Microstructure of TNB-V5 produced by MIM

One of the major concerns here is to preserve the low oxygen level and exact chemical composition of the powder in the MIM-processed part. To densify the specimens a rather high sintering temperature of 1500 °C was used which resulted in a porosity of less than 0.5 %. This compares well with cast material. Unfortunately at such high temperatures aluminum depletion at the surface can occur. This can be reduced to 0.4 at.% by generating an aluminum-rich atmosphere during sintering. Another problem is oxygen pick-up during the MIM-process and subsequent sintering. Oxygen pick-up can be reduced by good vacuum conditions during sintering but this again is detrimental with respect to aluminum depletion. Overall it is necessary to minimize the contact with air or oxygen as far as possible during all processing steps. Using clean processing techniques, oxygen contents of 1150 μg/g can be achieved in the sintered part. While the batch of powder used here was not characterized in this respect it is known from previous works that the powders have oxygen contents of around 500 μg/g [2]. The two-fold increase of the oxygen content during MIM-processing is significant. Nevertheless the final value is probably low enough to avoid detrimental effects on mechanical properties.

After sintering, the material was investigated by SEM and was found to exhibit a fine-grained fully lamellar microstructure with an average colony size of 60 μm (Fig. 4). The only phases present are the γ- and α_2-phase but no residual β-phase was observed. To achieve this microstructure the specimens were fast cooled from the sintering temperature by allowing a limited airflow to the furnace after shutdown.

Tensile tests were performed at room temperature and 700 °C. From the results presented in Table 1 it is obvious that especially at room temperature the results for the MIM-specimens are comparable with cast material exhibiting slightly lower strength but slightly better ductility. At 700 °C the cast material is superior. But it is important to mention that the MIM-specimens were tested without any further surface treatment after MIM-processing while the specimens from cast material where machined from bulk material and the surfaces subsequently ground and polished. So the results for the MIM-specimen give a baseline for the mechanical properties of TiAl-parts produced by this process. On the contrary the results for the cast specimens are probably not reached by an actual cast part with an as-cast surface. This partly explains the difference in performance between the MIM and cast specimens.

Table 1: Mechanical properties of TNB-V5 processed by MIM and by casting – tensile test results

	MIM		**Cast**	
Temperature	**UTS [MPa]**	**ε_{pl} [%]**	**UTS [MPa]**	**ε_{pl} [%]**
room temp.	630	0.2	745	0.1
700 °C	650	1.0	720	1.4

Summary

To sum up it is difficult to produce large parts as well as near-net shaped parts from actual high-strength TiAl-alloys. However, it was demonstrated that both is feasible by employing innovative processing techniques. By a combined joining and forging process large pancakes could be made from TNB-V5 which showed excellent isotropic mechanical properties over the whole specimen if properly heat treated. Near-net shape processing of parts from TNB-V5 by MIM was demonstrated. On MIM-processed parts mechanical properties comparable to cast material could be achieved without any further surface preparation or subsequent HIP treatment. The use of high-quality powder and clean processing conditions are however necessary.

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