Fracture behaviour of cast TiAl based intermetallic alloys

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ABSTRACT. The γ -TiAl based intermetallic alloys have received considerable attention as candidate materials for high-temperature aerospace applications, power generation and automotive industry, with the efforts being directed toward the replacement of Ni-based superalloys in many interesting applications. In fact TiAl-based alloys' density is about 4 g/cm^3 which is about half of that of commonly used Ni-based superalloys, and therefore these alloys have attracted broad attention as potential candidate for high-temperature structural applications in the fields for example of turbocharger manufacture. Specific composition/microstructure combinations are believed to be capable of improving mechanical properties while maintaining satisfactory oxidation resistance, creep resistance and high temperature strength for targeted applications.

Different casting methods such as conventional sand casting, investment casting, low pressure casting, centrifugal casting, shell mould casting have been used for producing TiAl based alloys.

In our experimental work specimens were produced by means of centrifugal casting, the main advantage of this method being the production of castings completely free from any porosity.

Tests carried out on several samples characterized by different alloy compositions highlighted that solidification shrinkage and solid metal contraction during cooling produce the development of relevant residual stresses that are sufficient to fracture the castings during cooling or to produce a delayed fracture. In this work cracks initiation and growth have been analysed in order to identify the factors causing these very high residual stresses that often produce explosive crack propagation throughout the casting.

SOMMARIO. Le leghe intermetalliche γ-TiAl sono particolarmente interessanti per applicazioni aerospaziali, automobilistiche e nel campo della generazione di potenza. Sono considerati importanti candidati per sostituire le superleghe base Ni che hanno una densità circa doppia di quella degli intermetallici considerati. Le leghe γ-TiAl sono particolarmente interessanti per applicazioni ad alta temperatura, per esempio per la costruzione di parti di turbine. Si ritiene che ci siano specifiche combinazioni composizione/microstruttura in grado di migliorare le proprietà meccaniche pur garantendo una soddisfacente resistenza all'ossidazione, resistenza al creep e resistenza meccanica alle alte temperature, qualità irrinunciabili per specifiche applicazioni.

Gli intermetallici TiAl possono essere colati utilizzando metodi diversi quali colata in sabbia, colata centrifuga, colata in conchiglia, investment casting.

Nel presente lavoro i campioni sono stati prodotti in un forno ad induzione in atmosfera di argon mediante colata centrifuga. Il principale vantaggio di questa tecnica dovrebbe essere quello di ottenere getti privi di porosità.

Prove condotte su alcuni provini, caratterizzati anche da composizioni diverse, hanno evidenziato che il ritiro e la contrazione del metallo solido durante il raffreddamento producono lo sviluppo di importanti tensioni residue che sono sufficienti a fratturare il getto durante il raffreddamento o anche dopo un certo tempo. In questo lavoro l'innesco e la crescita delle cricche sono stati analizzati per identificare i fattori che causano queste elevatissime tensioni residue che spesso producono propagazioni esplosive di cricche attraverso il getto.

KEYWORDS. Titanium aluminides; TiAl intermetallics; Fracture toughness.

INTRODUCTION

TiAl based alloys are interesting for high-temperature applications in aerospace and automotive industries. Their potential is seen in low density, high specific yield strength, high specific stiffness, good oxidation resistance at room temperature (RT), resistance against "titanium fire", and good creep properties up to high temperatures [1]. In fact the good specific mechanical properties of titanium aluminide alloys push the development of these materials.

Because of their ordered structure, intermetallics have high mechanical strength both at RT and at high temperature [2,3]. Despite that, TiAl-based alloys cannot be used as single phase alloys since they have a very low ductility at RT. The presence of a second α_2 phase (Ti_3Al) allows control of the microstructure. As far as mechanical properties are concerned, the addition of alloying elements such as Cr, V and Mn reduces the grain size with consequent ductility improvement. Depending on alloy composition and microstructure, these alloys exhibit good workability, medium-to-good tensile properties, tensile fracture strains in the range 1-3% at RT and fracture toughness values in the range 10- 25 $MPa\sqrt{m}$ [4-7]. Various TiAl-based alloys have been developed. Adding transition metals of a high melting temperatures is generally beneficial to increasing the high temperature strength of these alloys [8-10]. More recently the so-called 2nd and 3rd generation alloys have been developed in order to improve mechanical properties and high temperature properties [1] of those alloys. The 4th generation alloys, also called "air-hardenable", have been intensively studied as potential materials for investment casting of low pressure turbine blades [11].

