The Effect of Nb Content on the Thermal, Structural, and Magnetic Properties of FeNbB Ribbons


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1. Introduction

Fe-based amorphous and nanocrystalline soft magnetic alloys have been widely studied over the last decade [1–10]. Fe-based ribbons have good soft magnetic properties and are widely used as the electromagnetic materials. Many investigations focus on the FeNbB alloys [6–10]. The crystallization behaviors [6], crystallization process [7], and magnetic property [8] of FeNbB alloys were studied.

Itoi and Inoue [9] have reported the effect of B content on thermal stability of Fe-Ni-B alloys. Stokkoska [10] reported the influence of boron content on crystallization and magnetic properties of ternary FeNbB amorphous alloys.

The purpose of this study is to investigate the effect of Nb content on the thermal, structural and magnetic properties of Fe_{80–x}Nb_{x}B_{20} (x = 5, 10, 15) ribbons.

2. Experimental details

Amorphous ribbons of Fe_{80–x}Nb_{x}B_{20} (x = 5, 10, 15) with 4 mm width and 30 µm thickness were obtained by the single-roller melt spinning technique at a surface velocity of 38 m/s. The microstructure was examined by X-ray diffraction (XRD, D/max 2500/PC, Cu Kα, λ = 1.5406 Å). The thermal analysis was investigated by differential thermal analysis (DTA, TG/DTA-6300). The magnetic property was performed by the vibrating sample magnetometer (VSM, Lake Shore M-7407).

3. Results and discussion

Figure 1 shows the DTA curves of Fe_{80–x}Nb_{x}B_{20} (x = 5, 10, 15) ribbons at different heating rates. The first crystallization peaks \( T_p \) of Fe_{80–x}Nb_{x}B_{20} (x = 5, 10, 15) amorphous ribbons obtained at different heating rates are listed in Table I. \( T_p \) increases with the increase of Nb content. The increase of \( T_p \) should be related to the fact that Nb has higher melting temperature than Fe. The apparent activation energy of crystallization is calculated using the Kissinger equation [11], by plotting \( \ln(\nu/T^2) \) versus \( 1/T \) (a straight line with the slope of \( E/R \)), where \( R \) is the gas constant, \( \nu \) is the heating rate (K/min) and \( T \) is a specific absolute temperature such as crystallization peak \( T_p \).

![Fig. 1. DTA curves of Fe_{80–x}Nb_{x}B_{20} (x = 5, 10, 15) ribbons at different heating rates.](image_url)
The first crystallization peaks $T_p$ of Fe$_{80-x}$Nb$_x$B$_{20}$ ($x = 5, 10, 15$) amorphous ribbons obtained at different heating rates.

<table>
<thead>
<tr>
<th>$x$ [K/min]</th>
<th>$T_p$ [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>830.4</td>
</tr>
<tr>
<td>20</td>
<td>899.4</td>
</tr>
<tr>
<td>30</td>
<td>916.5</td>
</tr>
</tbody>
</table>

Table I

Figure 2 shows the Kissinger plots of Fe$_{80-x}$Nb$_x$B$_{20}$ ($x = 5, 10, 15$) ribbons for $T_p$; the apparent activation energies are 414.9, 323.0, and 425.7 kJ/mol, respectively. The thermal stability is the lowest for Fe$_{70}$Nb$_{10}$B$_{20}$ ribbon and the highest for Fe$_{65}$Nb$_{15}$B$_{20}$ ribbon.

Fig. 2. Kissinger plots of Fe$_{80-x}$Nb$_x$B$_{20}$ ($x = 5, 10, 15$) ribbons for $T_p$.

Table II

<table>
<thead>
<tr>
<th>$x$</th>
<th>$T_k$</th>
<th>$T_x$</th>
<th>$\Delta T_x$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>805.629</td>
<td>836.603</td>
<td>30.974</td>
</tr>
<tr>
<td>10</td>
<td>833.760</td>
<td>867.931</td>
<td>34.171</td>
</tr>
<tr>
<td>15</td>
<td>874.538</td>
<td>910.340</td>
<td>35.802</td>
</tr>
</tbody>
</table>

Figure 3 shows the DTA curves of Fe$_{80-x}$Nb$_x$B$_{20}$ ($x = 5, 10, 15$) amorphous ribbons at a heating rate of 30 K/min.

Fig. 3. DTA curves of Fe$_{80-x}$Nb$_x$B$_{20}$ ($x = 5, 10, 15$) amorphous ribbons at a heating rate of 30 K/min.

