ABSTRACT

On the splat-cooled metallic \((\text{Fe}_{79}\text{Si}_{21})_{1-x}\text{B}_x\) glasses the concentration dependence of the magnetic properties has been investigated. For representative specimens, magnetic domain structures have been observed. The crystallization temperature increases and the Curie temperature monotonously decreases from 713 K to 671 K contrary to the result for reported Fe-P-C or Fe-P-B glasses as the metalloid content is increased. The highest value of crystallization temperature (797 K) is about 150 K higher than those for iron-rich glassy alloys reported up to now. The coercive force also depends on the boron content and the lowest value (0.04 Oe) has been obtained at about \(x=0.10\). The magnetization process is discussed in the light of domain patterns observed.

INTRODUCTION

In recent years a number of studies on ferromagnetic metallic glasses have been performed. Most of these glasses have an atomic composition \((\text{TM})_{1-y}\text{M}_y\) where \((\text{TM})\) and \(\text{M}\) mean transition metal and metalloid, respectively. However, the dependence of magnetic properties of these metallic glasses on metalloid concentration has not been well investigated; hitherto only a few studies on Fe-P-C and Fe-P-B metallic glasses have been performed. In these metallic glasses, the substitutions of iron with metalloid in the range 0.175-0.23 for Fe-P-C and 0.17-0.22 for Fe-P-B, have been found to result in an increase of the Curie temperature and a decrease of magnetic moment. It seems to be of technical as well as fundamental interest to study the effects of the metalloid concentration higher than 25 at.% on the thermal stability, the Ferromagnetic Curie temperature, and the magnetization process of metallic glasses. We have extended boron content in \((\text{Fe}_{79}\text{Si}_{21})_{1-x}\text{B}_x\) metallic glasses in the range 0.06\(\leqslant x \leqslant 0.14\) and investigated their magnetic properties.

EXPERIMENTAL

The metallic glasses were prepared by the disk cooling technique from a melt of desired composition. The resulting ribbons are 0.5-1.0 mm wide and 10-25 \(\mu\)m thick, and checked to be in an amorphous state by X-ray diffractometry in the range 0.06\(\leqslant x \leqslant 0.14\). Chemically analyzed, the contents of Si and B in each ribbon deviated by less than 0.5 at.% from nominal values.

The specific magnetization at room temperature was measured with a vibrating sample magnetometer (VSM-3: Toei Industries Co.) at the field of 15 kOe. The Curie temperature \(T_c\) and crystallization temperature \(T_{cr}\) were determined by monitoring the magnetization variation with increasing temperature. The applied field is 150 Oe, which gives a sharp transition temperature on the magnetization versus temperature curve. The hysteresis loop was measured for a set of three ribbons (20 cm long) at the maximum field of 100 Oe. The domain structure observation was performed by the ferromagnetic colloid technique on the free surface without polishing.

All the data shown in this paper are on the as-quenched specimens.

RESULTS AND DISCUSSIONS

A. Crystallization Behaviour

Typical thermomagnetization curves, for \(x=0.06\) and for \(x=0.13\), are shown in Fig.1. The temperature \(T_{cr}\) at which crystallization is estimated to begin is shown by an arrow for each curve. The transformation to the crystalline state for the present metallic glass is clearly discernible from the variation of \(\mu\) with increasing temperature. Table I. Magnetic moment \(\mu\) in \(\mu_B\) per Fe atom, Curie temperature \(T_c\) (K) and crystallization temperature \(T_{cr}\) (K) of iron-rich metallic glasses.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>(\mu)</th>
<th>(T_c)</th>
<th>(T_{cr})</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>((\text{Fe}<em>{79}\text{Si}</em>{21})_{1-x}\text{B}_x)</td>
<td>(x=0.06)</td>
<td>713</td>
<td>758</td>
<td>present work</td>
</tr>
<tr>
<td>((\text{Fe}<em>{80}\text{B}</em>{20})</td>
<td>1.99</td>
<td>647</td>
<td>658</td>
<td>5</td>
</tr>
<tr>
<td>((\text{Fe}<em>{80}\text{P}</em>{16}\text{C}<em>{1}\text{B}</em>{1}))</td>
<td>2.13</td>
<td>565</td>
<td>600</td>
<td>4</td>
</tr>
<tr>
<td>((\text{Fe}<em>{80}\text{P}</em>{10}\text{C}_{7}))</td>
<td>2.10</td>
<td>586</td>
<td>690</td>
<td>6</td>
</tr>
</tbody>
</table>