For many years our research group produced and studied many TiAl intermetallic alloys with the aim of optimising both high temperature oxidation behaviour and fracture toughness. The difficulty of doing so is that alloying elements that are beneficial for improving the former property are usually detrimental for the latter. In order to achieve reliable results a high number of specimens have to be produced and tested. TiAl intermetallic specimens may be manufactured by using centrifugal casting, investment casting. In our research we obtained compact tension and tensile specimens via direct centrifugal casting. During specimens' manufacturing a large number of them fractured during cooling, while others showed a delayed fracture.

Considering that a large number of fractured specimens was available, a study has been carried out with the aim of finding the factors that determine this phenomenon. In this work specimens' structure and composition were analysed and crack paths were studied in order to identify causes determining high residual stresses that in many cases are able to produce an explosive crack propagation throughout the castings.

EXPERIMENTAL

The alloys used in this work were produced by induction melting under an Ar atmosphere from pure Ti, Al, Cr, Nb, Mo, Ni and B. The molten metal was cast directly into the rotating mould. In this work several samples fractured during cooling or showing a delayed fracture were studied and analysed. Tab. 1 shows the composition (at.%) of a representative sample of them.

In order to perform metallographic examinations on the specimen surfaces they 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, crack paths and fracture surfaces were inspected by scanning electron microscope (SEM) and microanalyses were carried out by energy dispersion spectroscopy (EDS).

RESULTS AND DISCUSSION

A representative sample of the fractured specimens has been selected and the compositions of the considered alloys are reported in Tab. 1. All the specimens listed in this table fractured either during cooling or after the extraction from the mould. As an example Alloy F showed an explosive fracture two hours after extracting it from the mould. After remelting, the casting showed again an explosive fracture after 3 days. The considered alloys are TiAl-Cr-Nb-Mo alloys with an aluminium content ranging from 43.5 to 53 at.%. Alloys G and H are the only ones containing nickel: they were reported in Tab. 1 because, despite the different composition, they showed the same behaviour as the Ni-free alloys. A close observation of the preferential paths of spontaneous fractures occurred in all the specimens highlighted that these paths are very similar (Fig. 1).

Alloy	Al	Ti	Cr	Nb	Mo	B	Ni
A	50.3	39.6	-	7.1	2.5	0.5	-
B	47.1	46.5	2.5	3.1	-	0.8	-
C	46.2	45.7	3.1	4.6	-	0.7	-
D	49.0	41.1	2.5	4.9	2.5	-	-
E	46.7	43.2	2.4	4.7	2.3	0.7	-
F	43.5	47.7	2.7	3.6	1.8	0.7	-
G	47.7	42.9	2.7	0.3	1.0	-	5.4
H	53.0	29.6	1.6	0.5	1.3	-	14.0
I	46.0	43.5	3.5	3.5	3.5	-	-

Table 1: Chemical composition (at.%) of nine TiAl based alloys whose castings showed fractures either during or after the cooling stage.

