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A comparative study of Ti-Al and Ti-Nb alloys for advanced technological applications

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ABSTRACT

Purpose: of this paper is to compare some properties of Ti-Al and Ti-Nb alloys to investigate on the possibility to jointly employed them industrially. Ti-Al alloys have been proposed because they present challenging characteristics for high temperature purposes and β type Ti-Nb alloy has specific mechanical properties at room temperature. Ti-Al alloys are very attractive materials and represent one of the most important materials employed for aero jet engines. The most promising alloy belonging to the above mentioned classes are predominantly based on simultaneously presence of two phases, namely γ-TiAl (gamma titanium aluminides) and α_2-Ti_3Al both with a fully lamellar microstructure and could replace Ni-based superalloys in some high temperature applications in aerospace and automotive industries. The most important advantages of such alloys compared to some superalloys consist in their low density correlated to their superior efficiency in service and reduced gas emission.

Design/methodology/approach: The Ti-Al alloy have been produced by gravity casting, using a vibrating furnace, while the Ti-Nb alloy samples have been realized by the cold crucible levitation melting (CCLM) casting technology. Microstructural and mechanical characterization have been performed.

Findings: The microstructural analysis for the Ti-Al alloy reveals a fully-lamellar microstructure with alternate plates of α_2-(Ti_3Al) and γ-(TiAl) plates. The grains have an average size of about 200 µm. For the Ti-Nb based alloy only a β mono-phase has been detected. This alloy has a equiaxed microstructure with an average grain dimension of about 170 µm. The Ti-Nb alloy presents a high mechanical strength while on the contrary that of the Ti-Al has been deleteriously affected by the presence of large gas porosities. Superior hardness values have been reached with Ti-Al alloy, due to the presence of hard γ-TiAl.

Practical implications: The most important implication is related to the transfer toward the proper choice of the correct parameters during manufacturing.

Originality/value: Investigation on the influence of the elemental composition enriched by other elements and casting processes on the defect development, the microstructural characteristics and on the mechanical behaviour of the alloys.

Keywords: Metallic Alloys; Intermetallic phase; Microstructural characterization

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ANALYSIS AND MODELLING

1. Introduction

Interesting advanced technological applications can be realized with Ti-based alloys. In particular, two categories of alloys present promising properties: Ti-Al and Ti-Nb based alloys. Thanks to their exceptional combination of light weight, mechanical properties and heat resistance, Ti-Al alloys represent a very attractive material for advanced structural applications in aerospace and automotive applications [1-3]. Some extremely interesting case in point of the use of these alloys are represented by: turbine blades employed in aero engines [4] and turbines and turbocharger rotors for the fabrication of automotive engine [2]. By using of Ti-Al alloys, it is possible to reduce by half the total weight of a turbo-charger. Moreover, thanks to the outstanding combination of their properties, these alloys represent a suitable solution to solve the turbo-leg problem, which constitutes a recurring problem for the turbo-charger rotor [5]. One of the main drawback for these alloys in high-temperature applications regards the severe oxidation, to which they are subjected, especially for temperature about 750-850°C [2]. Consequently, many possible different ways to increase their oxidation resistance have been studied and developed during the years. Some examples of protective coatings studied in research works are: alumina former coatings based on MCrAlY, aluminide coatings based on $TiAl_3$ and $TiAl_2$, Cr-rich coatings and the halogen effect, which is based on the preferential oxidation of aluminum, present in the alloy, in order to favor the deposition of a protective alumina oxide layer [2]. In all these evaluated and proposed solutions, it is fundamental to deposit an oxide layer, which plays a crucial role and acts as a barrier for the diffusion of oxygen and other aggressive species, into the substrate and so therefore limits the degradation of the alloys. Especially the Gamma Titanium Aluminides (γ-TiAl), with high Nb content are nowadays widely used in high-resistant application because they can be applied at high operating temperatures. Moreover they possess a good oxidation resistance with respect to the traditional Ti-Al alloys [6]. In particular, by the addition of Nb into Ti-Al-Nb alloys with 40-50 at.% Al, the presence of γ-TiAl + σ-Nb_2Al has been revealed allowing to increase the mechanical properties especially at high temperature [7].

