Effects of heavy rare-earth addition on glass-forming ability, thermal, magnetic, and mechanical properties of Fe-RE-B-Nb (RE = Dy, Ho, Er or Tm) bulk metallic glass

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A B S T R A C T

With the aim of investigating how the species of doped rare-earth (RE) elements affect the glass-forming ability (GFA), 5 at. % RE elements were added in Fe71Nb6B23 alloy to substitute Fe. Compared with the Fe66RE5Nb6B23 (RE = Ho or Dy), Fe66RE5Nb6B23 (RE = Er or Tm) possesses an extra competitive Fe3B crystallization phase, which leads to a better GFA by stabilizing the liquid phase structure. Moreover, Fe66Tm5Nb6B23 shows the lowest density of states near the Fermi level among four alloys, which contributes to its best GFA. The influences of RE addition on the thermal, magnetic, and mechanical behaviors were also investigated. With increasing atomic number of RE elements from Dy to Tm, the saturation magnetic flux density increases obviously accompanied by the improved flowability in the supercooled liquid region, which makes Fe66Tm5Nb6B23 as a potential functional soft-magnetic material for thermoplastic machining.

1. Introduction

Fe-based bulk metallic glasses (BMGs) are promising candidates as advanced structural/functional materials due to their excellent soft magnetic performances, unique mechanical properties, corrosion resistance and so on [1–4]. Among Fe-based BMGs, Fe71Nb6B23 is the strongest with outstanding fracture strength (σf) of about 4.85 GPa [5]. However, the low glass-forming ability (GFA) may restrain its potential industrial applications. The technology of microalloying has been widely applied in metallurgy field and played significant roles in the GFA, thermal stability or crystallization behavior of BMGs [6–8]. Through this method, we found that the thermal stability of supercooled liquid and GFA in FeNbB glassy alloy were enhanced appreciably by doping minor rare-earth (RE) elements [9,10]. Based on our previous work, it can be seen that the GFA of some Fe-based glassy alloys is not only affected by the content but also by the species of doped RE elements. Ab initio molecular dynamics simulation also shows that the different RE elements have a strong impact on the configuration of Fe-based alloy liquid, which results in a different GFA [11]. Besides of GFA, the local atomic structure, bonding environment, and mechanical properties are also influenced by minor RE elements addition [12–15]. Therefore, we have a great interest in how the RE elements affect us designing Fe-based BMGs on these aspects.

It has been reported that 5 at. % Ho or Er addition to Fe71Nb6B23 is optimum for improving the GFA and supercooled liquid region (SCLR) [9,10]. Moreover, doping 5 at. % Er elements can effectively tune the magnetic transition (Tc) near room temperature in FeErNbB alloy system. Thus, with the aim of better understanding how the GFA, thermal, magnetic, and mechanical properties of Fe71Nb6B23 BMG are affected by doping different RE elements, 5 at.% Dy, Ho, Er, and Tm elements were added to Fe71Nb6B23 alloy to substitute Fe, respectively. We found that the GFA of Fe66RE5Nb6B23 (RE = Dy, Ho, Er or Tm) glassy alloy has a strong correlation with primary crystallization phases and electronic structure. Doping different heavy RE elements precipitates into distinct crystallization phases and causes the disparity of density of states near the Fermi level N(Ef), which gives rise to different GFA in this alloy system. In addition, the investigations based on thermal and magnetic properties of these glassy alloys show that both the GFA and the saturation magnetic flux density (Bs) increase with an increasing atomic number of RE elements. Despise of the decrease of σf at room temperature with the addition of RE elements, the wide SCLR and the softened behavior in SCLR make Fe66RE5Nb6B23 as good candidates for thermal machining in the SCLR.
2. Experimental

