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Microstructures and mechanical properties of nano-WC reinforced Ti-44.5Al-5Nb-0.5W-0.5C-0.2B alloy prepared by hot isostatic pressing

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A B S T R A C T

With the aim of improving the strength and ductility of TiAl alloy, for the first time, nano-WC is introduced to reinforce the Ti-44.5Al-5Nb-0.5W-0.5C-0.2B through hot isostatic pressing (HIP). The effect of nano-WC contents on the microstructures and mechanical properties of Ti-44.5Al-5Nb-0.5W-0.5C-0.2B are systematically studied, specifically, the Ti-44.5Al-5Nb-0.5W-0.5C-0.2B alloy with 2 wt% nano-WC content shows the highest tensile strength (830 ± 33 MPa) and ductility ($3.9 \pm 0.2\%$), which are mainly attributed to the grain refinement strengthening and precipitate shearing strengthening effects. Our findings provide a realistic approach to design novel TiAl/WC nanocomposite processed by HIP with superior strength-ductility combination for practical structural applications.

1. Introduction

On account of the excellent benefits such as low density, superior elevated temperature mechanical properties and good corrosion resistance, TiAl alloys are regarded as the most promising candidates to replace Ni-based alloys used in aerospace and defense sectors [1–3]. However, Once TiAl alloys are involved in the loading phenomenon, their low fracture strength and poor ductility are considered as two significant disadvantages for practical application [4–6]. In this case, strategies to improve both the ductility and fracture strength of TiAl alloys have become the goals for scientists in the past three decades [3].

Nowadays, metal matrix nanocomposites reinforced with stiff nano-scale ceramics (such as WC, TiB and TiN and TiC) have been demonstrated to be a viable approach to improve both the ductility and strength of TiAl alloys [7,8]. In most of the nano-scale ceramics, WC is regarded as an ideal reinforcement for TiAl alloys due to its high hardness, good wettability and thermodynamic stability within the TiAl alloys [9]. In recent years, several special manufacturing techniques, such as pulsed current sintering [10], high frequency induction casting [11] and laser deposition [12] were introduced to fabricated nano-WC reinforced TiAl components. However, these processing methods have two significant limitations, (i) nano-WC are prone to agglomerate by van der Waals force; (ii) nano-WC are hardly to preserve due to excessive grain growth during high temperature processing [13,14]. Therefore, the reinforcement effect of nano-WC on TiAl alloys is not satisfactory. It is thus necessary to develop novel processing methods for fabricating bulk TiAl/WC nanocomposites.

Hot isostatic pressing (HIP), as a promising advanced manufacturing technology, enables rapid fabrication of bulk-form parts with good mechanical properties directly from loose metal powder [15,16]. For more details about the HIP process, the readers are referred to Ref. [16]. Currently, some preliminary studies had applied HIP in the fabrication of TiAl alloys, however, these works focused on the HIP parameters optimization to obtain full density TiAl parts [17–19]. Very recently, our previous work systematically investigated the effect of micro-sized TiB_2 reinforced Ti-43.5Al-6.5Nb-1.5Cr-0.5C alloy fabricated by HIP [16]. Nevertheless, to the best of the authors' knowledge, there is no previous reports on HIP processing of nano-WC reinforced TiAl alloys, and therefore the strengthening mechanisms of nano-WC in TiAl alloys are ambiguous. To this end, this paper mainly focuses on the influence of nano-WC contents on microstructures evolution and tensile properties of Ti-44.5Al-5Nb-0.5W-0.5C-0.2B alloy by HIP. In addition, the strengthening mechanisms of nano-WC in Ti-44.5Al-5Nb-0.5W-0.5C-0.2B alloy are discussed in detail.

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2. Experimental procedures

2.1. Materials

Gas atomized Ti-44.5Al-5Nb-0.5W-0.5C-0.2B powder with an average particle size of 27 μm (Fig. 1(a)) and nano-WC powder with an average particle size of 160 nm are selected as feedstock in this experiment. Prior to the HIP process, four different TiAl/WC nanocomposites containing 0 (blank contrast), 0.5, 1, and 2 wt% nano-WC are prepared by ball milling in a tumbling mixer, using a ball-to-powder weight ratio of 4:1, main disk rotation speed of 200 rpm and mixing time of 8 h. Fig. 1(b) and (c) shows the morphology of TiAl/WC nanocomposite with 2 wt% content of nano-WC. Apparently, the nano-WC is homogeneously attached to the surface of Ti-44.5Al-5Nb-0.5W-0.5C-0.2B powder.

2.2. HIP process

The HIP system is mainly consisted by a water cooled high pressure vessel, a compression engine, a vacuum pump and a computer system for process control. As illustrated in Fig. 2, the process of HIP mainly includes the following six main operations: (i) step1 design 3D-CAD model of target components; (ii) step 2 design and fabrication of capsule based on the target components; (iii) step 3 filling the capsule with TiAl powder; (iv) step 4 vacuuming and sealing the capsule by arc welding, then consolidating the TiAl powder in the capsule by the joint action of high temperature and high pressure; (v) step 5 remove the capsule by machining or electrochemical corrosion; (vi) step 6 acquisition of the target components by HIP. We optimized the HIP process of TiAl/WC nanocomposite with 2 wt% nano-WC addition. The experiment procedures are set as follows (see Tables 1 and 2):

We fabricate 5 tensile specimens of each HIP process, then we averaged the tensile results. The strain rate is kept as $1 \times 10^{-4}\ s^{-1}$ during the tensile test (We use a variable crosshead speed to ensure a consistent strain rate). The tensile results are illustrated in Table 3.

