[Article ID] 1003- 6326(2002)04- 0605- 05

Recent developments in engineering γ-TiAl intermetallics①

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[Abstract] γ-TiAl based alloys are rapidly being developed for elevated temperature applications, due to their high strength, light mass and good oxidation resistance. However, the disadvantages of TiAl based alloys are low ductility and toughness at room temperature, and poor workability. Grain refinement is one of the most effective ways for improving room temperature tensile properties and hot workability of ordered TiAl based alloys. At present, the majority of research works have focused on alloy modifications through compositional controls, alloying additions, thermo-mechanical processing and production techniques. This article discusses the research status of TiAl based alloys in the areas of microstructure, alloying, processing and applications.

[Key words] TiAl based alloys; intermetallic; properties; melting; processing
[CLC number] TG146.2 **[Document code]** A

1 INTRODUCTION

γ-TiAl based alloys are now finding growing application in the aerospace, power generation and automotive industry due to their high strength, light mass and good oxidation resistance. γ-TiAl based alloys have been vigorously researched for the past twenty years. As a result of these studies the fundamental behaviour of the alloys is now well understood, and a number of γ-TiAl based alloys with commercially acceptable properties have been developed. Future challenges for these alloys are focused on the development of large scale production routes.

The γ-TiAl phase has the $L1_0$ ordered face-centered tetragonal structure, with a wide range of homogeneity. The γ-TiAl phase remains ordered up to its melting point of roughly 1450 ℃. Gamma alloys may be used up to 760 ℃. However, the disadvantages of TiAl based alloys are low ductility and toughness at room temperature, and poor workability.

At present, a number of engineering alloys are emerging which have a good balance of physical and mechanical properties. Table 1 lists the selected classification of γ-TiAl based alloys for each generation[1].

Now the majority of research works have focused on alloy modifications through compositional controls, alloying additions and fabrication techniques, which can improve the low temperature ductility and toughness, high temperature creep resistance, processing properties and so on. This article discusses the research status of TiAl based alloys in the areas of microstructure, alloying, processing and applications.

2 MICROSTRUCTURE—PROPERTY RELATION

Many research works on TiAl based alloys have indicated that microstructure plays an important role in the tensile and fracture behaviors of alloys. At present, the majority of microstructure development studies have focused on ductility and toughness enhancement, deformation and fracture behavior, and creep behavior[2,3].

TiAl based alloys include single phase alloys and double phase alloys. Recent developments have concentrated on double phase Ti-rich alloys (Al content lies in the range of 46% ~ 49%, mole fraction), which usually contains a mixture of both γ phase and α_2 phase, with the ratio of γ grain to lamellar colony depending on alloy composition and heat treatment. In double phase alloys, both the amount of α_2 phase and the relative volume fraction of lamellar and equiaxed γ grains are important factors in controlling the tensile and fracture properties of two phase TiAl based alloys[4~6]. Maximum tensile ductility was obtained in a two phase TiAl based alloy containing approximately 10% (volume fraction) α_2 phase. The best balance of properties with good elevated temperature creep resistance and acceptable tensile strength and ductility in current two phase TiAl based alloys appears to occur at about 30% lamellar grains and 70% (volume fraction) equiaxed grains[7].

Double phase TiAl based alloys can be mani- pu-

① **[Foundation item]** Project supported by Chinese National Education Ministry Youth Foundation
[Received date] 2001- 10- 08

lated by heat treatment to obtain various microstructure, including near gamma (NG), duplex (DP), nearly-lamellar (NL), and fully-lamellar (FL) microstructures[8]. Lamellar colonies are comprised of alternating layers of α_2 and γ platelets aligned according to $(0001)_{\alpha_2}//\{111\}_\gamma$ and $\langle 11\bar{2}0\rangle_{\alpha_2} \parallel \langle 1\bar{1}0\rangle_\gamma$ crystallographic relations.

In general, DP microstructure can yield the good ductility and reasonable strength, but results in the low fracture toughness and high temperature creep resistance. NL microstructure results in the highest strength with reasonable ductility. FL micro-structures generally have large grains which result in low strength and poor ductility, but excellent fracture toughness. A general conclusion was drawn that materials with FL microstructure exhibit superior balanced properties over DP materials[9~12]. Table 2 lists mechanics properties of some typical γ-TiAl based alloys.

