S19-33
82156

DEVELOPMENT OF Y-Ba-Cu-O SUPERCONDUCTORS FOR MAGNETIC BEARINGS[†]

235623

V. Selvamanickam, K. Pfaffenbach, R. S. Sokolowski
Intermagnetics General Corporation
Latham, NY 12110

14 P.

Y. Zhang and K. Salama
Texas Center for Superconductivity at University of Houston
Houston, TX 77204

SUMMARY

The material requirements, material manufacturing and magnetic properties that are relevant to fabrication of High Temperature Superconductor (HTS) magnetic bearings have been discussed. It is found that the seeded-melt-texturing method can be used to fabricate the single domain material that is required to achieve the best magnetic properties. Trapped-field mapping has been used as a non destructive tool to determine the single-domain nature of the HTS material and quantify the quality of the HTS disks. Both the trapped field and the levitation force of the Y-Ba-Cu-O disks are found to be strongly sensitive to the oxygen content.

INTRODUCTION

Magnetic bearings have been used extensively in applications ranging from turbomolecular pumps, machine tool spindles for grinding and milling, compressors and blowers, pumps for gas pipelines as well as rotating machinery in power generating plants that must operate in hostile environments. Yet, despite the growing acceptance of this new technology, it remains expensive and complex. However, the discovery of new high temperature superconductors in 1986 created an opportunity to dramatically improve the performance of magnetic bearings, increase their reliability and lower overall system operational costs. In a HTS magnetic bearing, the repulsive force between a superconductor and a permanent magnet enables levitation and therefore there are almost no frictional losses (ref. 1). Since these

[†] This work was partially supported by Air Office of Scientific Research Contract F49620-95-C-0023

are non-contact bearings, the need for lubricant disappears and the associated plumbing for delivering lubricant to and from the bearing surface, which adds to size and weight, is eliminated. Further, HTS bearings offer high-speed concomitantly with high stability and thousands of times lesser friction than the best roller bearings.

HTS MATERIAL REQUIREMENT

Figure 1 shows a schematic of a HTS magnetic bearing. The bearing is a passive type where the levitative force of a ring of superconducting disks keeps a magnet suspended in equilibrium. The four properties that affect the performance of magnetically levitated bearings are levitation pressure, stiffness, damping and drag. Levitation pressure, the most important property of these four, is directly dependent on the magnitude of magnetization of the superconducting material. The magnetization is determined by two factors : critical current density and the size of the induced current loop. The high temperature superconducting materials are categorized as type II superconductors where the critical current density is determined by the degree of flux pinning, which can be tailored in the material by the inclusion of fine-scale defects. Due to the anisotropic properties of high temperature superconductors, the critical current

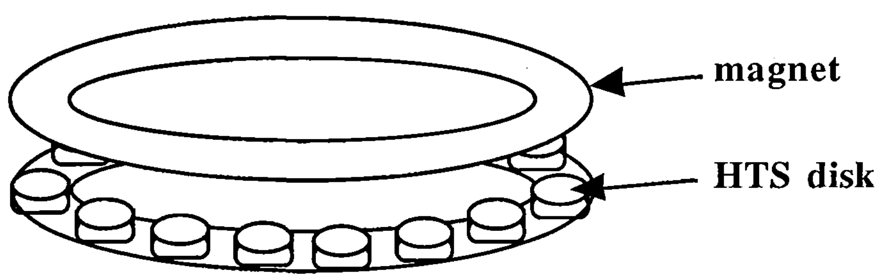

Fig. 1 Schematic of a passive superconductor magnetic bearing. The bearing is comprised of a permanent magnets levitated by a ring of superconductor disks.

density is also determined by the orientation of the strongly superconducting Cu-O planes with respect to the induced current. In order to achieve the maximum current density and hence the highest levitation pressures, it is essential to fabricate a material where the induced current flows only in the Cu-O planes. The second factor that influences the levitation pressure, namely the size of the induced current loop, can be maximized in a material where the current flows within a single grain without having to traverse through grain boundaries. Taking the above factors into account, the preferable geometry of a superconducting material for use in a magnetic bearing is shown schematically in Fig. 2.

The superconductor consists of a single 'grain' where the strongly superconducting Cu-O planes are aligned perpendicular to the direction of an external magnetic field. In this case the current loop induced by the magnetic field flows in the entire sample along the Cu-O planes resulting in a high levitation pressure.

