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# Production issues in the manufacturing of TiAl turbine blades by investment casting

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## Abstract

γ -TiAl based intermetallic alloys have attracted broad attention as a potential candidate for high-temperature structural applications.

A careful selection of their composition and microstructure allows to obtain an interesting combination of oxidation resistance, creep resistance and high temperature strength for specific applications.

Over the years, several complex manufacturing methods have been used for producing TiAl parts. In this work TiAl blades have been produced by means of investment casting. The work analyses the different production steps: design of a blade prototype, production of an ABS model by additive manufacturing that is used to make the wax model, preparation of the ceramic mold and centrifugal casting of the component. All the production issues related to TiAl alloy investment casting have been analyzed with the aim of setting up a tailored process able to produce sound components.

*Keywords:* Intermetallics; investment casting; TiAl alloys; TiAl manufacturing.

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## 1. Introduction

Titanium Aluminides have been a major topic of research for more than fifty years and still remain a hot research topic (Clemens et al. (2011), Thomas et a. (2011), Sheng et al. (2000), Kim et al. (2008), Kim (1995)). The first phase of the research focused on the evaluation of the various alloy compositions and on their effect on mechanical properties such as toughness and creep resistance. To increase high temperature properties as well as ductility and

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toughness at room temperature several alloying elements, besides Ti and Al, are usually added to the alloy (Brotzu et al. (2014)). The first generation of TiAl alloys was studied with the aim of obtaining acceptable strength and corrosion resistance up to 750 °C and acceptable ductility at room temperature. The research around the second generation of TiAl initiated around the 1980's in order to extend the application of this alloy beyond 750°C. This alloy was produced through rapid solidification and wrought processing with fine duplex microstructure and exhibited good ductility, strength and oxidation resistance. Those properties boosted the research toward its industrial applications with several attempts to improve TiAl casting process (Aguilar et al. (2011). By the start of the last decade, the research on the third generation of TiAl identified gamma titanium aluminides with a lamellar structure as the ones characterized by a set of properties that makes them of great engineering interest. This was possible due to the addition of high Nb percentage and B that allows to refine the alloy microstructure.

Driven by this discovery and along with its excellent properties such as good high temperature strength, stiffness and oxidation resistance at high temperatures with much lower density than most of superalloys, gamma TiAl has demonstrated to be a technologically sound material which can replace the nickel-based superalloy for selected engine components such as low-pressure turbine blades. Perhaps in recent years General Electric, started using gamma TiAl for producing low pressure turbine blades for its GE9X, which is supposed to take its first commercial flight in early 2020 after a lot of field trials from 2016. Rolls-Royce has also announced that they intend to use TiAl LPT blades for future medium thrust engines (Mitra et al. (2017)).

Titanium aluminides have seen similar trends in terms of manufacturing techniques as well. Techniques such as investment casting, ingot metallurgy (IM), powder metallurgy and additive manufacturing techniques have been used to produce TiAl components (Kothari et al. (2012)). One of the main drawbacks of TiAl compared to Nickel-based superalloy is its production cost which requires a huge capital investment in processing equipment. In fact, although investment casting, ingot metallurgy and powder metallurgy techniques have been used for the production of TiAl components having good mechanical properties, this has been possible only after applying post processing steps, like hot-isostatic pressing, complex heat treatments and hot working. These steps further increased production costs of these alloys. Considering that large scale production of TiAl parts would require low costs, this research analyses the various issues related to the manufacturing of Titanium Aluminide turbine blades by means of investment casting. Over the last years this research group tested many TiAl alloys with different compositions for studying their mechanical properties such as fracture toughness at room temperature and mechanical strength at high temperatures (Brotzu et al. (2014), Brotzu et al. (2018), Brotzu et al. (2012)) and oxidation resistance at high temperatures (Pilone et al. (2012), Pilone et al. (2013)). Moreover, the effect of manufacturing process parameters on the fracture behavior of these alloys was also studied (Brotzu et al. (2014) and, based on the obtained results, a proper composition and a manufacturing technique were selected for the process.