The microstructure of these alloys is mainly composed by TiAl (γ) and Ti_3Al (α_2) phases, with a fully lamellar microstructure. The mechanical properties and the microstructure are both influenced by the chemical composition and the adopted thermal heat treatment [8].

For example, Cr and Mn are suitable to increase the ductility, Mo and Nb both affect positively the creep and the oxidation resistance and B can be used as grain refiners [8]. In a recent research [4] it has been shown that, through the addition of C, both γ and the α_2 phases have been significantly hardened and so increased high-temperature strength as well as creep resistance have been achieved.

The main problems and limitations for these alloys are represented by their low ductility at room temperature, low fracture toughness and low machinability, which give rise to poor quality surface and limited tool life [9].

Another extremely interesting class of titanium alloys are called Gum Metal: these are β-type titanium alloys which present exceptional properties such as: ultra-low elastic modulus, high strength around 1.1 GPa, yield strength, superelastic behavior, superplastic-like cold working without work hardening at room temperature and finally Invar and Elinavar properties in a large range of temperature [10-12]. In a previous work [13] it has been observed that these alloys present a limited hardening, even after cold work, and for this reason it was concluded that these alloys seem to deform via a dislocation free mechanism, involving elastic instability at the limit of strength. Moreover, the authors of [13] have proposed the idea that no martensitic transformation was involved and that the unstable β-lattice readily formed giants faults by ideal shear and thus accommodated the plastic strain. By the in situ synchrotron X-ray (SXRD) technique [14-15] it has been demonstrated that the martensitic transformation is induced by reversible stress and so consequently the β (bcc) phase transforms into α'' (orthorhombic phase) allowing to justifies the superelastic behavior. The ability of these alloys to present an elastic behavior, also when they are subjected to a load close to the ideal strength, represents the most interesting and promising feature. Generally the characteristic chemical composition of a Gum Metal is Ti-23Nb-0.7Ta-2.0Zr-1.2O (at%). The properties of these alloys are due to the low elastic modulus originating from the low e/a ratio, the cold working and finally the oxygen content [11]. This latter is because oxygen stabilizes the bcc crystal structure for the reason that it allows to take under control the martensitic transformation temperature. Moreover, together with zirconium, oxygen favors the precipitation of nanoclusters which act as barrier for the dislocation movement [12]. Anyway up to now the complex mechanism that governs the mechanical behavior of Gum Metal still represents topic of many ongoing activities. Thanks to their low elastic modulus and the low toxicity of niobium, mainly used as a β stabilizing element [16], Gum Metal represents an interesting and suitable candidate for orthopedic implants.

The Ti-Al alloys are complicate to process because of their high melting temperature, poor fluidity, chemical reactivity and low density combined with high viscosity in the molten state [17]. Moreover, another important inconvenient for these alloys is represented by the development of porosities, associated to the turbulences present during the casting process, such as for example the centrifugal casting process [18]. The Hot Isostatic Pressing (HIP) technique can be applied to remove these porosities but nevertheless they affect deleteriously the mechanical properties of the alloys.

In this research work the porosity development, which takes place during the casting process, of both Ti-Al and Ti-Nb (Gum Metal) has been evaluated and some investigation on how the porosity affects the mechanical strength of the alloys has been carried out.

2. Experimental procedures

In the present study a Ti-Al alloy and a Ti-Nb (Gum Metal), which chemical compositions are reported in Tables 1 and 2, have been considered and investigated. Castings of the Ti-Al alloys have been realized by gravity casting process, using a vibrating furnace (INDUTHERM VTC 200 V-Ti), while for the Ti-Nb alloy samples the use of cold crucible levitation melting (CCLM) casting technology has been employed. Ti-Al and Ti-Nb alloys have been investigated, from microstructural and mechanical point of view, in the as-cast condition.

