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Effect of dispersed particles on TiAl alloys fracture behavior

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Abstract

γTiAl based alloys are very attractive for structural applications at high temperatures. The addition to the selected alloy of dispersed alumina particles increases the yield strength and the elastic modulus of γTiAl alloys but affects their fracture behavior by favoring the propagation of brittle fracture. The analysis of the fracture surface revealed that the addition to oxide particle, during component production by means of investment casting, favors brittle fracture propagation by intensifying stresses and by increasing the quantity of shrinkage cavities inside the casting.

Keywords: Brittle fracture;Dispersion hardening; TiAl based alloys.

1. Introduction

The study of γTiAl based alloy properties became a very attractive topic of research (Kim 1995; Appel et al. 2000; Clemens and Smarsly 2011). When evaluated considering their specific density corrected cost, TiAl alloys have a unique set of mechanical properties especially at elevated temperature where they can be even superior to some superalloys. Owing to its high temperature specific strength and modulus, good oxidation resistance and corrosion resistance combined with low density, TiAl is a viable material for a lot of applications. As a result of these properties these alloys find their use in wide range of applications such as low-pressure turbine blades (Bewlay et al. 2016; Clemens and Mayer 2016), turbocharger wheels (Tetsui 2007; Noda 1998) and automotive engine valves (Liu et al. 2005; Keller et al. 1997). Currently these alloys have become the most interesting candidates to replace

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Ni-based superalloys in gas turbine engines because they allow to reduce the weight of the engines by 30-40% and to increase their efficiency and performance.

Because of their low fracture toughness at room temperature, their proneness to form shrinkage cavities during solidification and their high reactivity in the molten state (Brotzu et al. 2020), that make very difficult their production by casting (Brotzu, Felli, and Pilone 2014), the use of TiAl based alloys is very limited. During the development of the first generation of TiAl, the main aim was to obtain acceptable strength up to 750℃ and acceptable ductility at room temperature. Over the last decades many efforts have been done to increase the service temperature of these alloys and to refine the microstructure to increase their mechanical properties (Guo et al. 2001). To improve the properties of γTiAl alloys, β-stabilizing elements, such as Nb, Mo, Cr, W, have been added into the alloys: the interest for these alloys is justified by the fact that β phase has a better processability than α phase at elevated temperature (Li et al. 2020). β-stabilized TNM alloys (TNM = TiAl-Nb-Mo) have been studied for many years because they exhibit low density associated with high specific elastic modulus, high specific yield strength at high temperature and good oxidation resistance up to 800 °C (Qiu et al. 2012; Schwaighofer et al. 2014). In current TiAl technology, as-cast and hot-isostatically pressed material is subjected to thermomechanical processing to obtain particular microstructures by means of forging and heat treatments. Performing these processes requires a careful selection of temperatures and stain rates (Appel and Oehring 2003).

Another interesting approach is increasing strength and stiffness of low density TiAl alloys by means of dispersion hardening. Among different reinforcing particles Al_2O_3 seems to be very attractive because of its thermal and environmental stability. The few data available in literature concern alloys obtained by means of powder metallurgy or additive manufacturing (Ai 2008; Rittinghaus and Wilms 2019), which are quite expensive processes.

The authors of this paper studied the mechanical properties of dispersion hardened TiAl alloys produced by centrifugal casting that is a viable and cheaper solution. The results highlighted that the addition of alumina particles allows to increase the elastic modulus and the yield strength of the alloy (Brotzu et al. 2018; Pilone et al. 2020), but it decreases its fracture toughness at ambient temperature. Aim of this work is to study how the addition of Al_2O_3 particles affects the fracture behavior of the alloy.

2. Experimental

In this research TiAl based specimens and blades were manufactured by centrifugal induction melting from pure Ti, Al, Cr and Nb. In order to study the effect of dispersion hardening, 3 vol% of nanometric alumina (Al_2O_3) was added to half of the specimens. The selected alloy compositions are shown in Table 1. The process to make the blades started with preparing a dimensionally optimized geometric model of the blade. Since TiAl alloys have poor oxidation resistance above 900℃, the blades were produced for gas turbine stages where the temperature is lower.