This work analyses the various steps starting from the design of the component in CAD to the final product. It starts from the design of the blade prototype in CAD, followed by the model formation by ABS material, which is used to make the wax model. The wax model is then used to prepare the ceramic mold for investment casting.

## 2. Experimental

The blades analysed in this work were produced by induction melting from pure Ti, Al, Cr and Nb. The mold was prepared by using a refractory material using as a model designed blade. The molten metal was cast directly into the rotating mold. In order to perform metallographic examinations specimens were ground to a mirror-like surface using SiC papers up to 1200 followed by 0.3 μm alumina and then etched in Keller's reagent. Metallographic structure and fracture surfaces were inspected by scanning electron microscope (SEM) and microanalyses were carried out by energy dispersion spectroscopy (EDS).

## 3. Blade manufacturing

Aim of this work was mainly studying the feasibility of blade production by means of the centrifugal casting technique: the main focus was on the metallurgical aspects and criticalities of the production process and not on the design of the blade. In order to obtain realistic blades, we started from a geometric model of a turbine blade upon which dimensional optimization was carried out.

Since TiAl intermetallic alloys above 900°C undergo a performance decay, due to their poor oxidation resistance, it was decided to consider the first stage of a gas turbine with an inlet temperature around 850°C. The parameters have been chosen trying to stay in line with those normally used for this type of machine. From these data it was possible to construct the velocity triangles in correspondence of the hub, the tip, and the average height of the blade.

After constructing the velocity triangles, the profile of the rotor blade in correspondence of the three blade sections was developed. The centrifugal force acting on the blade is high. This imposes strict requirements on the fixing system of the blade. The roots most commonly used are the fir-tree root with three or four lobes and the double dovetail root.

In the present work the root resistance is checked. Four-lobed fir-tree geometry was chosen. Starting from the determined data a CAD software allowed the construction of the blade profiles. From the knowledge of the three sections (Tip, Hub, Medium) the software allowed to draw the blade model.

The geometric model of the blade included the riser because it is used during the process, as a "master pattern" in the realization of the molds used in the production process by means of investment casting. To verify that there would be directional solidification, thermal modules of the different blade areas should be growing towards the riser, which will therefore be the last element to solidify.

The blade model, complete with root and riser, is shown in figure 1 together with the values of the calculated modules.

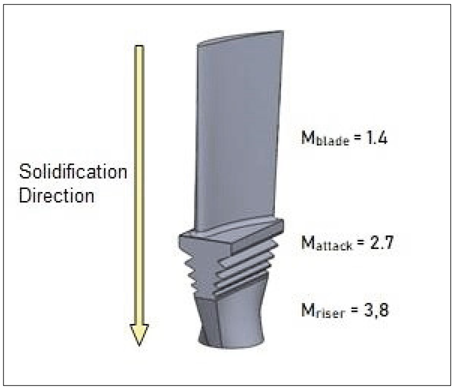

Figure 1. Blade model designed with CAD and related thermal modules which allow for directional solidification.

A "makerbot" 3D model "replicator 2X" based on fused deposition modeling (briefly FDM) was used to create the blade prototype. ABS was chosen as material for the prototype construction, and the "high definition" option was also selected, i.e. the material was deposited with 100-micron thick layers, thus obtaining a good surface finish. In figure 2 it is possible to observe two different moments during the production of the ABS blades.

