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Preparation of Ni-based bulk metallic glasses with high corrosion resistance

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ABSTRACT

Bulk $Ni_{77-x-y}Mo_xCr_yNb_3P_{14}B_6$ (x = 7 y = 0; x = 8 y = 0; x = 9 y = 0; x = 5 y = 3; x = 5 y = 5; x = 5 y = 8; x = 8 y = 3; x = 8 y = 5, all in at.%) glassy alloy rods with the diameters of 1.0–1.5 mm were synthesized by combining fluxing technique and J-quenching technique. The effects of Mo and Cr substitution for Ni on the glass forming ability (GFA), thermal stability, mechanical properties and corrosion properties of the present Ni-based bulk metallic glasses (BMGs) had been studied systematically. It is found that the substitution of an appropriate amount of Cr and Mo for Ni can enhance the GFA of the present Ni-based alloys, while excessive substitution will lead to the degradation of the GFA. The corrosion tests show that the corrosion current density and corrosion rate of most of the present Ni-based BMGs in 1 M NaCl and 1 M HCl solutions are in the order of 10^{-6} A/cm^2 and 10^{-2} mm/year, respectively, exhibiting very high corrosion resistance. The addition of the appropriate Mo content and the Cr content as much as possible are benefit for the enhancement of the corrosion resistance of the present Ni-based BMGs. The compressive tests show that that the present Ni-based BMGs exhibit a compressive strength of 2.5–3.4 GPa, but nearly zero compressive plasticity.

1. Introduction

Due to unique atomic arrangement in comparison to crystalline counterpart, amorphous alloys exhibit many excellent properties, such as high mechanical strength, excellent magnetic properties and good corrosion resistance [1,2], and thus are attracting more and more attentions and becoming one of hot topics in the research of new materials in recent decades. Conventionally, an alloy can only be amorphized at a very high cooling rate. As a result, at least one dimension of the resultant amorphous alloys is very small, which has so far limited commercial applications of this class of materials. Through the efforts of many researchers, a large number of bulk metallic glasses (BMGs) such as La-, Zr-, Fe-, Co- and Ni-based alloys [3–6] have been successively developed in the past three decades. Among these BMGs, Ni-based BMGs usually exhibit high thermal stability, good mechanical properties and excellent corrosion resistance [5,7–9]. For instance, the fracture strength of $Ni_{59}Zr_{16}Ti_{13}Si_3Sn_2Nb_7$ can be reached 3 GPa and the plasticity can be reached 6.5% [10]. The corrosion rate of $(Ni_{60}Nb_{10}Ta_{30})_{0.95}P_5$ BMG in 12 M HCl solution determined by weight loss of the immersion test is almost zero [11]. However, at present most of the research on Ni-based BMGs has focused on all-metal Ni-based alloy systems, and only a few has focused on Ni-metalloid based alloy systems. This may be due to the low glass forming ability (GFA) of Ni-metalloid based alloys. Further, many of the recently reported Ni-metalloid based BMGs contain a considerable number of precious metal element Pd [12,13], which greatly increases the production cost of these Ni-based BMGs and thus limits their commercial application. So it is of both academic and industrial significance to develop new Ni-metalloid based BMGs.

At present the $Fe_{80}P_{13}C_7$ BMG with a maximum diameter of 2.0 mm has been synthesized by means of the combination method of fluxing treatment and J-quenching technique [14]. This reveals that J-quenching technique has unique advantages in the preparation of BMGs compared with the conventional copper mold casting technique, and thus provides us a great opportunity to develop new Ni-based BMGs. In addition, it is found that the suitable addition of some elements to metallic glasses may produce significant changes of their GFA, magnetic properties, mechanical properties and corrosion resistance [15–19]. For example, through the substitution of 6 at.% Fe by Mo in $Fe_{80}P_{13}C_7$ alloy, the critical diameter for fully glass formation of the alloy increases from 2 mm to 6 mm, and meantime the compressive fracture strength and plasticity of the BMG are also greatly improved [18]. The appropriate addition of Cr and Mo results in the effective enhancement of the corrosion resistance of $Fe_{80}P_{13}C_7$ amorphous alloy [19]. Based on the above considerations, a new series of $Ni_{77-x-y}Mo_xCr_yNb_3P_{14}B_6$ (x = 7 y = 0; x = 8 y = 0; x = 9 y = 0; x = 5 y = 3; x = 5 y = 5; x = 5 y = 8; x = 8 y = 3; x = 8 y = 5, all in at.%) BMGs has been developed, and the effects Mo and Cr contents on the GFA, corrosion resistance and

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mechanical properties of the present NiMoCrNbPB BMGs are studied systematically in this work.