Fe₆₆RE₅Nb₆B₂₃ quaternary alloy ingots (RE = Dy, Ho, Er or Tm) were prepared in a copper crucible. The ribbon samples were produced by a single roller melt-spinning method. Glassy rods with diameters up to 4.5 mm were made by copper mold casting. The thermal behaviors were measured with differential scanning calorimetry (DSC, NETZSCH 404 F3) using Al₂O₃ crucible. Samples were crystallized by annealing at a pressure of 2 × 10⁻³ Pa for 600 s at 1043 K in the annealing furnace and crystallization phases were examined by X-ray diffraction (XRD, Bruker D8 Discover diffractometer). Transverse cross-section of the as-cast glassy alloy rods was examined by scanning electron microscopy (SEM, FEI Sirion 200). X-ray photoelectron spectrometer (XPS, ESCALAB 250XI) was employed to measure electronic structures with Al Kα X-ray source. Prior to XPS measurements, the sample surfaces were cleaned via argon ion sputtering for 500 s. The thermal dilatation (DIL) measurement was carried out by using the TMA (NETZSCH, 402C) with a dimension of 1.5 nm. Compressive fracture strength (σₘ) was measured using glassy rods with a diameter of 1 mm and a length of 2 mm by the testing machine (CMT 4503) with a compressive strain rate of 5 × 10⁻⁴ s⁻¹. Vickers hardness (Hᵥ) was measured by a hardness tester (FM-700) under a load of 9.8 N. The B₅ versus field (B–H) of the ribbons was measured by vibrating sample magnetometer (VSM, Lake Shore 7410). Coercivity (Hᵥ) was measured by a DC B–H loop tracer (RIKEN BHS-40). To estimate the uncertainty of each measurement of thermal, magnetic and mechanical properties, at least four measurements were conducted. The thermal parameters, magnetic parameters (Bᵥ, Hᵥ), and mechanical parameters (Hᵥ, σₘ) were determined by averaging the measured values.

3. Results and discussion

For the purpose of evaluating the GFA through an experimental method, BMG rods with different diameters were fabricated for the RE (RE = Dy, Ho, Er or Tm) doped alloys Fe₆₆RE₅Nb₆B₂₃. Fig. 1 shows the XRD patterns of the Fe₆₆RE₅Nb₆B₂₃ cast rods. They all show typical broad peak without sharp crystallization peak. Fig. 2(a)–(d) shows cross-sectional morphologies of the as-cast Fe₆₆RE₅Nb₆B₂₃ (RE = Dy, Ho, Er, and Tm) rods with critical diameters. No distinct crystalline grains can be seen in the cross-section by both low power and high power SEM observation, which is consistent with the XRD results. The critical diameters (Dₜ) of the BMG rods are 2, 3, 4, and 4.5 mm respectively for the Fe₆₆RE₅Nb₆B₂₃ (RE = Dy, Ho, Er or Tm) glassy alloys. However, the atomic mismatch and the mixing enthalpy between RE element and the other three elements are almost the same [16]. Thus, the increase in Dₜ as a function of an ordinal number of the heavy RE element should be taken into further consideration.

The DSC traces of the Fe₆₆RE₅Nb₆B₂₃ (RE = Dy, Ho, Er or Tm) glassy ribbons in the temperature range from 600 to 1220 K are shown in Fig. 3. They all exhibit an obvious glass transition and a wide SCLR. The glass transition temperature (Tg) and the onset temperature of crystallization (Tc) show no significant change by doping different RE elements. The SCLR (ΔTc = Tc − Tg) about 90 K is extended by adding a minor RE elements as compared with the initial composition of Fe₇₁Nb₅B₂₃ (ΔTc = 39 K) [7]. It indicates that the minor RE element addition is effective for the extension of SCLR in this alloy system. The abnormal exothermic peak marked as P₁ (corresponding to Tm₁) is observed in the SCLR for these alloys, and this phenomenon has been well discussed in our recent work [10]. In addition, they exhibit distinct crystallization behavior of DSC curve as shown in Fig. 3. It can be found that it appears a small divisive peak (marked as P₁) before the main exothermic peak (marked as P₂) upon Dy addition. While with Ho addition, P₁ becomes a shoulder-like peak (marked as P₁ho). For the alloy containing Er element, the shoulder-like peak (marked as P₁ho) emerges on the right of the P₂ peak, and when Tm element was doped, it forms a new peak marked as P₃. Anyway, the addition of different RE elements causes totally different crystallization behaviors, this may have a relationship with the variation in GFA.

