Effects of Electromagnetic Vibrations on Glass-Forming Ability in Fe-Co-B-Si-Nb Bulk Metallic Glasses

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It is known that cooling rate from the liquid state is an important factor for producing the bulk metallic glasses. However, almost no other factors such as electric and/or magnetic fields were investigated. The present authors have reported that a new method for producing Mg-Cu-Y bulk metallic glasses by using electromagnetic vibrations is effective in forming the metallic glass phase. Moreover, effects of the electromagnetic vibrations on glass-forming ability in other alloy systems are not investigated. Thus, this study aims to investigate effects of the electromagnetic vibrations on glass-forming ability in Fe-Co-B-Si-Nb bulk metallic glasses. As a result, it was found that glass-forming ability of Fe-Co-B-Si-Nb alloys also enhances with increasing the electromagnetic vibration force. Moreover, the electromagnetic vibrations were found to affect the increase of the cooling rate and the decrease in the number of crystal nuclei directly, but not to affect the crystal growing rate.

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1. Introduction

Different combinations of stationary and/or alternating electric and magnetic fields have been used for a wide range of purposes, including stirring, shaping, etc. Among these combinations, it was reported that electromagnetic vibrations induced by the interaction of alternating electric and stationary magnetic fields can act as powerful vibrating forces in the melt and affect microstructural refinements in the usual crystalline alloys. The simultaneous imposition of a stationary magnetic field with a magnetic flux density and an alternating electric field with a current density produces a vibrating electromagnetic body force with a density of

\[ F = J \times B \]

where \( F \) is the force in the liquid. This force, which has a frequency equal to that of the applied electric field, vibrates in a direction perpendicular to the plane of the two fields and puts particles constituting the conducting liquid into a vibrating motion.

The present authors reported that a new method for producing Mg-Cu-Y bulk metallic glasses by using the electromagnetic vibrations is effective in forming the metallic glass phase, and disappearance or decrement of clusters by the electromagnetic vibrations applied to the liquid state is presumed to cause suppression of crystal nucleation. Moreover, the present authors reported that it was found that the glass-forming ability of \( \text{Mg}_{65}\text{Cu}_{25}\text{Y}_{10} \) alloys increases with increasing the frequency of the electromagnetic vibrations. However, effects of the electromagnetic vibrations on glass-forming ability in other alloy systems are not investigated.

Thus, the purpose of this study is to investigate effects of the electromagnetic vibrations on glass-forming ability in Fe-Co-B-Si-Nb bulk metallic glasses. It was reported that the \((\text{Fe}_{0.6}\text{Co}_{0.4})_{72}\text{Si}_{4}\text{B}_{20}\text{Nb}_{4}\) bulk metallic glass rods were produced in a diameter of up to 3 mm by casting into a copper mold.

2. Experimental Procedures

The \((\text{Fe}_{0.6}\text{Co}_{0.4})_{72}\text{Si}_{4}\text{B}_{20}\text{Nb}_{4}\) alloys with a diameter of 2 mm were provided by RIMCOF Japan. Alloy ingots were prepared by induction melting the mixtures of pure metals under an argon atmosphere. The cylindrical samples were produced by casting into a copper mold.

The \((\text{Fe}_{0.6}\text{Co}_{0.4})_{72}\text{Si}_{4}\text{B}_{20}\text{Nb}_{4}\) alloy, which is cylindrical with a diameter of 2 mm and a length of 8 mm, was placed in an alumina tube of almost the same inner diameter and an outer diameter of 4 mm. The sample was held between two molybdenum electrodes. Details of the experimental apparatus has been described in the previous paper. Argon was passed through the inside of the stainless-steel cylinders to fix the sample in a superconducting magnet. The sample was heated at a rate of 10 K/min to 1573 K by the heating furnace which was set around the sample placed at the center of the magnet. The molten sample was kept at this temperature for 2 min and then water was sprayed on the alumina tube. The electromagnetic vibrations were applied by passing the alternating electric current through the sample at a preset magnetic field. Applied time of the electromagnetic vibrations for the alloys is shown in Fig. 1. The electromagnetic vibrations were applied for 10 seconds before the onset of the water spray and also 10 s after that.

