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Tougher TiAl alloy via integration of hot isostatic pressing and heat treatment

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ABSTRACT

A special processing method integrating the hot isostatic pressing and heat treatment was developed to produce TiAl alloy. As compared with the traditional two-step method, which consists of separate hot isostatic pressing and subsequent heat treatment in vacuum, the integrated approach will introduce an isostatic pressure throughout the whole process from the consolidation of powder to the heat treatment of coupon. Two types of microstructure, i.e., lamellar and duplex, have been generated by integrated and separate methods. Tensile test at room temperature indicates that the yield strength and tensile elongation of lamellar microstructure generated by integrated method are 650 ± 30 MPa and $2.1 \pm 0.2\%$ respectively, which are improved simultaneously as compared with 550 ± 28 MPa and $0.6 \pm 0.1\%$ for sample generated by separate approach. Moreover, such simultaneous enhancement of yield strength and ductility is also observed in duplex microstructure, where the yield strength and tensile elongation increase from 420 ± 18 MPa and $2.4 \pm 0.4\%$ in samples with separate method, to 540 ± 25 MPa and $3 \pm 0.3\%$ in those generated by integrated approach. Additionally, the microstructural examination also revealed the influence of microstructure to the mechanical performance. The results show that the simultaneous improvement of yield strength and tensile elongation is mainly attributed to the suppression of cracking, which is prone to happen during heat treatment without atmospheric pressure. Using the integrated method, the isostatic pressure could sustain the equilibrium pores during heat treatment, and provides an exterior force to balance the potential internal stresses due to phase transformation.

1. Introduction

TiAl intermetallic alloy is one of the most potential candidates for advanced aero-engine materials due to its high specific strength at elevated temperatures [1–6]. However, the extremely low tensile ductility at room temperature strongly hinders its applications in industry. For instance, the elongation to failure of many TiAl alloys is typically less than 1% at room temperature, which results in low damage tolerance and makes it difficult for manufacturing and component assembling. Therefore, strategies to improve the mechanical properties of TiAl alloys at ambient temperature have attracted much interest during last two decades [7–12].

In contrast to ductile metals and alloys, a significant improvement of tensile ductility for TiAl intermetallic alloys at room temperature is practically impossible and dispensable. The lattice dislocations of intermetallic alloys are hardly to be activated at relatively low temperature. Once they were activated substantially (followed by high tensile ductility in logic), their high temperature strength would be deteriorated drastically. Based on the design criteria for aero-engine components, an elongation to failure of 3% would be able to meet the requirements in industry [13]. The optimization of mechanical properties for TiAl alloys could be achieved through micro-alloying and microstructure controlling, which have produced attractive synergies of tensile strength and ductility [14–19].

The mechanical properties of TiAl intermetallic alloys are between brittle ceramics and ductile metals. When deformed at room temperature, a little dislocation behavior could be activated in equiaxed γ grains or special oriented γ lamellae, which results in strain hardening and thus uniform elongation [20,21]. However, the mechanical properties of intermetallic TiAl alloys are extremely sensitive to defects in microstructure. Therefore, the defects such as microcrack in TiAl alloys always result in premature failure during tensile deformation, leading to both low tensile strength and low elongation to failure [22]. In addition, in order to obtain an optimized combination of strength, ductility and toughness, heat treatments are always required to adjust the microstructure of TiAl alloys. Since the solid phase transformations are always prevalent and there is no atmospheric pressure during heat treatment, those microcracks would be generated as a result of internal

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stresses, which make the sample or component defective prior to testing or service. Accordingly, the modifications in traditional heat treatment processes to suppress the formation of defects and produce the defect-free samples or components would be significant step towards enhancing mechanical properties in TiAl alloys.

Atmospheric pressure during heat treatment has been developed in special field to recover the mechanical properties of turbine blades in industry [23,24]. With a hot isostatic pressing atmosphere, the micro-voids or microcracks could be reclosed and thus the rejuvenated mechanical properties would be obtained. Inspired by the advantages of pressure to heat treatment, we have taken the hot isostatic pressing (HIP) technique to provide a pressure environment during heat treatment to suppress the potential formation of microcracks in TiAl intermetallic alloys. Based on HIP technique, a special processing method integrating HIP and heat treatment (IHH) was designed. For comparison, traditional separated HIP and subsequent heat treatment (SHH) in vacuum was also conducted.

The present study explores the economical strategy for improving the mechanical properties of TiAl alloys, especially for components with relatively complex geometries and large-scale sizes. The mechanical properties for samples generated by two different methods were tested and analyzed, and corresponding microstructural evolutions as well as defect-induced deterioration in mechanical properties were investigated in detail.

2. Experimental procedures

The TiAl alloy used in this study has a nominal chemical composition (at%) of 47Al, 2Cr, 2Nb and Ti in balance. Alloy ingots were first prepared by arc melting and drop casting into Cu molds using commercially pure metals. The ingots were then remelted and atomized in argon atmosphere to generate alloy powders with mean particle size of about 100 μm. Powders were filled into 304 stainless steel cans with diameter of 60 mm and 150 mm in length, followed by degassing at room temperature, 623 K and 873 K for 1, 2, and 4 h, respectively. After degassing, cans were sealed in vacuum of about 10^{-1} Pa, which will be used for HIP and heat treatment.