For further studying the relationship between the GFA and crystallization behaviors, and figuring out how crystallization behaviors of this alloy system are affected by the RE elements, Fe₆₆RE₅Nb₆B₂₃ were isothermally annealed in an annealing furnace. Fig. 4 shows XRD patterns of the Fe₆₆RE₅Nb₆B₂₃ glassy ribbons annealed at 1043 K for 600 s. It can be seen that Dy- and Ho-containing glassy samples show the precipitation phases of Fe₂₃B₆ and RE₂Fe₁₄B, however, the precipitation phases are changed into Fe₂₁B₂(RE₁₋ₓFeₓ)₂B and Fe₆₋ₓBₓ with Er and Tm addition. Besides, the peak of RE₁₋ₓFeₓB₆ at 28° = 42.6° becomes gradually dominant compared with the appearance of the peak for Fe₂₁B₂ at 28° = 43.6° with increasing RE atomic number. Thus, the P₁ and P₂ peaks should correspond to the precipitation of RE₁₋ₓFeₓB₆ and Fe₂₁B₂ phases respectively in the DSC curve for Dy-containing BMG. Due to the increasing amount of precipitated Ho₂Fe₁₄B phase, the P₁ peaks becomes a shoulder-like peak (marked as P₁ho) with Ho addition. The P₁ho peak should be caused by the precipitation of Fe₂₁B₂ phase for the Fe₆₆Er₅Nb₆B₂₃ ribbon, and P₁ho peak becomes stronger to form a P₃ peak for Tm-containing alloy. It has been reported that the primary crystallization phase for the Fe₇₁Nb₅B₂₃ sample is the metastable Fe₂₁B₂ phase [5,7], and the new formed competitive RE₂Fe₁₄B phase makes atomic diffusion of the whole sample more difficult, leading to the increase of GFA in Fe₆₆RE₅Nb₆B₂₃ glassy alloys [10]. Besides, due to the fact that the amount of Ho₂Fe₁₄B precipitated phase is more than that of Dy₂Fe₁₄B phase, it causes a higher competition between Fe₂₁B₂ and RE₂Fe₁₄B phases, which might response for the higher GFA of Fe₆₆Ho₅Nb₆B₂₃ than that of Fe₆₆Dy₅Nb₆B₂₃. Because that Fe₆₋ₓBₓRE₅Nb₆B₂₃ (RE = Er or Tm) owns an extra Fe₃B precipitated phase, it may improve the GFA of RE-added Fe₆₆RE₅Nb₆B₂₃ (RE = Er or Tm) alloys systems.

The GFA is not only affected by atomic stacking but also by electronic structure [17–19]. With the aim of exploring the electronic structure, the core-level spectra of participating elements in the Fe₆₆RE₅Nb₆B₂₃ glassy alloys were measured, as seen in Fig. 5. The Fe 2p, B 1s, and Nb 3d level spectra derived from the Fe₆₆RE₅Nb₆B₂₃ ribbons are shown in Fig. 5(a), (b), and (c). The binding energy (BE) position of the Fe 2p₃/2 and B 1s changes very small (lower than 0.1 eV). The BE position of the Fe 2pₓ/2 has same tendency with the observation of (Fe₀.₇₁RE₀.₀₅B₀.₄₅)₉₆Nb₁₄ (RE = Gd, Tb, Ho, Er or Tm) glassy alloys [18], which may indicate the change of electronic density of state. There is no significant change in Nb 3dₓ/₂ BE (about 202.90 eV), probably because that the enthalpy of mixing between Nb and RE is positive and high, which may cause phase separation in this alloy system [20]. Meanwhile, since Er and Tm are more likely to form RE₂Fe₁₄B phase, it causes the Nb element is more likely to facilitate the

![Fig. 1. XRD patterns of the Fe₆₆RE₅Nb₆B₂₃ (RE = Dy, Ho, Er or Tm) glassy rods.](image-url)
formation of crystallization phases of $\text{Fe}_{23}\text{B}_6$ and $\text{Fe}_3\text{B}$ [21,22]. Fig. 5(d) shows the valence band structure of $\text{Fe}_{66}\text{RE}_5\text{Nb}_6\text{B}_{23}$ (RE = Dy, Ho, Er or Tm). The spectra are marked differently from that of pure Fe in the region from 6 to 10 eV. It is attributed to the overlapped B 2s and RE 4f state that leads to the enhancement of RE-B bonds [18]. Based on the nearly-free-electron model [23], the better GFA the alloy has, the lower the density of states near the Fermi level $N(E_F)$ is [17,23]. As shown in inset Fig. 5(d), it can be found that $N(E_F)$ decreases when Dy was substituted by Tm element, therefore, Tm doped alloy owns the most stable state and the best GFA among this alloy system [17].

