Mechanical Behavior of Ti-48Al-2Mn-2Nb Alloy Produced by Centrifugal Spray Deposition

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The mechanical behavior of Ti-48Al-2Mn-2Nb alloy produced by centrifugal spray deposition (CSD) was investigated. Tensile, compression and fracture toughness tests of CSD Ti-48Al-2Mn-2Nb alloy were carried out at room temperature (RT), and the comparison was made with the ingot metallurgy (IM) Ti-48Al-2Mn alloy at RT, as well as at 600 and 800°C. The results show that CSD Ti-48Al-2Mn-2Nb alloy exhibits a better elongation of 2.8%, and excellent compression properties with compressive strength of 2210 MPa and compressive ratio of 33.9% at room temperature, furthermore, higher compressive strength of 2625 MPa and better compressive ratio of 58.8% at 600°C. CSD alloy with a refined lamellar structure exhibits higher tensile and compressive properties and better plastic strain ability than that of IM alloy. CSD alloy also has a better fracture toughness of 23.6 MPa√m at RT, however, the IM alloy with coarse lamellar structure exhibits higher fracture toughness of 25.34 MPa√m at RT, and 31.5 MPa√m at 800°C.

Key words: Gamma titanium aluminides, Centrifugal spray deposition (CSD), Ingot metallurgy (IM), Mechanical behavior

1. Introduction

A great deal of attention has been paid to gamma titanium aluminides since 1980's because of their potentially attractive properties for high-temperature structural applications^(1,2). However, gamma titanium aluminides show poor ductility and low fracture toughness at ambient temperature because the ordered crystal structure of TiAl hinders the dislocation motion and offers only a limited number of independent slip systems. Over the past two decades much research effort has been concentrated on the development and improvement of second-generation gamma alloys, Ti-48Al-2(Cr or Mn)-2Nb and derivative, since these alloys exhibit properties meeting the requirements for some gas-turbine and automobile engine components that

may be used at high temperatures^(3,4). Moreover, it is well recognized that the new forming process, such as powder metallurgy and spray forming, can provide TiAl intermetallics with homogeneous and fine microstructure so that they could be beneficial to room temperature ductility. However, there are few reports treating of the mechanical behavior and fracture toughness of TiAl alloys produced by spray forming technique so far. Recently, the authors⁽⁵⁻⁸⁾ investigated systematically the microstructure and properties of Ti-48Al-2Mn-2Nb alloy produced by centrifugal spray deposition (so-called CSD) and found the plasticity of Ti-48Al-2Mn-2Nb alloy could be improved by CSD. In this paper, the authors want to study the mechanical behavior of Ti-48Al-2Mn-2Nb alloy produced by CSD at ambient temperature, and high temperature. In comparison, we especially studied the

mechanical behavior of TiAl alloy produced by ingot metallurgy (IM) to understand the effect of different processing technology on the mechanical and microstructure of TiAl alloys.

2. Experimental Procedure

2.1 Preparation of TiAl alloy

The nominal composition of γ -TiAl alloy in this study was Ti-48Al-2Mn-2Nb (at.%). The alloy was produced by centrifugal spray deposition (CSD) at Interdisciplinary Research Centre (IRC) in Materials for High Performance Applications, at the University of Birmingham, UK. The alloy was firstly melted by a plasma torch at argon atmosphere, and cast into 150 mm ingots. Then the ingots were remelted in a RF induction heated crucible to be sprayed under a low vacuum pressure condition of 3 Pa. During spray forming, the melt was bottom poured through a graphite nozzle under a positive pressure of 170 kPa, and fell freely onto a water-cooled copper disc which was positioned 250 mm below the graphite nozzle and rotated at up to ~ 3000 rpm. Centrifugal forces broke up the stream into droplets, which were sprayed approximately horizontally onto the inside surface of a steel ring substrate. A ring shape preform of 400 mm diameter, about 150 mm axial height and 10 mm thickness, was obtained, as shown in Fig.1. See details for CSD processing from references⁽⁹⁾.

Fig.1 A ring shape preform of CSD TiAl

In ingot metallurgy, the melting operation was conducted by the Institute of Metal Research, Chinese Academy of Sciences. The alloy with composition of Ti-48Al-2Mn was melted and remelted for many times in an argon arc furnace equipped with a non-consumable

tungsten electrode and a water-cooled cooper hearth, and then cast into a bar ingot of 50 mm diameter.

2.2 Mechanical property tests

The samples for mechanical property tests were cut from the CSD TiAl ring and IM ingot blanks using an electron discharge machine. And then machined, ground and polished to preset gauge dimension specimens to meet different tests requirements.

