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Electromagnetic Applications of Melt-Processed YBCO

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Abstract: Large persistent currents can flow in superconductors when they exhibit a large pinning force. The electromagnetic interaction between such persistent currents and magnetic field produces both repulsive and attractive forces. Various applications are now under consideration using such interactions. These include magnetic bearings, flywheels and transport systems. The pinned superconductor can also either shield or trap magnetic fields by persistent currents. Magnetic shield devices and superconducting permanent magnets can be made using such properties.

1 INTRODUCTION

The response of the superconductor to a magnetic field is attractive for various applications.[1] In magnetic fields below H_{c1}, type II superconductors can prevent magnetic flux penetration, which is known as the Meissner effect. Under such circumstances, a magnet can be levitated above the superconductor and vice versa. However, the repulsive force due to the Meissner effect is small and the levitation is unstable, which limits the applications. On the other hand, a repulsive force can also be obtained above H_{c1}, when the superconductor exhibits pinning.[2–4] Although the external field enters the superconductor, the internal field has a gradient corresponding to:

$$\mathrm{rot}\,\boldsymbol{B} = \mu_0 \boldsymbol{J}_c. \qquad (1)$$

In one dimension this equation is simplified as $dB/dx = \mu_0 J_c$, where B is the magnetic induction in T, μ_0 the permeability of free space, and J_c is the critical current density in A/m^2. The physical origin of the flux-density gradient is the pinning of the magnetic flux lines by structural defects in the material. In other words, large supercurrents (J_c) can flow in the superconductor by virtue of flux pinning. As will be shown below, the interaction between the magnetic field and such large supercurrents can bring various attractive applications of superconductors. In this review, possible applications of electromagnetic forces of high T_c superconductors will be introduced.

2 MAGNETIC FORCE

The force between a superconductor and a magnet is given by:

$$\boldsymbol{F} = \int (\boldsymbol{m} \cdot \nabla) \boldsymbol{H} dv \qquad (2)$$

In one dimension, this equation is simplified as $F = m\, dH/dx$, where m is the magnetic moment of a superconductor, and dH/dx is a field gradient produced by a magnet. m is equal to Mv, where M is the magnetization per unit volume and v is the volume. dH/dx is a constant, provided that we use the same magnet, while M is dependent on J_c and the size of the shielding current loop (r) according to the following relation: $M = A\, J_c\, r$, where A is a constant which depends on sample geometry and r is the radius of the shielding current loop. It should be borne in mind that, in contrast to conventional magnetic materials, M of a superconductor depends on its size, which is a peculiar characteristic of a superconductor, and is the key to a large levitation force.

Magnetic force is also given by the following expression:[5]

$$F = \int J_c \times B \mathrm{d}v \tag{3}$$

This is a more direct expression to show that the interaction of supercurrent (J_c) and magnetic induction (B) is the source of the magnetic force. In a static field, eqns (2) and (3) give the same results.

3 MELT-PROCESSED YBCO

It has been shown that a large electromagnetic force can be achieved in melt-processed YBCO.[6] It has also been demonstrated that even a person could be levitated by superconductors. Such a large force is attributed to a combination of large J_c and large grain size. It is also important to align crystal orientation in order to improve the force, since oxide superconductors are anisotropic materials. Recently it was found that crystal orientation of anisotropic materials such as YBCO can be controlled under two directional temperature gradients. Figure 1 shows an optical micrograph of a YBCO sample, slowly cooled at a rate of 1°C/h from 1030°C to 870°C, under the temperature gradients of 20°C/cm in a horizontal direction and 5°C/cm in a vertical direction. The c-axis is aligned along the horizontal direction. It was found that crystal orientation can be controlled by changing the ratio of the temperature gradients. The sample fabricated by this method exhibits a repulsive force three times larger than that of the sample made by the conventional method.

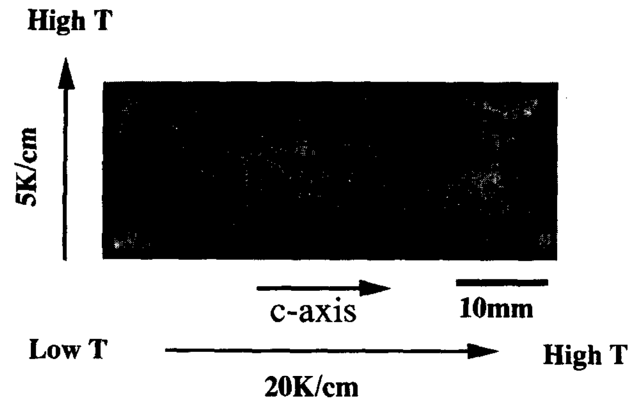

Fig. 1. Optical micrograph of a melt-processed YBCO sample grown under two directional temperature gradients. Note that the c-axis is aligned along a horizontal line.

