Brazilian Journal of Physics
ISSN: 0103-9733
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Sociedade Brasileira de Física
Brasil

Yang, W. M.; Zhou, L.; Feng, Y.; Zhang, P.X.; Zhang, C.P.; Yu, Z.M.; Tang, X.D.
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Brazilian Journal of Physics, vol. 32, núm. 3, septiembre, 2002, pp. 763-767
Sociedade Brasileira de Física
Sâo Paulo, Brasil

The Effect of Grain-Domain-Size on Levitation Force of Melt Growth Processing YBCO Bulk Superconductors

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Received on 28 February, 2002

Effects of grain-domain-size (GDS) on levitation force have been directly investigated and identified in well-textured YBCO bulks. A single-grain-domain YBCO bulk (ϕ=30mm) was prepared by a top seeded melt growth process, then divided into two, three and four grain-domain to acquire the levitation forces of samples with different GDS. It is found that the levitation force of the samples monotonously decreases with the decreasing of the average GDS (or with the increasing of the total length grain-boundaries of the sample). The maximum levitation force for the single-grain-domain sample is about 1.68, 2.05 and 2.4 times higher than that of the samples with two, three, and four grain-domains. It is concluded that the levitation force of a single-grain-domain YBCO bulk is higher than that of samples with multi-grain-domains. It is also found that the levitation force is proportional to the average grain-domain radius, but inverse proportional to the total length of grain-boundaries of the sample, a simple physical model has been provided and well interpret the experiment results.

I Introduction

High levitation force of single-domain YBCO bulk superconductors has made it possible for various applications, such as non-contacted superconducting bearing [1,2], flywheel [3-8], magnetic levitation transport systems [9,10] and motors [11,12]. It is believed that the energy loss of superconducting magnetic flywheel is as little as 0.1% per hour, only one tenth of that with conventional bearings. The commercialization of this technique will not only reduce the energy losses, but also make the electricity consumption more economical and reasonable to meet our demands.

The levitation force between a superconductor and a magnet is closely related with the critical current density Jc and the radius R of the induced shielding current loops (ISCL) in a superconductor. Higher Jc and larger R are very important to achieve higher levitation force [13]. Now single-domain YBCO bulk superconductors can be fabricated in many labs [14-21], so a relatively larger R of ISCL can be achieved while a magnet approaches to it. The size of single-domain YBCO bulk is generally about several centimeters in diameters, and limited to10 cm for high quality YBCO bulk up to now, because of the grains miss-orientation during the melt growth process.

The levitation force is also related with many parameters, such as thickness of the sample [22], grain-orientation [15,26-28], temperature, magnetic field distributions [23-25], and the gap between superconductor/magnet [29] etc. Recently, an electromaglev experiment performed on a single-domain YBCO bulk (ϕ = 30mm) and a multiple bulk comprised smaller disks (ϕ =10mm) [30]. It is found that the levitation force of a single larger YBCO disks is superior to assemblies of smaller disks, the experiments were done with different samples and especially the geometric shape of the assembled smaller discs could not well match the volume shape of the ϕ = 30mm single-domain YBCO sample. But the physical mechanisms governing the levitation force associated with the grain-domain-size (GDS) or ISCL are not clearly. We cannot see any report directly focused on the effect of GDS on levitation force of well-textured YBCO, especially all the experiments was directly done by using a single-grain-domain YBCO bulk superconductors. Identification of the relationship between the levitation force and GDS of YBCO bulk is not only interested to fundamental studies, but also very important for practical.

In this paper, a single-domain YBCO bulk (ϕ =0mm) was fabricated and divided into two, three, and four grain-domains. The levitation force measurements were done on the YBCO samples with a single, two, three, and four grain-domains to investigate the physical mechanisms of GDS on the levitation force of well-textured YBCO superconductors, and a simple physical model has been deduced and well explained the experimental data.