Table 1. Composition of the studied alloys.

	Al (%at.)	Ti (%at.)	Cr (%at.)	Nb (%at.)	Al_2O_3 (%vol.)
Alloy without dispersed particles	46	48.3	3.2	2.5	0.0
Alloy with dispersed particles	46	48.3	3.2	2.5	3.0

Once the geometric model was prepared, a CAD model was made consisting of the blade, the root and the riser. This CAD model was fed to an FDM (fused deposition modelling) machine to make the blade prototype with ABS material. By using this ABS blade, prototype silicon rubber molds (negative volume molds) were prepared to produce the wax model. The wax model produced from the silicon rubber mold was then used to prepare actual mold using a refractory material resistant to high temperatures.

After the mold was dry, it was subjected to heating to eliminate the residual moisture and melt the wax. Subsequently, the mold was baked in a furnace following a thermal cycle, which included:

- Heating the mold up to 250℃ and residing at this temperature for 30 minutes.
- Heating the mold up to 900℃ and residing at this temperature for 30 minutes.
- Cooling back to 450℃ until casting.

Finally, the blades were cast in a centrifugal induction furnace in a vacuum atmosphere. The casting was then slowly cooled back to ambient temperature in order to eliminate residual stresses. After cooling, the refractory material around the blade was removed and the riser was cut using a diamond blade cutter. The blade obtained was then ultrasonically cleaned followed by a preliminary grinding operation to eliminate the residual refractory material.

In order to perform mechanical tests, the alloys with and without alumina dispersion were cast in a ceramic mold: specimens were produced by means of investment casting following the procedure already described for the blade production. Fracture surfaces of TiAl alloys were analyzed by using scanning electron microscope (SEM) in order to evaluate the effect of dispersed particles on the fracture behavior of the alloy. In order to perform metallographic analyses of the selected alloys, the specimens were ground with SiC papers ranging from 80 to 2400 grith and polished with 0.3 µm alumina to get a mirror like finish. To highlight the alloy microstructure the polished specimens were then etched with the Keller's reagent.

3. Results and discussion

The metallographic analyses of the alloy reveal that both the alloys are characterized by lamellar α_2/γ colonies and gamma grains. Figure 1 shows the optical micrographs of the selected alloys.

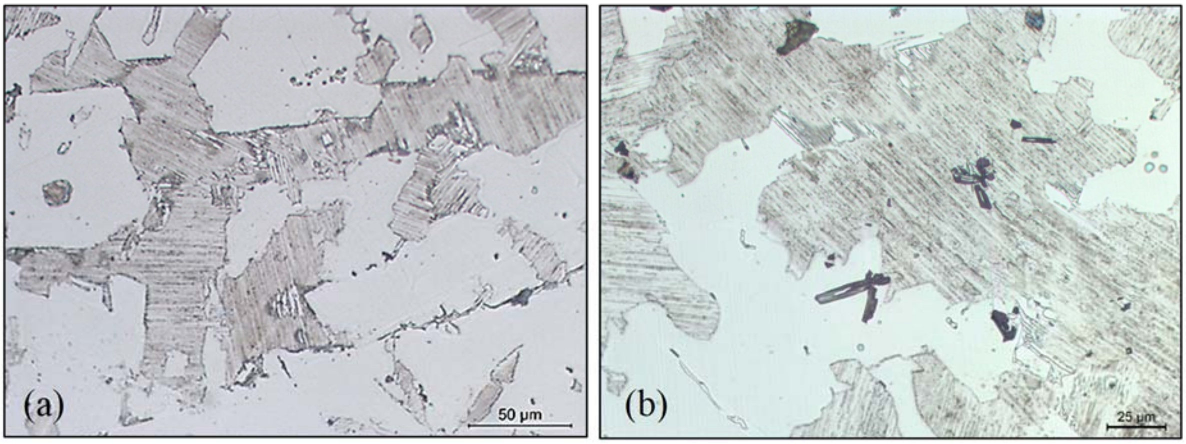

Figure 1. Optical micrographs showing the alloy microstructure of (a) the alloy without alumina dispersion and of (b) the alloy with alumina dispersion.