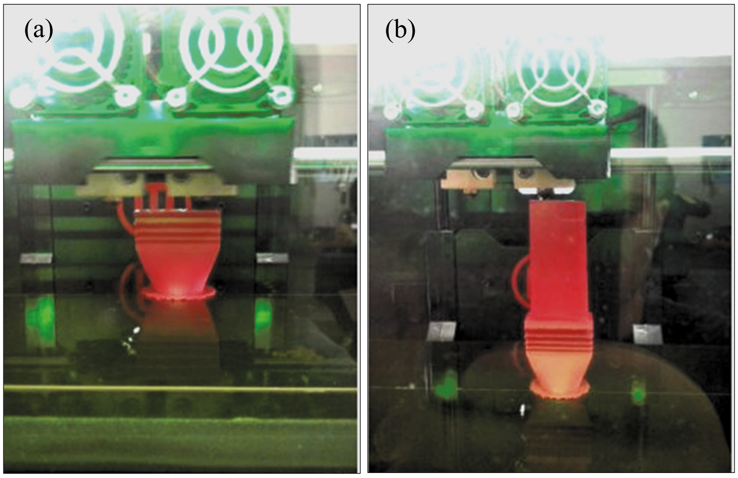

Figure 2. Picture showing the machine during the creation of the root (a) and in the final stages of the blade production (b).

To eliminate processing residues and improve the surface finish, the blade was polished with a cloth soaked in acetone with the aim of reducing surface roughness without damaging the surface of the part.

The prototype of the blade, made of ABS, is shown in figure 3. This has been used as a "model" for the creation of the mold used to manufacture the TiAl alloy component.

Figure 3. Prototype of the printed ABS blade.

Additional prototypes of turbine blades having smaller dimensions have also been produced starting from an Inconel 718 (nickel-chromium based austenitic superalloy) blade (figure 4).

Figure 4. Inconel 718 blade.

By using the ABS blade prototype, made by 3D printing, and the Inconel blade, silicone rubber molds (negative volume model) were prepared to produce the wax model.

The wax models of the blades obtained are shown in figure 5.

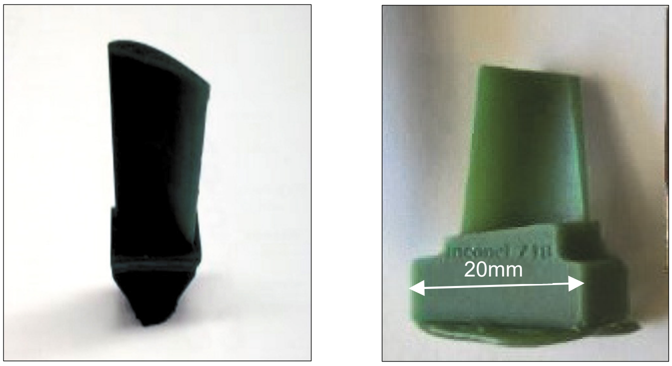

Figure 5. Wax models of two different blades.

A refractory material resistant to high temperatures, in particular to thermal shocks, and permeable to gases evolved by the molten metal was used to produce the molds. After drying, the molds were subjected to heating to eliminate the residual moisture and melt the wax.

Finally, the mold was baked in a furnace according to the following thermal cycle:

- Heating up to 250 °C and residence at this temperature for 30 min.
- Heating up to 900 °C and residence at this temperature for 30 min.
- Oven cooling up to 450 °C.

The blades were then cast using the centrifugal induction furnace in a controlled atmosphere. The casting was then subjected to slow cooling.

Once the mold was cooled (figure 6), the refractory material around the blades was mechanically removed. The riser was removed by using a diamond blade cutter.

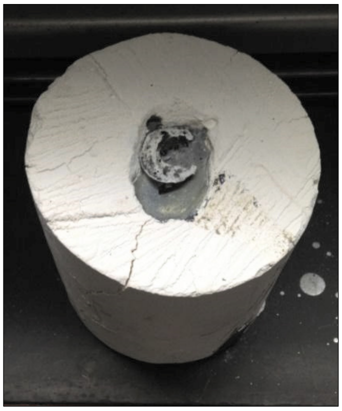

Figure 6. Mould along with the casting.

One of the problems encountered is due to the strong reactivity of the liquid metal that goes in contact with the mold at high speed at temperatures above 1700 °C. For solving this problem an attempt was done to protect the mold cavity surface by using, in the mold production stage, a coating applied on the surface of the wax model. Some casting tests have been done by using either boron nitride or alumina.