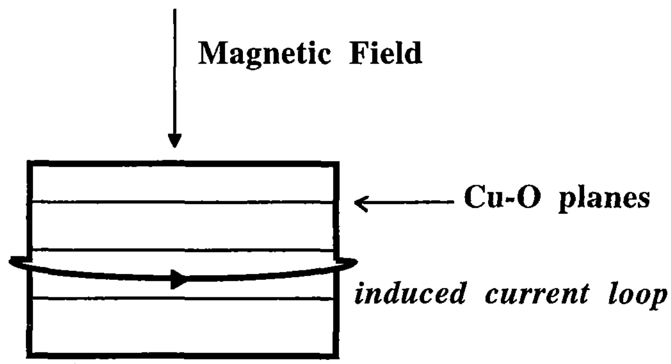

Fig. 2 Schematic of a microstructure that is desired to achieve high levitation pressure in a superconductor.

The microstructure shown in Fig. 2 cannot be achieved in $YBa_2Cu_3O_{7-x}$ by normal ceramic processing methods. Fig. 3 (a) is a schematic of the microstructure of a typical sintered $YBa_2Cu_3O_{7-x}$. As shown in Fig. 3 (a), this material consists of small grains of a few microns in dimension which are oriented randomly. Due to the small grain size and the random grain orientation, the flow of the induced current is restricted to within each individual grain as shown in Fig. 3 (a). As a result of the small size of the induced current loop, the levitation pressure of these sintered materials is low (ref. 2, 3). The sintered material shown in Fig. 3 (a) can be transformed into a material with grain size of about a centimeter by using a melt-texturing process (ref. 4). In this process, the sintered material is partially melted and solidified under controlled cooling conditions to yield a material which is locally textured as shown in Fig. 3 (b). This material would consist of about 10 to 20 grains which compares with thousands of grains in a sintered material. As a result of the large grain size, the size of the induced current loop is increased by several orders of magnitude. Furthermore, a number of fine-scale defects are created during the melt-texturing process which contributes to flux pinning which leads to high current density (ref. 5). Due to a combination of a large induced current loop and a high current density, the levitation pressure of melt-textured materials is much higher than that of sintered materials (ref. 2, 3, 6). Usually, the Cu-O planes of a few grains in a melt-textured material are aligned favorably with respect to the external magnetic field.

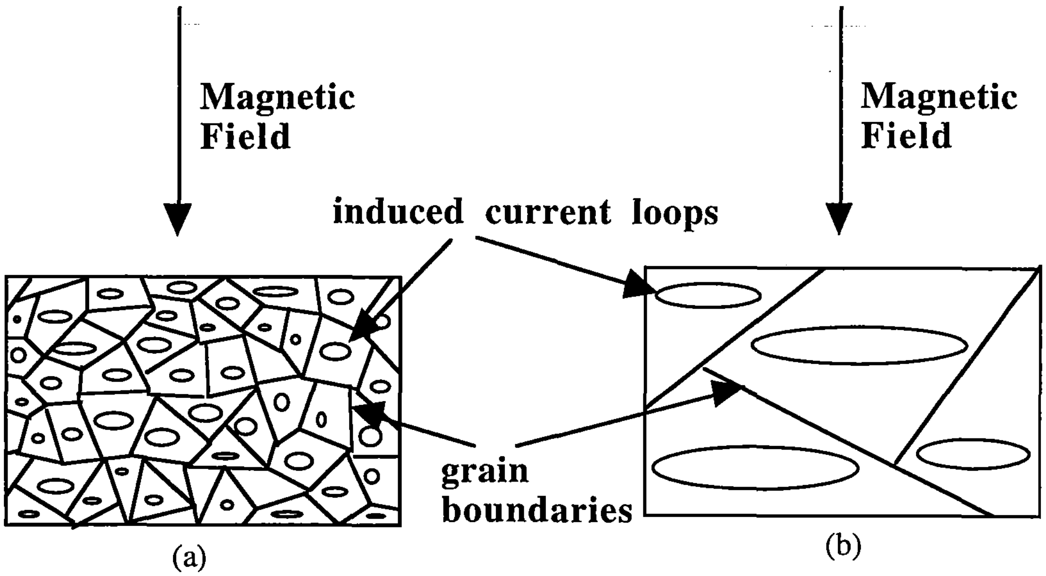

Fig. 3 Schematic of microstructure of (a) sintered superconductor having a number of small grains (grain size of a few microns) and (b) melt-textured superconductor having a few large grains (grain size of about a centimeter). The size of the current loop in the superconductor induced by an external magnetic field is much larger in melt-textured superconductors and therefore the levitation pressure is much higher.