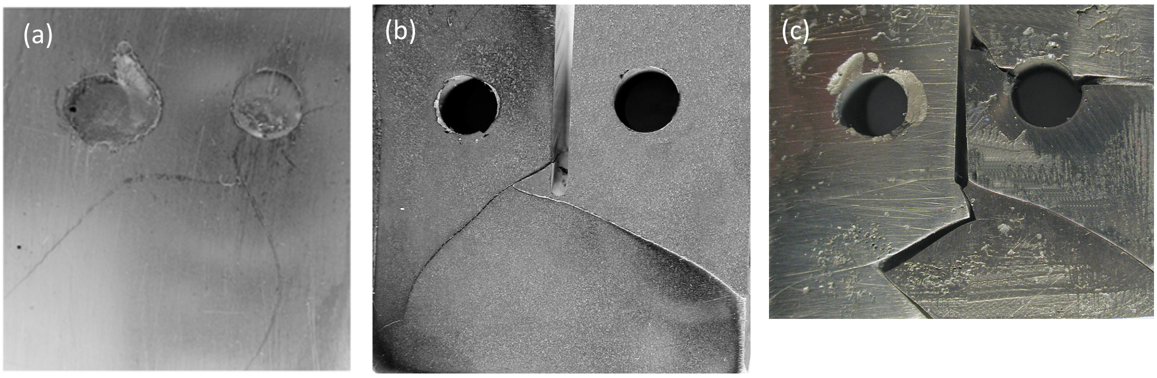

Figure 1: Macrograph showing three fractured specimens: (a) Alloy A; (b) Alloy B; (c) Alloy C.

This observation can be an important clue to identify the causes of sudden and, in some cases, explosive fractures. In particular centrifugal casting, used for manufacturing our specimens, may generate a turbulent flow that produces gas entrapment and then air pockets or porosity formation after solidification. Other casting techniques allow a slower filling of the mould: if the liquid metal enters the mould with quiescent flow gas defects are greatly reduced. The analysis of cracks highlights that fracture paths seem to follow the trend of the turbulent flow and fracture surfaces are characterised by the presence of gas defects. Fig. 2d shows a gas defect found on the Alloy C fracture surface, while Fig. 3 shows gas porosity found on the external layer of Alloy C specimen.

Those defects may result from entrapment of air during pouring or may be precipitated during solidification as a result of change in solubility with temperature. Defects take the form of internal blowholes, surface or subcutaneous pinholes or intergranular cavities. Gaseous elements may be absorbed by dissociation of compound gases in contact with the molten alloy. In our study the gas precipitated from the metal on cooling could be hydrogen whose source are moisture and organic compounds contaminating the charge materials. Since the most important safeguard against gas defects is a low gas content in the metal when poured, the charge materials should be degreased and afterwards they should be preheated together with the crucible in a muffle to evaporate surface moisture. If taking these preventive measures gas porosities and blowholes will be still found in the castings it would be clear that they come from air entrapment due to excessive turbulence in pouring.

Considering the high affinity between the alloying elements and oxygen, casting and pouring were performed in a centrifugal furnace after 8 vacuum-argon washing cycles. In order to improve casting soundness, castings could be manufactured by means of vacuum induction melting. This method should reduce the quantity of blowholes formed thanks to the reduced possibility of gas entrapment.

