Influences on the crystallization kinetics of iron-based amorphous alloys under high magnetic fields

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Introduction

Iron-based amorphous alloys are known as precursor materials of iron-based nano-crystalline alloys, which have excellent soft magnetic properties, such as low coercivity, high permeability and high saturation magnetization. These soft magnetic nano-crystalline alloys are produced by the crystallization of iron-based amorphous alloys, and have a unique texture, which consists of a nano-size bcc-Fe grain with a high volume fraction and an inter-granular amorphous layer. The characteristics of their texture dominate their soft magnetic properties. For instance, the coercivity highly depends on the grain size [1]. For improvement of the soft magnetic properties, therefore, the enhancement of a nucleation rate, the suppression of the grain growth and the stabilization of a residual amorphous phase on the crystallization of bcc-Fe are required. However, the nucleation and grain growth control by a simple thermal treatment and/or the adjustment of chemical composition are hardly to achieve homogeneous texture with ultra-fine grains. Thus, a new method is required for the accurate nano-crystallization control.

Recently, the material processing by applying magnetic fields has been investigated strenuously. A magnetic field is particularly important for the in-field processing of magnetic materials, because of the contribution of the magnetic energy to phase transformation and metallurgical effects. However, there are very few reports that dealt with the crystallization kinetics of amorphous alloys in high magnetic fields, although many studies for other magnetic materials such as steel, nickel and cobalt based alloys, have been reported. The detailed information about the crystallization kinetics in high magnetic fields is necessary for the development of the novel nano-crystallization process, which will achieve accurate control of the grain size and the precipitation of a crystal phase by applying a high magnetic field.

In this study, we have carried out differential thermal analysis (DTA) and magnetization measurements in high magnetic fields, in order to investigate the influence of a high magnetic field for the crystallization kinetics of iron-based amorphous alloys.

Experimental detail

$Fe_{83.3}Si_{4.2}B_{12.5}$ amorphous alloy, studied in this work, is the basic composition of $Fe_{83.3}Si_4B_8P_4Cu_{0.7}$ hetero-amorphous alloy, in which the nano-crystallization occurs by annealing. The sample ribbon was prepared by single-roll melt spinning with 3 mm in width and 27-29 μm in thickness. The DTA measurements in high magnetic fields were carried out at temperatures ranging from R.T. to 900 K in applied magnetic fields up to B = 20 T [2]. Magnetization measurements were carried out using a high field vibrating sample magnetometer (HF-VSM). The heating rate is 10 K/min for DTA and 5 K/min for magnetization measurements. The sample space was evacuated to ~ 10^{-3} Pa by a turbo-molecular pump system during the measurements. The structure of crystal phases was determined by X-ray diffraction.

Results and Discussion

Figure 1(a) shows the DTA curve at 0 T. Two exothermic peaks due to the crystallization reactions are observed. The first peak indicates the crystallization of bcc-Fe(Si) and the second peak the crystallization of iron-boron compounds such as Fe_2B and Fe_3B. The first and second crystallization temperatures, which are determined from the onset of the exothermic peaks, are T_{x1} = 706 K and T_{x2} = 795 K, respectively. Figure 1(b) shows the magnetic field dependence of the first crystallization peak up to B = 20 T. The crystallization peak of bcc-Fe(Si) shifts toward a lower temperature side under high magnetic fields, whereas the second crystallization peak shifts toward a higher side. The first crystallization temperature is decreased by 10 K and the second one is increased by 4 K at 20 T, compared with those at 0 T.

Figure 2 shows the magnetic field dependence of the growth curve of bcc-Fe(Si) at 660 K, which is obtained by isothermal magnetization measurements at 0.5 T and 10 T. The growth curve at 10 T shows abrupt time evolution, compared with that at 0.5 T. The magnetic field effect on the growth rate is discussed in terms of the elapsed time, $\tau_{0.5}$, which is defined as the time where the crystallization fraction, $x(\tau)$ attains $x = 0.5$. $\tau_{0.5}$ is decreased from 3.0 ksec at 0.5 T to 1.8 ksec at $B = 10$ T. This result suggests that the growth rate of the crystallization reaction increases under high magnetic fields. In this first crystallization reaction, ferromagnetic bcc-Fe crystallizes from paramagnetic amorphous matrix. Thus, the crystal phase gains lager magnetic energy, compared with the amorphous phase. Therefore, the gain of the magnetic energy decreases the activation energy required for the nucleation of the crystal phase. It is considered that the enhancement of the growth rate is caused by the increase of the nucleation rate due to decreasing of the activation energy by the magnetic field. We expect that the enhancement of the nucleation leads to the increase of the volume fraction of bcc-Fe(Si) with a small grain size, which results in the improvement of the saturation magnetization.