However, in order to maximize the levitation pressure, the grains have to be formed during the melt-texturing process in a controlled way such that their Cu-O planes are aligned perpendicular to the magnetic field, as shown earlier in Fig. 2. For this purpose, an extended version of the melt-texturing process, namely seeded melt-texturing, has been developed. The detail of this process is shown in Fig. 4.

In this process, a sintered material similar to that shown in Fig. 3 (a) is partially melted and solidified under controlled cooling conditions as described before, but with the grain nucleation initiated with a 'seed'. This seed is preferably a material of $YBa_2Cu_3O_{7-x}$ superconductor family such as $SmBa_2Cu_3O_7$ or $NdBa_2Cu_3O_7$ which melts at a higher temperature than $YBa_2Cu_3O_{7-x}$ and does not react with the Y-Ba-Cu-O melt. These seeds are also grown by the melt-texturing process, cut, and shaped so that the Cu-O planes of their grains are oriented parallel to their large faces. As the schematic in Fig. 4 shows, the seed is then placed on top of the sintered material during the melt-texturing process which then acts as a template for textured growth of the $YBa_2Cu_3O_{7-x}$ grains. By this technique, a microstructure similar to that described in Fig. 2 can be achieved.

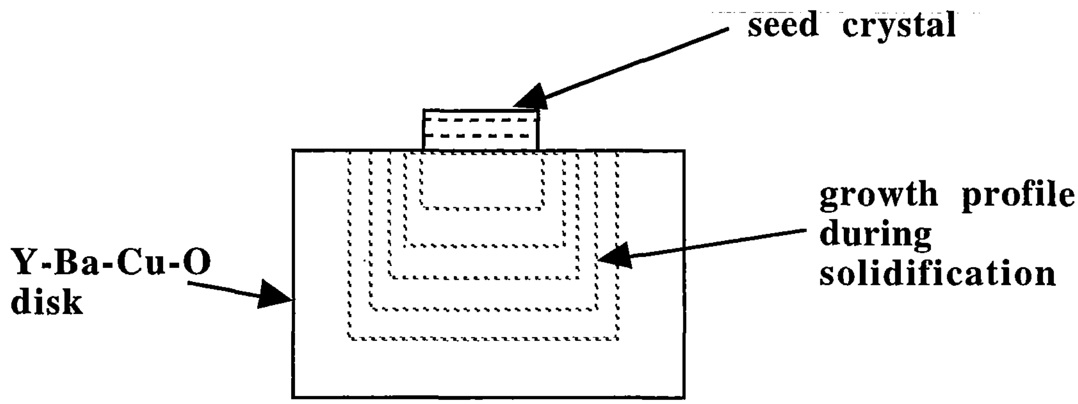

Fig. 4 Schematic showing the microstructure development in a $YBa_2Cu_3O_{7-x}$ disk during seeded melt-textured growth. Nucleation is initiated from the seed crystal of $SmBa_2Cu_3O_7$ which then acts as a template for subsequent growth as shown in the growth profile during solidification. By this technique, a microstructure similar to that shown in Fig. 2, which is required for high levitation pressures, can be achieved.

Since the material manufactured by seeded melt-texturing consists of one large 'grain', the size of the induced current loop is as big as the sample itself. Also, since the Cu-O planes of the grains of this material are all aligned perpendicular to the external magnetic field, the current flows only within these planes. As a result, materials fabricated by seeded melt-texturing exhibit the highest levitation pressures. Even higher levitation pressures can be attained by increasing the current density which can be achieved by controlled doping of the 'raw' material with platinum. Platinum doping has been observed to refine the size of Y_2BaCuO_5 particles which are created during the melt-texturing process (ref. 7). These particles and the defects such as stacking faults and dislocations associated with them have been found to be strong flux pinning centers in the melt-textured material (ref. 8). Refining the size of these particles leads to a higher defect density, hence a high current density which in turn results in high levitation pressures.

