

## Some New Aspects in Developing TiAl Based Alloys as Competitive High Temperature Materials

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**Abstract:** In order to make the TiAl Intermetallics-based materials more competitive with conventional superalloys, further work on microstructure modification and alloying process has been carried out specific to the cast and wrought process, respectively. It is proved that directional lamellar microstructures can be formed in the cast TiAl. Those microstructures have demonstrated preponderant mechanical properties under unidirectional load after the cast porosity being removed by HIP at proper temperatures. This microstructure design specific to the rotating parts has benefited the endurance capacity of cast TiAl turbochargers. On the other hand, the additions of Gd have shown significant effect in refining the lamellar microstructures of forged TiAl alloys but do not bring out the detrimental influence to the tensile ductility. The reason is that the Gd-containing precipitates can greatly impede the growth of  $\alpha$  grains while themselves dispersing during the thermal process. Upon those technology advances, the further success of TiAl alloys' applications is prospected.

### Introduction

Titanium Aluminides are promising to be developed as substitutes for Ni-based superalloys due to their attractive specific strength and excellent oxidation resistance [1, 2]. In the last decades, certain applications of two-phase TiAl alloys such as automobile turbochargers [3] and low-pressure turbine blades for air engines [4] have been successfully accomplished and well demonstrated their light-weight preponderance. However, those Intermetallics-based materials for cast or ingot metallurgy are still not yet very competitive with conventionally used superalloys due to their intrinsic brittleness and the comparatively higher manufacturing cost. Thus, it is clear that the further success of TiAl applications depends on a step forward of microstructure modification and alloying process specific to the cast and wrought process, respectively [5].

According to the mechanical anisotropy of the PST crystals [6], forming directional  $\gamma$ -TiAl/ $\alpha_2$ -Ti<sub>3</sub>Al lamellar microstructures in the cast samples has shown great promise to achieve an improved ambient ductility and better strength retention at elevated temperatures during loading along their lamellar interface [7]. While, in principle, cast flaws like gas and shrinkage pores inevitably exist in the final solidification area of cast plain specimens and blades, they will deteriorate the mechanical properties. So, the current research examines the samples' section by optical metallographic observation. Subsequently, hot isostatic pressing (thereafter abbreviated as HIP) is employed to remove the cast flaws but to keep the orientation characteristics of the cast microstructure at meanwhile. The mechanical experiments and the endurance tests of the turbocharger components have been finally conducted to investigate the benefits of the proposed casting and HIP techniques.

Along a different development line, thermo-mechanical treatment has shown a significant effect in refining the microstructures of ingot metallurgy TiAl. Nevertheless, fully lamellar or near fully lamellar microstructures that are believed to have desirable strength retention as well as fracture and creep resistance generally consist of large-size colonies which are definitely detrimental to the ductility of the alloys [2]. According to the well-understood transformation mechanism of fully lamellar microstructures, the introduction of finely dispersed secondary phase particles which are thermodynamically stable at single  $\alpha$ -phase temperatures may serve as obstacles to retard the growth of  $\alpha$  grains. Several trials have proved that using borides, carbides or oxides can significantly decrease the size of lamellar colonies while in many cases those hard phases deteriorate the ambient ductility [8, 9]. So, there is still a need to find out new pinning phases without detrimental influence on ductility. A possible way is to reduce the size and distribution of the particles. A recent work suggested that the Gd-containing phase that was tentatively identified as  $\text{Gd}_2\text{TiO}_5$  in Ti-44Al-0.15Gd alloy had a complicated finger shaped morphology in the as-cast material but changed to become discrete particles in the form of particulates after solution treatment at 1350°C. But, it is still unclear at the moment why these oxides could dissolve and re-precipitate in this alloy [10]. Therefore, this study prepared a TiAl alloy with minor Gd additions by thermal mechanical process and carefully observes the evolution of the microstructures, especially the Gd-containing phases. The advance of the wrought TiAl containing Gd is also evaluated preliminarily by tensile testing.

### Materials Preparation and Test Methods

The cast Ti-47.5Al-2.5V-1.0Cr alloys was smelted in a vacuum cold crucible induction levitation-melting furnace and cast into an investment ceramic mould to produce  $100 \times 80 \times 10 \text{ mm}^3$  plain plates for mechanical property experiment and  $\phi 135 \text{ mm}$  turbocharger for the endurance test in a diesel engine. Thereafter, the samples were compacted by HIP at 1240 – 1320°C temperature range in 120 – 150MPa Argon for 2.0 – 3.0 hours. The specimens for mechanical property tests were cut from the cast plates along their longitudinal direction by spark erosion technique and then ground to the final dimensions according to the Chinese national standard GB/T series that are basically coincident with the ASTM standard. The testing items include normal and notch tension tests, fracture resistance, creep rupture life and high cycle fatigue.