4 APPLICATIONS

4.1 Levitation

A heavy object can be levitated by the repulsive force between a magnet and melt-processed YBCO superconductors.[6] Various applications using such levitation have been proposed.

4.1.1 Physics experiment

Since an object can be levitated without contact, several physics experiments have been proposed. One example is the experiment in the field of fluid dynamics. If we support an object in mid-air, the fluid-flow around the object can be analysed under ideal conditions.

4.1.2 Lunar telescope

The moon is the best site for an astronomical observatory. It is a stable platform with a dark sky, perfect visibility, and offers wavelengths not accessible from the Earth. Long observation times are possible, ranging from 14 days to forever (in the poles). However, the limited payload weight of existing launch vehicles and lack of maintenance were obstacles to building telescopes on the moon.

Recently, Chen *et al.*[7] proposed the design of a lunar telescope using a combination of advanced optical fabrication techniques and levitation by oxide superconductors. Melt-processed YBCO superconductors are used to levitate, steer and position the telescopes.

The moon has several advantages for levitation by superconductors. The ground temperature is estimated to be 40 K if permanently shielded from sunlight. This temperature is low enough for $YBa_2Cu_3O_x$ compounds to be superconducting. It is also important to note that the gravity on the moon is seven times smaller than that on the Earth. This means that an object seven times heavier can be levitated on the moon.

4.1.3 Display

Levitation itself might be used for various applications. One such example is the display of jewels. Although this is out of the scientific area, it might be commercially attractive. A Japanese department store is interested in displaying precious metals and stones on a turntable levitated by superconductors. A Japanese hotel is also interested in levitating a married couple as one of the attractions in the wedding party. Levitation of a person has been demonstrated in many exhibitions, and has attracted the attention of a number of people.

4.2 Suspension

It is very interesting to note that a superconductor can be suspended below a magnet, and vice versa. Figure 2 shows a suspension of a large terrestrial globe which weighs 10 kg, using the attractive force of a melt-processed YBCO made by a newly developed 2D temperature gradient technique. This clearly demonstrates that the suspension is due to flux pinning.

4.2.1 Transport system on a guide rail

When we construct a guide rail such that a number of magnets are placed with the same pole facing the same direction, there is no friction for the translational motion of the superconductor. Furthermore, by virtue of flux pinning, the levitated superconductor will not deviate from this magnetic guide.

Recently, Toshiba corporation has succeeded in constructing a transport system of LSI in a clean room.[8] In this system, the motion of the LSI container with four bulk YBCO superconductors can be controlled electromagnetically.

4.2.2 Transport system without a magnetic guide rail

It is also possible to construct a non-contact transport system without a magnetic guide rail. Here we use a pair of a superconductor and a magnet. The motion of the levitated magnet can be controlled by moving the superconductor. Such a system has already been constructed by ULVAC[9] and was used as a transport system for the analytical equipment.

4.3 Rotation device

4.3.1 Magnetic bearing

Several groups[10–13] have succeeded in fabricating bearings using melt-processed bulk YBCO. Superconducting bearings are very simple devices; bulk YBCO is used as a stator and a permanent magnet is used for the rotor. The attractive and repulsive forces between the rotor and the stator cause the stator to be suspended in mid-air, where it is thus able to spin freely.

However, in the case of actual devices, the space in which the rotor can move is extremely limited and therefore, the distance between the superconducting stator and a magnetic rotor is too small to obtain a repulsive force large enough to suspend the rotor, since in such a case a magnetic field is trapped by the superconductor. The problem has recently been solved by utilizing the attractive force, which is greatest when the superconductor is placed in contact with the magnet before cooling.[12] Figure 3 is a schematic illustration showing how the attractive force is obtained. It is also important to note that the stiffness can be improved by this technique. Utilizing the attractive forces, NSK bearing and ISTEC[12] have made a superconducting bearing, in which a 2.4 kg rotor could rotate at 33,000 rpm. Although, the shaft vibration amplitude had been relatively large (about 100 μm peak to peak) in the first run, it could be reduced to 2 μm by increasing the stiffness with newly developed bulk YBCO superconductors melt-grown under 2D temperature gradients.