Conclusion

The crystallization kinetics of $Fe_{83.3}Si_{4.2}B_{12.5}$ amorphous alloy in high magnetic fields has been investigated by the DTA and magnetization measurements. In the DTA, the crystallization peak of bcc-Fe(Si) shifts toward a lower temperature side by applying magnetic fields. In the magnetization measurements, the growth curves of bcc-Fe(Si) were obtained by isothermal measurements. The growth curve at 10 T shows the acceleration of crystal growth, compared with that at 0.5 T. These magnetic field effects indicate that the nucleation of bcc-Fe(Si) is enhanced under high magnetic fields.

References

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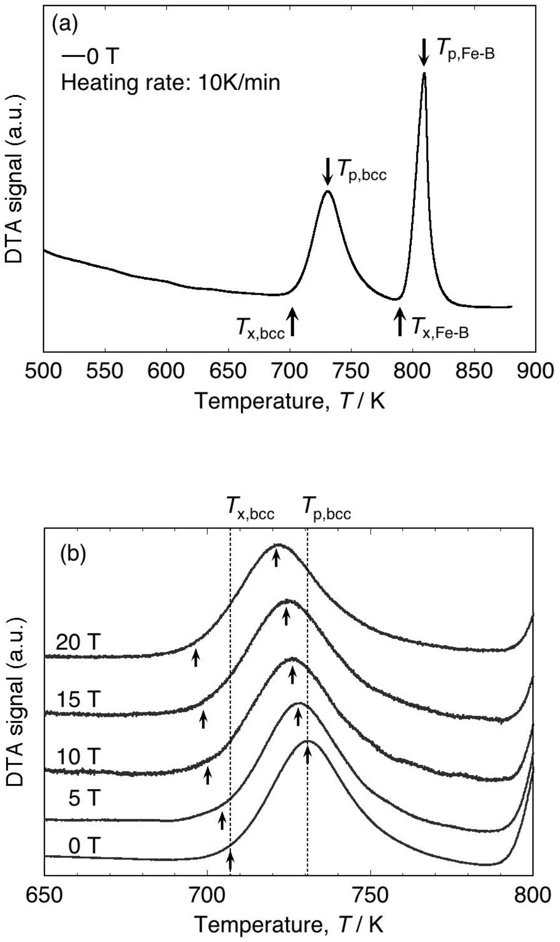

Fig.1 (a) DTA curve of $Fe_{83.3}Si_{4.2}B_{12.5}$ amorphous alloy at 0T. (b) Magnetic field dependence of the first crystallization peak in fields up to 20 T.

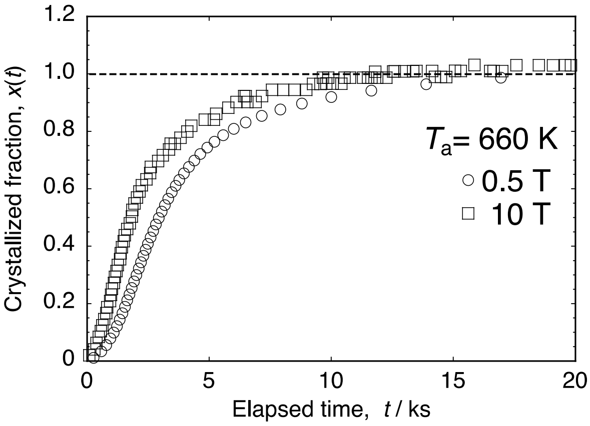

Fig.2 Magnetic field dependence of the growth curve of bcc-Fe(Si) at 660 K.