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A novel near α-Ti alloy prepared by hot isostatic pressing: Microstructure evolution mechanism and high temperature tensile properties

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ABSTRACT

This work presents a comprehensive study of the densification behavior, phase and microstructure development, high temperature tensile performance of a novel near-α high-temperature titanium alloy fabricated by hot isostatic pressing (HIP) at representative temperatures. The results indicated that numerous rod-like S_2 silicides ($(TiZr_{0.3})_6Si_3$) and α_2 phase (Ti_3Al) precipitated from α matrix. The microstructural characteristics of HIP-fabricated parts experienced a successive change on increasing the HIP temperature: lathlike structure + little equiaxed grains → equiaxed grains + little lathlike structure → fully equiaxed grains. In addition, the grain size of samples unceasingly growed up with the increase of HIP temperatures. Over the entire tensile tests temperature range, the equiaxed grains plus little lath-like structure (HIP-B) exhibited the highest tensile strength. As to the ductility, the elongation of specimens increased successively with the increase of HIP temperatures, which is mainly due to the type of microstructure and the diffusion-metallurgical bond.

1. Introduction

With the development of aerospace industry, high temperature mechanical properties and large thrust-weight ratio of engine were required [1–2]. In order to meet these requirements, a series of near-α high-temperature titanium alloy have been developed by many countries during the past decades [3–6]. For example, MIM834 (Ti5.8Al4.0Sn3.5Zr0.7Nb0.5Mo0.35Si0.06C, UK) [7–8], Ti1100 (Ti6Al2.75Sn4Zr0.4Mo0.45Si, USA) [9], BT36 (Ti6.2Al2Sn3.6Zr0.7Mo0.15Si, Russia) [10] and Ti60 (Ti6Al2.8Sn4Zr0.5Mo0.4Si, China) [11] were used to fabricate compressor disks and gas turbine blades of advanced jet engine because of their high specific strength, good high temperature creep properties and superior corrosion resistance at elevated temperature up to 600 °C [12–14]. These near-α titanium alloys belong to the series of Ti-Al-Sn-Zr-Mo-Si alloy. A mass of α phase stable elements (such as Al, Sn, Zr) are added to enhance its heat-resistance [15]. Besides, a certain amount addition of Si element improves its creep properties at high temperatures [16]. The oxidation resistance of these alloys is also a very important factor for application at high temperature. However, above mentioned alloys conclude no element, which can increase the oxidation behavior. Ta and Nb elements can raise the anti-oxidation performance at high temperature due to the formation of compounds with high melting point [17]. In this work, a novel Ti-Al-Sn-Zr-Mo-Si-Nb-Ta near-α titanium alloy was designed. And it was found that this titanium alloy showed an excellent high temperature oxidation resistance in our previous study [18]. It can be known that traditional processing methods such as forging and machining were used to fabricate the key parts of aerospace engine mentioned above, in order to ensure good performance of the parts. Nevertheless, the disadvantages of these conventional methods, in terms of low availability of material and productivity as well as high cost of production, have obstructed its usage in practical applications [19]. Bowden et al. appointed that about 83% of raw titanium was wasted in the form of machining chips during the fabrication of the airframe of Boeing 787 [20].

Nowadays, near-net shape hot isostatic pressing (NNS-HIP), combined with mould technology, was applied to fabricate fully dense parts with complex geometry from metal powder. As shown in Fig. 1, the production process of a near net shape (NNS) component using HIP process includes the following main operations: (i) design and fabrication of capsule; (ii) filling of the powder into capsule; (iii) evacuation and sealing of the capsule; (iv) consolidation of the powder in the capsule by the combined action of high temperature and pressure; (v) acquisition of the near net shape part after removal of the capsule. Based on above description, HIP technology has three significant advantages when compared with traditional manufacturing methods: (i) high material utilization; (ii) ability to form full dense and complex shape parts with homogeneous microstructure; (iii) fabricated parts with excellent mechanical properties equivalent to forgings. Due to the potential economic advantages of producing complex geometry components from titanium and nickel based alloys and offering an attractive set of properties, HIP technology has been widely exploited in the aerospace

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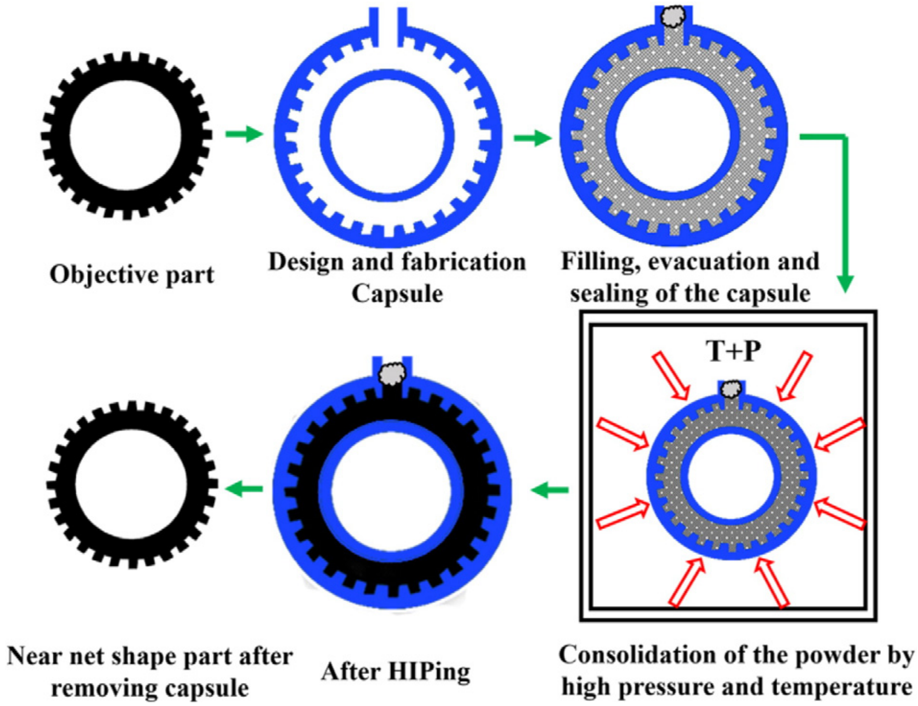

