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Study on the characteristics of magnetic levitation for permanent magnets and ferromagnetic materials with various sizes using stacked HTS bulk annuli

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ABSTRACT

We achieved stable levitation of cylindrical permanent magnets and irons using stacked ring-shaped high temperature superconducting (HTS) bulks with 20 mm ID, 60 mm OD and 50 mm height, and those were magnetized by field cooling method. The levitation characteristics of permanent magnets and iron samples located in the inner space of that levitation system were investigated experimentally. Iron samples with needle-shape and smaller than 1 mm diameter could not levitate stably. However, we found that the high strength of magnetized field was not necessary to levitate small needle-shaped irons. In order to levitate them, we need a uniform magnetic field in radial direction, so, a spherical solenoid magnet that can easily make a homogeneous magnetic field in inner space of HTS bulk annuli was developed. The spherical solenoid magnet, composed of seven solenoid coils with different inner and outer diameters, was designed by an electromagnetic analysis and fabricated.

1. Introduction

The trapped HTS bulks by the field cooling method have a trapped magnetic field and exhibit diamagnetic behavior. Recently, Ninomiya et al. showed the stable levitation of ferromagnetic materials, such as pure iron located at the free space between two HTS bulks which were magnetized by the field cooling method [1]. It seems that the levitation of the ferromagnetic substances is very similar to the levitation principle of Mixed-μ system [2–4] composed of the ferromagnetic substance, diamagnetic material and superconducting magnet. It means that the HTS bulk plays the roles of the diamagnetic substance and the superconducting magnet at same time.

In this study, the levitation properties of permanent magnets and iron samples with various sizes were studied using stacked HTS bulks magnet, and a spherical solenoid magnet was designed and fabricated to levitate ferromagnetic substances with very small size.

2. Magnetic levitation system and experimental details

Fig. 1 shows three-stacked HTS bulk annuli as a levitation system, and the ID, OD and height of HTS bulks are 20 mm, 60 mm and 15, 20 mm respectively. Three HTS bulk annuli are fixed by installing bakelite in the upper and lower sides. The stacked HTS bulk annuli were put into the room temperature bore of a superconducting magnet, and then magnetized by the superconducting magnet with field cooling method. The trapped magnetic field of stacked HTS bulk annuli was used for a levitation system after it was removed from the superconducting magnet (Fig. 2). The stacked HTS bulk annuli were placed in liquid nitrogen to keep the superconducting state during the experiment. In order to observe the levitation of samples clearly, liquid nitrogen in the levitation space of stacked HTS bulk annuli was removed by setting the copper cover. Measurement of levitation height was carried out after dropping a sample to HTS bulk annuli. The samples are irons and permanent magnets with a height of 10 mm and a diameter of 1–10 mm. In addition, B_z distributions of upper part of the irons and permanent magnets in stacked HTS bulk annuli were measured by Hall sensor. The measuring position is shown in Fig. 2.

3. Experimental results

Fig. 3 shows the photograph of levitation of iron sample with a diameter of 1 mm and height of 10 mm in the stacked HTS bulk annuli. Until now, we have succeeded in the levitation of irons more than 1 mm in diameter. Tables 1 and 2 show the levitation height of permanent magnets and irons with various sizes respectively. Levitation height means the distance of center of samples from the axial center of stacked HTS bulk annuli. The permanent magnet comes to levitate near the entrance of stacked HTS bulks when a magnetization field becomes small and diameter of permanent magnet becomes large. Here, the attractive force and

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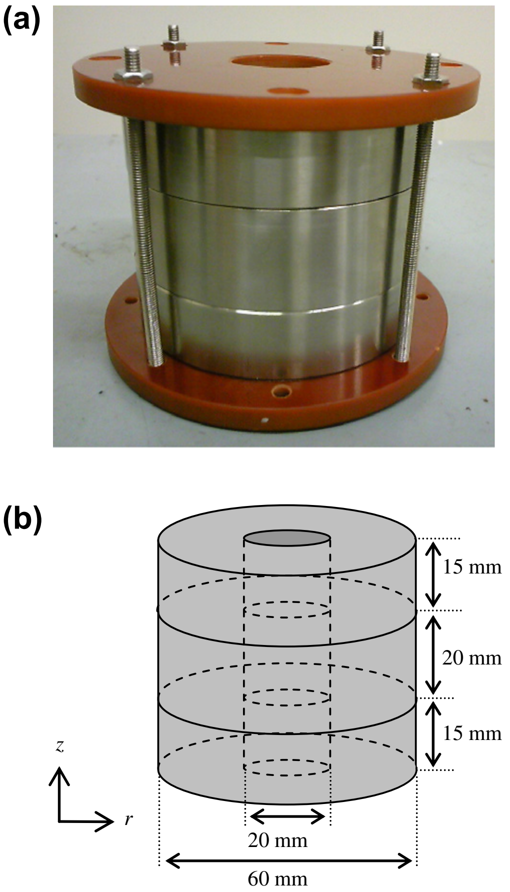

Fig. 1. (a) Photograph of stacked HTS bulk annuli; (b) Schematic drawing of stacked HTS bulk annuli.