2. Experimental procedure

$Ni_{77-x-y}Mo_xCr_yNb_3P_{14}B_6$ (x = 7 y = 0; x = 8 y = 0; x = 9 y = 0; x = 5 y = 3; x = 5 y = 5; x = 5 y = 8; x = 8 y = 3; x = 8 y = 5, all in at.%) master alloy ingots were prepared by torch-melting the mixtures of high-pure Ni powder (99.9 mass%), Cr powder (99.9 mass%), Mo powder (99.9 mass%), Boron particle (99.9 mass%), Niobium powder (99.9 mass%) and Ni_2P powder (99.5 mass%) in a clear fused silica tube under a high-purity argon atmosphere by a torch. Subsequently the *as*-prepared master alloy ingots were fluxed in a fluxing agent composed of B_2O_3 and CaO with the mass ratio of 3:1 at an elevated temperature for 4 h under a vacuum of ~50 Pa. After cooling down to room temperature, the alloy ingots were cleaned in an ultrasonic cleaner with absolute ethyl alcohol. Subsequently the alloy ingots were casted to be the alloy rods by J-quenching technique of which details can be found elsewhere [1]. As a result, $Ni_{77-x-y}Mo_xCr_yNb_3P_{14}B_6$ (x = 7 y = 0; x = 8 y = 0; x = 9 y = 0; x = 5 y = 3; x = 5 y = 5; x = 5 y = 8; x = 8 y = 3; x = 8 y = 5, all in at.%) alloy rods with the various diameters and the length of a few centimeters had been fabricated by J-quenching technique.

The glassy nature of the as-cast specimens was confirmed by X-ray diffraction (XRD, Bruker D2 PHASER) with Cu K α radiation (30 kV and 30 mA) at room temperature. The thermal behavior of the as-cast specimens was examined by differential scanning calorimetry (DSC, NETZSCH DSC 404F1) at a heating rate of 0.33 K/s under an Ar atmosphere. Electrochemical measurements were conducted in a three-electrode cell using a platinum counter electrode, a K/KCl reference electrode and a working electrode which is the as-prepared glassy alloy rod. Potentiodynamic polarization curves were measured with a potential sweep rate of 1 mV/s in both 1 M HCl and 1 M NaCl solutions open to air at room temperature after having immersed the specimens for about 20 min in order to make the open-circuit potential steady. The corrosion rates were evaluated from the weight loss after immersion for 1 week in 1 M NaCl solution at room temperature. Three specimens for each alloy in the same solution were examined for the weight loss test and the average value was used for corrosion rate estimation. Electrochemical impedance spectroscopy (EIS) of the specimens in both 1 M HCl and 1 M NaCl solutions was measured at room temperature using CS350 electrochemical workstation (Wuhan CorroTest Instrument Co. Ltd., China). EIS were recorded at open circuit potentials in the frequency ranging from 10^5 to 10^{-2} Hz, with a sinusoidal signal perturbation of 5 mV. The specimens held in the corrosion solutions at open circuit potential for 20 min to get a stationary open circuit potential before the test of EIS. Compressive tests of the specimens were performed on a testing machine (Reger, RGM-4100) at a strain rate of $5 \times 10^{-4}\ s^{-1}$ at room temperature. The compression specimens were prepared in the shape of cylindrical rods with a diameter of 1 mm and a length of 2 mm, and both end faces were polished carefully to ensure parallelism.

3. Results and discussion

Fig. 1 shows the XRD patterns of the *as*-cast $Ni_{77-x-y}Mo_xCr_yNb_3P_{14}B_6$ (x = 7 y = 0; x = 8 y = 0; x = 9 y = 0; x = 5 y = 3; x = 5 y = 5; x = 5 y = 8; x = 8 y = 3; x = 8 y = 5, all in at.%) glassy rod specimens with the maximum diameter (D_{max}). The XRD patterns of all the specimens reveal only a broad diffuse peaks and no apparent crystalline phase peaks, indicating that all the specimens just consist of a single glass phase at the sensitivity of XRD. When Ni is substituted solely by Mo in the $Ni_{77}Nb_3P_{14}B_6$ alloy, the bulk glassy alloy rods with the diameter of 1.0 mm can be prepared for the Mo substitution content of 7, 8 and 9 at.%, respectively. When the Mo content is fixed and Ni is further substituted by Cr in the present Ni-based alloys, the D_{max} of the obtained