Tension and compression tests were performed on an Instron 1185 testing machine in air at room temperature at a crosshead speed of 0.1-0.05 mm/min. The gauge sections of tensile specimens were rectangular, having dimensions of 4mm in width, 0.5 mm in thickness and 12 mm in gauge length. The compressive specimens were square section columns with dimensions of $4 \times 4 \times 8$ mm. Compression tests were also performed in air at 600°C. To avoid the end effect, the upper and lower contact surfaces of the specimens were lubricated with grease before loading.

Fracture toughness testing was carried out in three-point bend testing using an Instron 1185 testing machine in air at room temperature and 800°C at a crosshead speed of 0.1mm/min. The specimens for fracture toughness testing were $4 \times 8 \times 40$ mm with single-edge-notched, which was notched to a depth of 0.5mm and pre-cracked to 2mm using a Shimadzu EHF-F05 servo-hydraulic testing machine in compressing cycling at a ratio of 0.1. Nominal fracture toughness values were calculated from the load-displacement curves.

2.3 Microstructure observation

The microstructure was examined with an optical microscope and a scanning electron microscope (SEM). The deformation feature and fracture surfaces were also observed by means of SEM.

3. Results and discussion

3.1 Microstructure of TiAl alloys

The optical micrograph of CSD samples in Ti-48Al-2Mn-2Nb alloy shows a full lamellar microstructure in Fig.2. It consists of finer and random arrangements of lamellar colonies with some small pores. The average size of lamellar colonies is about 50~200 μ m in diameter. Within a lamellar colony, the laths of lamellar align themselves in nearly the same orientation, but they are

randomly arranged from lamellar colony to colony which intersect serrated-like each other among colonies without clear grain boundaries. The 2% porosity level of the samples was quantitatively measured using a Quantimet image analysis system. The interstitial pick up showed that there existed 300~750ppm of oxygen and 100~200ppm carbon (wt.%). In the lamellar structure of CSD samples, the spacing of laths varied from $1\mu\text{m}$ to $2\mu\text{m}$, which was observed by TEM and analyzed by diffraction patterns using selected area electron diffraction (SAED). In comparison, the microstructure of IM sample was also observed, which showed a typical full lamellar structure in Fig.3. It is clearly seen from Fig.3 that IM sample exhibits a coarse lamellar structure and a bigger colony grain size of 250-500 μm . Furthermore, they show the align directional lamellar of columnar grains. Comparing Fig.2 with Fig.3, we can find that the lamellar structure and colony of CSD is much finer than that of ingot metallurgy.

Fig.2. OM micrograph of CSD TiAl sample

Fig.3 OM micrograph of IM TiAl sample

3.2 Tensile and compressive properties of TiAl alloys

The mechanical properties of CSD alloy have been investigated at ambient temperature^(5,6). The tensile and compressive tests for IM samples were also carried out at ambient temperature. The tensile data are summarized in Table 1 for both CSD and IM alloys testing at RT. The results show that the mechanical properties of CSD alloy, including yield strength, tensile strength and elongation, are all higher or better than that of IM alloy.

Table 1 Tensile properties of TiAl alloys at RT

	Yield strength $\sigma_{0.2}$ (MPa)	Tensile strength σ_b (MPa)	Elongation δ (%)
CSD	251	305	2.8
IM	202	298	2.01

The results of Table 1 show the plastic strain values of TiAl alloys produced by CSD and IM are still low. However, it is important to note that the CSD alloy with a refined lamellar structure exhibits a better plastic strain than that of IM alloy, especially the elongation for CSD samples reaches 2.8%. According to the previous research results^(5,8), the tensile and compressive tests usually show that the plasticity with a duplex microstructure is better than that of fully lamellar microstructure because the former is more beneficial to improve the ability of homogeneous plastic deformation of samples than the latter. Here, CSD processing produced an essentially fully lamellar structure with a refined colony size of $50\mu\text{m}$. As expected, the CSD alloy with the refined lamellar structure exhibited considerably improved balances in mechanical properties over coarse full lamellar structure. It is interesting to point out that the plastic strain ability of CSD alloy with the refined lamellar structure can be comparable to those obtained from the fine duplex structure. Recently, efforts have been made in improving properties in cast alloys through alloy modification and by microstructure control⁽¹⁰⁾. In fact, IM processing contains many irregular and short segments, and such imperfections in the lamellar structure reduce its beneficial effect on mechanical properties and cause degradation of the lamellar structure at high temperature. This reasoning is supported by the fact that the coarse lamellar structure of IM alloy has a

very low tensile ductility at room temperature. The refined lamellar structure displayed by TEM suggests that the superior strength of CSD be mainly caused by a combination of extremely fine lamellar colony size and interlamellar spacing.