Figure 4 shows the XRD patterns of as-quenched and annealed Fe$_{80-x}$Nb$_x$B$_{20}$ ($x = 5, 10, 15$) ribbons. FeNbB system is favored in the three empirical rules [12]. FeNbB system consists of three components (Fe, Nb and B). There is significant difference in atomic size ratios above 12% among the main constituent elements and the sequence of atomic size is $R_{\text{Fe}} > R_{\text{B}} > R_{\text{Nb}}$. The negative heats of mixing of Fe–B, Nb–Fe and Nb–B are −26, −16 and −54 kJ/mol [13], respectively. This system has high negative heats of mixing.

The primary stage of crystallization of the three ribbons changes with Nb content addition. The primary devitrification phase of Fe$_{70}$Nb$_{10}$B$_{20}$ and Fe$_{75}$Nb$_{5}$B$_{20}$ are similar, which is the metastable phase of Fe$_2B$ type. It seems that the Fe$_{23}$B$_6$ type was formed by annealing at lower temperatures; 843 K for Fe$_{70}$Nb$_{10}$B$_{20}$ and 803 K for Fe$_{75}$Nb$_{5}$B$_{20}$, which coincides with the results of Imafuji et al. [14]. Fe$_{65}$Nb$_{15}$B$_{20}$ is still in amorphous state at 843 K, which is related to its high thermal stability. The primary devitrification phase of Fe$_{65}$Nb$_{15}$B$_{20}$ is very different from Fe$_{70}$Nb$_{10}$B$_{20}$ and Fe$_{75}$Nb$_{5}$B$_{20}$. The primary devitrification phase of the Fe$_{65}$Nb$_{15}$B$_{20}$ is α-Fe type crystalline phase.

Figure 5 shows the hysteresis loops of as-quenched Fe$_{80-x}$Nb$_x$B$_{20}$ ($x = 5, 10, 15$) ribbons at room-temperature. Fe$_{80-x}$Nb$_x$B$_{20}$ ($x = 5, 10$) ribbons are ferromagnetic and Fe$_{80}$Nb$_{15}$B$_{20}$ ribbon is paramagnetic. The inset shows the $M$-$T$ curve of Fe$_{65}$Nb$_{15}$B$_{20}$ ribbon at low temperature. The Curie temperature of Fe$_{65}$Nb$_{15}$B$_{20}$
ribbon is 225 K. The saturation magnetization \( M_s \) decreases with increasing Nb content. The variation can be related to the variation in the magnetic moment. On the one hand, due to the Fe substitution for Nb, the Fe content decreases, so the magnetic moment of sample decreases. On the other hand, the variation of \( M_s \) is related to the competition between ferromagnetic and antiferromagnetic exchange interaction. Antiferromagnetic coupling was formed between Fe and Nb [15]. Antiferromagnetic exchange interaction increases and ferromagnetic exchange interaction decreases with increasing Nb content, so \( M_s \) decreases [16].

4. Conclusions

(1) The apparent activation energies of the Fe\(_{80-x}\)Nb\(_x\)B\(_{20}\) \((x = 5, 10, 15)\) ribbons are 414.9, 323.0, and 425.7 kJ/mol, respectively. The thermal stability is the lowest for Fe\(_{70}\)Nb\(_{10}\)B\(_{20}\) ribbon and the highest for Fe\(_{65}\)Nb\(_{15}\)B\(_{20}\) ribbon. Along with the increase of Nb content, the supercooled liquid region \( \Delta T_s \) \((\Delta T_s = T_s - T_k)\) increases gradually, indicating that the amorphous formation ability improves.

(2) The primary devitrification phase is metastable Fe\(_{23}\)B\(_6\) type for Fe\(_{70}\)Nb\(_{10}\)B\(_{20}\) and Fe\(_{75}\)Nb\(_{5}\)B\(_{20}\) ribbons, which is formed by annealing at low temperatures: 843 K for Fe\(_{70}\)Nb\(_{10}\)B\(_{20}\) ribbon and 803 K for Fe\(_{75}\)Nb\(_{5}\)B\(_{20}\) ribbon. Fe\(_{65}\)Nb\(_{15}\)B\(_{20}\) ribbon is still in the amorphous state at 843 K, which is related to its high thermal stability. The primary devitrification phase is \( \alpha\)-Fe type for the Fe\(_{65}\)Nb\(_{15}\)B\(_{20}\) ribbon.

(3) Fe\(_{80-x}\)Nb\(_x\)B\(_{20}\) \((x = 5, 10)\) ribbons are ferromagnetic and the Fe\(_{65}\)Nb\(_{15}\)B\(_{20}\) ribbon is paramagnetic. The saturation magnetization \( M_s \) decreases with increasing Nb content, which is related to the magnetic moment.

Acknowledgments

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References