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Effect of the Nb and Cu Addition on Thermal Stability and Glass-Forming Ability of the $Fe_{36}Co_{36}Y_8B_{20}$ BMG

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A series of the $(Fe_{36}Co_{36}Y_8B_{20})_{100-x}Nb_x$ (x = 0, 0.1, and 0.5 at.%) and $(Fe_{36}Co_{36}Y_8B_{20})_{100-x}Cu_x$ (x = 0 and 0.1 at.%) amorphous alloys were fabricated by a conventional copper mold casting technique. The effects of the minor addition of niobium (Nb) and copper (Cu) on their thermal properties and glass-forming ability were discussed in detail. The results of X-ray diffraction and differential scanning calorimetry tests showed that the partial addition of Nb and Cu can effectively change the thermal properties and thermal stability of the investigated alloys. Hence, the glass-forming ability criteria, including supercooled liquid region (ΔT_x), reduced glass transition temperature (T_{rg}), criterion α, and criterion β, were calculated to evaluate the thermal stability. The supercooled liquid region was increased from 120°C for Nb-free alloy to 138 and 127°C for the alloy with 0.5 at.% Nb and 0.1 at.% Cu, respectively. As a result, the high glass-forming ability of the FeCo-based glass alloys and the improvement of this property by adding Nb and Cu may encourage the use of these alloys in future industrial devices.

topics: bulk metallic glass (BMG), glass-forming ability, thermal stability, differential scanning calorimetry

1. Introduction

The Fe-based metallic glasses alloys are a group of materials with suitable mechanical and magnetic properties [1–7], such as relatively high corrosion resistance [8, 9], high compressive strengths [10–12], and low cost [13–15], that have led to their widespread applications in various industries. On the other hand, the Fe-based soft magnetic amorphous alloys have attracted the attention of many researchers due to their relatively favorable saturation magnetization [16–19] and low core losses [20, 21]. According to the mentioned studies, the glass-forming ability (GFA) of the amorphous structure is measured using the cooling rate index. Indeed, the cooling rate should be high enough to prevent the crystallization of the melt and facilitate the creation of an amorphous structure [22, 23]. However, the thermal stability of iron-based soft magnetic amorphous alloy is low, and the melt-spinning method can be used to produce them [24, 25]. As a result, proper solutions such as adding an alloying element should be utilized to improve their thermal stability. For instance, Yang et al. [26] confirmed that appropriate Mo addition to $Fe_{80x}Mo_xP_{13}C_7$ (x = 0, 3, 6, 9, and 12 at.%) can improve their GFA and delays the formation of crystallites phases [23]. In this regard, the addition of alloying elements has a significant influence on the production method and thermal properties improvement. Similarly, the impact of tungsten (W) on the mechanical and thermal characteristics of $Fe_{47-x}Cr_{20}Mo_{10}W_xC_{15}B_6Y_2$ (x = 0, 2, 4, 6 at.%) alloy was investigated [27]. The results validated that increasing the critical diameter (d_c) and ΔT_x parameters with the addition of W (4 at.%) leads to enhanced thermal stability due to the delay of the formation of the $Fe_{23}B_6$ phase [27]. Therefore, the aim of this study is to investigate the effect of partial addition of copper (Cu) and niobium (Nb) on the thermal properties, such as thermal stability of $Fe_{36}Co_{36}Y_8B_{20}$ soft magnetic alloy, utilizing X-ray diffraction (XRD) and differential scanning calorimetry (DSC) tests.

2. Experimental procedure

Multicomponent alloy ingots with composition of $(Fe_{36}Co_{36}Y_8B_{20})_{100-x}$ Nb_x (x = 0, 0.1, and 0.5 at.%) and $(Fe_{36}Co_{36}Y_8B_{20})_{100-x}$ Cu_x (x = 0 and 0.1 at.%) were fabricated by arc-melting using a mixture of pure Fe, B, Co, Y, Nb, and Cu elementals (99.99%) under an argon atmosphere. Then, all alloys were remelted at least five times to homogenize the composition. The initial metallic glassy

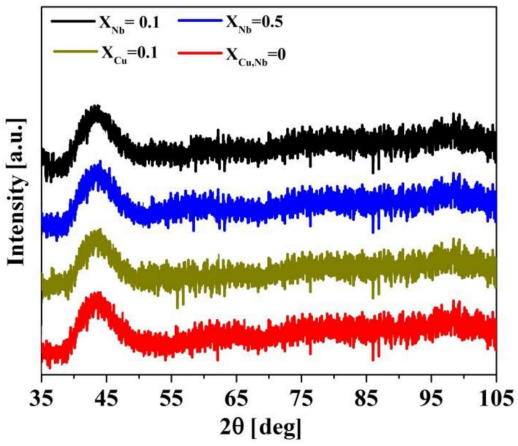

Fig. 1. XRD patterns of the $(Fe_{36}Co_{36}Y_8B_{20})_{100-x}Nb_x$ (x=0, 0.1, and 0.5 at.%) and $(Fe_{36}Co_{36}Y_8B_{20})_{100-x}Cu_x$ (x=0 and 0.1 at.%) amorphous alloy.