HTS MATERIAL FABRICATION

Powders of $YBa_2Cu_3O_{7-x}$ (Seattle Specialty Ceramics (SSC) Inc.) with 20 wt.% Y_2BaCuO_5 (SSC Inc.) and 0.5 wt.% Pt were pressed in the form of disks 1" in diameter. These disks were densified by heat treating them at 950°C for 24 hours in air. Disks of $SmBa_2Cu_3O_7$ (SSC Inc.) with 10 wt.% Sm_2O_3 were also compacted and sintered at 1000°C for 24 hours. The Sm-Ba-Cu-O disks were then melt-textured with a MgO single crystal of <100> orientation similar to the schematic shown in Fig. 4. A sintered Y_2BaCuO_5 disk was used to support the Sm-Ba-Cu-O disk. The Sm-Ba-Cu-O disk was melted at 1135°C for 30 minutes and cooled fast to 1067°C and subsequently cooled at a rate of 0.5°C/h to 987°C. The melt-processed material was analyzed by optical microscopy and was found to contain a single domain extending half-way through the thickness of the sample. This process yielded a single grain of 20 mm in length that could be cleaved from the bulk sample. A single grain of 5 mm × 5 mm was cut and used for seeded-melt-texturing of Y-Ba-Cu-O disks.

The Y-Ba-Cu-O disks were melt-textured with the seed crystal of $SmBa_2Cu_3O_7$ as shown in Fig. 4. As in the case of Sm-Ba-Cu-O, the Y-Ba-Cu-O disk was also supported with a sintered Y_2BaCuO_5 disk during melt-texturing. The Y-Ba-Cu-O disk was melted at 1058°C in air and cooled fast to 1028°C from which it was cooled at a rate of 1°C/h to 930°C. Quench experiments during the slow cooling process revealed that the growth of the single domain of $YBa_2Cu_3O_{7-x}$ was only half-completed at 985°C and not fully completed even at 968°C. The melt-textured Y-Ba-Cu-O disk was analyzed by optical microscopy and then annealed in oxygen at 480°C for 48 hours. The magnetic properties of the disk were investigated following which it was annealed under the same conditions for 160 more hours.

HTS MATERIAL MAGNETIC PROPERTIES

Figure 5 shows the top surface of an as-melt-textured Y-Ba-Cu-O disk. The square impression of the Sm-Ba-Cu-O seed can be seen in the middle of the disk. Also, the growth fronts extending from the four sides of the seed to the periphery of the disk can be observed. This feature is representative of a single domain material which forms from a single grain seed. In order to verify if the material was composed of only one domain, trapped-field measurements were conducted. In the trapped-field measurements, the disk was field-cooled at 77 K in a magnetic field of 1.5 T. The disk was then transferred quickly to a trapped-field measurement rig where the field trapped in the sample was measured over the top surface using a hall probe (ref. 9). The measurements were taken over the entire top surface of the sample so that a complete map of the trapped field could be obtained. Figure 6 shows a 3-dimensional map of the trapped field in a melt-textured Y-Ba-Cu-O disk after an oxygen anneal of 48 hours. A single cusp in the field profile can be observed in Fig. 6 indicating the presence of a single domain. If more than one domain had been present, several cusps would have been obvious in the trapped field profile. The trapped-field measurement is