Fig. 1. Schematic diagram of NNS-HIP process.

[21–22]. For instance, a cryogenic impeller for the liquid hydrogen turbo-pump in aerospace, which was fabricated from Ti6Al4V powders using NNS-HIP process, exhibited excellent mechanical properties equivalent to those of parts fabricated by forgings [23]. In our previous work, a monolithic Ti6Al4V disk was successfully fabricated using NNS-HIP and the relative density of the disk reached 99.5% [24]. So far, HIP processing of Ti6Al4V [25–27], TiAl [28–29], Nickel-based superalloy [30–34], and Al-based powders [35], etc., has been studied. However, up to now, to the best of authors' knowledge, there was no literature reported on the fabrication of a near-α high temperature titanium alloy (the series of Ti-Al-Sn-Zr-Mo-Si) by HIP process and the study of high temperature mechanical performance was rarely involved. Therefore, the present work studied the evolution mechanism of phase and microstructure of the novel near-α high temperature titanium alloy at various HIP processing parameters. The aim of this work is to establish a relationship between processing temperatures, microstructural characteristics, and high temperature mechanical performance of the novel near-α high titanium alloy parts produced by HIP process.

2. Experimental procedures

2.1. Powder material

Firstly, a novel near-α titanium alloy ingot with diameter of 30 mm was prepared by consumable electrode arc melting. Then, the alloy powder was produced by this bar using gas atomization in this study. The chemical composition of the powder is listed in Table 1. Fig. 2 shows the morphology, powder size distribution and the DSC curve of the novel Ti alloy. The distribution size is homogeneous and the average size of the spherical particles (D50) is 92.6 μm, which is suitable for the HIP process. In order to determine the optimal HIP temperature range, the DSC curve of the new Ti alloy was detected under a heating rate of 20 °C/min. It can be found that the β transition temperature (β_{tr}) of this alloy is about 978 °C. Besides, the HIP pressure can affect the phase transformation of titanium alloy, and Cao et al. pointed out that the pressure depressed the beta transus temperature by 0.08 K/MPa [36]. Therefore, the β_{tr} of this alloy is approximately 965 °C under HIP process.

Table 1
Chemical composition(in wt%)of the novel Ti alloy powders.

Element	Ti	Al	Sn	Zr	Mo	Nb	Ta	Si	O
Content (wt%)	Bal.	5.5	3.4	3.0	0.7	0.4	0.35	0.3	0.08

2.2. HIP process

The SAE 1045 steel capsules with a three dimension (internal diameter 60 mm, the length 150 mm and wall thickness 2 mm) were fabricated by machining process. The powder particles were filled into the capsules by the plug on a vibrating platform, which resulted in a relatively high packing density (65%–68%). The capsules were degassed at 600 °C by the vacuum pump to remove air and contaminations from the surface of powder, and then the stem on the top of capsules was welded when the vacuum level of the sealed capsules reached 1×10^{-3} Pa. Finally, the sealed capsules were put into the QIH-15 Hot Isostatic Pressing machine (ABB Company, USA). The capsules were heated to 900, 950 and 1000 °C at a heating rate of 5 °C/min and pressurized up to 120 MPa for 3 h, followed by cooling at 5 °C/min to room temperature. The HIP conditions 900 °C/120 MPa, 950 °C/120 MPa, 1000 °C/120 MPa were respectively designed as HIP-A, HIP-B, HIP-C. The temperature of HIP-A and HIP-C was below and above the β transition temperature (β_{tr}), respectively. The temperature of HIP-B closed to that of the β_{tr}.

2.3. Microstructural and mechanical properties testing

Phase identification of HIP-processed specimens was performed by an X-ray diffractometer (XRD) (XRD-7000S, Japan) operating with a Cu anticathode ($\lambda = 1.5406$ Å) at 35 kV and 40 mA, using a continuous scan mode. A scan at 5° min^{-1} was conducted over a wide range of $2\theta = 30–80°$ to give a general overview of the diffraction peaks. TEM examination together with EDX analysis (Tecnai G2 F30, FEI, Holland) was also conducted to observe the precipitates in the parts. Disks for TEM examination were cut from the HIPed parts and subsequently ground and ion milling at 5 eV.