4.3.2 Flywheel system using bulk superconductors

The flywheel system has long been studied as a candidate for an energy storage system. However, the stored energy was dissipated in a relatively short period, because of the friction in the mechanical bearings.

Superconductive magnetic bearings will make it possible to store energy for a longer period, since there is no friction. A flywheel system spinning in a vacuum with no friction can store kinetic energy

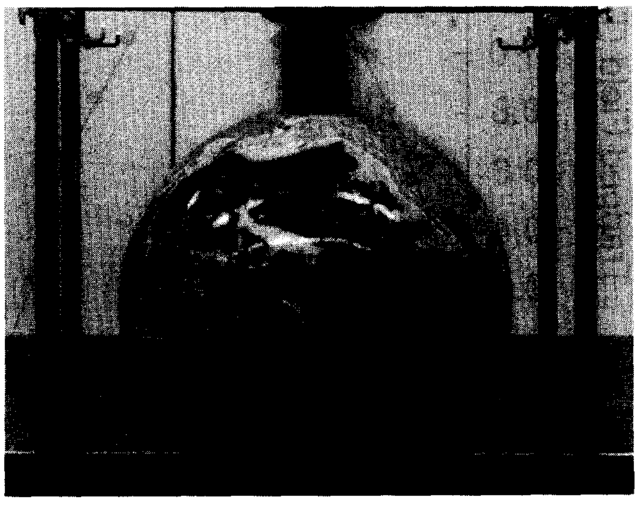

Fig. 2. A terrestrial globe, which weighs 10 kg, can be suspended below a melt-processed YBCO superconductor, 6 cm in diameter and 3 cm in thickness, cooled by liquid nitrogen.

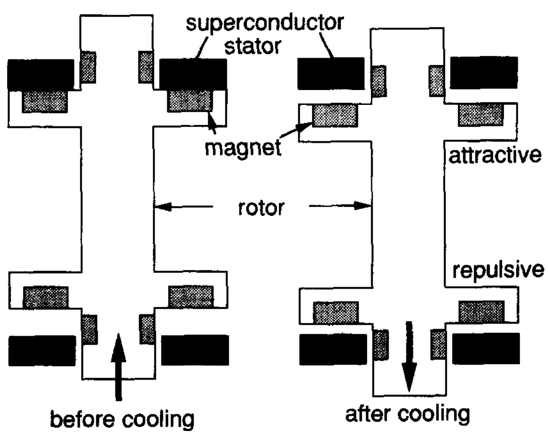

Fig. 3. Schematic illustration of a method to support the rotor in mid-air by using the attractive force of a superconductor. This technique was used in constructing a superconductive bearing.

imparted to the disk from outside, and whenever necessary, can discharge the stored energy in the form of electric energy.

The energy [E (J)] stored by the flywheel is given by:

$$E = (1/4)Mr^2\omega^2 \qquad (4)$$

where M is the mass (kg), r is the radius (m), and ω is the angle velocity (rad/s) of the rotating disk. It is clear that it is possible to increase the amount of stored energy by increasing the diameter of the disk.

However, if we simply increase the size of a magnet, the strength of the magnet is weakened. This problem can be solved by arranging ring magnets concentrically with non-magnetic aluminium spacers between the rings.

It is also important to improve the strength of the rotating disk against the centrifugal force for scaling up. Recently, it was proposed that the problem of the centrifugal force is greatly reduced by constructing a ring flywheel.[14] The beneficial point of the superconducting flywheel is that the wheel can be supported by a large area instead of the axis. In the case of a ring flywheel, the concentration of the force at the rotating axis is no longer a serious problem. There are two groups which have constructed superconducting flywheels. Tokyo Electric power company, Hitachi and ISTEC[15] have made the flywheel system in which a stainless steel disk, 1 m in diameter and 140 kg in weight, can be rotated at 1400–2000 rpm with an energy output of 2 kW and a stored energy of 50 Wh. Shikoku Electric power company and Mitsubishi Electric[16] have also manufactured a flywheel with a stored energy of 55 Wh. They have also proposed a conceptual design of a superconducting flywheel system which can store an energy of 8 MWh.[17] In the future, it might be possible to convert solar energy into electricity by solar cells, and to store the energy in a superconducting flywheel, and to discharge it when it is necessary.

4.4 Application of flux trapping

It is possible to construct a kind of superconducting permanent magnet using a pinned superconductor. A significant magnetic field can be trapped by a superconductor when it exhibits a large flux pinning force.