Table 2 shows the compressive properties of both CSD and IM TiAl alloys at RT. The results show that CSD alloy has excellent compressive properties with a higher compressive strength 2210MPa, and excellent plastic strain. An outstanding advantage of the CSD materials is the quite high plasticity obtained in compression conditions, in which the maximum compressive ratio is 33.9%, while the elongation for CSD samples is only 2.8%. Also we can find the similar results obtained by IM, where the compressive strength is 2047MPa, and the maximum compressive ratio of 29.5%. It is clear that the compressive strength and plasticity under compression is much higher than that in tension. It is well known that the shear stress is responsible to slip whereas normal stress to cleavage. Particularly, although some minute discrete cracks appear in both tension and compression conditions, and the cracks are open and quickly coalesce in tension, yet the cracks are closed in compression, and transfer of stress is still available to yield deformation go through the entire section of the specimens. The deformation and fracture mechanisms could be well characterized by means of a series of compressive strain tests.

Table 2 Compressive properties of TiAl alloys at RT

	Yield strength $\sigma_{0.2c}$ (MPa)	Compressive strength σ_{bc} (MPa)	Compressive ratio ε_c (%)
CSD	488	2210	33.9
IM	345	2047	29.5

Table 3 Compressive properties of TiAl alloys at 600°C

	Yield strength $\sigma_{0.2c}$ (MPa)	Compressive strength σ_{bc} (MPa)	Compressive ratio ε_c (%)
CSD	269	2625	58.8
IM	326	1594	38.3

It should be noted that there is a remarkable effect of temperature on the compressive strength and fracture toughness. Table 3 shows the effect of temperature on the compressive properties of both alloys. Generally speaking, the mechanical properties of alloy decrease with the increasing of temperature. Comparing to the results of room temperature, however, we can find an interesting result got at 600°C, which shows high compressive strength of 2625 MPa and better compressive ratio of 58.8% for CSD alloy. It is much higher than that of room temperature. Also, the ductility of IM alloy shows a moderate increase with temperature and reaches the maximum of 38.3% at 600°C, but the compressive strength decreased with the increasing of temperature. It is obvious that CSD alloy has a better high temperature compressive properties than that of IM alloy. In the case of compressive tests, it seems that there is a critical transition temperature for compressive strength with the change of temperature. Under this transition temperature, the compressive strength decreases with increasing of temperature, but the compressive strength increases abnormally with increasing of temperature above this critical temperature. The detail is under investigation.

3.3 Fracture toughness of TiAl alloys

Table 4 lists the fracture toughness of CSD and IM TiAl alloys at room temperature and 800°C.

Table 4 Fracture toughness of TiAl alloys

	Toughness K_{IC} (MPa $\sqrt{m}$) at RT	Toughness K_{IC} (MPa $\sqrt{m}$) at 800°C
CSD	23.6	---
IM	25.34	31.48

It can be seen that CSD alloy also shows a better fracture toughness of 23.6 MPa $\sqrt{m}$ at room temperature. It indicates that the lamellar structure for CSD has a better resistance to crack growth at high temperature. In the case of the lamellar structure, which possess good creep resistance at elevated temperature and fracture toughness at room temperature, the mechanical properties are strongly dependent on the colony size and interlamellar spacing. The previous research results⁽⁵⁻⁷⁾ also indicate

that the lamellar structure for CSD samples has a better resistance to crack growth than a duplex structure for HIP samples, although there are some pores existed in CSD samples. Therefore, CSD samples with the refined lamellar structure exhibit a better toughness. However, it is interesting that the IM alloy with the coarse lamellar structure exhibits higher fracture toughness value than that of CSD. It is proved that coarse lamellar structure has a better resistance to crack growth than finer lamellar structure. Another important result is that fracture toughness increases with increasing of temperature within the ranges of testing temperature. The fracture toughness for IM alloy increases to 31.48 MPa $\sqrt{m}$ at 800°C. This is consistent with the higher tensile ductility of TiAl alloy at high temperature.

4. Conclusions

(1) CSD samples in Ti-48Al-2Mn-2Nb alloy show a finer full lamellar microstructure with lamellar colonies of 50~200 μm , while IM samples exhibit a coarse lamellar structure with a bigger colony of 250-500 μm .

(2) In tensile tests, both CSD and IM show still low plastic strain, but CSD alloy with a refined lamellar structure exhibits a better value than that of IM alloy, and the elongation for CSD samples reaches 2.8%. The tensile properties of CSD alloy are also higher or better than that of IM alloy.

(3) The compressive results show that CSD alloy has excellent compressive properties with a higher compressive strength 2210MPa and excellent compressive ratio of 33.9%, while the compressive strength of IM alloy is 2047MPa, and the maximum compressive ratio of 29.5%. Moreover, CSD alloy exhibits higher compressive strength of 2625 MPa and better compressive ratio of 58.8% at 600°C.

(4) CSD also shows a better fracture toughness of 23.6 MPa $\sqrt{m}$ at room temperature, while the IM alloy

with coarse lamellar structure has a higher fracture toughness of 25.34 MPa $\sqrt{m}$ at room temperature, and 31.5 MPa $\sqrt{m}$ at 800°C.

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