* at room temperature
glass was found to take place at higher temperature than the Curie temperature. In Fig.1(a) for (Fe.79Si.21).94B.06, it can be seen that there exist two crystalline phases with different Curie temperatures (about 870 K and 1020 K). The phase with higher Curie temperature is identified as $\alpha$-Fe phase ($T_C=1043$ K). In the range 0.11$\leq$X$\leq$0.14 $\alpha$-Fe crystalline phase was not magnetically detected as typically shown in Fig.1(b). The values of $T_C$ determined from the thermomagnetization curve are plotted as a function of boron content in Fig.2. The crystallization temperature $T_{cr}$ increases up to about X=0.10 and tends to saturate. The decreased crystallization temperature for X$\leq$0.10 is considered to be associated with the nucleation of $\alpha$-Fe phase. The behaviour is quite similar to that of Co-Si-B system reported by Funakoshi et al. They reported that the first stage of crystallization proceeds by the nucleation of hcp cobalt and that the nucleation temperature increases with increasing metalloid content.

The value of $T_{cr}$ for X=0.06 is compared in Table I with those of other iron-rich metallic glasses. In the system of (Fe.79Si.21).X$\alpha$-Fe x, the highest value of $T_{cr}$ (797 K) is about 150 K higher than that of Fe$\alpha$CoB$\alpha$($T_{cr}$=600 K) or Fe$\alpha$B$\alpha$ ($T_{cr}$=568 K). This is favorable in terms of the thermal stability of the material.

B. Magnetic Moment and Curie Temperature

The value of $T_C$ and the magnetic moment $\mu$ per iron atom are plotted as a function of the boron content in Fig.3. Both $T_C$ and $\mu$ decrease with increasing boron content. The behaviour is quite different from those of Fe-P-C$^1$ and Fe-P-B$^2$ amorphous alloys for which increase of $T_C$ and decrease of $\mu$ were reported with increasing metalloid content. The total amount of metalloids is more than about 25.7 at.% for present Fe-Si-B alloys, and less than 23 at.% for Fe-P-C alloys. The difference in $T_C$ is considered to be due to the different metalloid content.

As noticed in Table I, the value of $T_C$ (713 K) for (Fe.79Si.21).98B.06 , which is maximum in the range 0.06$\leq$X$\leq$0.14, gives the highest Curie temperature among the iron-rich glasses reported up to date. This leads to a smaller temperature dependence of magnetic properties such as the saturation induction around room temperature and gives an advantage for magnetic device application.

C. Magnetization Behaviour

In Fig.4 the value of the specific magnetization $\sigma_s$ and the coercive force $H_c$ are plotted as a function of the boron content X in (Fe.79Si.21).X$\alpha$-Fe glasses. Both the specific magnetization and the coercive force decrease with increasing boron content.

The magnetic behaviour is different between the specimens with X=0.06 and X=0.10. The hysteresis loops of (Fe.79Si.21).94B.06 and (Fe.79Si.21).90B.10 are shown in Fig.5. The magnetization is normalized to the value for the applied field of 100 Oe. The former shows remanence ratio of 0.44 and $H_c$ of 0.19 Oe. The latter showing remanence ratio of 0.60 and $H_c$ of 0.04 Oe is superior to the former as a soft magnetic material, but very brittle. Two different behaviours correspond to the change of domain structure in each specimen as described below.

For the specimen with X=0.06 a complicated domain structure as reported in Fe-P-C$^1$ and Fe-Ni-P-B$^2$ glasses is shown in Fig.6. The structure suggests the existence of magnetic anisotropy having components perpendicular to the ribbon plane. But a simple domain structure was observed at the demagnetized state of
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REFERENCES