A melt-processed YBCO sample with dimensions of $0.1 \times 3 \times 3$ mm^3 exhibits MH_{max} of 80 MGOe at 5 K, which is larger than that of any conventional magnetic materials.[17] In a large YBCO sample, 4 cm in diameter and 1.5 cm in thickness, a field exceeding 1 T can be trapped at 77 K, as shown in Fig. 4. The trapped field can be increased to 3 T if the sample is cooled down to 60 K.

5 NEW COMPOUND WITH NEW PINNING CENTRE

As mentioned above, a quasi-permanent magnet can be produced which can generate 1 T at 77 K. Theoretically, this field can be increased by simply enlarging the grain size. However, it was found that the trapped field saturates at around 1 T, as long as we use melt-processed YBCO. Weinstein *et al.*[18] could increase the trapped field in a heavy-ion irradiated melt-processed YBCO, but it is desirable to increase flux pinning without irradiation.

Recently, it was found that a new type of pinning centre can be introduced in $NdBa_2Cu_3O_y$ (Nd123) and $SmBa_2Cu_3O_y$ (Sm123) superconductors, which show larger flux pinning forces than Y123 containing finely distributed Y211 inclusions.[19]

Rare earth (RE) ions with large radii easily substitute for Ba site, which leads to a reduction in T_c in these 123 systems. This reduction in T_c was attributed to the fact that the carrier density decreased when trivalent RE ions substitute for divalent Ba. Therefore, RE123 samples with large RE ionic radii (RE: La, Nd, Sm, Eu and Gd) always exhibited relatively low T_c values. However, it was found that this substitution can be largely suppressed when the superconductors are melt-processed in a reduced oxygen atmosphere. The zero resisitvity temperature of Nd and Sm123 exceeded 94 K. More surprisingly, the J_c values of

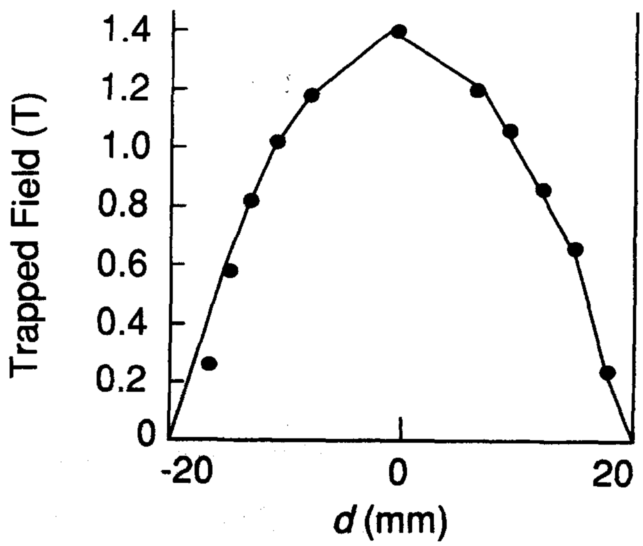

Fig. 4. Distribution of the trapped field in melt-processed YBCO superconductors at 77 K. The sample had been cooled in 3 T down to 77 K and the external field was removed. Note that a field higher than 1 T can be trapped.

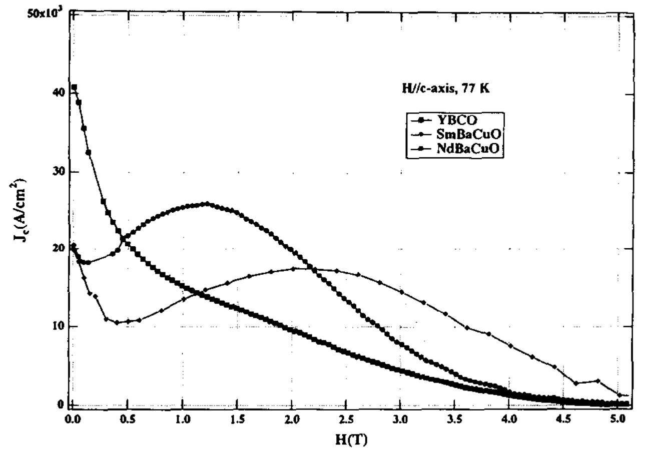

Fig. 5. J_c–B properties at 77 K for Y123, Nd123 and Sm123 melt-processed in a reduced oxygen atmosphere.

these compounds were higher than those of Y123 in a high field region, as shown in Fig. 5.