2.1 Grain refinement

It is now well known that the room temperature tensile yield strength, fracture strength, and ductility of TiAl based alloys increase with decreasing the colony size of the lamellar structure (as shown in Fig. 1). For example, grain refinement in materials with FL microstructure appears to improve RT strength and ductility. Therefore searching a cost-effective approach to refine the coarse FL structure becomes critical to the engineering application of this material. By applying a serious of heat treatment procedures, the fine FL microstructure can be obtained, which exhibits a better combination of toughness and ductility. Mechanical testing in tension shows that with the grain refinement from 500 μm to 10 μm, the room temperature yield strength increased from 330 MPa to 610 MPa, fracture strength from 415 MPa to 825 MPa and ductility from 0.7% to 3.3%, although the fracture toughness decreased only slightly from 24 MPa·m$^{1/2}$ to 19 MPa·m$^{1/2}$[13]. Investigations were conducted to develop refined FL microstructures though the designated means[1] — RFL (Refined fully-lamellar) and TMTL (Thermo-mechanically treated lamellar) by alloy modification being often with innovative heat-treatment cycles, and TMPL (Thermomechanically processed lamellar) by non-isothermal hot-work in the high temperature alpha phase field. This is also benefits for promoting the practical engineering applications of TiAl based alloys.

Tabel 1 Classification of γ-TiAl based alloys[1]

Generation	Composition (mole fraction) / %	Processing
1st	Ti-48Al-1V-0.3C	Exploratory
2nd	Ti-47Al-2(Cr, Mn)-Nb Ti-(45~47)Al-2Nb-2Mn-0.8TiB$_2$	Cast Cast XD
3rd	Ti-47Al-2W-0.5Si Ti-47Al-5(Cr, Nb, Ta) Ti-46.2Al-2Cr-3Nb-0.2W	Cast Cast Wrought
4th	Ti-(45~47)Al-(1~2)Cr-(1~5)Nb-(0~2)(W, Ta, Hf, Mo, Zr)-(0~0.2)B-(0.03~0.3)C-(0.03~0.2)Si-(0.15~0.25)O-X	Wrought/Cast

Table 2 Mechanics properties of typical TiAl based alloys at room temperature

Alloy composition (mole fraction) / %	Treatment and microstructure	σ_s/MPa	σ_b/MPa	δ/%	K_{IC}/(MPa·m$^{1/2}$)
Ti-48Al-1V-0.2C-0.14O$_x$	Cast	490			24.3
Ti-48Al-2Cr-2Nb	Cast, HIP, HT(DP)	331	413	2.3	20~30
Ti-47Al-1Cr-1V-2.6Nb	Wrought, HIP, HT(FL)	508	588	1.1	22.8
Ti-47.3Al-0.7V-1.5Fe-0.7B	Cast		520	0.6	
Ti-47Al-2W-0.5Si	Cast, HT	425	520	1.0	22
Ti-47Al-2Nb-2Mn-0.8B	Cast, HIP, HT(NL)	402	482	1.5	15~16
Ti-46.2Al-xCr-y(Ta, Nb)	Cast, HIP, HT(NL)	442	575	1.5	34.5
Ti-47Al-2Nb-2Cr-4Ta	Cast, HIP, HT	430	515	1.0	
Ti-46.5Al-2Cr-3Nb-0.2W	Wrought, HT(FL)	475	550	1.1	21.5

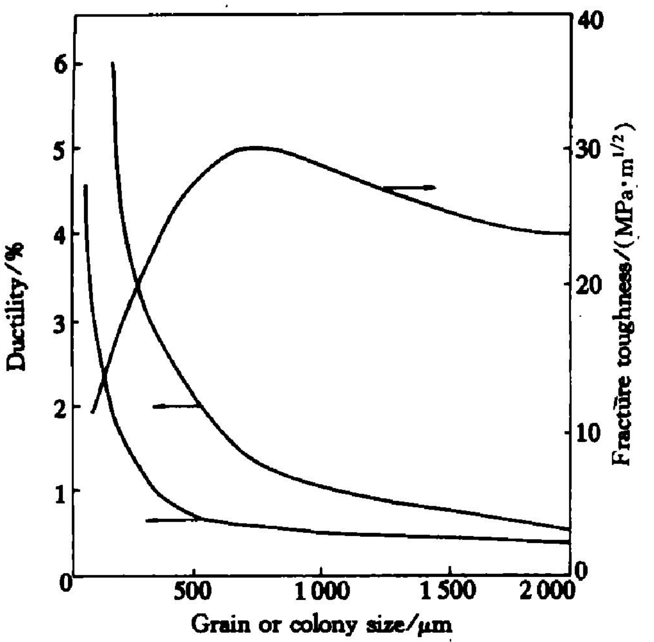

Fig. 1 Inverse ductility/fracture toughness characteristic of TiAl based alloys[18]