The morphological analysis has been performed on samples prepared by a standard metallographic technique by mounting and polishing procedures, using Light Microscope, (LM, MeF4 Reichart-Jung) and Scanning Electron Microscopy (SEM, Leo 1450VP) equipped with Energy X-rays Dispersive Spectroscopy unit (EDS, Oxford microprobe).

Table 1. Chemical composition (wt%) of the Ti-Al alloy

Elements	wt%
Ti	52.0
Al	29.6
Nb	14.4
Cr	1.2
Ta	2.2
Ni	0.4
Si	0.1

Table 2. Chemical composition (wt%) of the Ti-Nb Gum alloy

Elements	wt%
Ti	61.7
Nb	30.4
Zr	4.75
Ta	2.8
Al	0.144
Fe	0.098
Si	0.007
Ni	0.033

Furthermore, the porosities content has been evaluated by Leica microscope image analysis software, using samples etched with Keller reagent for 7 minutes and samples etched using a water solution with 10 % vol of HF and 10%vol of HNO_3, for Ti-Al and Ti-Nb respectively.

The mechanical performances have been investigated by tensile test, carried out according to the UNI-EN 10002/1 standard, using a dynamometer (Zwick Z100 tool) with a cell load of 100 kN and setting a deformation speed of 10mm/min. On the polished samples hardness measurements have been performed using a Emco test machine. A force of 500 N has been applied for 15 s for each measurement. Finally, fracture surface analysis has been carried out on the fractured surfaces, after mechanical tests, to assess some reasons related to the samples failure.

3. Results and discussion

3.1. Microstructure and porosity evaluation

Ti-Al samples were produced by gravity casting and the approach considered leads obtaining a fully-lamellar microstructure, with alternate plates of α_2 (Ti_3Al) and γ (TiAl) plates, as shown in Fig.1a. This microstructure allows to reach important properties, such as: high room-temperature ductility, fracture toughness, high-temperature strength and creep resistance, which according also to some literature data, make the alloy suitable to produce a wide range of components, especially for automobile and aerospace applications [19-20].

The grains have an average size of about 200 μm, but their dimensions change in a massive range between 10 μm up to 1 mm. As can be observed in Fig.1b, some grains do not present a lamellar morphology: some micrometric porosities have been detected in limited areas, as can be observed in Fig. 1a. In Fig. 2 the LM microstructure of

Ti-Nb alloy is reported, where it can be observed that the samples show an equiaxed microstructure and the grains have an average dimension of about 170 μm.

a)

