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EFFECT OF FREQUENCY OF ELECTROMAGNETIC VIBRATIONS ON GLASS-FORMING ABILITY IN Fe-Co-B-Si-Nb BULK METALLIC GLASSES

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Abstract. 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 the glass-forming ability of Mg-Cu-Y and Fe-Co-B-Si-Nb alloys is enhanced with increasing the electromagnetic vibration force. This study aims to investigate effect of the frequency of the electromagnetic vibrations on glass forming ability in Fe-Co-B-Si-Nb bulk metallic glasses. As a result, it was found that the electromagnetic vibrations affect the increase in the cooling rate and the decrease in the number of crystal nuclei directly.

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.* [1]. 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 [2-9]. The simultaneous imposition of a stationary magnetic field with a magnetic flux density B and an alternating electric field with a current density J and a frequency f on a conducting liquid results in the induction of a vibrating electromagnetic body force with a density of $F=J\times B$ inside 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 results in vibrational motion of the constituent particles of the conducting liquid.

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 [10,11]. Moreover, the present authors reported that it was found that the glass-forming ability of Fe-Co-B-Si-Nb alloys also increases with increasing the intensity of electromagnetic vibrations. The decrement of crystal particles with increasing the intensity of electromagnetic vibrations differed from that with increasing the cooling rate. The electromagnetic vibrations were found to act mainly on decreasing the number of crystal nuclei [12,13]. When molybdenum was used as the electrodes for the electromagnetic vibrations, it was found that there was influence of electrodes in the Fe-Co-B-Si-Nb alloys. However, when tungsten was used as the electrodes, there was no influence of electrodes in the center of the samples. When molybdenum or tungsten was used as the electrodes, the effect of the electromagnetic vibrations was found to be the same, namely the vibrations act on

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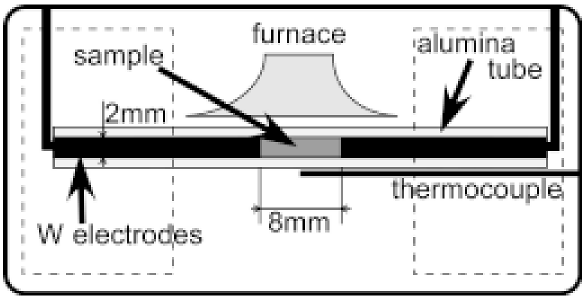

Fig. 1. A schematic illustration of the experimental apparatus.

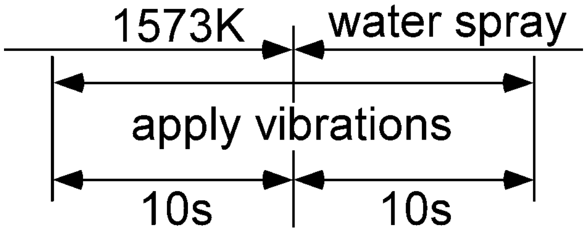

Fig. 2. Applied time of the electromagnetic vibrations.

decreasing the number of crystal nuclei [13]. Thus, the purpose of this study is to investigate effect of the frequency of the electromagnetic vibrations on glass forming ability in Fe-Co-B-Si-Nb bulk metallic glasses when tungsten is used as the electrodes.

2. EXPERIMENTAL APPARATUS

The experimental apparatus is based on a superconducting magnet, which is able to deliver a magnetic flux density of up to 10 Tesla at the center of a bore of 150 mm diameter. It was designed and assembled to hold the sample by stainless-steel cylinders as firmly as possible against the mechanical vibrations of the system when electromagnetic vibrations are applied, and prevent the vibrations from being transferred to the magnet.

The cylindrical sample is placed between two tungsten electrodes in an alumina tube and set in the experimental apparatus (Fig. 1). The electrodes are firmly fixed in the tube to prevent leakage of the molten liquid when vibrations are applied. The electric current for the electromagnetic vibrations is supplied to the sample by the two electrodes on both ends of the sample. The temperature is measured by a K-type thermocouple on the exterior of the tube. Two nozzles are positioned to spray the tube with water. An electric heating furnace is used to heat and melt the sample, and is removed when water is sprayed. It is important to note the temperature of the sample was known when the sample was heated, but when the sample was cooled, the temperature was unknown as water is sprayed onto the thermocouple directly. Thus, when the cooling curves were measured, another grounded stainless steel sheath thermocouple which was set instead of one electrode was used. This thermocouple touches the sample directly.