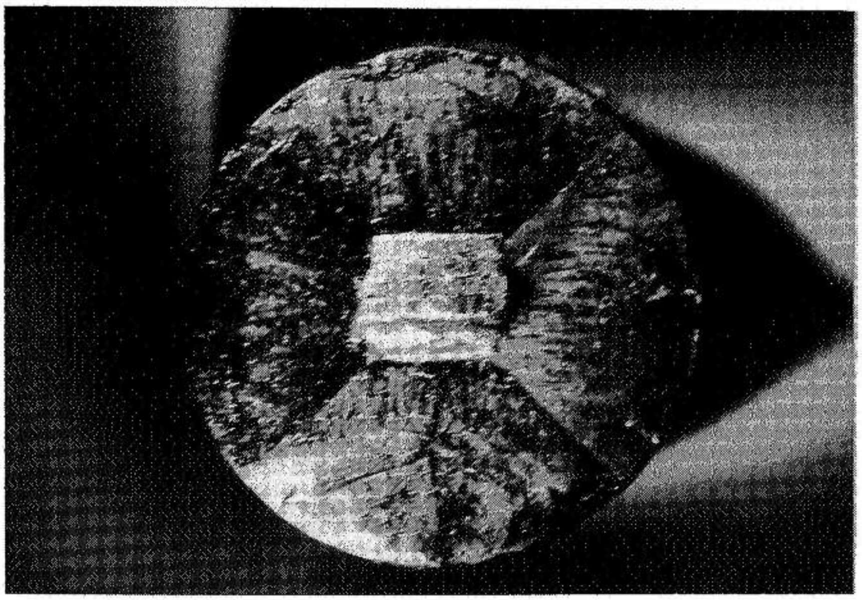

Fig.5 Top surface of a Y-Ba-Cu-O disk fabricated by the seeded-melt-texturing process. The square impression of the seed and the growth fronts emanating from the sides of the seed can be observed.

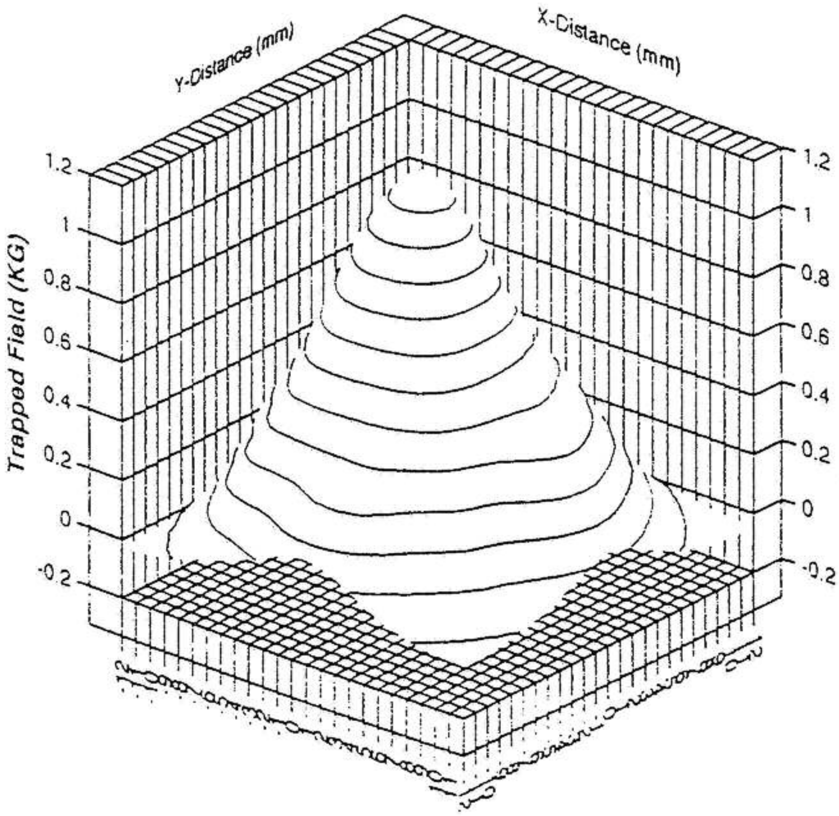

Fig.6 A 3-dimensional trapped field profile of a melt-textured Y-Ba-Cu-O disk after a short oxygen anneal. The presence of a single domain is evident from the single cusp in the trapped field profile.

among the best non-destructive tools available for the characterization of superconducting disks. The trapped-field profile can be used to quantify the quality of the disks and used to make appropriate modifications to the manufacturing process.

Figure 6 reveals that a maximum field of 1 kG was trapped in the disk. Since the seeded-melt-textured Y-Ba-Cu-O disks consist of a single domain, diffusion of oxygen is expected to be very slow in these materials. In order to increase the oxygen content to an optimum value, the disk described in figures 5 and 6 was annealed in oxygen for 160 more hours. Trapped-field measurements were then conducted on the disk as described previously. Figure 7 shows a 2-dimensional trapped-field map of the disk after the extended anneal. The presence of a single domain is obvious in this figure as evident by a single peak contour in the field profile. It can be also seen from the figure that the maximum trapped field in the disk has increased to 2.4 kG. Therefore, it is clear that a long oxygen anneal is required in order to achieve the maximum performance of single domain Y-Ba-Cu-O materials.