As discussed above, the atomic stacking can be affected by the heavy RE elements alloying, DIL measurement was carried out by using the TMA to measure the changes of expansion coefficients and thermal behaviors in this alloy system. Fig. 6 shows the DIL traces of $\text{Fe}_{66}\text{RE}_5\text{Nb}_6\text{B}_{23}$ (RE = Dy, Ho, Er or Tm) glass alloys. It can be found that the glassy specimen expands linearly with rising temperature, this may be caused by enhanced the atomic thermal vibration behaviors [24]. Doping different heavy RE elements in $\text{Fe}_{71}\text{Nb}_6\text{B}_{23}$ alloy show a similar linear expansion process and the average coefficient of the linear expansion marked as $\alpha_L$ is about $7 \times 10^{-6}$ K$^{-1}$. It indicates that the addition of RE elements may influence the atomic packing, however such effect before $T_g$ is very small and can be neglected. A rapid contraction arises when the samples are heated to SCLR. The softness denoted as $(\Delta L/L_0)_{\text{max}}$ of SCLR usually has a close correlation with the viscosity that affected by heavy RE elements [25], as shown Fig. 6. Based on the rheological model that describes viscosity and isoconfigurational shear modulus $G$ [26], Hu Q. et al. considered that the softness relates to $\Delta G = G(\text{Fe}_{71}\text{Nb}_6\text{B}_{23}) - G(\text{RE})$ [25]. The $G$ of $\text{Fe}_{71}\text{Nb}_6\text{B}_{23}$ BMG reported by Park J. is 73.4 GPa [27], and for the pure Dy, Ho, Er, Tm, Gs are 25, 26, 28, and 31 GPa [28], respectively. The $\Delta G$ can be obtained using the formula $\Delta G = G(\text{Fe}_{71}\text{Nb}_6\text{B}_{23}) - G(\text{RE})$. Its relation with softness is plotted in the inset of Fig. 6. It can be found that the softness shows a good linear negative correlation with $\Delta G$ in $\text{Fe}_{66}\text{RE}_5\text{Nb}_6\text{B}_{23}$ alloy system. Smaller $\Delta G$ corresponds to a better
flowability in SCLR [25], therefore, Fe66Tm5Nb6B23 alloy may be more suitable for thermoplastic machining in the SCLR among these four alloys.

The soft magnetic properties of Fe66RE5Nb6B23 (RE = Dy, Ho, Er or Tm) glassy alloys were also investigated. Fig. 7 displays the $B-H$ hysteresis curves measured by VSM. It can be seen that in $B-H$ loop tracer, the rapidly saturated magnetization indicates the excellent soft magnetic properties. It ascribes to the homogeneous structure of this metallic glass alloy without grain boundary to nail the domain wall. The $B_s$ increases gradually from 0.46 to 0.58 T with doping RE element from Dy to Tm. It is known that the electron in the 3d shell of Fe atom couples is antiferromagnetic with the electron in the 4f shell of RE atom, the smaller magnetic moment of RE element is, and the higher $B_s$ of this glassy alloy shows [29]. The magnetic moments of Dy, Ho, Er, and Tm are 10.6, 10.6, 9.6, and 7.6 $\mu_B$, respectively. Therefore, Tm-containing sample has the highest $B_s$ among these four glassy alloys. On the other hand, B element has a negative effect on the ferromagnetism of the FeNbB alloy system in B-rich compositions [30]. The overlapping of B 2$s$ and RE 4$f$ state discussed in core-level spectra correspond to the strong RE-B bonds near the Fermi level [18]. According to the near neighbor model of B-centered atom, the increase of interaction between

![Fig. 5. XPS spectra of the Fe66RE5Nb6B23 (RE = Dy, Ho, Er or Tm) glassy ribbons: (a) core-level spectra of Fe 2p, (b) core-level spectra of B 1s, (c) core-level spectra of Nb 3d, and (d) valence band spectra.](image)

![Fig. 6. DIL traces of Fe66RE5Nb6B23 (RE = Dy, Ho, Er or Tm) glassy alloys, the inset shows the correlation between ($\Delta L/L_0$)max and $\Delta G$.](image)