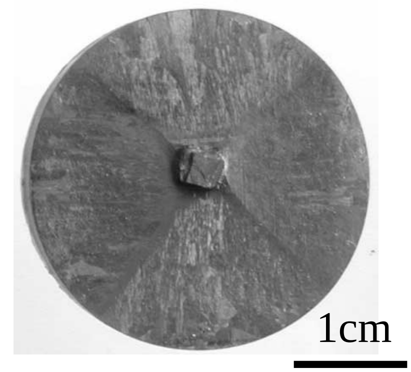

Figure 1. Optical photograph of single-domain YBCO bulk superconductor.

II Experiments

Samples preparation. X-ray Pure $YBa_2Cu_3O_y$, 4N purity Y_2O_3 and PtO_2 powders were weighed and mixed in the weight ration of 90.5:8.5:1. The well-mixed powder was uniaxially pressed into pellets of ϕ=35mm$\times$15mm in a steel mould. The $Nd_{1+x}Ba_{2-x}Cu_3O_y$ single crystals were prepared in air [32] and used as seeds in this study. The pellets with seed were put into a furnace with a temperature gradient 1-4 ^{o}C/cm in vertical direction. The samples were heated up to 1040-1060^{o}C at a rate of 120^{o}C/h, and held for 2-6 hours for homogenous melting. After that, the samples were cooled to about 1020 ^{o}C at a rate of 10-30^{o}C/h, and further cooled to 940-960 ^{o}C at a rate of about 1 ^{o}C/h, then the samples were cooled to room temperature at a rate of 120 ^{o}C/h. Finally the as-grown samples were annealed at 400-550 ^{o}C for a week in flowing O_2.

The typical photograph of a single-domain YBCO bulk (ϕ=30mm) is shown in Fig. 1. The grain-orientation of the sample was investigated by XRD, optical, SEM and ϕ-scan examinations. All results indicate that the YBCO sample is a single-domain with c-axis normal to its top surface (results not shown here). The sample was firstly divided into two grain-domain after levitation force measurement, and then divided into three and four grain-domains by a line-saw, so that we can make four well-textured YBCO samples, each of them has the same size (ϕ=30mm) and grain-orientations, but only with different GDS. The samples with a single, two, three and four grain-domains are named as a, b, c and d respectively, as schematically shown in Fig. 2. The volume and shape of four samples are considered as the same because the diameter of the line-saw is very thin and only about 0.1 mm.

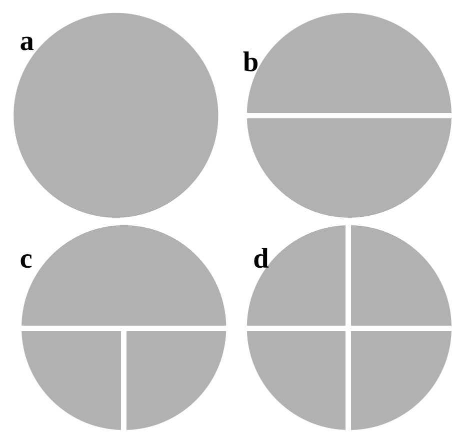

Figure 2. Schematic diagram of the configuration of YBCO bulk samples with different grain-domains. a) Single-grain-domain; b) two grain-domain; c) Three grain-domain; d) Four grain-domain.

The levitation forces were measured in a homemade device [24,25]. A magnet of 30 mm in diameter was used for all the levitation force measurements. The magnetic field is about 0.5 T at the center of the top surface. At the beginning of each measurement, the sample was symmetrically fixed on the axial line of the magnet and kept 50-60 mm below the magnet. After the sample was completely cooled to liquid nitrogen temperature (zero field cooling), then the magnet was moved towards to and away from the sample by a controlled motor. Thus the levitation force as a function of distance between the magnet and the sample can be obtained. The maximum levitation force was measured at a gap of 0.1 mm between the two nearest surfaces of the sample and the magnet in this experiment.

III Results and discussion

The levitation force values were measured in zero field cooled state at 77 K for the samples a, b, c and d, shown in Fig.3. As we can see from this figure, the levitation forces are much different for the samples with different GDS. The maximum levitation force is 67.5 N obtained in the single-grain-domain sample a, and the minimum one is 28.15 N obtained in the sample d with four grain-domains. The curve of levitation forces is shifting to the left side and the slop of the curves is gradually decreasing with the increasing of grain-domain numbers from one to four corresponding to the curves a, b, c and d in Fig.3. These mean that the levitation force decreases with the increasing grain-domain numbers (or with the decreasing of grain size), while the shape, size and volume of the YBCO bulks are the same.