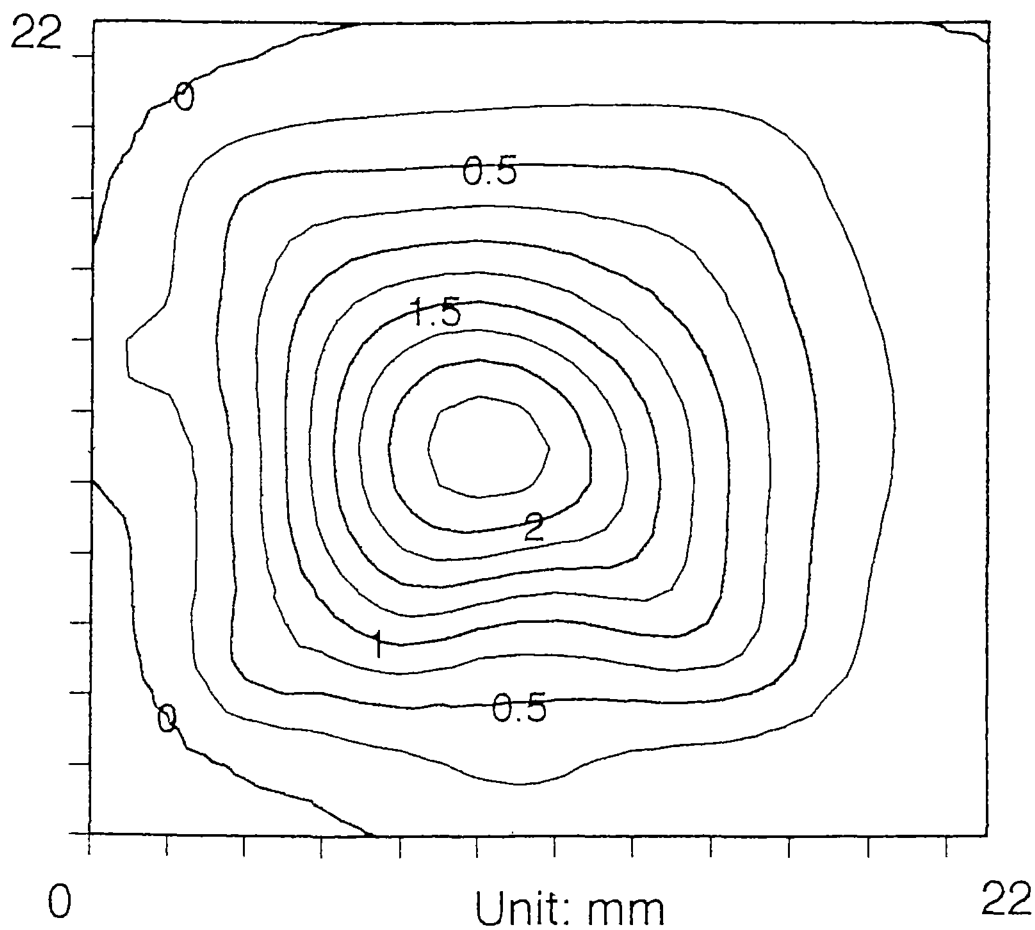

Fig. 7 A 2-dimensional trapped-field profile of a melt-textured Y-Ba-Cu-O disk after an additional oxygen anneal. The maximum trapped field has increased to 2.4 kG.

As mentioned earlier, magnetic levitation force is the most important property that determines the quality of a HTS magnetic bearing. The magnetic levitation force was determined in a test rig where the Y-Ba-Cu-O disk was cooled to 77 K in zero field and a 1" diameter permanent magnet of field strength of approximately 4 kG was moved in steps of 1 mm towards the disk . The levitation force was monitored at every step, as the magnet was moved first towards the disk and then away from the disk. The maximum levitation force was recorded at a distance of 0.5 mm which was the closest distance between the magnet and the disk. Figure 8 shows the levitation force of the melt-textured disk described in fig. 6 (after an oxygen anneal of 48 hours) over a distance of 30 mm.