For the purpose of dispersion hardening 0.04 µm size alumina powders were used, but microstructural analysis revealed that the particles are dispersed as microparticles after agglomeration and as nanoparticles. Comprehensively there is a quite uniform distribution of the alumina particles in the intermetallic matrix.

Since these TiAl alloys are specifically designed to produce mechanical components working at high temperature, mechanical tests performed over the range 800-900 °C allowed to evaluate the effect of alumina particles on the mechanical behavior of the alloy. The results published in previous papers (Brotzu et al. 2018; Pilone et al. 2020) highlighted that the dispersion of alumina particles in the alloy allows to considerably increase the Young's modulus that in the lower temperature range is 30% higher than that of the reference alloy. The analysis of the yield stress over the temperature range 800–900 °C pointed out that dispersion strengthening affects the yield stress by increasing its value of about 20% even at 800 °C. Moreover these alloys are characterized by a ductile-brittle transition temperature and then, although at high temperatures they can have a ductile behavior, at room temperature they can exhibit a very low fracture toughness that can easily produce the fracture of the components under the effect of residual stresses in presence of defects or edges (Figures 2a and 2b).

It is then essential to analyse the fracture surfaces in order to study the effect of the alumina dispersion on TiAl intermetallic alloys.

The images in Figure 2 show different fractured components made of TiAl base alloy. Figures 2a and 2b show that the most critical area for the blades is the hub area. This is due to the design of the blade, as well as to the brittleness of the alloy. Sharp corners and edges give rise to high stresses intensification that can produce initiation and propagation of cracks. The TiAl specimen with dispersed alumina (Figure 2c) shows again a brittle behavior, well evident from the macrograph. A careful observation of the macrographs suggests that the presence of alumina seems to increase the brittleness of the alloy.

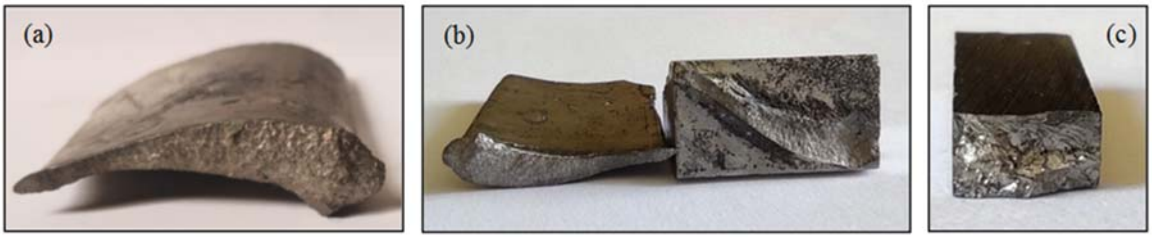

Figure 2. Macrographs showing (a, b) TiAl blades without alumina dispersion and (c) TiAl specimen with alumina dispersion.

In order to understand the alumina effect on the fracture behavior, the fracture surfaces were analysed by means of SEM. In the case of the alloy without alumina dispersion the fracture was a typical cleavage fracture which was trans-lamellar and trans-granular in nature (Figures 3(a) and 3(b)). There are areas in which the fracture propagates through the γ phase and areas in which the trans-lamellar fracture occurs. After performing a careful inspection we can say that the fracture occurs starting from areas with high stress concentration like sharp edges and defects constituted by the presence of micro-shrinkage cavities evident inside the casting. Figure 3c shows a secondary shrinkage cavity present on the fracture surface.