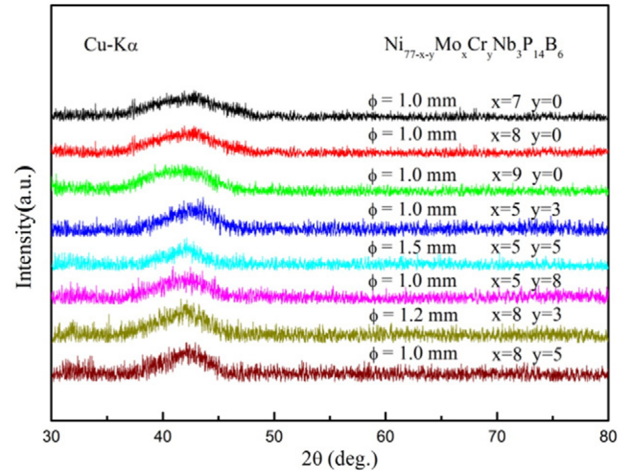

Fig. 1. XRD patterns of as-cast $Ni_{77-x-y}Mo_xCr_yNb_3P_{14}B_6$ glassy rod alloys with the corresponding maximum diameters for fully glass formation.

bulk glassy alloy rods are 1.0, 1.5 and 1.0 mm for the Mo content of 5 at.% and the Cr substitution content of 3, 5 and 8 at.%, respectively, and are 1.2 and 1.0 mm for the Mo content of 8 at.% and the Cr substitution content of 3 and 5 at.%, respectively. When the Mo and Cr contents are beyond the above range, the glassy alloy rod with a diameter larger than 1 mm cannot be obtained for the present Ni-based alloys in our experiment. It is indicated that the proper substitution of Mo and Cr for Ni can effectively enhance the GFA of the present Ni-based alloys. Based on Inoue's three principles for BMG formation [1], the larger negative heats of mixing among the constituent elements will facilitate the glass formation of alloy. The heats of mixing for Mo–P, Cr–P, Ni–P, Mo–B, Cr–B and Ni–B atomic pairs are −53.5, −49.5, −34.5, −34, −31 and −24 kJ/mol, respectively [20]. Therefore, the substitution of Mo and Cr for Ni will increase the average bond energy of the alloy and improve the stability of liquid phase, thus enhancing the GFA. Moreover, since the atomic sizes change in the order of Mo > Cr ≈ Ni > P > B [20], the substitution of Ni by Mo and Cr will lead to the wider atomic size distribution, which is favorable to increase the atomic packing density of the molten alloy. So this will improve the stability of liquid phase and increase the difficulty of the atomic rearrangement, thus leading to the enhancement of the GFA of the present Ni-based alloys [1]. Additionally, compared with the solely addition of Mo, the co-addition of Mo and Cr can more effectively enhance the GFA of the present Ni-based alloys. According to the "confusion principle" [21], the co-addition of Mo and Cr further increases the entropy and dense random packing of the molten alloy, thus leading to the enhancement of the GFA. However, it can be noted that the too much substitution content of Mo and Cr for Ni will degrade the GFA of the present Ni-based alloys. As mentioned previously, Mo and Cr have the larger negative enthalpy of mixing with the metalloid elements of P and B compared with Ni. Therefore, the excessive substitution of Mo and Cr for Ni could induce the formation of the Mo/Cr-contained intermediate phases in the molten alloy [18], which leads to the degradation of the GFA of the present Ni-based alloys.

Fig. 2 displays the DSC thermal scans for the *as*-cast $Ni_{77-x-y}Mo_xCr_yNb_3P_{14}B_6$ (x = 7 y = 0; x = 8 y = 0; x = 9 y = 0; x = 5 y = 3; x = 5 y = 5; x = 5 y = 8; x = 8 y = 3; x = 8 y = 5, all in at.%) glassy rod specimens at the heating rate of 0.33 K/s. All the specimens show a clear glass transition, followed by an extended supercooled liquid region and a single-stage crystallization process. The glass transition temperature (T_g), the onset crystallization temperature (T_x), the melting temperature (T_m), and the liquidus temperature (T_l) parameters (marked by arrows in Fig. 2) are summarized in Table 1. It can be seen that the T_g values of the present Ni-based BMGs increase with the total content of Mo and Cr. It is known that the T_g of amorphous alloys mainly depend on the atomic bonding strength between the constituent elements [22].