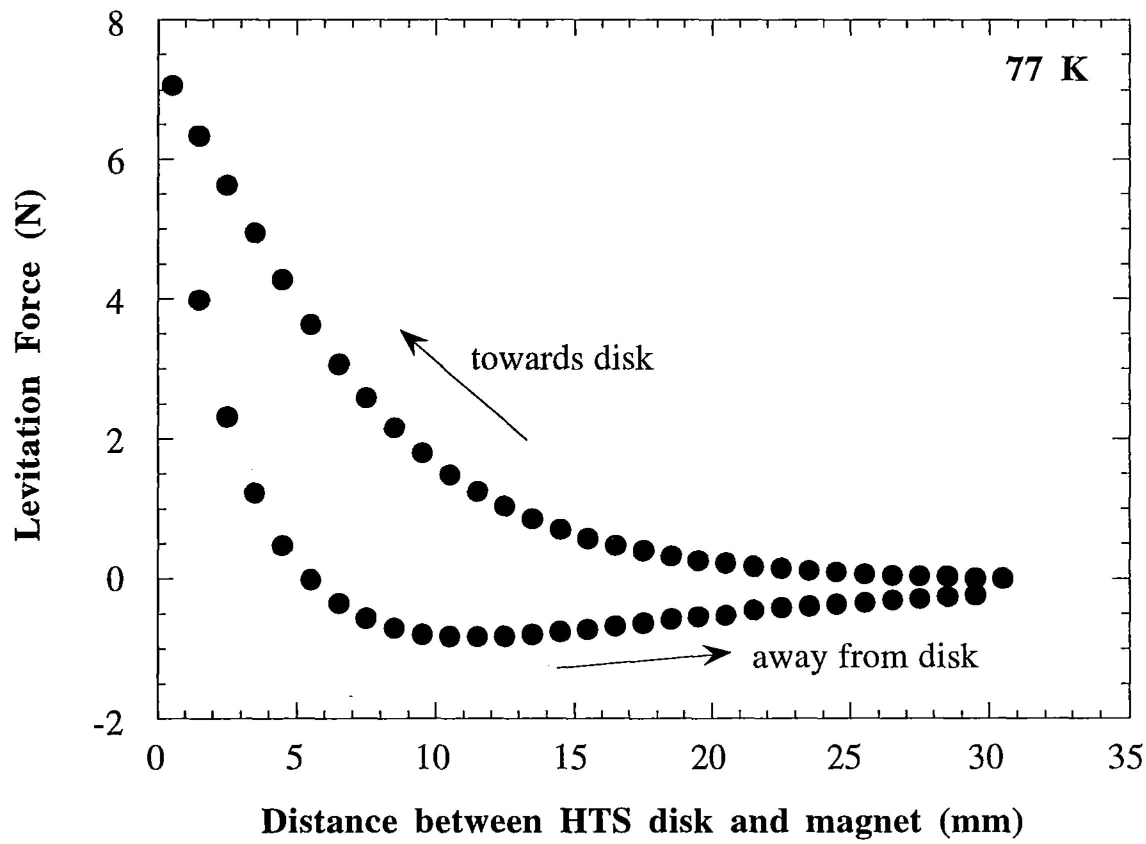

Fig. 8 Levitation force of a melt-textured disk as a permanent magnet is moved towards and then away from the disk. A maximum levitation force of 7 N is observed in the disk that was subjected to a short oxygen anneal.

It can be seen that the levitation force rises sharply as the magnet is brought closer to the disk and peaks at 7 N at a distance of 0.5 mm. A large hysteresis can be observed in the levitation force as the magnet is moved away from the disk. In order to determine if the levitation force increased after an extended oxygen anneal, as did the trapped field, the same disk was characterized after the additional oxygen anneal of 160 hours. The levitation force characteristics of this disk are shown in fig. 9. It can be seen from the figure that the maximum levitation force has increased to about 16 N.