As can be seen from Table 3, both the engineering tensile strength and strain of HIP-processed TiAl/WC nanocomposite parts show a trend of increasing first and then decreasing with the increase of HIP temperature (from 1130 °C to 1170 °C) and pressure (from 115 MPa to 125 MPa). Hence, the HIP parameters are optimized as follow: pressure (P) 120 MPa, temperature (T) 1150 °C and duration time (D) 3 h. For simplicity, nano-WC content of 0, 0.5, 1 and 2 wt% HIP-processed samples are named by S0, S1, S2 and S3, respectively.

2.3. Microscopic and mechanical property characterization

Electron backscattered diffraction (EBSD) tests are carried out on a HKL Nordlys system (Oxford Instruments, UK) with a step size of 0.5 μm. It is worth noting that the HKL Nordlys system is mounted on a JSM-7600F type field emission scanning electron microscope (JEOL, Japan). Prior to the EBSD tests, all the HIP-processed samples are electrolytic polished (LectroPol-5, Struers, Denmark) with A3 reagent (vol. 90% ethanol, vol. 10% perchlorate) at 15 V for 25 s. After EBSD tests, all the EBSD data is interpreted by a Channel-5 software packages (HKL, Oxford Instruments). Transmission electron microscope (TEM) as well as high resolution transmission electron microscope (HRTEM) measurements are executed on a JEOL-2100 type machine (JEOL, Japan) to analysis the phases evolution mechanism of HIP-processed TiAl/WC samples. Disks for TEM and HRTEM analysis are cutting from the HIP-processed samples, then the disks are ground to a thickness of 50–60 μm and ion milling at 5 eV. Tensile testing specimens are

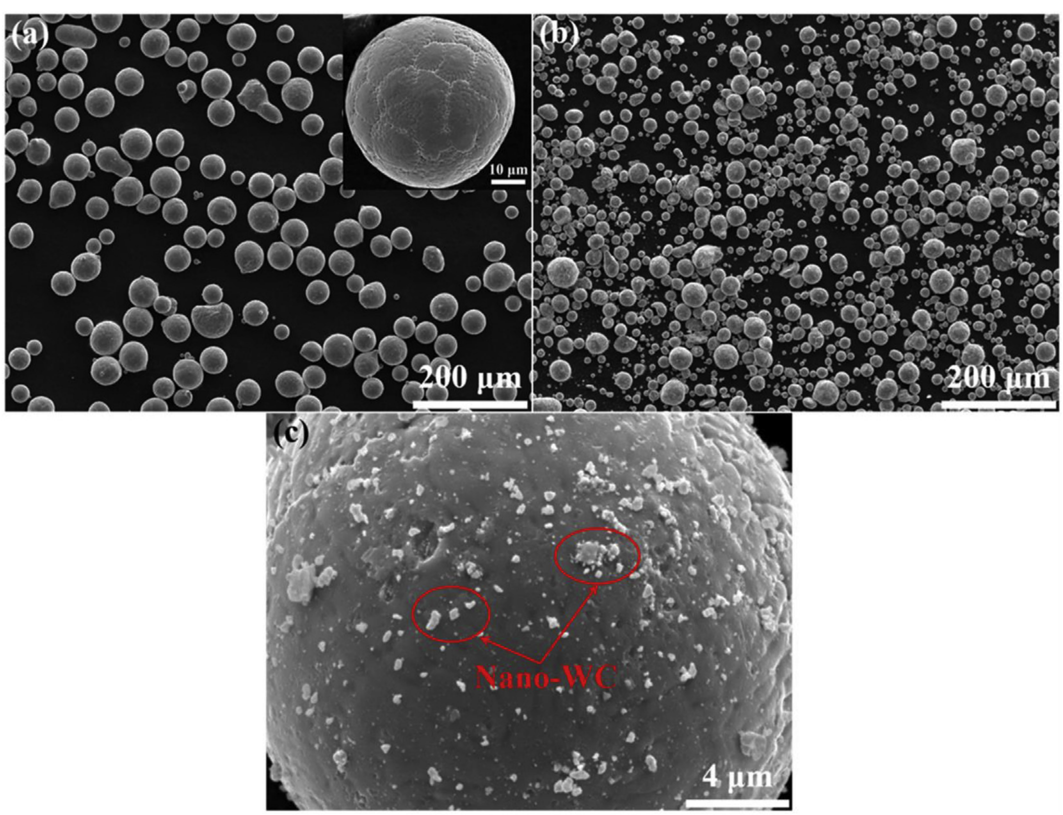

Fig. 1. (a) SEM morphology of Ti-44.5Al-5Nb-0.5W-0.5C-0.2B powder; (b) and (c) particle morphology of Ti-44.5Al-5Nb-0.5W-0.5C-0.2B/WC nanocomposite with 2 wt% content of nano-WC.