The ingot of Ti-46.5Al-2.5V-1.0Cr -0.15Gd alloy was also prepared in the vacuum cold crucible induction levitation-melting furnace and forged to 85% height reduction in two-step process at 1100°C, and then treated at 1300°C for 2 hours to get near fully lamellar microstructure. The tensile specimens were taken along the radius of forged pancake after heat treatment.

All the metallographic specimens of both cast and wrought TiAl were mechanically polished. Then, the cast flaws before and after HIP were examined under optical microscopes. The precipitates in the Gd-containing wrought ingots were identified using the back-scattering images and their compositions were analyzed by EDS in a scanning electronic microscope (abbreviated as SEM). All samples for optical and SEM microstructure observations were dip-etched by a hydro-solution containing 2%HF and 10% $\text{HNO}_3$ .

### Results and Discussion

#### Microstructures and porosity in cast TiAl plates

Macro observation showed that columnar grains fully permeate the cast plain plates and the turbocharger blades from the both outer surfaces when the pouring temperatures and cooling rates are well controlled (Fig.1). Under the optical microscope, the  $\gamma$ -TiAl/ $\alpha_2$ - $\text{Ti}_3\text{Al}$  lamellae in the cast samples and turbochargers preferentially align parallel to the plates' or the blades' surfaces that is

vertical to the growing direction of the columnar crystal (left picture in Fig.2). It is reasonable, if referring to HCP structure, that the  $\alpha$  columnar crystal usually grows preferably along its [0001] direction [11] and then the  $\gamma/\alpha$  lamellae and thereafter  $\gamma/\alpha_2$  lamellar structure are generated during the cooling process through the  $\gamma$  plates precipitating on the  $(0001)_\alpha$  habit plane of  $\alpha$  columnar crystal.

It was found that the lamellar structure is stable at temperatures up to 1280°C and 3 hours annealing time (right picture in Fig.2). So, HIP should be employed to remove the gas and shrinkage pores at 1280°C or lower but with a longer time in order to keep the orientation characteristics of the cast microstructures.

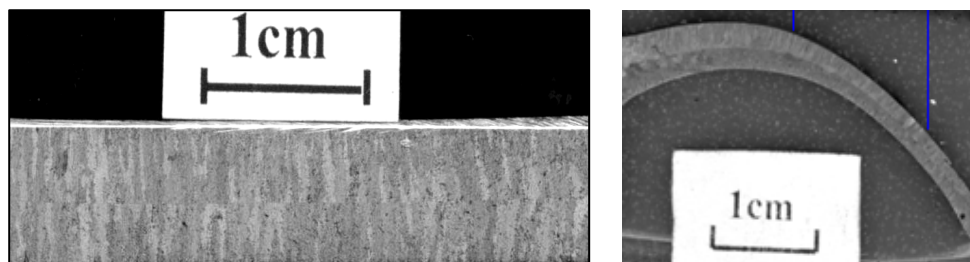


Fig.1 Macro morphologies of the cast plain plates and turbocharger blades

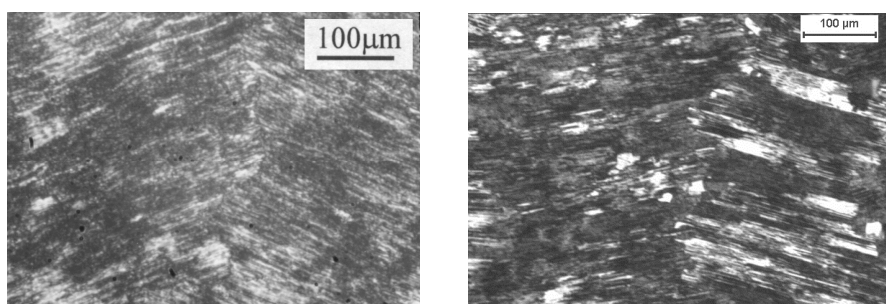


Fig.2 Optical microstructures of cast plates before (left) and after (right) HIP at 1280°C for 3 hours.

Quantitative metallographic examination indicated that the cast flaws at the central line area include gas and shrinkage pores ranging from 10 to 300 μm (left picture in Fig.3), while those in the outer part are only gas pores smaller than 10 μm. Usually, the final solidification part should be shifted to the feeding head and then cut out in the normal casting processes. However, the directional lamellar microstructures obtained as cast are intended to be adopted for applications. So, the central cast flaws formed during final solidification can only be removed through HIP. It was found that the HIP at 1280°C for 3 hours or at 1260 °C for 4 hours is effective to remove and/or compact the cast pores in the both TiAl plates and turbochargers. No porosity was found larger than 20 μm after the HIP (right picture in Fig.3).