3. EXPERIMENTAL PROCEDURES

The $(Fe_{0.6}Co_{0.4})_{72}Si_4B_{20}Nb_4$ 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 $(Fe_{0.6}Co_{0.4})_{72}Si_4B_{20}Nb_4$ alloy, which is cylindrical with a diameter of 2mm and a length of 8mm, was placed in an alumina tube of almost the same inner diameter and an outer diameter of 4 mm. Argon was passed through the inside of the stainless-steel cylinders to fix the sample in a superconductingmagnet. The sample was heated at a rate of 20 K/min to 1573K 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 minutes and then water was sprayed on the alumina tube. The flow rate of cooling water was fixed at 3 L/min. 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. 2. The electromagnetic vibrations were applied for 10 seconds before the onset of the water spray and also 10 seconds after that.

The cooling curves were measured by a grounded stainless steel sheath thermocouple which was set instead of one electrode. If the Fe based alloys were used as samples, the sample attacked the stainless steel sheath hard. Thus, for the measurement of the cooling rates, pure Cu rods were used as samples instead of the $(Fe_{0.6}Co_{0.4})_{72}Si_4B_{20}Nb_4$ alloys, because the melting point of Cu is very close to that of the $(Fe_{0.6}Co_{0.4})_{72}Si_4B_{20}Nb_4$ alloys.

The metallic glass or crystalline structures were examined by optical microscopy. For optical micros-

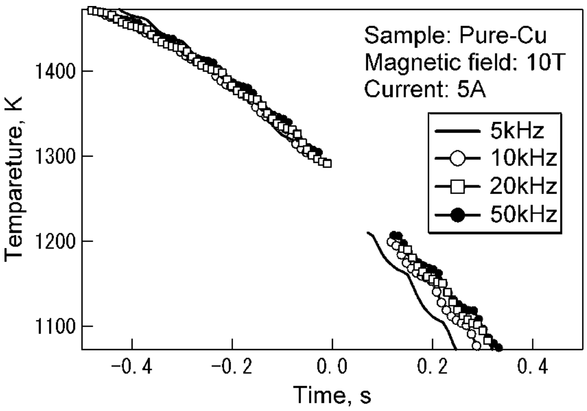

Fig. 3. Cooling curves in Cu. Those were measured at a magnetic field of 10 T and an alternating electric current of 5 A. The frequency of the electromagnetic vibrations was varied by that of the alternating electric current.

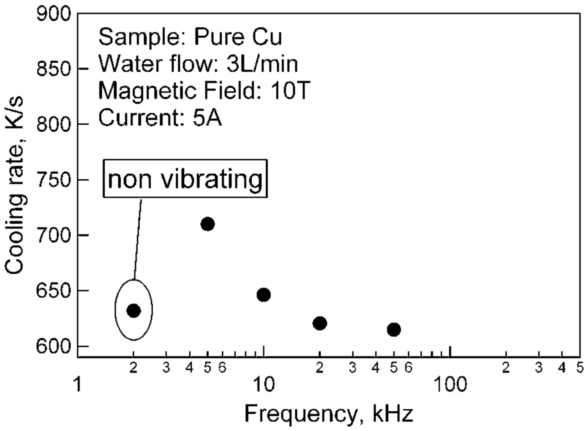

Fig. 4. Effect of the frequency of the electromagnetic vibrations on the cooling rates. The frequency of the electromagnetic vibrations was varied by that of the alternating electric current. The magnetic field and the alternating electric current were fixed at 10 T and 5 A, respectively. The alloy without the electromagnetic vibrations was produced at a magnetic field of 0 T and an electric current of 5 A.