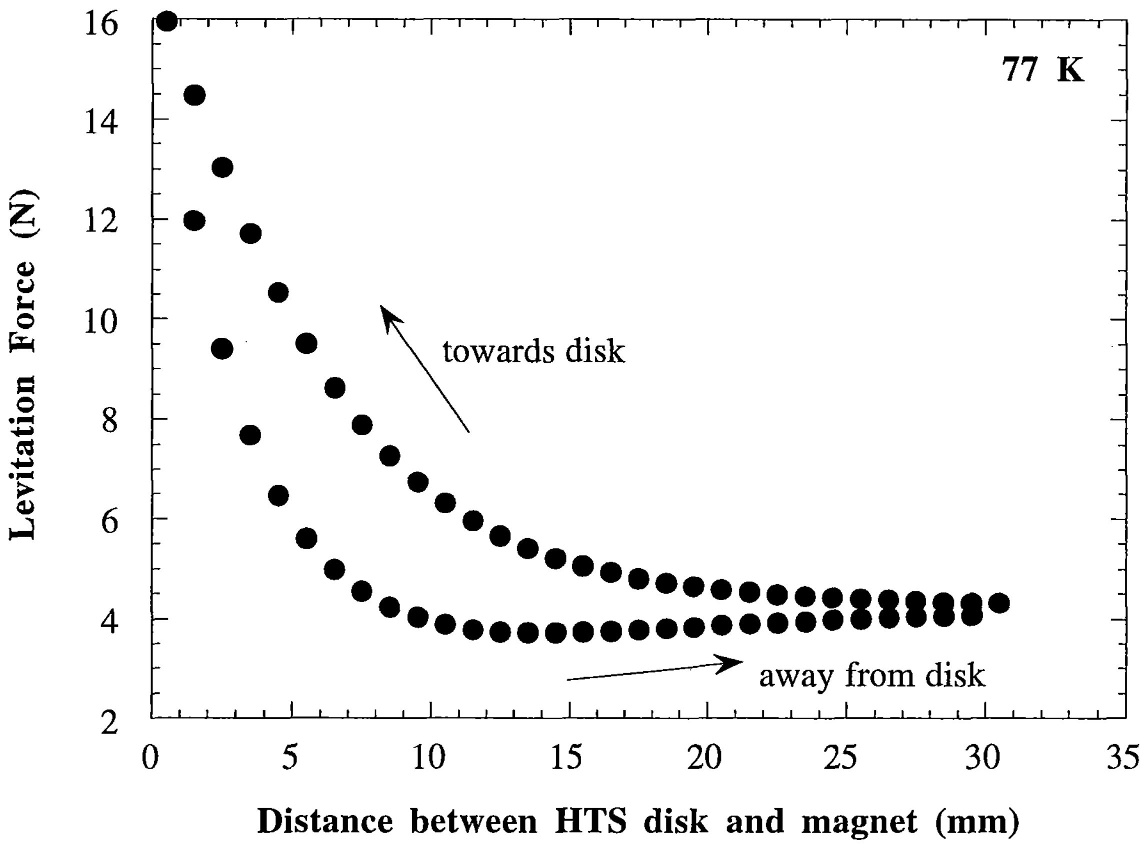

Fig. 9 Levitation force of a melt-textured disk after an additional oxygen anneal. The maximum levitation force can be seen to be improved to 16 N.

The results show that both the trapped field and the levitation force are more than doubled after the additional oxygen anneal. Additonal annealing in oxygen is being performed to determine if the magnetic properties could be further improved.

CONCLUSIONS

The development of Y-Ba-Cu-O superconductors for magnetic bearings has been addressed. It is found that seeded-melt-texturing of $YBa_2Cu_3O_{7-x}$ using a seed crystal of $SmBa_2Cu_3O_7$ can yield single-domain materials needed to achieve high levitation forces. The single-domain nature of the Y-Ba-Cu-O disks has been examined by trapped-field measurements. A levitation force of 16 N and a trapped field of 2.4 kG have been measured in the single-domain Y-Ba-Cu-O disks. Further development of these materials will involve optimizing the oxygen content, introducing defects for flux pinning and reducing microcracks which will all lead to higher levitation forces and trapped fields.

REFERENCES

1. Moon F. C. : Superconducting Levitation. John Wiley & Sons Inc. 1994.
   Chen Q. Y., Xia Z., Ma K. B., McMichael C. K., Lamb M., Cooley R. S., Fowler P. C., and Chu W. K. : Hybrid High T_c Superconducting Magnetic Bearings for Flywheel Energy Storage Systems. *Appl. Supercond.,* vol. 2, 1994, pp. 457 - 464.
2. Murakami M. : Melt Process, Flux Pinning, and Levitation. *Processing and Properties of High T_c Superconductors,* vol.1 ed. S. