Effects of the Intensity and Frequency of Electromagnetic Vibrations on Glass-Forming Ability in Mg–Cu–Y Bulk Metallic Glasses

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The present authors 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, and disappearance or decrement of clusters by the electromagnetic vibrations applied to a liquid state is presumed to cause suppression of crystal nucleation [Nature Materials 4 (2005) 289]. This paper aims to investigate the effects of the intensity and frequency of electromagnetic vibrations on apparent glass-forming ability in the Mg–Cu–Y bulk metallic glasses. It was found that the apparent glass-forming ability of Mg\textsubscript{65}Cu\textsubscript{25}Y\textsubscript{10} alloys increases with increasing the frequency of electromagnetic vibrations up to 5000 Hz. The effects of frequency more than 5000 Hz could not be investigated because of alternating current power devices. Moreover, it was found that the apparent glass-forming ability of Mg\textsubscript{65}Cu\textsubscript{25}Y\textsubscript{10} alloys increases with increasing the intensity of electromagnetic vibrations by an electric current or a magnetic flux density. However, increasing excessively the electric current was found to weaken the enhancement of the apparent glass-forming ability by using the electromagnetic vibration process because the crystalline particles grow larger by the Joule heat.

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1. Introduction

Recently new multicomponent metallic glasses (amorphous alloys) with high glass-forming ability have been found and bulk metallic glasses in rod and sheet have been produced in these new alloy systems by copper mold casting, arc melting and suction casting etc.\textsuperscript{3} It was reported that amorphous materials can be formed not only by rapid quenching but also by relatively slow cooling if nucleation of crystals can be suppressed.\textsuperscript{1} Applications of the electric and/or magnetic fields for the materials processing and treatment has been of interest for almost 2 decades. Different combinations of stationary and/or alternating fields have been used for a wide range of purposes, including stirring, shaping, etc.\textsuperscript{2,3} 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.\textsuperscript{4–11} 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 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.\textsuperscript{12} However, effects of the intensity and frequency of electromagnetic vibrations on apparent glass-forming ability are not fully investigated so far. Thus, the purpose of this study is to investigate the effects of the intensity and frequency of electromagnetic vibrations on the apparent glass-forming ability in the Mg–Cu–Y bulk metallic glasses.

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 (Fig. 1). 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 sample, which is cylindrical, is placed between two molybdenum electrodes in an alumina or a molybdenum tube and set in the experimental apparatus (Fig. 2). The electrodes are firmly fixed in the tube to prevent the leakage of molten liquid when vibrations are applied. Electric current for the electromagnetic vibrations is supplied to the sample by the two electrodes on both ends of the sample. Temperature are measured by a K-type thermocouple which is put on the tube. Two nozzles are set and enable the water spray to the tube. An electric heating furnace, which is used to heat and melt the sample, is removed when water is sprayed. Thus, the temperature of samples were able to be measured when the samples were heated. But when those were cooled, the temperature of those were not able to be measured because water is sprayed to the thermocouple directly.

3. Experimental Procedures

The Mg\textsubscript{65}Cu\textsubscript{25}Y\textsubscript{10} alloys with a diameter of 2 mm were provided by RIMCOF Japan. Alloy ingots were prepared by induction melting the mixtures of pure Mg, Cu and Y metals under an argon atmosphere. The cylindrical samples were
produced by casting into a copper mold.

The Mg$_{65}$Cu$_{25}$Y$_{10}$ alloy, which is cylindrical with a diameter of 2 mm and a length of 12 mm, was placed in an alumina tube of almost the same inner diameter and an outer diameter of 3 mm or a molybdenum tube of almost the same inner diameter and a thickness of 0.05 mm, between two molybdenum electrodes. Argon was passed through the inside of the Stainless-steel cylinders. The sample was heated at a rate of about 10 K/min to 823 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 tube. The electromagnetic vibrations were applied by passing the electric current through the sample at a preset magnetic flux density. Applied time of the electromagnetic vibrations for the alloys is shown in Fig. 3. The electromagnetic vibrations were applied for 10 s before the onset of the water spray and also 10 s after that.

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 and optical microscopy were taken from the central regions in the transverse cross section. For optical microscopy observations, 1% nitric acid–ethanol solution was used for etching the sample surface.