b

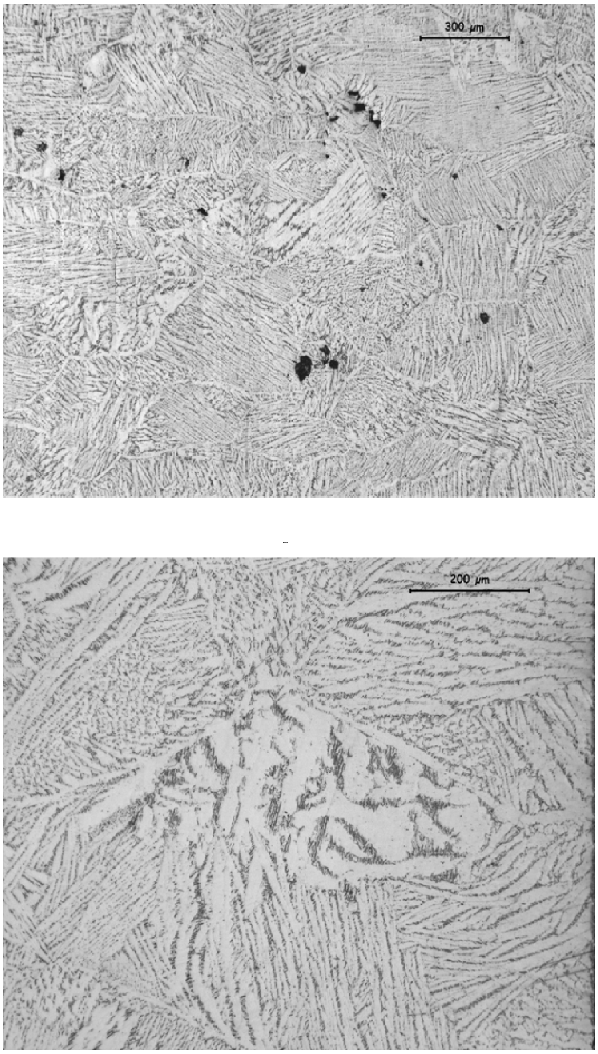

Fig. 1. LM microstructure of Ti-Al alloy samples obtained by gravity casting,using a vibrating furnace, at a magnification of: a) 50X and b) 100X

For the Ti-Al alloy a low average value of porosity (about 0.11%) has been estimated. This low value is mainly due to the high vacuum value reached during the casting and also to the vibration of the mould, during the casting operation, which allowed to guarantee a complete filling of the mould itself. Some porosities, with an average dimension around 200-250 μm, have been individuated in the center of the cross-section of the Ti-Al alloy samples, likely caused by some imperfections during the casting procedure.

An average porosity of about 0.1%, has been individuated also in the Ti-Nb samples, as reported in Fig. 4. These samples show small pores which are uniformly distributed along the whole cross-section.

The low porosity values achieved for both the investigated alloys, represent an interesting result, especially considering that these alloys can be used in advanced technological applications, which require high mechanical performances. Occasionally, due to some laboratory imperfections some few gas porosities have been developed in the casting (Fig. 3 and 7).

3.2. Tensile test

The results of the tensile tests are summarized in Fig.5. Ti-Al alloy reveals a very low mechanical strength, as a matter of fact both R_m and $R_{p0.2}$ show an average value close to 100 MPa. This features is mainly due to the large porosities illustrated in Fig. 3 and 7, individuated in the middle of the cross-section. These porosities present a dimension far from the average porosities dimension observed, as illustrated earlier. The mechanical strength can be improved by reducing the fully lamellar grain size through the adoption of innovative heat treatments and thermomechanical processing, according to [21]. Another important microstructural feature that strongly affects the tensile strength of these alloys, as expected considering also the Hal-Petch relationship, is the grain size [19]. The Ti-Nb Gum alloy shows higher mechanical properties compared to those achieved with Ti-Al, especially they have a higher R_m value. Even though the presence of small pores, which are uniformly distributed in the metal matrix, they have negatively affected the sample mechanical strength. If these alloys are submitted to a cold working process both the yield strength as well as the elastic limit increase, while the elastic modulus decreases [13, 22]. The elastic deformability after cold working can reach a value of about 2.5%, which is about twice that before cold working. Young's Modulus values of about 145 GPa and of about 59 GPa have been measured for the Ti-Al and Ti-Nb alloys respectively. The Ti-Nb alloys have a so called Elinvar behavior, which means that the elastic modulus maintains a constant value over a certain range of temperature. Thanks to this characteristic, this type of alloys can represent a perfect material for precision instrument production.