Here, the following mechanism is proposed in order to explain flux pinning in the Nd and Sm123 system. As mentioned before, there is a wide range of composition in the RE–Ba solid solution when these compounds are fabricated in air. When this compound is synthesized in a reduced oxygen atmosphere, the chemical composition becomes close to 123. However, even in such a case, regions with slight chemical variation exist. In low fields, such regions will exhibit good superconducting transition, and therefore the flux pinning force is small. As the strength of the magnetic field is increased, some of these regions will become normal, and can then contribute to flux pinning. The field for these regions to be driven normal depends on chemical composition. This is why magnetization curves show anomalous peaks and J_c is high under large magnetic fields.

6 SUMMARY

Until recently, major applications of superconductors had been confined to products in the form of wires and thin films. However, the development of melt-processed YBCO superconductors with a strong pinning force has opened up the possibility of many new applications in the bulk monolithic form. It is also notable that Nd and Sm123 superconductors, which show better flux pinning than Y123, were recently synthesized. The applications of bulk superconductors will be accelerated if these compounds are made in large dimensions.

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REFERENCES

1. WOLFSTEIN, D., SEIDEL, T. E., JOHNSON, D. W., Jr & RHODES, W. W., *J. Supercond.*, **2** (1989) 211.
2. MOON, F. C., YANOVIAK, M. M. & WARE, R., *Appl. Phys. Lett.*, **52** (1988) 1534.
3. BRANDT, E. H., *Appl. Phys. Lett.*, **53** (1988) 1554.
4. HARTER, W. G., HERMANN, A. M. & SHENG, Z. Z., *Appl. Phys. Lett.*, **53** (1988) 1119.
5. MURAKAMI, M., OYAMA, T., FUJIMOTO, H., TAGUCHI, T., GOTOH, S., SHIOHARA, Y., KOSHIZUKA, N. & TANAKA, S., *Jpn J. Appl. Phys.*, **29** (1990) L1991.
6. UESAKA, M. & MIYA, K., In *Melt Processed High Temperature Superconductors*, ed. M. Murakami. World Scientific, Singapore, 1993, p. 284.
7. CHEN, P. C., OLIVERSEN, R. J. & HOJAJI, H., In *Proc. TCSUH Workshop.* World Scientific, Singapore, 1992, p. 513.
8. OGIWARA, H., AZUKIZAWA, T. & MORISHITA, M., *Appl. Supercond.*, **1** (1993) 1185.
9. MINAMI, H. & YUYAMA, J., *Jpn J. Appl. Phys.*, **34** (1995) 346.
10. MOON, F. C., CHANG, P. Z., HOJAJI, H., BARKATT, A. & THORPE, A. N., *Jpn J. Appl. Phys.*, **29** (1990) 1257.
11. YOTSUYA, T., SHIBAYAMA, M. & TAKAHATA, R., *Advances in Cryogenic Engineering*, **37** (1992) 519.
12. TAKAICHI, H., MURAKAMI, M., KONDOH, A., KOSHIZUKA, N., TANAKA, S., FUKUYAMA, H., SEKI, K., TAKIZAWA T. & AIHARA, S., In *Proc. 3rd Int. Symp. on Magnetic Bearings.* Technomic, PA, 1992, p. 10.
13. TAKAHATA, R., UEYAMA, H. & KUBO, A., *Advances in Supercond.*, **5** (1993) 1309.
14. SHIMADA, R. & CHIKARAISHI, H., Paper presented at *Electrical Society Meeting*, 1989.
15. SUZUKI, T., SUZUKI, H., ENDO, N., YASAKA, Y., MORIMOTO, H., TAKAICHI, H. & MURAKAMI, M., *Advances in Supercond.*, **6** (1994) 1237.
16. HIGASA, H., KAWAUCHI, N., NAKAMURA, S. & ITO, N., *Advances in Supercond.*, **6** (1994) 1231
17. GOTOH, S., MURAKAMI, M., FUJIMOTO, H. & KOSHIZUKA, N., *J. Appl. Phys.*, **72** (1992) 2404.
18. WEINSTEIN, R., REN, Y., LIU, J., CHEN, I. G., SAWH, R., OBOT, V. & FOSTER, C., *Advances in Supercond.*, **6** (1994) 855.
19. MURAKAMI, M., YOO, S. I., SAKAI, N., HIGUCHI, T., WELTZ, J., KOSHIZUKA, N. & TANAKA, S., *Jpn J. Appl. Phys.*, **33** (1994) L715.