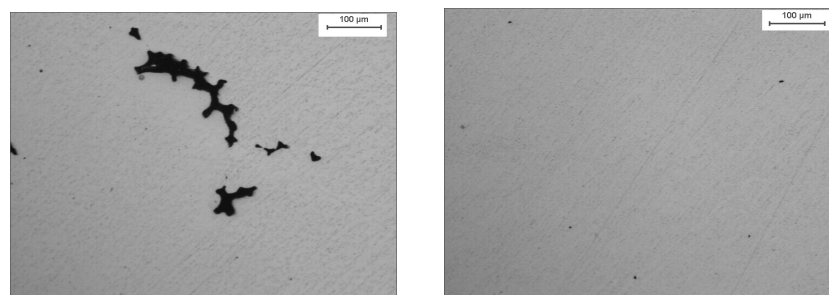


Fig.3 Micrographs showing porosities at center of cast plates before (left) and after (right) HIP.

### Mechanical properties of the cast samples and turbochargers

The tensile properties of the specimens taken from both as-cast and HIP plates were listed in Table 1 for comparison. As expected, the results of as-cast specimens vary in a wide range while those of HIP samples exhibit a rather small scatter with dramatically improved lower bounds for ductility and strength. So, it is reasonable to assume that the porosity has significant influence on the tensile properties of cast TiAl and that the HIP is effective to make the directional lamellar microstructures demonstrate their mechanical preponderance. Thus, other mechanical properties were also tested for assessing the materials properties after HIP. Results include an ambient tensile strength of R=0.2mm notched specimens of 680MPa, a fracture toughness  $K_{IC} = 25 \text{ MPa}\sqrt{\text{m}}$ , a 800°C/200MPa creep rupture life longer than 200 hours and 750°C/240MPa high cycle fatigue life  $> 10^7$ . Those results clearly demonstrate the advantages of the cast directional lamellar microstructures.

Table1 Mechanical test results taking samples from cast and HIPed TiAl plates

		Minimum result	Maximum result
As Cast	$\delta_5$ at 20°C	< 0.5%	2.0
	$\sigma_b$ at 20°C	200 MPA	640MPa
After HIP	$\delta_5$ at 20°C	1.5%	2.5%
	$\sigma_b$ at 20°C	610MPa	650MPa
	$\sigma_b$ at 800°C	550MPa	560MPa

The most fragile parts of turbochargers are the thin blades, thus, forming directional lamellar microstructures in the blades should be beneficial to the mechanical reliability of TiAl turbocharger wheels. Recently, such wheels have successfully passed a 100 hours rig test with rotating tribulation up to 91,000 rpm, acceleration pedal response evaluation (from the tape rate to the normal speed) and 500 hours running operation in a diesel engine. No any mechanical damage was found on all the tested TiAl turbochargers (Fig.4).

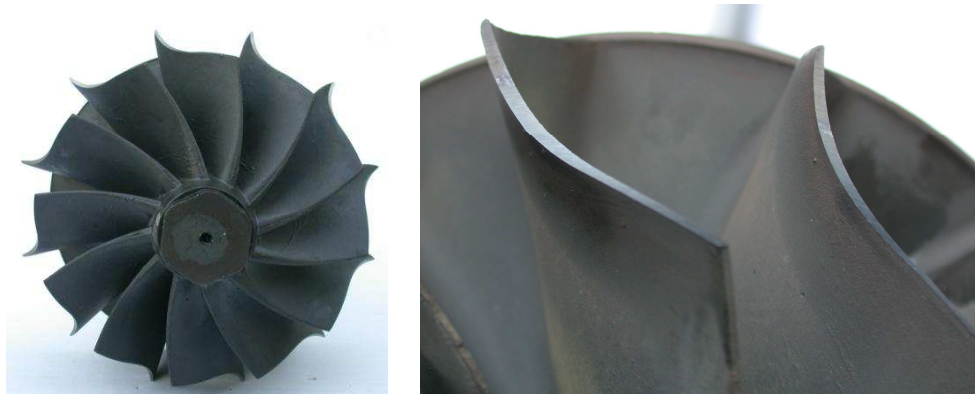


Fig.4 Turbocharger wheels after 500 hours running operation in a diesel engine.

### Evolution of microstructure and Gd-containing precipitates in the wrought TiAl

Optical observation shows a greatly refined and homogenized near full lamellar microstructure that was produced in the wrought Gd-containing TiAl alloy (Fig.5). The microstructure contained about 90% volume fraction of lamellar colonies with an average colony size of 40 $\mu\text{m}$ . The precipitates were clearly seen located mostly along the colony boundaries.