4. Results and Discussion

4.1 The effects of the frequency of electromagnetic vibrations on the apparent glass-forming ability

Figure 4 shows optical micrographs for the Mg$_{65}$Cu$_{25}$Y$_{10}$ alloys produced by using the electromagnetic vibrations in the alumina tube with various kinds of frequency. The electric current and magnetic-flux densities were fixed at 5 A and 10 T, respectively, and the frequency of the electric current was varied as follows: (a) 5000 Hz, (b) 1000 Hz and (c) 500 Hz. The present authors show that Mg$_{65}$Cu$_{25}$Y$_{10}$ alloys can be identified by the optical micrographs. The micrograph for the alloy with the vibrations of 5000 Hz shown in Fig. 4(a) shows featureless metallic glass structures without crystalline particles. However, the micrographs for the alloys with the vibrations of 1000 Hz and 500 Hz shown in Fig. 4(b) and (c) show featureless metallic glass structures with a lot of crystalline particles. The alloy with the vibrations of 500 Hz seems to have more crystalline particles than the alloy with the vibrations of 1000 Hz. Thus, it was found that the apparent glass-forming ability of these alloys increases with increasing the frequency of electromagnetic vibrations up to 5000 Hz. The effects of frequency more than 5000 Hz could not be investigated because of alternating current power devices.

4.2 The effects of the intensity of electromagnetic vibrations on the apparent glass-forming ability

Figure 5 shows optical micrographs for the Mg$_{65}$Cu$_{25}$Y$_{10}$ alloys produced by using the electromagnetic vibrations in the alumina tube with various kinds of electric current. The frequency and magnetic flux density were fixed at 1000 Hz and 10 T, respectively, and the electric current was varied as follows: (a) 0 A, (b) 5 A and (c) 10 A. The micrograph for the alloy without the electromagnetic vibrations, namely, that produced at an electric current of 0 A shown in Fig. 5(a) shows crystalline structures alone. The micrograph for the alloy with the vibrations at an electric current of 500 Hz shown in Fig. 5(b) shows featureless metallic glass structures with a lot of crystalline particles. Moreover, the micrograph for the alloy with the vibrations at an electric current of 10 A shown
in Fig. 5(c) shows the metallic glass structures with a few crystalline particles. However, the crystalline particles shown in Fig. 5(c) seems to grow larger than that shown in Fig. 5(b).

Figure 6 shows optical micrographs for the Mg$_{65}$Cu$_{25}$Y$_{10}$ alloys produced by using the electromagnetic vibrations in (a) the alumina tube and (b) the molybdenum tube. The electric current, frequency and magnetic flux density were fixed at 5 A, 1000 Hz and 10 T, respectively. The micrograph for the alloy in the alumina tube shown in Fig. 6(a) shows the metallic glass structures with a lot of crystalline particles. On the other hand, The micrograph for the alloy in the molybdenum tube shown in Fig. 6(b) shows the metallic glass structures with small crystalline particles. This result is considered to be caused by that the alloy in the molybdenum tube have higher cooling rate than that in the alumina tube because of the thickness of the tubes.

Figure 7 shows optical micrographs for the Mg$_{65}$Cu$_{25}$Y$_{10}$ alloys produced by using the electromagnetic vibrations in the molybdenum tube with various kinds of magnetic flux density. The electric current and frequency were fixed at 5 A and 1000 Hz, respectively, and the magnetic flux density was varied as follows: (a) 10 T, (b) 1 T and (c) 0 T. The XRD pattern of the alloy produced at 10 T consists mostly of the broad peak from the metallic glass phase and has a small quantity of the crystalline peaks. However, the XRD pattern of the alloy produced at 1 T consists of sharp crystalline peaks and a broad peak from the metallic glass phase. Moreover, the alloy produced at 0 T shows sharp crystalline peaks alone. These results are in good agreement with the results of the optical micrographs.

As these results, it was found that the apparent glass-forming ability of these alloys increases with increasing the intensity of electromagnetic vibrations by the electric current or magnetic flux density. However, the electric current makes Joule heat which is proportional to the square of the electric current. If the electromagnetic vibration force is increased by the electric current, the sample is considered to have lower cooling rate because of increasing Joule heat. The reason why the crystalline particles for the alloy with the vibrations at an electric current of 10 A shown in Fig. 5(c) grew larger is...
considered to be lower cooling rate because of increasing Joule heat. Thus, increasing excessively the electric current was found to weaken the enhancement of the apparent glass-forming ability by using the electromagnetic vibration process because the crystalline particles grow larger by the Joule heat.

5. Conclusions

The effects of the intensity and frequency of electromagnetic vibrations on the apparent glass-forming ability in the Mg–Cu–Y bulk metallic glasses have been investigated, and the following conclusions have been derived.

(1) It was found that the apparent glass-forming ability of Mg$_{65}$Cu$_{25}$Y$_{10}$ alloys increases with increasing the frequency of electromagnetic vibrations up to 5000 Hz. The effects of frequency more than 5000 Hz could not be investigated because of alternating current power devices.

(2) It was found that the apparent glass-forming ability of Mg$_{65}$Cu$_{25}$Y$_{10}$ alloys increases with increasing the intensity of electromagnetic vibrations by the electric current or the magnetic flux density. However, increasing excessively the electric current was found to weaken the enhancement of the apparent glass-forming ability by using the electromagnetic vibration process because the crystalline particles grow larger by the Joule heat.
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