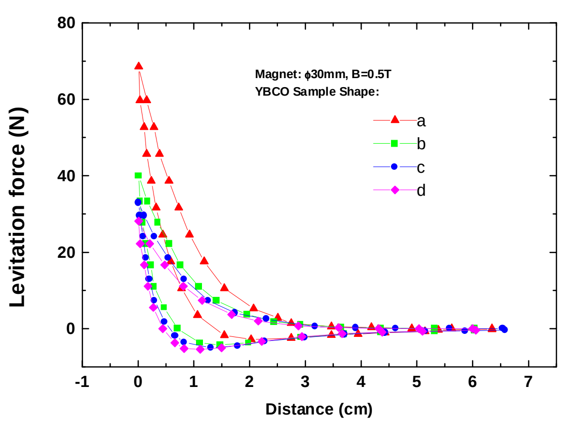

Figure 3. The levitation forces verses distance at 77K for the melt grown YBCO bulk sample with different grain-domain size.

In order to make clearly the relationship between the levitation force and the GDS, the maximum levitation forces of the four samples were collected and drawn as a function of the corresponding average grain-domain radius R, as shown in Fig. 4. As we can see from Fig. 4, the levitation force monotonously increases from 28.15N to 67.5N while the R increases from 0.75cm to 1.5 cm, the increasing factor is around 2.4. The experimental showed that the levitation force is nearly proportional to the average radius of grain size, this results is in agreement with reference [13]. But the levitation force will not go to zero while R is extrapolated to zero.

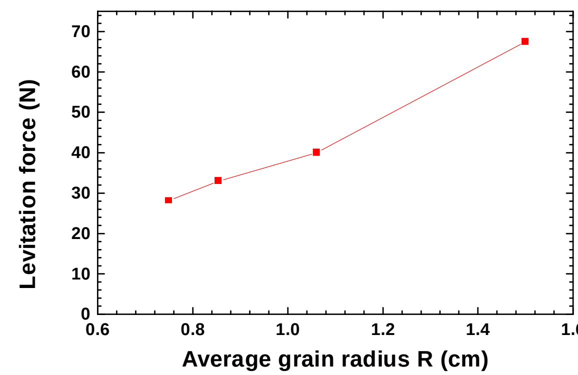

Figure 4. Maximum levitation force versus the average grain radius of samples with different grain-domain numbers at liquid nitrogen temperature.

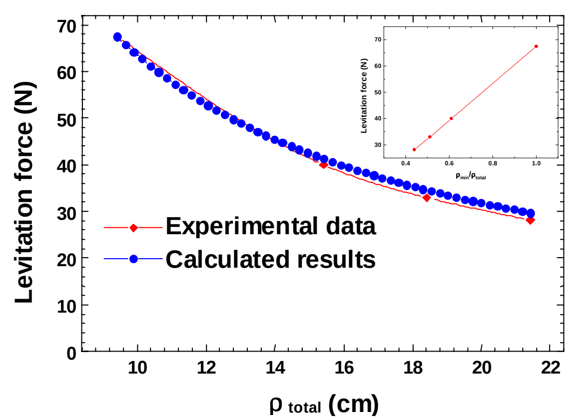

Figure 5. The maximum levitation force versus the total grain-boundary length ρ_{total} of samples with different grain-domain numbers at liquid nitrogen temperature.