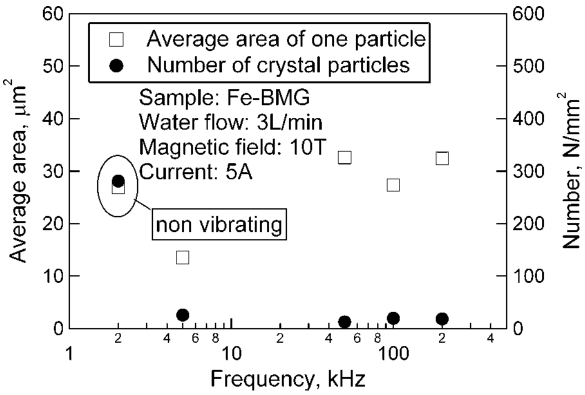

Fig. 5. Effect of the frequency of the electromagnetic vibrations on the crystal particles. The magnetic field and the alternating electric current were fixed at 10 T and 5 A, respectively. The alloy without the electromagnetic vibrations was produced at a magnetic field of 0 T and an electric current of 5 A.

copy observations, 10% nitric acid - ethanol solution was used for etching the sample surface. This technique was confirmed by XRD [12] and TEM [13].

4. RESULTS AND DISCUSSION

Fig. 3 shows cooling curves in Cu. Those were measured at a magnetic field of 10 T and an alternating electric current of 5 A. The frequency of the electromagnetic vibrations was varied by that of the alternating electric current. It was not possible to measure temperature near 1273K because of automatic scale change in a thermometer. The cooling rates were derived from the cooling curves showed about from 1373 to 1073K, because the melting point of the $(Fe_{0.6}Co_{0.4})_{72}Si_4B_{20}Nb_4$ alloys is about 1373K. This region is considered to be important for crystal growth.

Fig. 4 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 magnetic field and the alternating electric current were fixed at 10 T and 5 A, respectively. The alloy without the electromagnetic vibrations was produced at a magnetic field of 0T and an electric current of 5 A. The cooling rate with the electromagnetic vibrations at a frequency of 5 kHz was found to be larger than that without the electromagnetic vibrations. However, the cooling rates with the electromagnetic vibrations at frequencies of more than 10 kHz indicated about the same value as the cooling rate without the electromagnetic vibrations. If it is supposed that only the alloy sample exists in free space, and that the electric current is passed through the sample uniformly, it is calculated that the amplitudes of the electromagnetic vibrations at 5 kHz are micrometer-sized, but those at higher frequencies are nanometer-sized. Thus, it is considered that a macroscopic stirring causes the increase of the cooling rate with the electromagnetic vibrations at a frequency of 5 kHz. However, the macroscopic stirring is considered not to occur in the alloys with the electromagnetic vibrations at frequencies of more than 10 kHz because the amplitudes of the electromagnetic vibrations were small.

The small crystal particles were observed in a glassy phase for the alloys. It had been found that one crystal particle grew from one crystal nucleus in $(Fe_{0.6}Co_{0.4})_{72}Si_4B_{20}Nb_4$ alloys [12,13]. Fig. 5 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 magnetic field and the alternating electric current were fixed at 10 T and 5 A, respectively. The alloy without the electromagnetic vibrations was produced at a magnetic field of 0 T and an electric current of 5 A. The number of crystal particles, namely the number of crystal nuclei, was decreased by the electromagnetic vibrations. This result is in agreement with that shown in previous papers [11-13]. Moreover, it was reported that the crystal particle growth radius is affected only by the cooling rate [12]. The average area of one particle, which is considered to correspond to the square of crystal particle growth radius, was decreased for the alloy with the electromagnetic vibrations at a frequency of 5 kHz. The cooling rate with the electromagnetic vibrations at a frequency of 5 kHz shown in Fig. 4 was larger than others. Thus, it was found that the crystal particle growth radius is affected by the cooling rate. This result was in agreement with that shown in a previous paper [12]. As a result, it is considered that the electromagnetic vibrations don't affect the crystal growing rate.

5. CONCLUSIONS

The effects of the electromagnetic vibrations have two effects. The first effect is the increase of the cooling rate. It is considered that a macroscopic stirring causes the increase of the cooling rate with the electromagnetic vibrations. However, the increase of the cooling rate by the electromagnetic vibrations disappears with the electromagnetic vibrations at frequencies of more than 10 kHz. It is considered that the nanometer-sized amplitudes result in the disappearance of the macroscopic stirring with the electromagnetic vibrations at frequencies of more than 10 kHz. The second effect is the decrease in the number of crystal nuclei. However, the electromagnetic vibrations don't affect the crystal growing rate.

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