Crystallization Behavior of Amorphous Fe–Mo Alloys*

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Abstract

New alloys of $\text{Fe}_x\text{Mo}_{100-x}$ over the whole composition range have been prepared by the sputtering method. It was found by X-ray diffraction that samples with $40 \leq x \leq 80$ are amorphous, while the remaining alloys are single phase with the b.c.c. structure. In this paper, we report that a very high crystallization temperature T_{cr} of around 1100 K has been observed from the electrical resistivity measurements for amorphous $\text{Fe}_x\text{Mo}_{100-x}$ samples and that T_{cr} rises as the molybdenum content increases. After crystallization, the magnetic properties of these samples were studied using a vibrating-sample magnetometer. The results indicate that compositional dependence of the magnetic ordering temperatures T_c of these crystallized samples can be well described by the same equation as that for as-made crystalline samples, which is

$$T_c(x) = 39(x - 20)^{0.75}$$

Also, further heating at high temperatures causes the segregation of α -Fe and molybdenum atoms.

1. Introduction

The application of amorphous magnetic materials requires good magnetic properties as well as high crystallization temperatures. As is well known, the iron-based metallic glasses are technologically important in this regard (see for example ref. 1). Therefore a systematic study of the magnetic and thermal properties of amorphous iron-based alloys is very important. In particular, in the last few years, the development of the vapor-quenched technique pro-

vides a useful method for preparing alloys over a very wide composition range so that we can make suitable alloys with adequate compositions (see for example ref. 2). This work is the beginning of an investigation into a series of iron-based binary alloy systems in order to understand why some systems are more stable against crystallization than others are. The crystallization process is also discussed.

2. Experimental details

The samples approximately 10 μm thick were prepared using a d.c. magnetron sputtering device at a deposition rate of 0.05–0.1 $\mu\text{m min}^{-1}$. During deposition, the substrates were cooled at liquid-nitrogen temperature and then removed from samples for later measurements.

The structures of all samples were analyzed by X-ray diffraction. It was found that samples with $40 \leq x \leq 80$ are in the amorphous state, which is consistent with the prediction of the theory of Egami and Waseda [3].

The crystallization temperatures T_{cr} were determined from electrical resistivity measurements. The conventional four-probe method was used. T_{cr} is defined as the point of initial decrease in resistivity. The magnetic ordering temperatures T_c of the samples were studied using a vibrating-sample magnetometer. In order to investigate the thermal effects on these samples, different pieces were annealed under various treatments before the magnetization (M vs. T) measurements were performed.

3. Results and discussion

The initial crystallization temperature T_{cr} is shown in Fig. 1 as a function of iron concentration. In the intermediate region $40 \leq x \leq 60$, the samples display a very high T_{cr} (≈ 1100 K) which slightly decreases with increasing iron content. This behavior of a high

*Paper presented at the Sixth International Conference on Rapidly Quenched Metals, Montréal, August 3–7, 1987.

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Fig. 1. T_{cr} determined from resistivity measurements of $Fe_x Mo_{100-x}$ alloys as a function of iron content (heating rate, 2.5 K min^{-1}).

T_{cr} is also observed in the amorphous Fe-W alloy system [4]. Furthermore, this region of high T_{cr} is not related to the eutectic compositions in the phase diagram [5]. It should be noted that both molybdenum and tungsten solids have high melting points. Thus, it seems to imply that the strength of chemical bondings mainly causes the stability against crystallization [6]. For $x > 60$, T_{cr} starts to drop very sharply. This result suggests that T_{cr} for amorphous iron solid is below room temperature by extrapolation. The decrease in T_{cr} for iron-rich alloys, which is due to the effect of iron, is also found in many metallic glasses (see for example ref. 7).

Figure 2 indicates that the magnetic ordering temperatures T_c of the as-made crystalline samples can be described by the equation

$$T_c(x) = 39(x - 20)^{0.75}$$

In the Fe-Mo system, molybdenum atoms are non-magnetic and they act as a diluent in magnetism. Thus the above equation suggests the existence of percolation behavior of b.c.c. structure with the threshold of $x_c = 20$ [8, 9]. Furthermore, it is also interesting to find from Fig. 2 that the T_c values for the crystallized samples fall on the same fitting curve. This result leads

Fig. 2. Magnetic ordering temperature *vs.* iron content for $Fe_x Mo_{100-x}$ alloys: Δ , crystallized; $\bullet$, amorphous; $\circ$, crystalline.

us to believe that the first crystallization stage involves only the local atomic rearrangement of structure. No intermediate compounds are formed.

Figure 3(a) and Fig. 3(b) show the temperature dependence of magnetization for amorphous

Fig. 3. (a) Temperature dependence of the normalized magnetization at 5 kOe for the amorphous $Fe_{50}Mo_{50}$ alloy under two different annealing conditions: Δ , 900°C for 6 h; $\circ$, 900°C for 19 h. (b) Temperature dependence of the normalized magnetization at 5 kOe for the amorphous $Fe_{60}Mo_{40}$ alloy under three different annealing conditions: Δ , 900°C for 2 h; $\circ$, 900°C for 19 h; $\square$, 900°C for 21 h.

Fig. 4. Temperature dependence of the normalized magnetization at 5 kOe for the as-made crystalline $\text{Fe}_{80}\text{Mo}_{20}$ alloy with ($\circ$) and without (800°C for 15 h) ($\triangle$) annealing before the measurements were done.

$\text{Fe}_{50}\text{Mo}_{50}$ and $\text{Fe}_{60}\text{Mo}_{40}$ alloys respectively under various annealing conditions. The Curie temperature of α -Fe is also indicated with an arrow in the figures. It is apparent that decomposition into α -Fe and b.c.c. molybdenum begins after the first-stage crystallization and it speeds up with increasing annealing time. Eventually, the whole crystallized Fe–Mo alloy has decomposed into the mixture of α -Fe and b.c.c. molybdenum after a long period of heating. As is shown in Fig. 4, the as-made crystalline $\text{Fe}_{80}\text{Mo}_{20}$ alloy is also in the metastable state, which exhibits the same thermal characteristic as that of crystallized Fe–Mo alloys.

4. Conclusion

All amorphous Fe–Mo alloys have the same crystallization processes and the initial crystallization is the formation of a corresponding b.c.c. crystalline alloy of original composition. The continuous heating causes decomposition into α -Fe and b.c.c. molybdenum.

Acknowledgment

This work is supported by National Science Council, Taiwan, under Grant NSC-76-0208-M002-40.

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