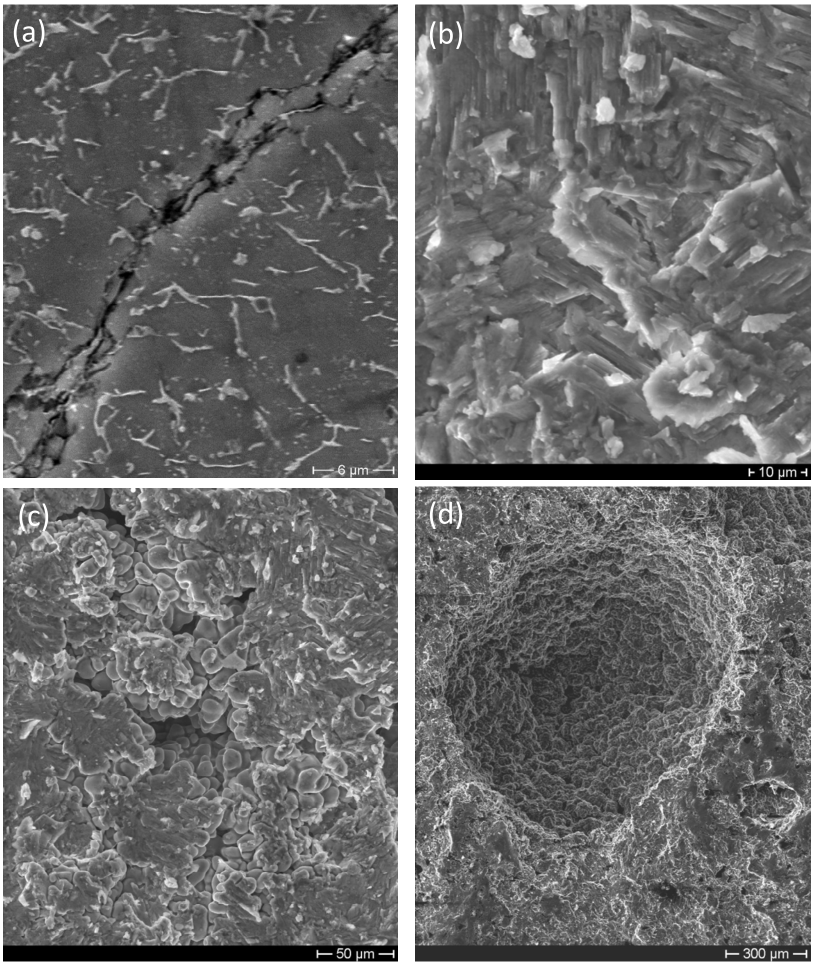

Figure 2: SEM micrographs of the Alloy C specimen showing one of the cracks (a). On the fracture surface the lamellar structure (b), the presence of microshrinkage cavities (c) and gas porosities (d) can be clearly observed.

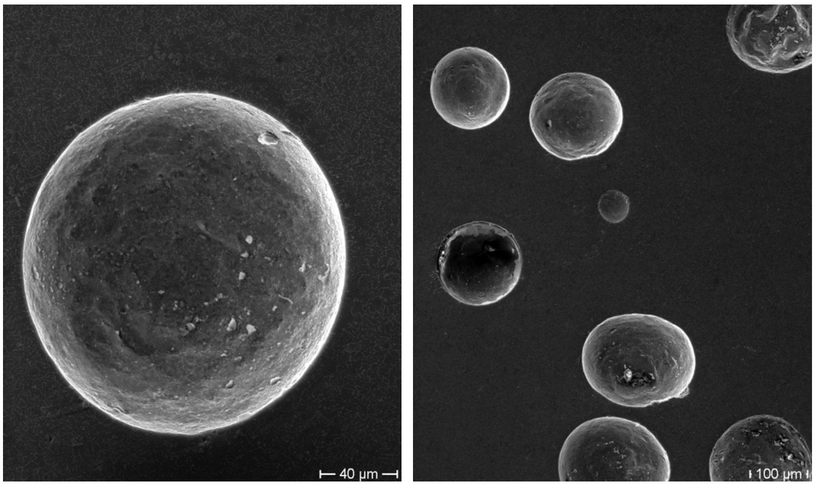

Figure 3: SEM micrographs showing gas porosity on the external surface of Alloy C specimen.

A further critical aspect that comes to light in the presented investigation is the presence of shrinking cavities that seem to favour crack initiation and propagation. Shrinkage should not be a problem when manufacturing by centrifugal casting, since the material is constantly forced to instantly fill any vacancies that may occur during solidification and then it is important to evaluate if gas porosities and blowholes favour the formation of shrinkage cavities by avoiding locally compensation of liquid and solidification contraction. Fig. 2c and 4b show shrinkage cavities found on the fracture surfaces of Alloy C and Alloy B respectively.

Investigations carried out on several specimens highlighted also that boron, added to the alloy to refine the microstructure, considerably increases its tendency to crack during or after cooling. Recently, it has been suggested that grain refinement using boron addition can increase the number of potential crack propagation sites, due to the appearance of aciculated boride particles. Therefore, a new heat treatment process based on massive transformation, that does not rely on boron, is under development as a way of achieving grain refinement and thus improved mechanical properties [12, 13].

As far as the fracture is concerned it appears transgranular since it travels through the grains. Fig. 2b and 4c show also that fracture propagates predominantly in a translamellar mode perpendicular to the lamellar interfaces although in localized areas propagation occurs in an interlamellar mode with crack advance occurring along α_2/γ interfaces.