2.2 Yield strength —microstructure relationships

The relationship between the yield strength and microstructure parameters of a FL TiAl based alloy has been studied systematically. The grain size and the lamellar spacing were chosen as microstructure parameters. Plenty of experimental results showed that the yield strength increases with the decrease of grain size and more obviously with the decrease of the lamellar spacing. The relationship between yield strength and grain size and lamellar spacing can be approximately described by Hall-Petch relation[14].

2.3 Methods of improving ductility

The ductility of gamma alloys is a strong function of alloy composition and microstructure. The methods of improving ductility of TiAl based alloys are as follows[15]: 1) the ductility improvement can be caused by decreasing lattice tetragonality or decreasing unit cell volume; 2) decreasing Al content in γ-TiAl may be responsible for the increased ductility; 3) additions of V, Cr, Mn (1% ~ 3%, mole fraction) can increase ductility; 4) a decrease in impurity level can increase ductility, an experiment on a two-phase binary Ti-48Al showed that the tensile elongation increased from 1.9% to 2.7% when the oxygen level was decreased from 0.08% to 0.03%; 5) for a given alloy composition, the ductility strongly depends on the L/γ grain volume ratio and α_2/γ phase volume ratio as well as grain size, so we can increase ductility through controlling L/γ grain volume ratio and α_2/γ phase volume ratio; 6) the presence of twins and lamellar microstructure, and a decrease in grain size can increase ductility of TiAl based alloys; 7) some special processing methods, such as cycling heat-treatment, HIP technology, thermomechanically treated technology, directionally solidifying technology, rapid solidification technology and so on, are also effective ways for improving room temperature ductility; 8) decreasing environmental embrittlement of TiAl based alloys can improve ductility[16].

2.4 Fracture toughness —microstructure relation

In general, fracture toughness (K_{IC} or K_{S}) increases with colony size (as shown in Fig. 1). Fracture toughness of lamellar TiAl based alloys increase with decreasing lamellae spacing in a manner similar to the Hall-Petch relation. Control of lamellae spacing is essential for improving the fracture toughness of lamellar TiAl based alloys with a large colony size[17].

2.5 Balance of properties

Because an inverse relationship exists between the ductility and toughness (as shown in Fig. 1), each feature should be combined to yield a synergistic balance of properties. Currently, a desired microstructure may then be selected from FL materials having the following microstructural features and ranges[1]: 1) FL microstructures; 2) average α_2/γ volume ratio of 0.05~ 0.25; 3) grain size range of 50~ 250 μm; 4) lamellar spacing (λ) in the range of 0.05 μm~ 0.5 μm; 5) serrated grain boundaries with a minimum number of small grains or coarsened features; 6) textured lamellar structures when anisotropic properties are required.

3 ALLOY COMPOSITION

The mechanical properties of TiAl based alloys have been improved in recent years by alloy additions. Alloying elements of TiAl based alloys include C, N, B, V, Cr, Mn, Fe, Co, Ni, Ce, Zr, Nb, Mo, Hf, Ta, W, Ge, In, Sb, Ga etc[18].

Currently TiAl based alloys have compositions based on Ti-(44~ 51)Al-(1~ 10)M-(0~ 1)N (mole fraction, %), where M represents at least one element from V, Cr, Mn, Nb, Ta, W, Mo etc, and N represents at least one element from C, N, B, O, Si etc.

The alloying elements can be categorized in five group. The elements in the first group, which includes V, Mn, Cr, Mo, B, RE, Sn, Ni and C, increase the ductility of TiAl based alloys. The second group of elements includes Nb, Cr, W, Mo, Ta, Si, P and Sb, which are effective in enhancing oxidation resistance. The third group of elements is represented by Si, Er, Nb, W, Ta, C, N and O. Small additions of this group of elements in TiAl based alloys lead to improvements in creep resistance. The fourth group of elements is represented by Cr, C and N, which can improve fracture toughness of TiAl based alloys. The fifth group of elements is represented by Nb, Mo and B, which have been developed to improve strength of TiAl based alloys.

