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Effects of Ni substitution for Fe on magnetic properties of $Fe_{80-x}Ni_xP_{13}C_7$ ($x = 0$–30) glassy ribbons

Qingling Liu [a], Haishun Liu [a,*], Mingzi Wang [a], Yue Zhang [a], Zhanguo Ma [b], Yucheng Zhao [b], Weiming Yang [b,*]

[a] School of Physics, China University of Mining and Technology, Xuzhou 221116, People's Republic of China
[b] State Key Laboratory for Geomechanics and Deep Underground Engineering, School of Mechanics and Civil Engineering, China University of Mining and Technology, Xuzhou 221116, People's Republic of China

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ABSTRACT

The effects of Ni substitution for Fe in $Fe_{80-x}Ni_xP_{13}C_7$ ($x = 0$, 10, 20, and 30) glassy ribbons on magnetic properties as well as the thermal stability were systematically investigated. It was found that the glassy ribbons exhibit excellent soft magnetic properties, i.e., the coercive force decreases from 4.0 to 1.4 A/m, the effective permeability increases from 12,000 to 25,000, and the saturation flux density of 1.57–1.25 T when increasing Ni substitution for Fe from 0 to 30. Moreover, the Curie temperature increases through a broad maximum at $x = 20$ for the $Fe_{80-x}Ni_xP_{13}C_7$ system and then decreases dramatically as x increases. The variation mechanism of magnetic properties in $Fe_{80-x}Ni_xP_{13}C_7$ ($x = 0$, 10, 20, and 30) glassy ribbons were discussed in detail. This work may shed light on the design of Fe-based amorphous alloys with good soft magnetic properties.

1. Introduction

The combination of outstanding magnetic properties, excellent mechanical properties and low material cost make Fe-based amorphous alloys suitable candidates as functional and structural materials [1–3]. Minor element substitution or addition has been proved as an effective approach to tune magnetic, mechanical or other properties of amorphous alloys [4], and numerous studies already revealed that partial Ni substitution/addition may remarkably change the glass-forming ability and mechanical properties in Fe-based amorphous alloys due to their similar ferromagnetic properties [5]. As a kind of typical magnetic material system, FePC amorphous alloy has excellent soft magnetic properties, and now are used as key parts in magnetic devices, such as anti-theft labels in supermarkets or libraries [6–8], its first preparation by Duwez et al. [9] opens up the research of Fe-based amorphous alloy [10–16], which is still a research hotspot. Recently, Yang et al. indicated that significant improvement in plasticity at room temperature was achieved through substitution of Fe by Ni in FePC glassy system [17]. Subsequently, Guo et al. reported an even improved super large plasticity of above 50% in $Fe_{62}Ni_{18}P_{13}C_7$ amorphous alloy [18]. A more recent study reported the effect of Ni substitution for Fe on corrosion resistance of FePC amorphous alloy [19], which manifests FeNiPC amorphous alloys exhibit high corrosion resistance. Above investigation indicates that FeNiPC amorphous alloys exhibit high corrosion resistance and remarkable mechanical property (e.g., plasticity). It is known that soft magnetic properties, including coercive force and effective permeability, are crucial for the efficiency improving and energy saving in magnetic devices, such as magnetic sensors, amplifiers and transformers etc. However, the study concerning soft magnetic properties with the substitution of Fe by Ni in FePC amorphous alloy is insufficient and the related mechanism is still unclear.

In the present work, we investigated the effects of partial substitution of Fe by Ni on the thermal characteristics and magnetic properties of $Fe_{80}P_{13}C_7$ amorphous alloys, and the variation of magnetic properties was analyzed and interpreted in detail. We believe this study can provide useful reference for obtaining multicomponent amorphous alloys with combination of good magnetic properties and excellent mechanical properties.

2. Experimental procedures

Master alloys with nominal compositions of $Fe_{80-x}Ni_xP_{13}C_7$ ($x = 0$, 10, 20, and 30) were prepared by arc melting the mixtures of high-purity elements (Fe: 99.99 wt.%, Ni: 99.9 wt.%, P: 99.5 wt.%, C: 99.99 wt.%) under an argon atmosphere. Glassy ribbons were produced by melt-spun method. The structures of as-quenched samples were identified by X-ray diffraction (XRD) with Cu K_α radiation. The thermal stability of the glassy samples was examined using a NETZZSCH 404 C differential scanning calorimeter (DSC) under a flow of high purity argon. The thermomagnetic curves of samples were measured by the physical property measurement system (PPMS). All of the as-quenched ribbons were isothermally annealed at a temperature 50 K below the glass transition temperature for 600 s under vacuum followed by

* Corresponding authors.
E-mail addresses: liuhaishun@126.com (H. Liu), wmyang@cumt.edu.cn (W. Yang).