The grain boundary of the sample increases gradually with the increasing of grain-domain numbers after each cutting, the boundaries formed by cutting will entirely stop the induced shielding current to cross the narrow cutting gap, and lead to some new and smaller induced shielding current loop (ISCL) (compared with that before each cutting), and finally result in a reduction in levitation force. The total length of grain-domain boundaries increases from sample a to d with increasing of the grain-domain numbers. Let us assume ρ_{total} represent the total length of grain-domain boundaries of YBCO sample, then $\rho_{\text{total}} = \pi R_s$, $2\pi R_s + 4R_s$, $2\pi R_s + 6R_s$ and $2\pi Rs + 8R_s$ for samples a, b, c and d respectively, where R_s is the radius of sample a. Fig. 5 shows the maximum levitation force of the samples with different ρ_{total}. As we can see from Fig.5, the levitation force decreases quickly with the increasing of ρ_{total}. The flux pinning force is very strong for the well-textured YBCO samples under 0.5 T at 77 K, so the flux penetration layer is very thin. It means that the induced electric current can only flow in a very narrow layer along the grain-domain-boundaries of the sample. Here the induced current can be regarded as only a constant surface current, so the total length of ISCL is equal to the ρ_{total}. Based on this, ρ_{total} is related with the levitation force of corresponding YBCO samples.

The levitation force F is proportional to the radius of ISCL [13]. How about the relationship between the levitation force and ρ_{total}? Considering a set of samples with different GDS. Let A denote the top surface area of a single-grain-domain superconducting sample, and then the sample was

$$n = \frac{R^2}{r_n^2} \tag{1}$$

divided into several equivalent smaller grain-domains (n=1, 2, 3..., represent the numbers of smaller grain-domains). R and r_n denote the radius of the single-domain sample and the samples with n smaller grain-domain respectively. Then $A = nA_n$, where A_n is the top surface area of the smaller grain-domains. So the n can be described as:

Then the total grain-boundary length of the sample with n smaller grain-domains can be written as:

$$\rho_{\text{total}} = n \cdot 2\pi r_n \tag{2}$$

Substitute equation (1) to (2), the average grain-domain radius of the sample with multiple

$$r_n = \frac{\rho_{\min}}{\rho_{\text{total}}} R \tag{3}$$

grain-domains can be formulated as:

Where $\rho_{\min}$ is the grain-boundary length (or perimeter) of the single-grain-domain sample without any cutting. $\rho_{\min} = 2\pi R = \rho_{\text{total}}$, corresponding to $n = 1$.

According to Ref [13], the levitation force is proportional to the radius r_n of the grain-domains, thus the levitation force of sample with n grain-domain can be described as:

$$F_n = \frac{\rho_{\min}}{\rho_{\text{total}}} F_1 \tag{4}$$

Where F_1 is the maximum levitation force of the single-domain sample corresponding to $\rho_{\text{total}} = \rho_{\min}$. This means that the levitation force is inverse proportional to ρ_{total}.

In this experiment, $\rho_{min} = 2\pi R_s$, $\rho_{\text{total}} = 2\pi R_s + L, F_1 = 67.5N$, and $R_s = 15$mm. L, the length of introduced grain boundaries by cutting, is of $0, 4R_s$, $6R_s$ and $8R_s$ for the samples with single, two, three and four grain-domains respectively. Then, in this experiments, the levitation force can be formulated as:

$$F_L = \frac{2\pi R_s}{2\pi R_s + L} F_1 \tag{5}$$

The levitation force of the sample with different L values has been calculated using formula (5) and shown in Fig.5. As we can see from Fig.5, the calculated result is in good agreement with the experimental data. The insert in Fig.5 shows that the experimental data forms a straight line between the levitation force and $\rho_{\min}/\rho_{\text{total}}$. This conforms that the levitation force is really inverse proportional to the total grain-boundary length of the superconducting sample.

IV Conclusion

A single-grain-domain YBCO sample ($\phi = 30$mm) has been prepared by a top seeded melt growth process and separated into two, three and four grain-domains after each levitation force measurements. The maximum levitation force of the single-domain sample is about 1.68, 2.05 and 2.4 times higher than that of the samples with two, three, and four grain-domains respectively. It is found that the levitation force of a single-domain YBCO bulk is much higher than that of the same sized samples with smaller gain-domains. The levitation force is inverse proportion to the total length of grain-boundaries of the sample, and a simple physical model has been suggested and well interpreted the experiment results.

This work is supported by the Ministry of Science and Technology of China (NKBRSF-G19990646), Project “973”.

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