4 MELTING AND PROCESSING

The gamma ingots have been prepared using various melting methods, including induction skull melting, vacuum arc remelting, plasma arc melting, electronic beam melting and vacuum induction melting[19]. Both single phase and two phases gamma alloys can be processed via ingot metallurgy (extrusion, forging, rolling), powder metallurgy (PM) and precision casting routes[20~24].

Ingot metallurgy (IM) processing, such as forging of cast products, has been the primary method of materials fabrication. Refining of grains and subgrains by multistep forging appreciably improves ductility of the TiAl based alloy. Isothermal forging is an extremely effective process for manufacturing TiAl products. It is confirmed that it is possible to work plastically even from cast ingot samples and that the mechanical properties can be improved by isothermal forging. However, frequently the cast forging stock has not been homogenized to eliminate casting segregation inherent in these alloys.

At present, powder metallurgy technique is another important TiAl based alloy processing method. Through a relatively low temperature, but high pressure HIP process, fully dense gamma titanium aluminide prealloyed powder compacts with very fine grain were obtained. The microstructure refinement was the result of retention of the rapidly solidified powder particle. Powders with finer particle grain resulted in finer compact microstructures.

The gamma TiAl based alloy casting technology has advanced considerably after solving various problems such as cracking, hot tearing, surface-connected porosity, filling, and dimensional accuracy. For example, the casting duplex Ti-47Al-2Cr-2Nb alloy exhibits a reasonable balance of properties[25].

Investment casting is regarded as an economic processing and viable technology for the production of γ-TiAl based components. However, as-cast TiAl based alloy was unacceptably low values in ductility and strength for many applications, due mainly to the coarse and nonuniform cast lamellar microstructure. Most of the large grains of casting TiAl based alloy can be refined after hot-isostatic pressing and heat treatment.

Mechanical properties of the lamellar of casting TiAl based alloys are extremely anisotropic with respect to the lamellar orientation. If the lamellar microstructure can be aligned parallel to the growth direction, the resulting material should possess a good combination of strength and ductility. Unfortunately, simple casting operations often lead to a solidification texture with the lamellar boundaries all perpendicular to the heat flow direction. This difficulty can be overcome by directionally solidified (DS) TiAl based alloys[26]. Successful DS structures were produced in Ti-48Al-2Nb-2Cr with a specially developed ceramic shell system designed to limit reactivity with alloys. The DS ingots were also found to exhibit a high yield stress with a reasonably large tensile elongation at room temperature.

5 APPLICATIONS

TiAl based alloys exhibit high temperature mechanical properties that make them attractive candidates for a variety of applications in advanced turbine engines, aircraft engines and automotive engines. They were developed for engine hot parts in an effort to replace current Ni-based superalloys. For example, TiAl based alloys are intended for use in turbine engines parts such as low-pressure turbines, high-pressure compressor blades, high-pressure turbine blade cover plates, transition duct beams, vanes, swirlers and so on.

TiAl based alloys are very suitable materials for engine valves in the automobile industry. The application of TiAl based alloys as an exhaust valve material would allow automotive engines to operate at higher temperatures with increased efficiencies. Although TiAl based alloys suffer from low ductility and toughness at ambient temperatures which, along with poor formability, appears to be the single most serious obstacle to their full utilization, the key to successful application of TiAl based alloys for automotive engine valves is not optimization of formability and ductility, but rather the development of a low-cost, high-volume manufacturing method. Recently TiAl turbocharger wheels have finally started being used for turbochargers for commercial passenger cars of a special type. However, these automotive engines tests have indicated that TiAl based alloys parts will require tip protection and stem coating.

6 SUMMARY

With the development of alloy composition and processing technologies, TiAl based alloys are becoming more and more important engineering materials.

Although the fundamental understanding of TiAl based alloys has progressed greatly over the last decade, there are still some problems to solve. Key shortcoming of the current properties include[27]: inverse relations between tensile properties and fracture/creep resistance, resulting in unbalanced properties; relatively low high-temperature strengths for many of the turbine engine parts in use up to 1000 ℃; low oxidation resistance above 800 ℃.

So the relationships between microstructure, composition, processing methods and properties must be identified. More research work, including melting technology, microstructure control, advanced processes technology and so on, is thus needed to achieve an improved balance of tensile strength, ductility, creep rupture strength, fracture toughness and some other properties.

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(Edited by YANG Bing)