Two different processing routes were then conducted respectively, which are schematically illustrated in Fig. 1. During SHH processes,

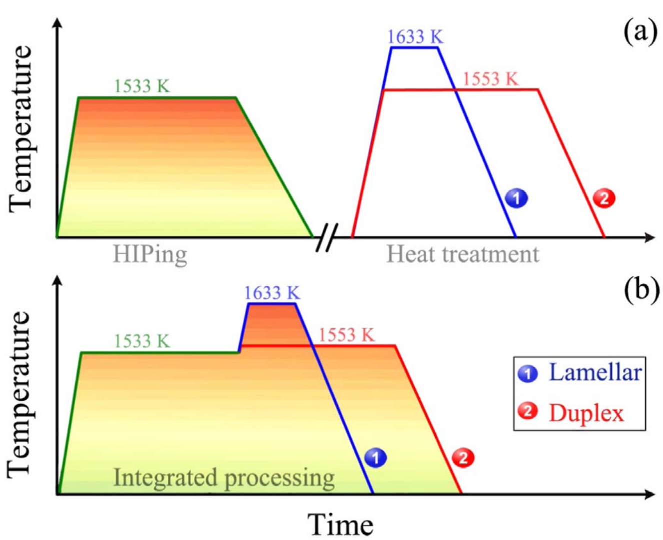

Fig. 1. Schematic illustration of two different processing routes. (a) Traditionally separated route (SHH) HIPing first at 1533 K and 160 MPa for 4 h, followed by heat treatment in vacuum at 1633 and 1553 K for 0.5 and 4 h, respectively. (b) Integrated processing route (IHH) undertaking heat treatment immediately at the end of HIP with pressure atmosphere of 160 MPa.

the cans filled with TiAl powders were compacted via HIP technique at 1533 K and 160 MPa for 4 h with heating rate of about 4 K per min, and then furnace cooled to room temperature. The stainless steel containers were removed by lathe machining and consolidated bulk samples were obtained (designated as HIPed sample). In order to generate duplex or lamellar structure, the HIPed samples were annealed at 1553 K for 4 h or 1633 K for 0.5 h in vacuum, with furnace cooling in both conditions (designated as D_{sep} and L_{sep} samples, respectively).

For IHH processing route, the first HIP stage had the same parameters as that in SHH route. The difference is that at the end of HIP process, temperature were straight elevated to 1553 or 1633 K and maintained for 4 or 0.5 h to generate duplex or lamellar structure, followed by furnace cooling in both conditions (named as D_{int} and L_{int} samples, respectively).

The gauge size of tested samples is $\phi 8\ \mathrm{mm} \times 40\ \mathrm{mm}$, and the tensile tests were carried out using MTS Landmark testing system with uniaxial quasistatic strain rate of $2 \times 10^{-4}\ \mathrm{s}^{-1}$ at room temperature.

The microstructure was investigated by backscattered electronic (BSE) imaging using a field emission gun scanning electron microscope. Specimens for BSE investigation were electro-polished using a solution of 95% ethylalcohol and 5% perchloric acid ($HClO_4$) at 253 K with voltage of 40 V.

3. Results

3.1. Mechanical properties

Fig. 2 exhibits the tensile properties of TiAl samples produced by different processing routes. The typical engineering stress–strain curves are shown in Fig. 2(a) and (b). The mean yield stress and elongation to failure of HIPed samples are measured as 480 ± 21 MPa and 2 ± 0.3%. When subjected to annealing at 1553 K to form duplex microstructure via SHH route, the D_{sep} samples have an average yield stress and elongation to failure of 420 ± 18 MPa and 2.4 ± 0.4%, while D_{int} samples produced by IHH route have higher yield stress and elongation to failure up to 540 ± 25 MPa and 3 ± 0.3%. When it comes to L_{sep} samples with lamellar structure which were annealed at 1633 K, as exhibited in Fig. 2(b), the yield stress and elongation to failure are measured as 550 ± 28 MPa and 0.6 ± 0.1%, respectively. In contrast, the L_{int} samples treated by IHH route have higher yield stress and elongation to failure up to 650 ± 30 MPa and 2.1 ± 0.2%.

According to the results of mechanical properties, the HIPed samples have moderate yield strength and tensile ductility. When the traditional heat treatment in vacuum was applied to generate the lamellar or duplex microstructure, it is hard to achieve a good combination between the strength and tensile ductility. Taking the lamellar structure as an example, the yield stress could be improved; however, such improvement is accompanied by a significant sacrifice of tensile ductility. In contrast, when processed through IHH route, the yield stress and elongation to failure of both duplex and lamellar structures are increased simultaneously.

Corresponding to Fig. 2(a) and (b), the true stress and strain hardening rate were plotted against true strain in Fig. 2(c) and (d). As compared with the D_{sep} sample, the D_{int} sample produced by IHH route shows higher strain hardening rate during tensile deformation, indicating stronger strain hardening ability and hence enhanced tensile ductility, which is in line with the experimental results exhibited in Fig. 2(a). For the lamellar structure, the L_{sep} sample is quickly failed at early stage of tensile deformation, while L_{int} sample sustains to relatively higher tensile strain. According to Considère theory, plastic instability during uniaxial tensile deformation sets in as strain hardening rate decreases to the same level as true stress [25]. However, all samples do not follow the prediction of Considère criterion. Instead, failures all occurred at low strains where the strain hardening rates are still much greater than true stresses, which means that the failure of