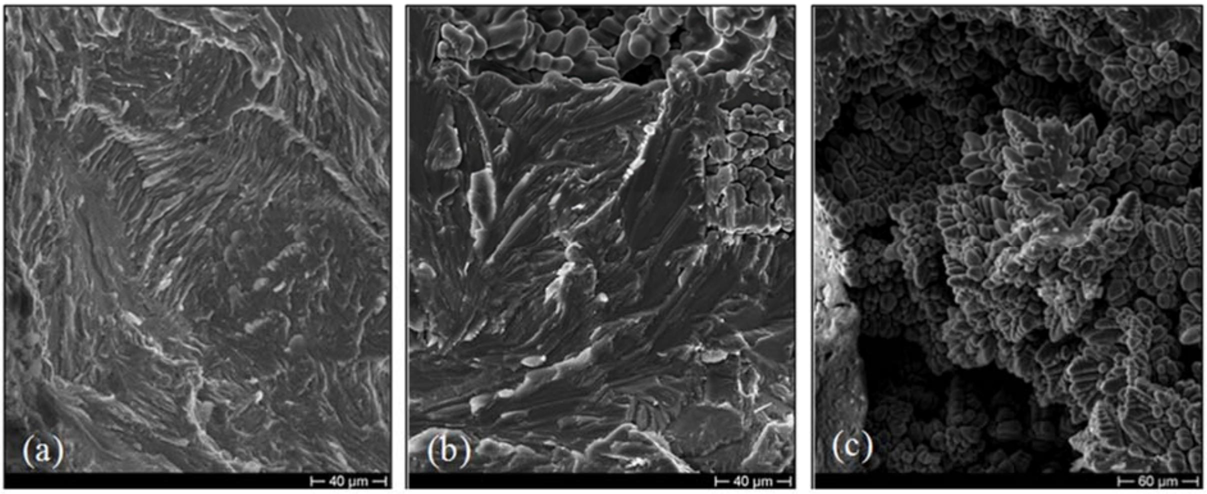

Figure 3. SEM micrographs showing (a, b) the fracture surfaces and (c) a shrinkage cavity in TiAl alloy.

The alloy with alumina dispersion shows a fracture morphology which is very similar to the one observable without alumina. Figure 4 shows brittle cleavage fracture surfaces characterized by transgranular and translamellar propagation. The analyses carried out on the fracture surfaces highlight that alumina agglomerates are visible on them, suggesting that their presence favors the fracture propagation trough the grains. By observing the micrographs in Figure 4 it is possible to see some micro-holes formed as a consequence of the dislodgement of alumina agglomerates during fracture propagation. Some of these micro-holes are indicated by arrows. There are also some secondary micro-cracks (Figure 4(c)) in the alloy matrix that affect the fracture behavior. Although alumina dispersion allows to increase the alloy mechanical strength due to the reinforcement effects, which depend on the opposition to the climb mechanism and on the Orowan mechanism, the presence of alumina particles seem to favor crack propagation through the alloy grains.