The use of boron nitride turned out to be rather deleterious because it promoted the formation of a reaction layer on the blade that was very difficult to remove. Alumina gave slightly better results. Figure 7 shows some blade just after the extraction from the mold: a layer of refractory material adherent to the surface is well evident. Surface protrusions, visible in the figure, are due to the reaction of the alloy with the mold refractory material.

In order to eliminate the residual refractory material from the blade surface an ultrasonic cleaning process was carried out. A following grinding operation allowed the removal of coarse protrusions.

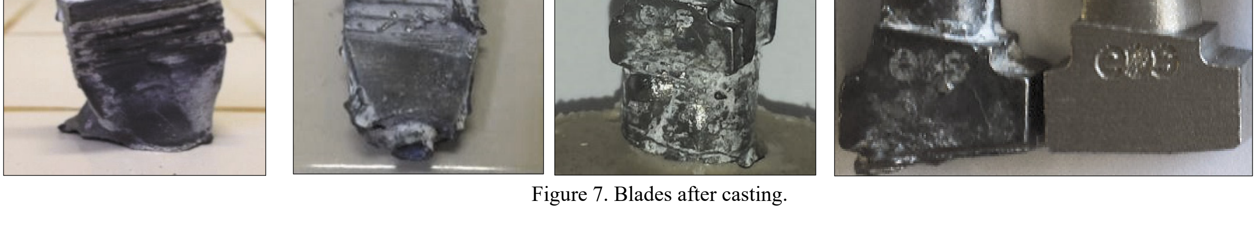

Figure 7. Blades after casting.

In figure 8 the final blade appearance is visible. Blade production tests gave satisfactory results and they were very useful to highlight some critical issues and possible corrective actions and remedies for improving the blade quality.

Figure 8. Blade after preliminary surface polishing.

As far as the surface finish is concerned, further studies are necessary to find refractory ceramics more resistant to the aggressiveness of the molten metal. In any case, the liquid metal that reacts with the ceramic creates protrusions that can be removed by subsequent machining. Formation of cavities, which could not be eliminated, would have been more critical. Barrel finishing tests carried out on a rough blade, not subjected to a preventive surface finish operation, showed the formation of a smooth and shiny work-hardened surface as shown in figure 9.

Figure 9. Barrel Finished Blade.

Some blades showed criticalities in the hub area under impulsive loads and fractured (Figure 10). This was due to the design of the blade and to the brittleness of the alloy.

In that area in which there are greater stresses and stress intensification due to the blade profile, the thickness must be increased to obtain a lower curvature at the connection between airfoil and platform. The produced blades do not show relevant quantities of micro shrinkage cavities or macroscopic internal defects. Figure 11 shows the section of the blade root without any defect.

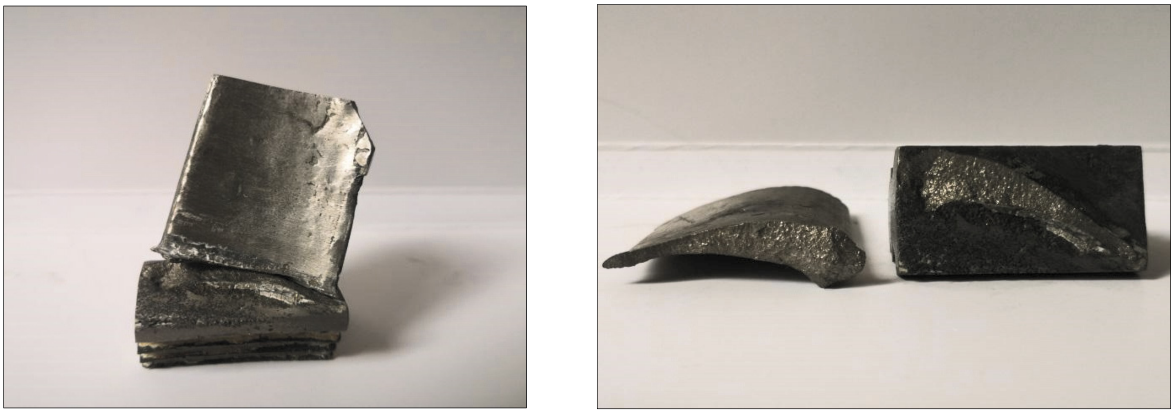

Figure 10. Broken hub of the blades.