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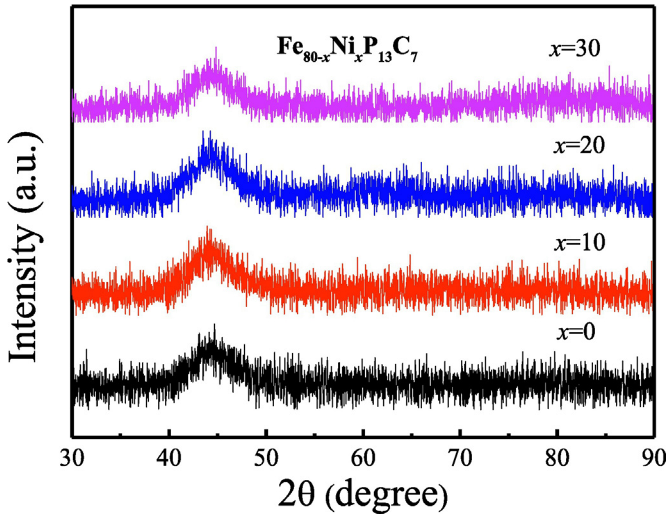

Fig. 1. XRD patterns of $Fe_{80-x}Ni_xP_{13}C_7$ ($x = 0$, 10, 20, and 30) melt-spun ribbons.

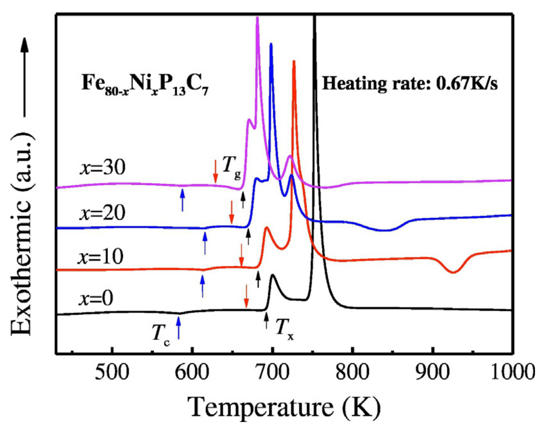

Fig. 2. DSC curves of $Fe_{80-x}Ni_xP_{13}C_7$ ($x = 0$, 10, 20, and 30) melt-spun ribbons.

water quenching. Magnetic properties such as saturation flux density (B_s), coercive force (H_c) and effective permeability (μ_e) at 1 kHz were measured with a vibrating sample magnetometer (VSM) under an applied field of 800 kA/m, the *B-H* loop tracer under a field of 800 A/m and impedance analyzer under a field of 1 A/m at room temperature, respectively. The data were measured >3 times. The relative errors for the B_s and μ_e is <2%. The errors of H_c and thermal stability data are <0.5 A/m and 3 K, respectively.

3. Result and discussion

Fig. 1 shows the XRD patterns of $Fe_{80-x}Ni_xP_{13}C_7$ ($x = 0$, 10, 20, and 30) melt-spun ribbons. All XRD patterns exhibit only one broad diffraction peak without any evidence of crystalline phases, which is the typical characteristic of fully amorphous structure.

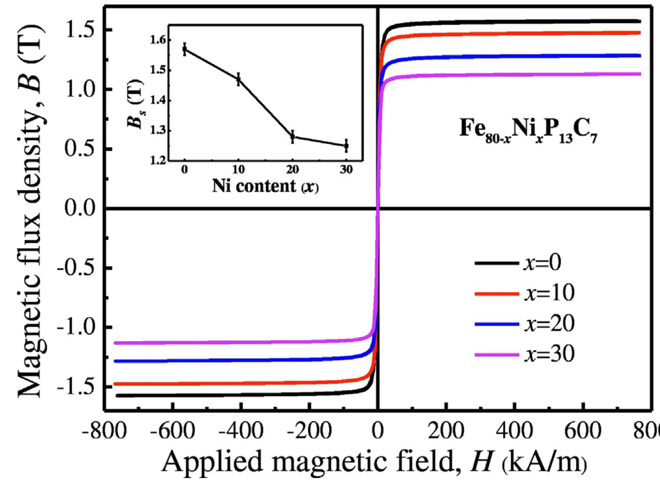

Fig. 3. *B-H* hysteresis curves of $Fe_{80-x}Ni_xP_{13}C_7$ ($x = 0$, 10, 20, and 30) glassy ribbons, inset shows Ni substitution dependence of saturation flux density.