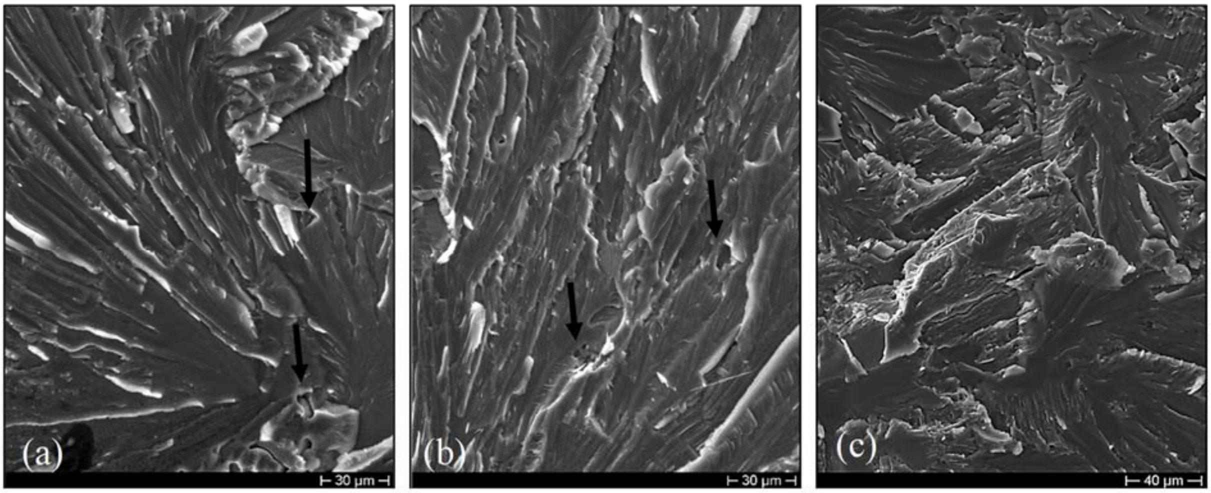

Figure 4. SEM micrograph showing (a, b) the fracture surfaces and (c) the presence of micro-cracks in reinforced TiAl alloy.

Figure 5 highlights that also reinforced alloys contain secondary shrinkage cavities. By comparing the two alloys, it was noticed that the amount of shrinkage cavities found in the alloy with alumina dispersion was much greater than the alloy without alumina dispersion. It seems that alumina presence hinders the correct feeding of the liquid in the areas where shrinkage occurs. One more interesting observation concerns the shrinkage cavities: in presence of alumina, inside the cavities there are crystals with sharp edges together with dendrites. This was typical in all the castings with alumina dispersion. Hence, this can be attributed to the presence of nanometric alumina in the metal matrix. A detailed study is need in order to explain the origin of this phenomenon and its effect on mechanical and fracture behavior.

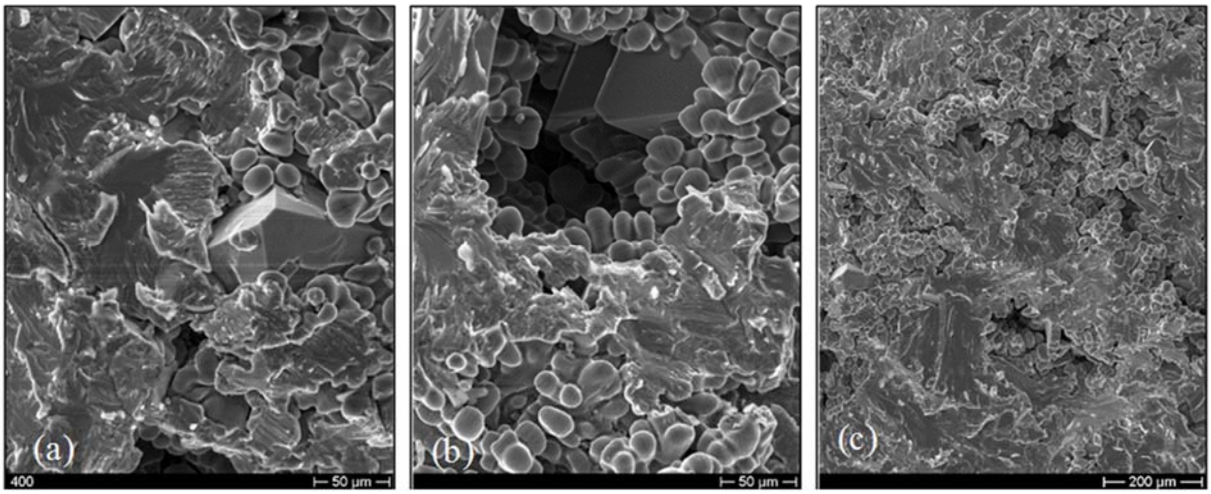

Figure 5. SEM micrographs showing (a, b) the presence of crystals with sharp edges inside the cavities and (c) the presence of shrinkage cavities inside the matrix with alumina dispersion

4. Conclusions

The research carried out in this paper highlighted that the addition of dispersed alumina particles, that increases the mechanical strength of γTiAl alloys, affects the fracture behaviour of the alloy by favoring the propagation of a brittle fracture. The study carried out in this paper highlighted also that the addition of dispersed particles also increases the quantity of shrinkage cavities inside the casting. Hence, a further research is needed to optimize the shape, the distribution and the quantity of the dispersed particles with the aim of increasing the alloy fracture toughness at ambient temperature without compromising mechanical properties at high temperature.

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