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Original Research

Microstructure, phase stability and mechanical properties of Nb–Ni–Ti–Co–Zr and Nb–Ni–Ti–Co–Zr–Hf high entropy alloys

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Abstract

Owning to their excellent thermal stability and high strength at elevated temperature, high entropy alloys (HEAs) possess great potential for the application in aviation and aerospace fields. In present work, two novel Nb–Ni–Ti–Co–Zr and Nb–Ni–Ti–Co–Zr–Hf HEAs were prepared by arc melting and copper mold suction-casting method. The microstructure, phase stability, mechanical properties at room temperature and elevated temperature of the two HEAs were studied. Both of the HEAs possess high yield stress at room temperature, especially for the Nb–Ni–Ti–Co–Zr (with 2331 Mpa). In addition, the Nb–Ni–Ti–Co–Zr HEA exhibited high yield stress of 564 Mpa at elevated temperature of 800 °C and large compressive plastic strain (more than 50% at 800 °C). Nb–Ni–Ti–Co–Zr–Hf alloy showed new phase precipitation at 800 °C, whereas the structure of Nb–Ni–Ti–Co–Zr was more stable, which is one of the reason why it possesses high strength at room temperature and elevated temperature. The high temperature properties of the Nb–Ni–Ti–Co–Zr HEA make it promising for high temperature application.

Keywords: High entropy alloy; Mechanical property; Microstructure, Stability

1. Introduction

High entropy alloys (HEAs), which contain at least 5 components in equiatomic or near-equiatomic ratio, have been considered as a new material in recent years [1–4]. It is known that the high mixing entropy could decrease the Gibbs free energy and result in the formation of solid solution phase of HEAs. Due to the high entropy and their complex microstructure in the multi-elements alloys, HEAs exhibit many attractive properties, such as high strength at both cryogenic temperatures [5–7] and high temperatures [8–12], strong corrosion resistance [13,14], outstanding wear resistance [15,16], excellent magnetic properties [17] and good glass-forming ability [18-19].

In particularly, the refractory high entropy alloys (HEAs) possess dramatic mechanical properties at high temperatures due to their high meting temperature and strong solid solution strengthening, and possess very high yield strength ($\sigma_{0.2}$) in the temperature range from 20 °C to 1000 °C. Although there are several refractory HEA systems with a simple solid solution structure, including Nb–Ta–Mo–W [10,11], Nb–Ti–Zr [8,12,20–24] and Nb–Ti–V–Al [25], have been successfully developed, the components of the reported refractory HEAs are limited in Nb, Ta, V, W, Ti, Zr, Hf and Al. Thus, developing refractory HEAs with other elements is of importance.

Since Ni-based and Co-based superalloys have been wildly applied [26,27] due to their excellent mechanical properties at elevated temperature, Ni and Co elements could be served as alloying elements in the refractory HEAs. In present work, by selecting Ni, Co, and the commonly used constituent elements such as Nb, Ti, Zr and Hf in refractory HEAs, two new refractory HEAs of $Nb_{20}Ni_{20}Ti_{20}Co_{20}Zr_{20}$ and $Nb_{16.7}Ni_{16.7}Ti_{16.7}Co_{16.7}Zr_{16.7}Hf_{16.7}$ were developed. The structural stability, mechanical properties at both room temperature and elevated temperatures have been investigated.

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2. Experimental procedures

The $Nb_{20}Ni_{20}Ti_{20}Co_{20}Zr_{20}$ and $Nb_{16.7}Ni_{16.7}Ti_{16.7}Co_{16.7}Zr_{16.7}Hf_{16.7}$ HEAs in equiatomic ratio were prepared by vacuum arc melting of the mixtures of the metals in a Ti-gettered pure argon atmosphere. The purities of Nb, Ni, Co and Ti are over 99.9 mass%, and the purities of Zr and Hf are over 99.2 mass%. Each ingot was re-melted at least five times to ensure the compositional homogeneity. Then cylindrical rods were prepared by copper mold suction casting. The structure of the as-cast rods and anneal samples was characterized by Rigaku D/max-RB X-ray diffraction (XRD) using a Cu Kα radiation. To measure the room temperature mechanical properties of the alloys, the compression tests were performed on WDW-50 testing machine at a strain rate of $4\times10^{-4}\ s^{-1}$. The samples were cut out from the as-cast ϕ3 mm rods with gage aspect ratio of 2:1. The elevated temperature compression tests were carried out with Gleeble3500 thermal simulator at a strain of $1\times10^{-3}\ s^{-1}$ using samples with a dimension of ϕ6 mm × 9 mm. The fractured samples were examined by Quanta 200 FEG scanning electron microscope (SEM). The hardness and elastic constants of the novel HEAs were measured by MH-3 vickers hardness tester and Teclab resonance ultrasonic spectrometer, respectively.