The cooling rates were measured by a grounded stainless steel sheath thermocouple which was set instead of one Mo electrode. If the Fe based alloys were used as samples, the

![Fig. 1 Applied time of the electromagnetic vibrations.](image-url)
sample attacked the stainless steel sheath hard. Thus, for the measurement of the cooling rates, we used pure Cu rods as samples instead of the \((\text{Fe}_{0.6}\text{Co}_{0.4})_{72}\text{Si}_4\text{B}_{20}\text{Nb}_4\) alloys, because the melting point of Cu is very close to that of the \((\text{Fe}_{0.6}\text{Co}_{0.4})_{72}\text{Si}_4\text{B}_{20}\text{Nb}_4\) alloys.

The metallic glass or crystalline structures were examined by Rigaku micro-area X-ray diffractometer (XRD) using Cr-K\(\alpha\) radiation and optical microscopy. The examination regions for micro-area XRD were taken from the central regions in the transverse cross section. For optical microscopy observations, 10% nitric acid–ethanol solution was used for etching the sample surface.

3. Results

3.1 The measurement of cooling curves in Cu

Figure 2 shows cooling curves in Cu. Those were measured at a magnetic field of 0 T and an alternating electric current of 0 A, namely without the electromagnetic vibrations, by varying the flow rate of cooling water, 3, 5.5 and 9.3 L/min. It was not possible to measure temperature near 1273 K because of automatic scale change in a thermometer. The cooling rate was increased by increasing the flow rate of cooling water. The cooling rates were derived from the cooling curves showed about from 1373 to 1073 K, because the melting point of the \((\text{Fe}_{0.6}\text{Co}_{0.4})_{72}\text{Si}_4\text{B}_{20}\text{Nb}_4\) alloys is about 1373 K. This region is considered to be important for crystal growth. The cooling rates are shown in the next chapter. In addition, we measured other cooling curves by varying the intensity and frequency of the electromagnetic vibrations.

3.2 The effects of the intensity of the electromagnetic vibrations

Figure 3 shows optical micrographs for the \((\text{Fe}_{0.6}\text{Co}_{0.4})_{72}\text{Si}_4\text{B}_{20}\text{Nb}_4\) alloys. The alloys were produced by using the electromagnetic vibrations with various kinds of the electromagnetic vibration force. The electromagnetic vibration force was varied by the magnetic field. The water flow and the alternating electric current were fixed at 3 L/min and 5 A, 5 kHz, respectively. The volume fractions of crystals showed 3.10% at 0 T, namely without the electromagnetic vibrations, 1.22% at 1 T, namely with the weak electromagnetic vibrations, and 0.13% at 10 T, namely with the strong electromagnetic vibrations.

Figure 4 shows XRD patterns corresponding to the optical micrographs shown in Fig. 3. The sharp crystalline peaks decreased with increasing the magnetic field, namely the intensity of the electromagnetic vibrations. However, the XRD patterns at 1 and 10 T didn’t change clearly because the samples had few volume fractions of crystals for the micro-area XRD.

As these results, it was found that the glass-forming ability of the \((\text{Fe}_{0.6}\text{Co}_{0.4})_{72}\text{Si}_4\text{B}_{20}\text{Nb}_4\) alloys enhances with increasing the electromagnetic vibration force. In addition, we measured others by varying the water flow and the frequency of the electromagnetic vibrations. These are shown in the next chapter.

4. Discussions

Figure 5 shows a optical micrograph enlarged that of the \((\text{Fe}_{0.6}\text{Co}_{0.4})_{72}\text{Si}_4\text{B}_{20}\text{Nb}_4\) alloys shown in Fig. 3(a). The crystal particles were spherical. This result shows that a
starting point of crystallization is the center of the crystal particle. Thus, an assumption, that one crystal particle grew from one crystal nucleus, is considered to hold. From this assumption, we can consider that the number of crystal particles and the area of one crystal particle correspond to the number of crystal nuclei and the square of crystal growth radius, respectively. Therefore, we evaluated the electromagnetic vibration process by comparison between the measurement of the cooling rates in Cu and the observation of the crystal particles in the Fe-Co-B-Si-Nb alloys.

4.1 The effect of the flow rate of cooling water

Figure 6 shows the effect of the flow rate of cooling water on the cooling rates without the electromagnetic vibrations. The magnetic field was fixed at 0 T, and the alternating electric current was fixed at 0 or 5 A, 5 kHz. The cooling rates were found to be decreased by passing the electric current. The electric current makes Joule heat which is proportional to the square of the electric current. Thus, the cooling rates were considered to decrease because of the Joule heat. Moreover, it was found that the cooling rates were increased linearly by increasing the water flow.