The TiAl based alloys produced in this research are characterized by uniformly distributed fine lamellar colonies and a small quantity of residual primary β phase (so defined as it forms at high temperature) distributed around colony boundaries (bright phase in Fig. 2a, 5a and 5b). Residual β phase is due to the presence in these alloys of β stabilising elements such as Nb and Mo. The disordered bcc structure of β phase is softer than α and γ phases at elevated temperature and it is expected to facilitate thermomechanical processing of TiAl alloys. However, it has been reported that both the coarse β particles existing in colony boundaries and excessive β phase precipitating from lamellar interfaces deteriorates creep behaviour and room-temperature ductility, while the precipitation of fine β particles is considered as intrinsic toughening mechanism [14]. By examining the path of cracks developing through the TiAl alloys produced in this work it can be seen (Fig. 2a, 4a and 5) that cracks do not propagate along the β/lamellar colonies interfaces. In fact it seems that β phase distribution does not affect crack propagation.

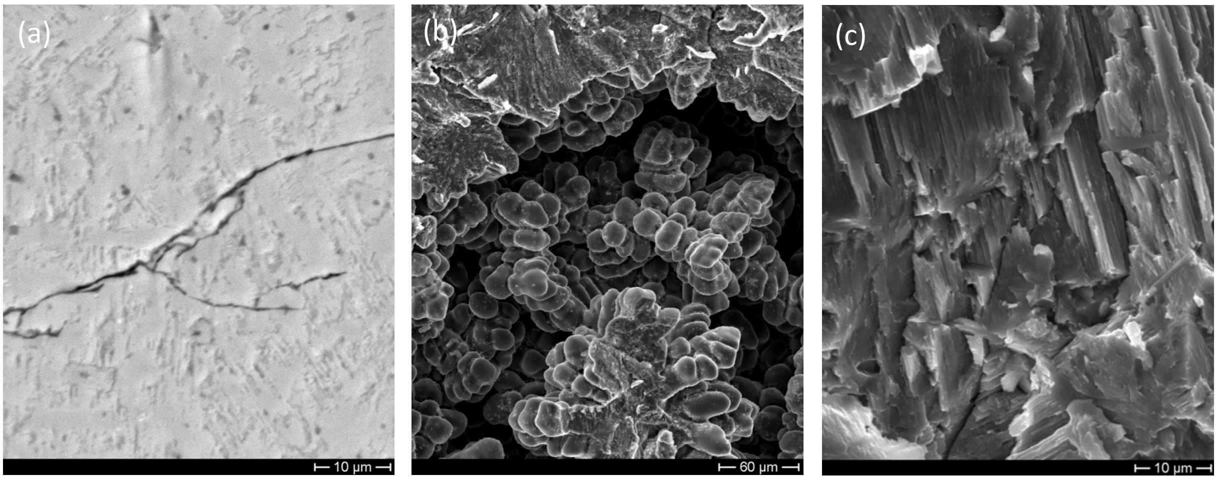

Figure 4: SEM micrographs of the Alloy B specimen showing a crack (a), a shrinkage cavity on the fracture surface (b) and the transgranular fracture (c).

A final factor that has to be considered is the effect of residual stresses. It is well known that internal stresses play an important role in determining the mechanical properties of materials. It is therefore worthwhile to evaluate the influence of the internal stresses on the fracture behaviour of TiAl-based alloys. Owing to the tetragonal crystal structure of γ phase and the hexagonal crystal structure of α_2 phase, there is a lattice misfit between them. Deformation incompatibility across the lamellar interfaces and grain boundaries may occur. Moreover the presence of coarse β particles may increase this incompatibility: in fact it seems that the tendency to cracking increases by increasing the amount of β stabilising elements added to the alloy. Local accumulation and non-uniform distribution of internal strain and stresses introduced by all these effects may relate to brittle fracture behaviour. In order to understand whether internal stresses play an important role in the phenomenon we observed, many of the considered alloys were poured in a mould preheated at 550 °C and the castings were subjected to a very slow cooling in a furnace. By using this methodology the alloys' tendency to cracking was strongly reduced and explosive cracking was not observed for the first eight alloys, while these preventive measures proved to be ineffective for Alloy I that contains the higher quantity of β stabilising elements and then the higher quantity of β phase.