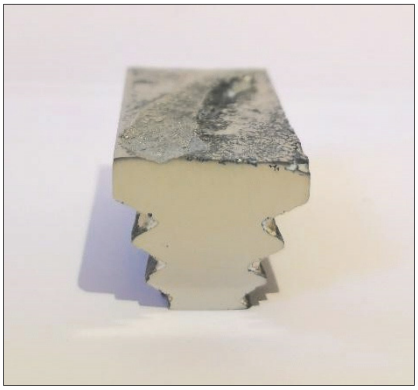

Figure 11. Cross Section of the root.

## 4. Microscopic characterization of the alloy

Metallographic analyses of the blades show (figure 12) that the microstructure of the alloy is characterized by fine lamellar colonies of $\alpha_2/\gamma$ and $\gamma$ grains.

EDS analyses carried out on the two different types of blades show the composition reported in Table1. As it can be seen, the compositions are slightly different due to the difficulties in avoiding aluminum evaporation during casting.

Table 1. EDS analyses of the alloys.

| | Ti (%at.) | Al (%at.) | Cr (%at.) | Nb (%at.) |
|---|---|---|---|---|
| Alloy 1 (Blade with fir-tree root) | 54.0 | 40.4 | 3.1 | 2.5 |
| Alloy 2 (blade without fir-tree root) | 48.6 | 45.4 | 2.9 | 3.1 |

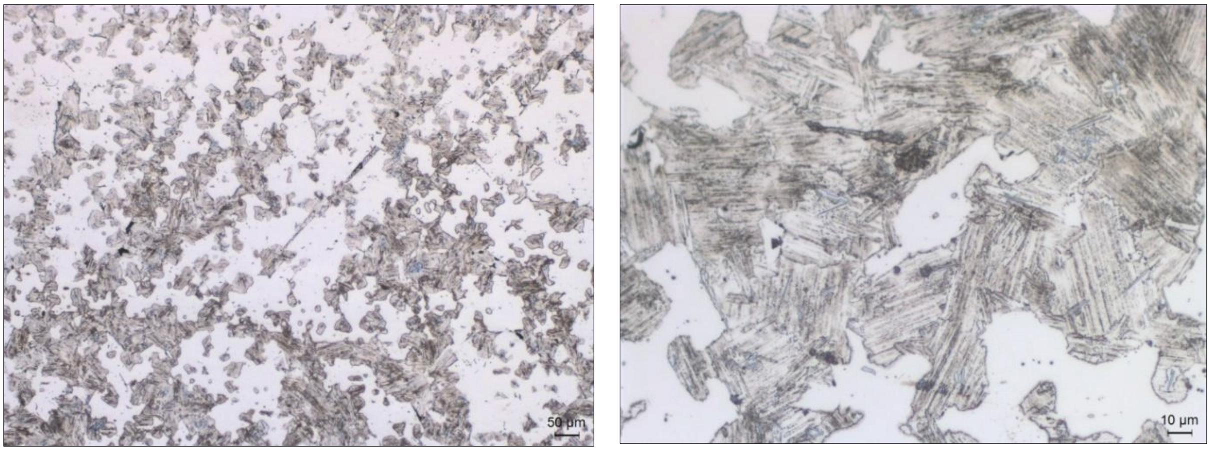

Figure 12. Optical micrographs showing lamellar colonies ($\alpha_2$+$\gamma$) and $\gamma$ grains.