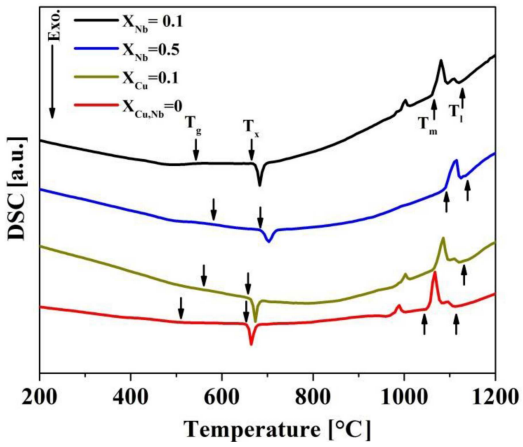

Fig. 2. DSC curve of the as-cast $(Fe_{36}Co_{36}Y_8B_{20})_{100-x}Nb_x$ (x=0, 0.1, and 0.5 at.%) and $(Fe_{36}Co_{36}Y_8B_{20})_{100-x}$ Cu_x (x=0 and 0.1 at.%) bulk metallic glasses (BMGs).

alloys were produced by suction casting in a water-cooled copper mold in the form of a rod with a diameter of 1 mm and a length of 70 mm under argon gas, and eventually, the amorphous structure was created by X-ray diffraction (XRD, Bruker D8 Advance) with Cu K_α radiation. It is worth mentioning that the differential scanning calorimetry test (DSC, Netzsch STA 449 F5 Jupiter) was used to evaluate the thermal properties and temperature characteristics during crystallization with a heating rate of 20°C/min from room temperature up to 1200°C.

3. Results and discussion

Figure 1 exhibits the XRD patterns of the $(Fe_{36}Co_{36}Y_8B_{20})_{100-x}Nb_x$ (x=0, 0.1, and 0.5 at.%) and $(Fe_{36}Co_{36}Y_8B_{20})_{100-x}Cu_x$ (x=0 and 0.1 at.%) amorphous alloys. The amorphous nature of the mentioned alloys can be confirmed by the wide peak in the range of $2\theta = 20$–$40°$ and the absence of crystalline phases. Moreover, the DSC curves of alloys are illustrated in Fig. 2. The critical temperatures extracted from the DSC, including T_g (glass transition temperature), T_x (onset of crystallization temperature), T_m (melting temperature), and T_l (liquid temperature), are given in Table I.

TABLE I

Thermal properties of $(Fe_{36}Co_{36}Y_8B_{20})_{100-x}$ Nb_x ($x = 0$, 0.1, and 0.5 at.%) and $(Fe_{36}Co_{36}Y_8B_{20})_{100-x}$ Cu_x ($x = 0$ and 0.1 at.%) amorphous alloy.

X_M [at.%] (M = Nb, Cu)	T_g [°C]	T_x [°C]	T_m [°C]	T_l [°C]
Nb = 0.1	540	670	1058	1127
Nb = 0.5	548	686	1053	1125
Cu = 0.1	535	662	1056	1129
Nb, Cu = 0	529	649	1062	1133

TABLE II

Summary of glass forming ability criteria for the investigated alloys.

X [at.%]	ΔT_x [°C]	T_{rg}	ω	New β
Nb = 0.1	130	0.48	0.22	2.18
Nb = 0.5	138	0.49	0.23	2.19
Cu = 0.1	127	0.47	0.21	2.17
Nb, Cu = 0	120	0.46	0.19	2.15

According to the results, only one exothermic peak is observed during the crystallization process. On the other hand, the glass transition temperature increases by adding 0.2 and 0.1 at.% of niobium (Nb) and copper (Cu), respectively. Therefore, the addition of these alloying elements can shift the glass transition temperature to a higher temperature. Furthermore, the results of other studies validate that the design of alloys with high thermal stability for various applications has been significantly improved by adding 0.5 and 0.1 at.% of Nb [28–30] and Cu [31, 32], respectively. In fact, the mentioned properties can be controlled by proper adjustment of the competing crystalline phase and modification of liquid chemistry [33, 34]. The super-liquid region (ΔT_x) is one of the critical parameters for determining the resistance to crystallization, which is usually not wide in magnetic soft iron-based alloys. This study confirms that the addition of an alloying element leads to an increment in the range of T_g and T_x. For instance, the temperature difference between T_g and T_x has increased from 120°C for Nb-free alloy to 138 and 127°C for the alloy with, respectively, $x = 0.5$ at.% Nb and $x = 0.1$ at.% Cu.

It should be noted that Table II lists the results obtained according to other criteria, i.e., $T_{rg} = T_g/T_l$ [35], $\omega = T_g/T_x - 2T_g/(T_l + T_g)$ [36],

and new $\beta = T_x T_g/(T_l - T_x)$ [37]. The results of these criteria also confirm the presented results. Thereupon, Nb and Cu elements have a useful role in the GFA of bulk metallic glasses and increase the packing density of the amorphous phases and their potential application in various industries.

4. Conclusions

In this study, the improvement of GFA in the $(Fe_{36}Co_{36}Y_8B_{20})_{100-x}Nb_x$ (x=0, 0.1, and 0.5 at.%) and $(Fe_{36}Co_{36}Y_8B_{20})_{100-x}Cu_x$ (x=0 and 0.1 at.%) bulk metallic glasses (BMGs) using the appropriate addition of Nb and Cu have been confirmed. In this regard, it was shown that the criteria parameters related to the thermal stability (especially ΔT_x) increased sharply with the addition of 0.5 and 0.1 atomic percentages of Nb and Cu, respectively. Therefore, according to the three empirical rules, the addition of niobium and copper to the mentioned alloys leads to achieving a high GFA amorphous alloy.

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