![Fig. 7. B–H hysteresis curves of the annealed melt-spun Fe66RE5Nb6B23 (RE = Dy, Ho, Er or Tm) glassy ribbons measured by VSM. The insert is the enlarged B–H loop tracer.](image)
RE and B atoms may weaken the interaction between atom B and Fe atoms, which may reduce the negative effect of B on the ferromagnetism of Fe-based alloys and response for the small change of RE position of the B 1s as shown in Fig. 5(b). Thus, minor RE addition may be beneficial for high magnetic performances in some cases. The $H_c$ value is highly affected by magnetic anisotropy and sample quality \[18,31\]. It is difficult to control the same size and quality of the prepared ribbons because the samples are very brittle after doping RE elements. Thus, no gradual regularity of $H_c$ is observed in this alloy system. However, due to the reason that the exchange energy of Tm–Fe is lower than the other three RE-Fe atomic pairs, it may have the smallest magnetic anisotropy constant $K$ \[18\], which results in the lowest $H_c$ value among these four alloys. On the other hand, because that the saturation magnetostriction ($\lambda_s$) can be enhanced by doping RE element in Fe-based glassy alloy \[32\], and it has a positive correlation with $H_c^{\sigma}$ \[33\],

$$H^e_c \approx |\sigma | \lambda_s / |M_s|$$  \hspace{1cm} (1)

where $M_s$ is the saturation magnetization and $H^e_c$ coercivity which originates from the magnetoelastic coupling. Therefore, the contribution of $H^e_c$ and magnetic anisotropy to the total $H_c$ of Fe$_{66}$RE$_5$Nb$_6$B$_{23}$ (RE = Dy, Ho, Er or Tm) is larger than that of Fe$_{71}$Nb$_6$B$_{23}$ ($H_c = 3.9$ A/m).

Except for excellent GFA and soft magnetic properties, Fe$_{66}$RE$_5$Nb$_6$B$_{23}$ (RE = Dy, Ho, Er or Tm) also shows superhigh $\sigma_f$ and Vickers hardness which are summarized in Table 1. The stress-strain curves show a downtrend in Fig. 8. By doping 5 at. % RE elements, the discrete nature of $\sigma_f$ becomes much more obvious, especially for the composition containing Er and Tm elements. It has been proposed that the fracture strength and toughness of BMG can be manipulated by the degree of bonding hybridization \[34,35\], i.e., the density of state at the Fermi level. As shown in Fig. 5(d), the lowest $N(E_f)$ of Tm-containing glassy alloy indicates a weaker atomic bonding than that of other three RE elements containing system \[35\], which causes the decrease of both fracture strength and Vickers hardness. Meanwhile, as reported in the work of Liu \[36\] and Li \[37\] et al., the minor RE alloying may cause the high flaw sensitivity and porosity, which easily causes a premature fracture before the intrinsic strength of materials. This might be another reason that decreases the $\sigma_f$ of Er- or Tm-containing sample. However, although $\sigma_f$ of Tm-containing sample is lower than that of Dy- and Ho-containing samples, it still exceeds $\sigma_f$ of many metal materials.

In our recent work, thermoplastic deformation of Fe$_{66}$Ho$_5$Nb$_6$B$_{23}$ glassy alloy has been investigated \[10\]. It was found that RE-containing Fe-based BMGs own a wide SCLR, which can be used for thermoplastic processing at the temperature above room temperature. The present studied RE-added Fe$_{66}$RE$_5$Nb$_6$B$_{23}$ BMGs also exhibit a wide SCLR of about 90 K, which make them be suitable for thermoplastic processing in the SCLR as well. Based on the further analysis of the DIL measurement and magnetic properties, it is proposed that Fe$_{66}$Tm$_5$Nb$_6$B$_{23}$ alloys with good flowability and soft magnetic property can be as a promising thermoplastic-machining functional material for industrial applications in the near future.

Based on the above experimental results, heavy RE elements addition on Fe$_{71}$Nb$_6$B$_{23}$ can improve comprehensive performance effectively. The radius of heavy RE element decreases and the electron number of 4f electronic shell increases as the atomic number increases, which leads to the changes of atomic stacking and electronic structures of FeRENbB alloy system. The XPS result shows that $N(E_f)$ decreases when Dy was substituted by Tm element, it means Er and Tm doped alloy owns the more stable glassy state than that of Dy and Ho doped alloys. The crystallization behavior depends on the structural state of the glassy alloy, it may be the reason why Er and Tm containing alloys possesses an extra competitive Fe$_2$B crystallization phase. The competition of multiphase in Er- and Tm-containing alloys is beneficial for the stabilization of the liquid phases, which causes the better GFA. Meanwhile, the DSC traces show that these four alloys almost have the same SCLR, however as indicated by DIL measurements, their softness are different as a result of the distinction on the shear modulus $G$. Thus, Tm-containing alloy may be more suitable for thermoplastic machining among these four alloys due to the reason that it is relatively softer (smaller $\Delta G$). On the other hand, with the increase of atomic number from Dy to Tm, $\sigma_f$ shows decreasing trend because of the weak atomic bonding and the increase in flaw sensitivity and porosity, while the soft magnetic properties are significantly improved, which gives a better magnetic performance of the Tm-containing alloy. Fe$_{66}$Tm$_5$Nb$_6$B$_{23}$ that possesses an excellent GFA and magnetic properties, thereby, can be as a functional soft-magnetic material for the application of thermoplastic machining.