Fig. 2 presents the DSC curves of the melt-spun $Fe_{80-x}Ni_xP_{13}C_7$ ($x = 0$, 10, 20, and 30) ribbons measured at the heating rate of 0.67 K/s. All the DSC curves exhibit the glass transition and crystallization events, further confirming the glassy structure in these ribbons. The thermal parameters including the glass transition temperature (T_g), crystallization temperature (T_x), and the supercooled liquid region (ΔT_x) obtained from the analysis of the DSC curves were listed in Table 1. The Curie temperature (T_c) can be also indicated in the DSC curves. It was found that, with the increase of Ni content, T_g decreases from 662 to 624 K, the T_x decreases gradually from 689 to 662 K, and the corresponding ΔT_x decreases from 27 to 20 K firstly, and then increases to 38 K. These glassy ribbons have the $\Delta T_x > 20$ K between the glass transition and the onset of crystallization when x from 0 to 20, it is suggested that the thermal stability of supercooled liquid decrease slightly with minor Ni addition.

Fig. 3 exhibits the *B-H* hysteresis curves of the glassy $Fe_{80-x}Ni_xP_{13}C_7$ ($x = 0$, 10, 20, and 30) ribbons. As can be seen from Fig. 3, B_s decreases gradually from 1.57 to 1.25 T with increased Ni substitution for Fe. Although a little deterioration is shown with Ni substitution, $Fe_{50}Ni_{30}P_{13}C_7$ glassy ribbons still remain a fairly high saturation flux density.

The H_c and μ_e of $Fe_{80-x}Ni_xP_{13}C_7$ ($x = 0$, 10, 20, and 30) glassy ribbons are present in Fig. 4. It can be seen that with increasing Ni content from $x = 0$ to 30, the H_c decreases monotonically from 4.0 to 1.4 A/m, while μ_e exhibits noticeable increases from 12,000 to 25,000, indicating the greatly improved soft magnetic properties with proper Ni substitution for Fe in $Fe_{80-x}Ni_xP_{13}C_7$ ($x = 0$, 10, 20, and 30) glassy system. Moreover, an approximate inverse variation relationship between H_c and μ_e is shown with Ni substation, the change trend is consistent with previous studies [20,21].

The temperature dependence of magnetization for $Fe_{80-x}Ni_xP_{13}C_7$ ($x = 0$, 10, 20, and 30) glassy ribbons are shown in Fig. 5(a). Here, the T_c is defined by the maximum in the "absolute value" of dM/dT, determined from the *M-T* curves [22]. The dM/dT vs. T of $Fe_{80-x}Ni_xP_{13}C_7$ ($x = 0$, 10, 20, and 30) glassy ribbons are shown in Fig. 5(b), and the

Table 1
Thermal stability data and magnetic properties for $Fe_{80-x}Ni_xP_{13}C_7$ ($x = 0$, 10, 20, and 30) glassy ribbons.

Alloys	Thermal stability				Magnetic properties		
	T_g (K)	T_x (K)	ΔT_x (K)	T_c (K)	B_s (T)	H_c (A/m)	μ_e
$Fe_{80}P_{13}C_7$	662 ± 3	689 ± 3	27	579 ± 3	1.57 ± 0.02	4.0 ± 0.5	12,000 ± 200
$Fe_{70}Ni_{10}P_{13}C_7$	661 ± 3	682 ± 3	21	606 ± 3	1.47 ± 0.02	3.0 ± 0.5	20,000 ± 200
$Fe_{60}Ni_{20}P_{13}C_7$	649 ± 3	669 ± 3	20	613 ± 3	1.28 ± 0.02	2.3 ± 0.5	22,000 ± 200
$Fe_{50}Ni_{30}P_{13}C_7$	624 ± 3	662 ± 3	38	588 ± 3	1.25 ± 0.02	1.4 ± 0.3	25,000 ± 300