Figure 7 shows the effect of the flow rate of cooling water on the crystal particles without the electromagnetic vibrations for the Fe-Co-B-Si-Nb alloys. The magnetic field and the alternating electric current were fixed at 0 T and 5 A, 5 kHz, respectively. The crystal particles with the area of more than $3 \mu m^2$ were counted by computer. The average area of one particle (shown in the broken line) and the number of particles (shown in the solid line) were decreased alike linearly by increasing the water flow.

As these results, the number of crystal nuclei and the square of crystal growth radius were found to be decreased linearly by increasing the cooling rate without the electromagnetic vibrations. This means the enhancement of the glass-forming ability of this alloy by increasing the cooling rate.
4.2 The effect of the electromagnetic vibration force

Figure 8 shows the effect of the electromagnetic vibration force on the cooling rates in Cu. The electromagnetic vibration force was varied by the magnetic field. The water flow and the alternating electric current were fixed at 3 L/min and 5 A, 5 kHz, respectively. The cooling rate was found to be increased linearly by increasing the magnetic field, namely the electromagnetic vibration force. It is presumed that a macroscopic stirring causes the linear increase of the cooling rate with the electromagnetic vibrations.

Figure 9 shows the effect of the electromagnetic vibration force on the crystal particles for the Fe-Co-B-Si-Nb alloys. The electromagnetic vibration force was varied by the magnetic field. The water flow and the alternating electric current were fixed at 3 L/min and 5 A, 5 kHz, respectively. The average area of one particle, namely the square of crystal growth radius, was found to be decreased linearly. This result is in agreement with the result shown in Fig. 7 that the average area of one particle was decreased linearly by increasing the cooling rate. However, the number of particles, namely the number of nuclei, was found to be decreased rapidly by the electromagnetic vibrations. This result shows that the decrease in the number of particles is affected by not only the cooling rate but also the electromagnetic vibrations directly.

As these results, it is considered that the electromagnetic vibrations affect the decrease in the number of nuclei and the increase in the cooling rate, and the crystal growth radius is affected only by the cooling rate.

4.3 The effect of the frequency of the electromagnetic vibrations

Figure 10 shows the effect of the frequency of the electromagnetic vibrations on the cooling rates. The frequency of the electromagnetic vibrations was varied by that of the alternating electric current. The water flow, the magnetic field and the alternating electric current were fixed at 3 L/min, 10 T and 5 A, respectively. The cooling rates with the electromagnetic vibrations at a frequency of more than 10 kHz indicated about the same value as the cooling rate without the electromagnetic vibrations at 0 T shown in Fig. 8. Thus, the increase of the cooling rate by the electromagnetic vibrations as shown in Fig. 8 was found to disappear with the electromagnetic vibrations at a frequency of more than 10 kHz. We presume that disappearance of a macroscopic stirring with the electromagnetic vibrations at a frequency of more than 10 kHz causes the disappearance of the increase in the cooling rate by the electromagnetic vibrations.

Figure 11 shows the effect of the frequency of the electromagnetic vibrations on the crystal particles. The frequency of the electromagnetic vibrations was varied with that of the alternating electric current. The water flow, the magnetic field and the alternating electric current were fixed at 3 L/min, 10 T and 5 A, respectively. The decrease in the number of particles, namely the number of nuclei, by the electromagnetic vibrations as shown in Fig. 9 was found to weaken with the electromagnetic vibrations at a frequency of more than 10 kHz. Moreover, the average area of one particle, namely the square of crystal growth radius, was found to be proportional to the inverse of the cooling rate as shown in Fig. 10. This result proves that the crystal growth
radius is affected only by the cooling rate. Thus, the electromagnetic vibrations were found not to affect the crystal growing rate.

5. Conclusions

The effects of the electromagnetic vibrations on the glass-forming ability in Fe-Co-B-Si-Nb bulk metallic glasses have been investigated, and the following conclusions have been derived.

1) The glass-forming ability of Fe-Co-B-Si-Nb alloys also enhances with increasing the electromagnetic vibration force.

2) The number of crystal nuclei and the square of crystal growth radius are decreased linearly by increasing the cooling rate.

3) The effects of the electromagnetic vibrations have two effects. The first effect is the increase of the cooling rate. However, the increase of the cooling rate by the electromagnetic vibrations disappears with the electromagnetic vibrations at a frequency of more than 10 kHz. It is presumed that disappearance of a macroscopic stirring with the electromagnetic vibrations at a frequency of more than 10 kHz causes the disappearance of the increase in the cooling rate by the electromagnetic vibrations. The second effect is the decrease in the number of crystal nuclei. However, the electromagnetic vibrations were found not to affect the crystal growing rate.

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