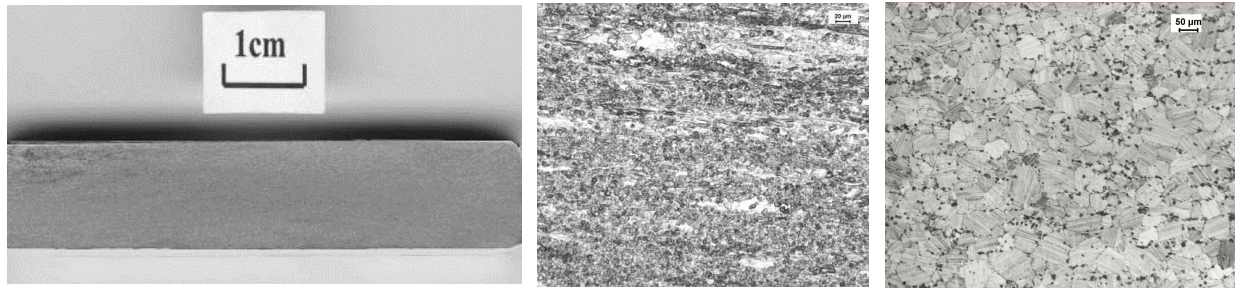


Fig.5 Optical micrographs from left to right showing the macro-and micro-structure of as forged TiAl, and near fully lamellar microstructure obtained by heat treatment in the Gd-containing TiAl

The configuration and evolution of Gd-containing phases in the as-cast, as-forged and heat treated conditions showed obvious dispersion process (Fig.6). At higher magnification it is noteworthy that the precipitates show different contrast grades in the back-scattering mode (Fig.7). Additional EDS analyses (Table 2) suggest that these precipitates may represent Gd-containing aluminides and oxides, respectively. Also, it seems as if the aluminides possess a larger volume fraction. In conclusion, it may be reasonable to assume that the Gd-containing precipitates can dissolve and re-precipitate in the thermal process. However, the detailed transformation mechanism is still under investigation.

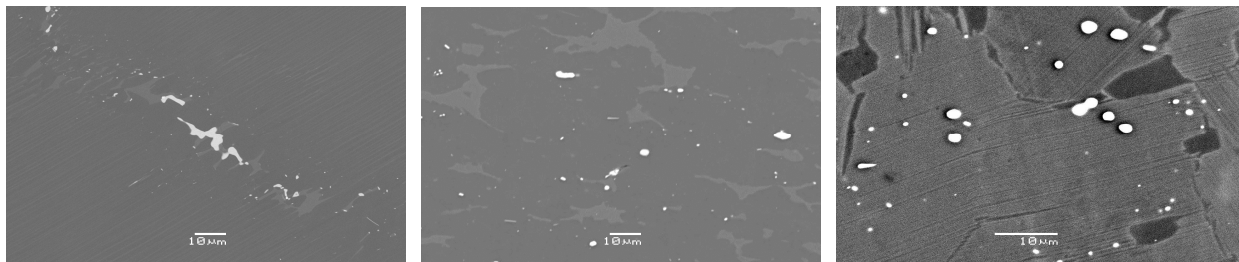


Fig.6 Back scattering images of Gd-containing phases in cast, forged and heat treated specimens

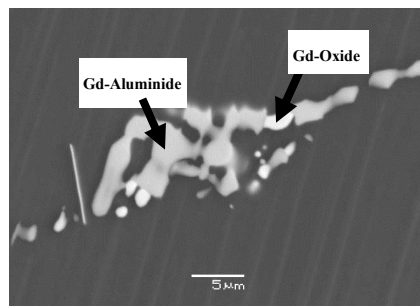


Fig.7 Back scattering image showing contrast grades of the precipitates in cast specimens

Table2 EDS results of precipitates showing different contrast grades

Precipitates	Composition (at.%)		
	Gd	Al	O
Lighter phase	50.76	- - -	49.23
Grey phase	33.89	64.11	- - -

A first preliminary tensile test of the wrought TiAl refined by minor Gd addition revealed surprisingly good values of 3.5% ductility and 710MPa ultimate strength at room temperature. This significant advancement of the ambient tensile properties of the lamellar microstructures is probably due to the contribution of the reduced lamellar colony size and the well dispersed precipitates.



## Summary

Directional lamellar microstructures can be formed in cast and subsequently HIP-modified TiAl using properly selected temperatures. Those microstructures designed specific for the rotating parts have demonstrated preponderant mechanical properties under unidirectional load and in addition shown benefit in the endurance tests of cast TiAl turbocharger wheels.

Refined lamellar microstructures of Gd-containing TiAl can be obtained by heat treatment at the temperatures near the single  $\alpha$  phase transition point after forging. No detrimental influence on the tensile ductility was found since the Gd-containing precipitates can greatly impede the growth of  $\alpha$  grains. It may be concluded that the present advances will promote the TiAl intermetallics-based materials to be more competitive with conventional superalloys.

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