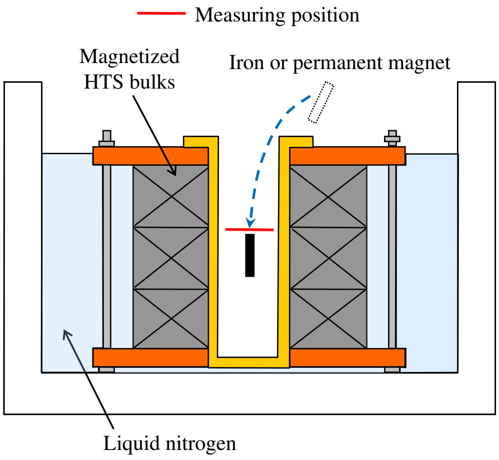

Fig. 2. Schematic drawing of levitation system for the ferromagnetic substance using stacked HTS bulk annuli.

the repulsive force effect of superconductors act between the HTS bulks and samples. When the magnetized field increases, the small sample is pulled to inside wall of stacked HTS bulk annuli because attractive force increases. In addition, the samples levitate near an axial center as the magnetic field becomes strong and the weight of sample effects to the levitation height.

Fig. 4 shows the measured B_z profiles along the radial position of upper part of permanent magnets and irons as the functions of sample size when the magnetized field is 0.1 T. The magnetic field gradient of the permanent magnets is larger than irons and this result shows that the permanent magnets are more stable than irons. However, we will discuss only the levitation characteristic of irons henceforth. Fig. 5 shows the measured B_z profiles along the radial position of upper part of irons as the functions of sample size and strength of magnetized field. The magnetic field gradient increases with increasing the magnetized field because the number of magnetic flux at inner space of HTS bulk annuli increase and they concentrate in an iron sample when the magnetized field becomes large. In addition, the position of the peak moves to the center as a magnetized field becomes large. It means an iron sample levitates in the vicinity of the center as a magnetized field becomes large.

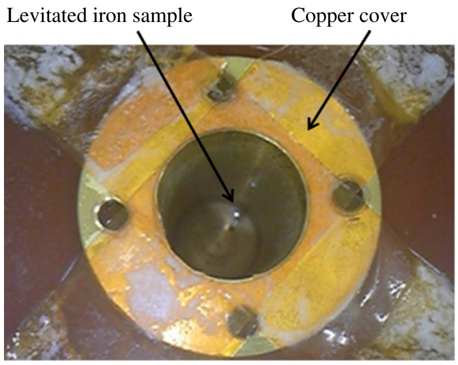

Fig. 3. Photograph of levitation of iron sample with a diameter of 1 mm and height of 10 mm in the stacked HTS bulk annuli.

Fig. 6 shows the relationship between the levitation height of iron samples, the weight of samples and dependence of weight of samples. The levitation forces were smaller than the gravity when magnetized fields were less than 0.1 T. However, the influence of gravity disappears when the magnetized field becomes larger than 0.2 T, because magnetic force acting on the iron sample becomes large with increasing the magnetized field.

Fig. 7 shows the relationship between weight and diameter of samples and the minimum values of magnetization field to obtain stable levitation. The relationship between weight of samples and the minimum values of magnetization field to obtain the stable levitation is shown in the following equation:

$$f(m) = 0.02256 \times \ln\left(\frac{m}{2.43073 \times 10^{-5}}\right). \tag{1}$$

The relationship between diameter of samples and the minimum values of magnetization field to obtain the stable levitation is shown in the following equation:

$$f(d) = 0.28 - 0.27704 \times \exp\left(-\frac{d}{1.88123}\right). \tag{2}$$

From those results, high strength of magnetized field is not necessary to levitate the small iron samples. For example, a magnetic field strength is only 0.0438 T to levitate the iron with a diameter of 0.3 mm. In this study, we used a superconducting magnet for magnetization of HTS bulks. However, in our research, the small size iron samples with needle shape and smaller than 1 mm diameter could not be levitated stably. To levitate the needle-shaped small size iron sample, a uniform magnetic field is needed. Therefore, in order to realize the levitation of the small iron samples, a spherical solenoid magnet for magnetization of HTS bulks has been developed.

4. Development of spherical solenoid magnet

The spherical solenoid magnet can easily make a homogeneous magnetic field. Fig. 8 shows the to-scaled schematic drawing of the