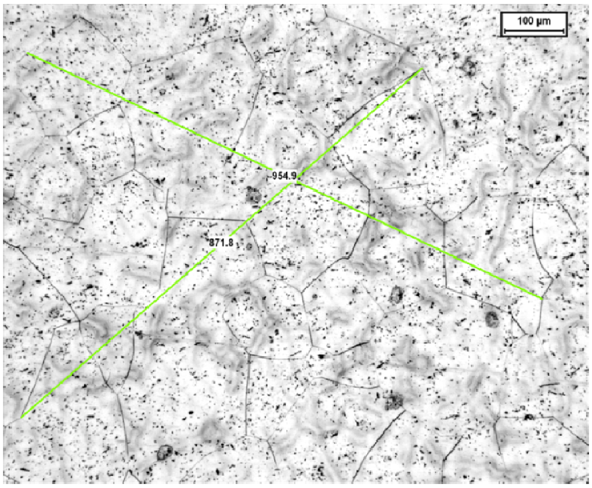

Fig. 2. LM microstructure of Ti-Nb (Gum Metal) in the as cast conditio

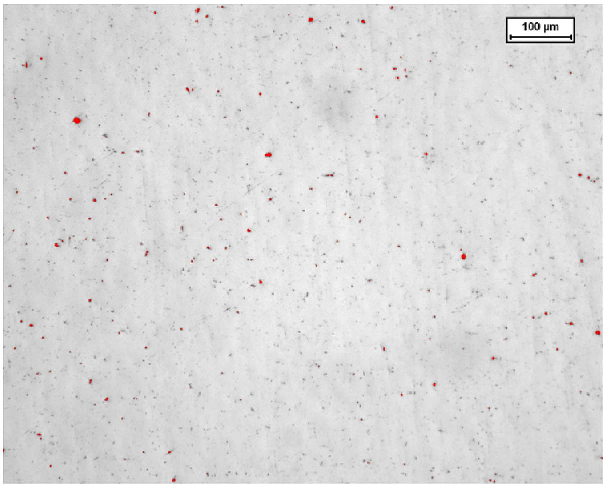

Fig. 4. Porosities individuated in the cross-section of Ti-Nb (Gum Metal)

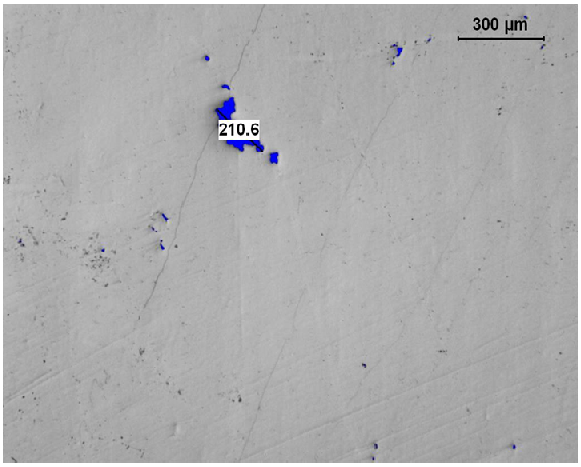

Fig. 3. Porosity detected in the center of the cross-section of Ti-Al alloy

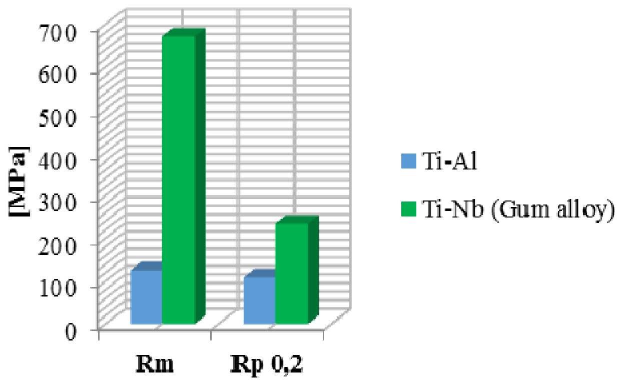

Fig. 5. Results of the tensile test

Figure 6 reports the average results corresponding to 10 Vickers measurements. Higher hardness values have been achieved in the case of Ti-Al alloy, due to the presence particles with high-hardness γ (TiAl): they are also brittle and negatively affect the machinability of these alloys. This is the reason why they are not widespread used in certain applications at industrial level [8].

Fracture surface analysis has been performed. Large gas porosity, with an average diameter close to 2 mm, have been detected on the surface and this can be considered the main cause of the samples failure at the applied low stress level. These defects have a very important effect on the mechanical performances of such alloys, especially for the yield strength and the ultimate tensile strength.