## 5. Characterization of fracture surfaces

SEM micrographs reported in figure 13(a). show a typical cleavage fracture. Figures 13(b) and 13(c) highlight the presence of areas in which fracture propagates through the $\gamma$ phase and areas in which a translamellar fracture occurs. SEM micrographs shown in figure 14 show the area from where the fracture initiates. In this area some microshrinkage defects can be seen: they could contribute to stress intensification and crack initiation. In the inner part of the blade microshrinkage cavities are also visible, but they seem to be less critical for fracture propagation.

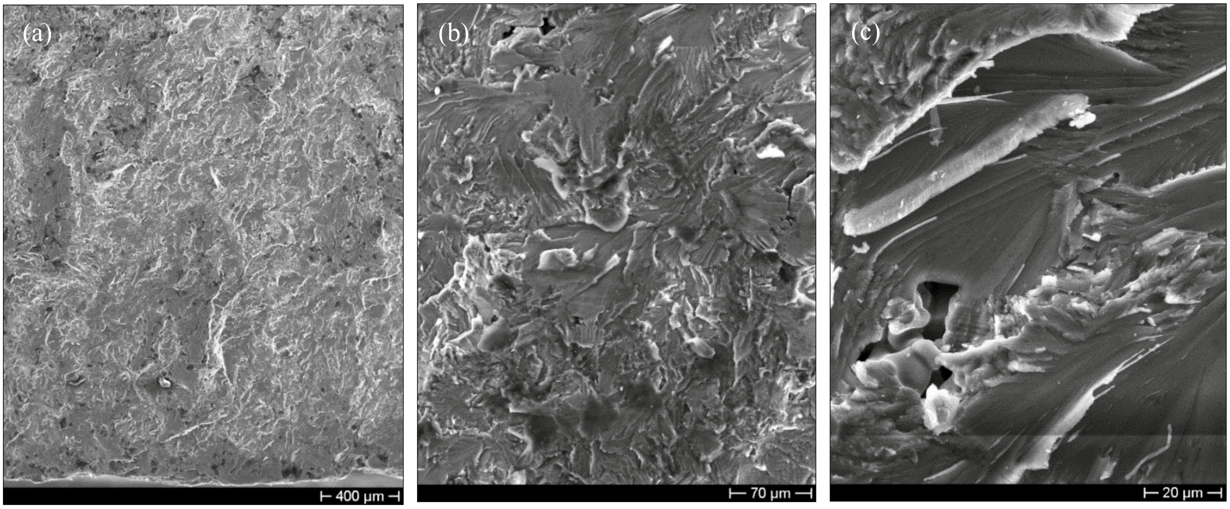

Figure 13. SEM micrographs showing at low magnification cleavage fracture (a) and at higher magnifications transgranular and translamellar fracture (b and c).

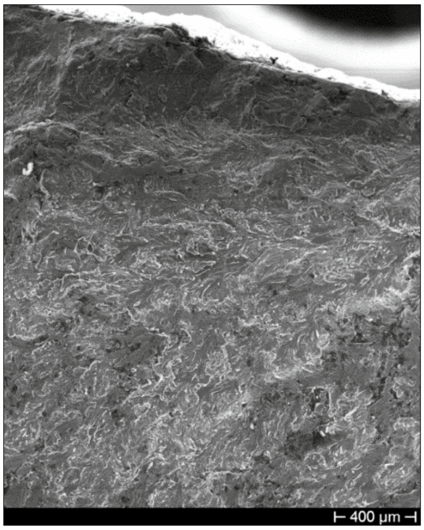

Figure 14. SEM micrograph showing crack initiation at the edge and dispersed microshrinkage cavities.

## 6. **Conclusions**

Tests carried out in this work highlighted that the selection of process parameters in the blade manufacturing stage is very critical. A careful choice of casting temperatures and cooling rates allowed to obtain castings that do not show macroscopic defects throughout the all section of the component. Moreover, the selection of the mold material appears to be of paramount importance to obtain a good surface finish. The blades produced by using the selected mold material are still characterized by some protrusions on the surface that should be removed by means of post processing steps. Further improvements could include a structural change in the radius of the edges at the contact points between airfoil and root in order to reduce stress concentration.

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