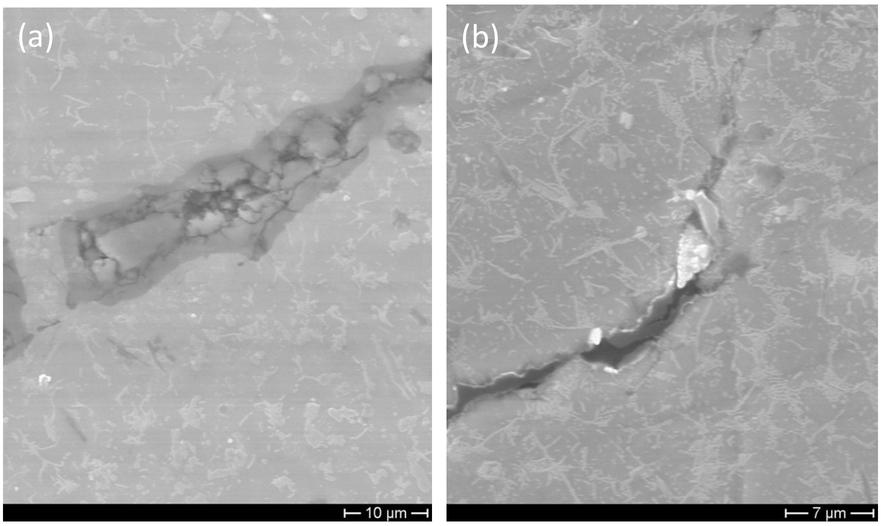

Figure 5: SEM micrographs showing two details of cracks that propagated in the Alloy A casting

CONCLUSIONS

The study carried out on cracks and fracture surfaces of TiAl based alloy specimens fractured during or after cooling highlighted that there are many concurrent factors that produce specimen fracture. SEM analyses showed that microshrinkage cavities and gas porosity coupled with relevant residual stresses, probably related to the quantity of β phase, favour the explosive fracture of the considered alloys. This suggests that in order to prevent this phenomenon the charge materials should be degreased and afterwards they should be preheated together with the crucible in a muffle to evaporate surface moisture. Further improvement can be obtained by pouring the alloy in vacuum in a preheated mould, leaving the casting to cool down in a furnace.

Further studies are required to understand the influence of quantity and distribution of β phase on internal residual stresses.

REFERENCES

[1] H. Clemens, W. Smarsly, Advanced Materials Research, 278 (2011) 551.
[2] S. Djanarthany, J.C. Viala, J. Bouix, Materials Chemistry and Physics, 72 (2001) 301.
[3] D.M. Dimiduk, Materials Science and Engineering, *A*263 (1999) 281.
[4] Y-W. Kim, H. Clemens, A. Rosenberger, Gamma Titanium Aluminides 2003, The Minerals, Metals and Materials Society (TMS), Warrendale, PA, USA (2003).
[5] Y-W. Kim, D. Morris, R. Yang, C. Leyens, Structural Aluminides for Elevated Temperature Applications, The Minerals, Metals and Materials Society (TMS), Warrendale, PA, USA (2008).
[6] M. Peters, C. Leyens, Titanium and Titanium Alloys, Wiley-VCH, Weinheim, Germany (2003).
[7] A. Brotzu, F.Felli, D. Pilone, Frattura ed Integrità Strutturale, 22 (2012) 20.
[8] H.Q. Ye, Materials Science and Engineering, A263 (1999) 289.
[9] M. Yamaguchi, H. Inui, K. Ito, Acta Materialia, 48 (2000) 307.
[10] J.P. Lin et al., Intermetallics, 15 (2007) 668.
[11] J. Lapin, Z. Gabalcová, Intermetallics, 19 (2011) 797.
[12] X. Wu, Intermetallics, 14 (2006) 1114.

[13] D.J. Jarvis , D. Voss, Materials Science and Engineering, A413–414 (2005) 583
[14] Y.Chen, H. Niu, F. Kong, S. Xiao, Intermetallics, 19 (2011)1405.