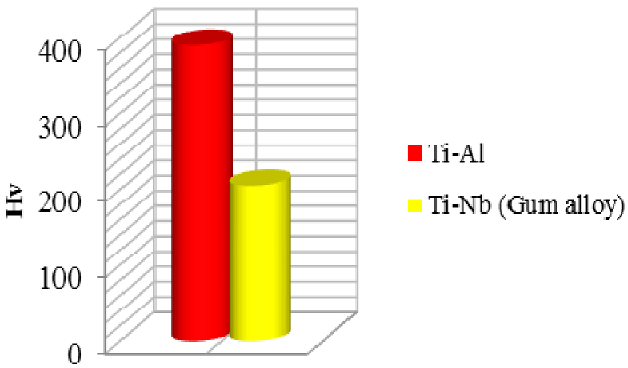

Fig. 6. Average values results of Vickers hardness test

4. Conclusions

In this paper a comparison of some properties related to Ti-Al and Ti-Nb alloys for possible advanced technological applications was carried out. Ti-Al and Ti-Nb based alloys were proposed because they present interesting features for specific purposes. In particular, the attention was oriented to study the porosity development in both alloys, during casting. Additionally, some investigations on how the porosity influences the mechanical strength of the alloys were performed.

Based on the results obtained up to now the following conclusions can be drawn:

- the Ti-Al alloy presents a fully-lamellar microstructure, with alternate α_2 (Ti_3Al) and γ (TiAl) plates and an average grain size of about 200 µm; while the Ti-Nb alloy shows an equiaxed microstructure with an average grain dimension of about 170 µm;
- an average porosities of about 0.1% has been obtained for both alloys, as a consequence of some problems occured during the casting, additionally to some larger gas porosities, negativelly influencing the mechancical properties, especially in the case of the Ti-Al samples;
- superior hardness values have been achieved for the Ti-Al alloy, due to the presence of γ (TiAl) particles.

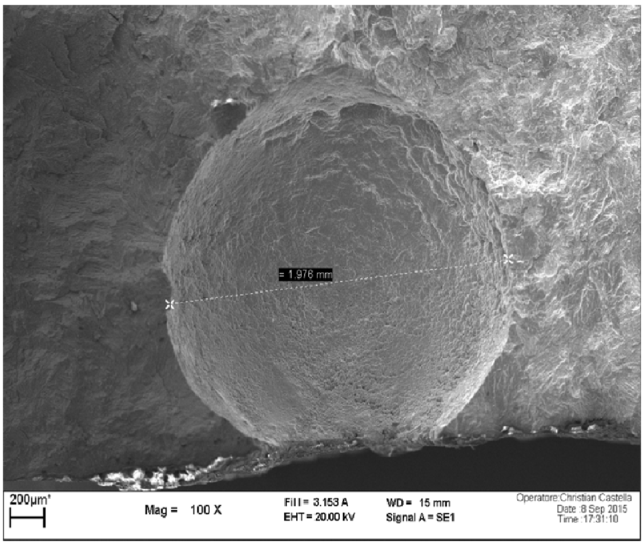

Fig. 7. SEM image showing a large gas porosity detected on the fractured surface of Ti-Al sample

Some on-going activities are focalized on the optimization of the casting processes obtaining low defect content and consequently improved mechanical performances.

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Additional information

Selected issues related to this paper are planned to be presented at the 22nd Winter International Scientific Conference on Achievements in Mechanical and Materials Engineering Winter-AMME'2015 in the framework of the Bidisciplinary Occasional Scientific Session BOSS'2015 celebrating the 10th anniversary of the foundation of the Association of Computational Materials Science and Surface Engineering and the World Academy of Materials and Manufacturing Engineering and of the foundation of the Worldwide Journal of Achievements in Materials and Manufacturing Engineering.

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