### 4. Conclusions

The influences of heavy RE addition on comprehensive properties of Fe$_{66}$RE$_5$Nb$_6$B$_{23}$ (RE = Dy, Ho, Er or Tm) glassy alloy system were investigated. The results are summarized below:

1. Doping 5 at. % heavy RE elements into Fe$_{71}$Nb$_6$B$_{23}$ glassy alloy effectively improves the GFA with $D_c$ up to 4.5 mm. The SCLR and the crystallization process are varied by adding different heavy RE

### Table 1

<table>
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<tr>
<th>Alloy</th>
<th>$\Phi$ (mm)</th>
<th>$T_c$ (K)</th>
<th>$T_m$ (K)</th>
<th>$\Delta T$ (K)</th>
<th>$B_t$ (T)</th>
<th>$H_c$ (A/m)</th>
<th>$\sigma_f$ (GPa)</th>
<th>$H_v$ (kg/mm$^2$)</th>
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<tr>
<td>Fe$_{66}$Dy$_5$Nb$<em>6$B$</em>{23}$</td>
<td>2</td>
<td>882 ± 2</td>
<td>972 ± 1</td>
<td>90 ± 3</td>
<td>0.46 ± 0.02</td>
<td>10.49 ± 0.12</td>
<td>3.65 ± 0.03</td>
<td>1060 ± 5</td>
</tr>
<tr>
<td>Fe$_{66}$Ho$_5$Nb$<em>6$B$</em>{23}$</td>
<td>3</td>
<td>883 ± 1</td>
<td>972 ± 2</td>
<td>90 ± 3</td>
<td>0.51 ± 0.03</td>
<td>11.28 ± 0.15</td>
<td>3.42 ± 0.05</td>
<td>1045 ± 5</td>
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<tr>
<td>Fe$_{66}$Er$_5$Nb$<em>6$B$</em>{23}$</td>
<td>4</td>
<td>882 ± 3</td>
<td>972 ± 1</td>
<td>90 ± 4</td>
<td>0.54 ± 0.02</td>
<td>8.78 ± 0.08</td>
<td>3.32 ± 0.07</td>
<td>1040 ± 5</td>
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<tr>
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<td>881 ± 2</td>
<td>971 ± 2</td>
<td>90 ± 4</td>
<td>0.58 ± 0.04</td>
<td>8.57 ± 0.14</td>
<td>3.15 ± 0.08</td>
<td>1020 ± 5</td>
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elements.

(2) The GFA is affected by both atomic stacking and electronic structures. Fe66RE5Nb6B23 (RE = Er, Tm) owns three competitive formations of Fe23B6, RE2FeFe2B, and FeB, much more complex than that of Fe66RE5Nb6B23 (RE = Ho, Dy), which contributes to the excellent GFA of Fe66RE5Nb6B23 (RE = Er, Tm). Besides, based on the XPS spectra, the Fe66Tm5Nb6B23 shows the lowest N(Ef), which causes Tm doped alloy owns the most stable state with a shortened interatomic distance and the best GFA among these alloy systems.

(3) Consistent with the observation in Zr-based BMG, a negative correlation between the (ΔL/L0)max and ΔG = (G(Fe21Nb5B23) - G(RE) is found in Fe66RE5Nb6B23. Fe66Tm5Nb6B23 alloy owes the smallest ΔG corresponding to a good flowability in SCLR, which is more suitable for thermomachining in the SCLR among these four alloys.

(4) Although η of Tm-containing sample decreases because of the weak atomic bonding and the increase in flaw sensitivity and porosity, the soft magnetic properties of Fe66Tm5Nb6B23 are significantly improved as compared to other RE-containing alloys due to the low magnetic moments of Tm and the weakened negative effect of B. Combined with the DIL measurement, it is expected that Fe66Tm5Nb6B23 with a good flowability and soft magnetic property can be as a potential functional materials.

Declaration of Competing Interest

The authors declared that they have no conflicts of interest to this work. We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

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