3. Results and discussions

Fig. 1a shows the XRD spectrum of the as-cast $Nb_{20}Ni_{20}Ti_{20}Co_{20}Zr_{20}$ alloy sample. Two body-centered cubic (BCC) phases with lattice constants of 3.14 Å and 3.33 Å were indexed., The XRD spectrum of the annealed $Nb_{20}Ni_{20}Ti_{20}Co_{20}Zr_{20}$ alloy sample after annealed at 800 °C for 1 h is shown in Fig. 1b, where the characteristic peaks are nearly the same as those in the XRD spectrum of as-cast sample. The indexing of the XRD spectrum confirmed that the annealed sample was still consisted of two BCC phases with lattice constants of 3.14 Å and 3.33 Å. Thus, the $Nb_{20}Ni_{20}Ti_{20}Co_{20}Zr_{20}$ alloy possesses excellent structural stability below 800 °C.

Fig. 1c shows the XRD spectrum of the as-cast $Nb_{16.7}Ni_{16.7}Ti_{16.7}Co_{16.7}Zr_{16.7}Hf_{16.7}$ HEA sample, where a BCC crystal structure, a faced-centered cubic (FCC) crystal structure and a NbNi intermetallic phase were indentified. The lattice constants of the BCC and FCC phases were measured to be 4.48 Å (a′1) and 4.74 Å (a′2), respectively. By comparing the XRD results of the as-cast $Nb_{20}Ni_{20}Ti_{20}Co_{20}Zr_{20}$ and $Nb_{16.7}Ni_{16.7}Ti_{16.7}Co_{16.7}Zr_{16.7}Hf_{16.7}$ alloys, it could be found that the addition of Hf can promote the phase transformation from BCC phase to FCC phase. Similar FCC to BCC phase transformation phenomenon has been observed in $CuCrFeNiCu_{1-x}Al_x$ HEAs when increase the Al content [28]. The phase transformation phenomenon was reported to be closely related to the great lattice constant difference between the Al and other elements.

After annealing at 800 °C for one hour, a new $NbHf_2$ phase was observed in the XRD spectrum of the annealed $Nb_{16.7}Ni_{16.7}Ti_{16.7}Co_{16.7}Zr_{16.7}Hf_{16.7}$ HEA sample, as shown in Fig. 1d. The precipitation of new phase might be on account of

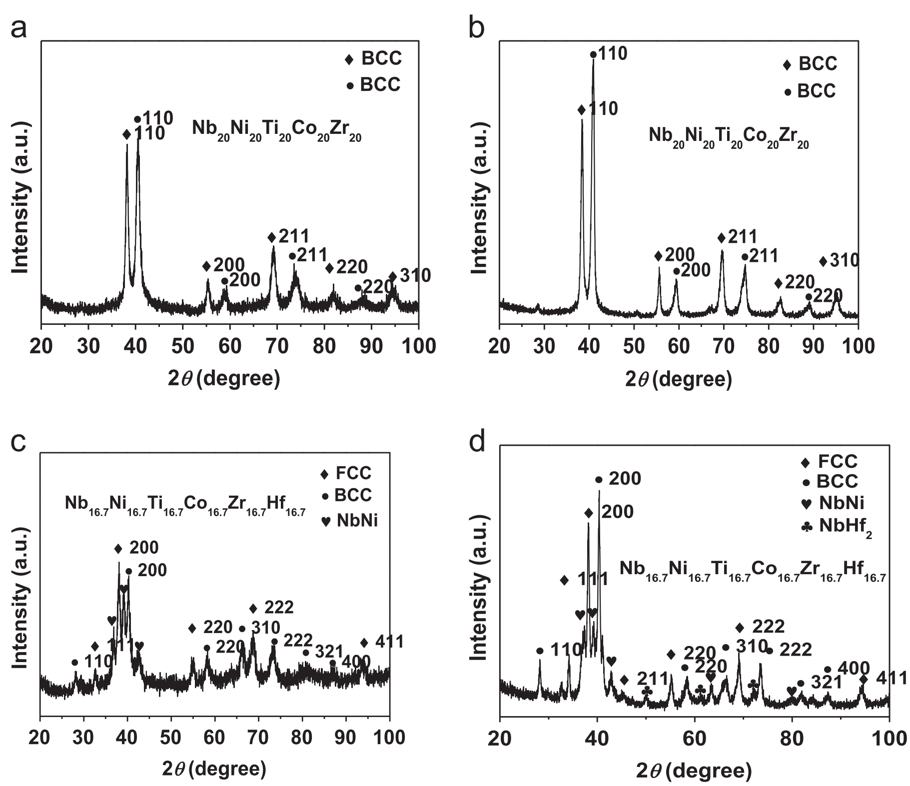

Fig. 1. XRD patterns of (a) the as-cast and (b) the annealed $Nb_{20}Ni_{20}Ti_{20}Co_{20}Zr_{20}$ HEA samples, and (c) the as-cast and (d) the annealed $Nb_{16.7}Ni_{16.7}Ti_{16.7}Co_{16.7}Zr_{16.7}Hf_{16.7}$ HEA samples.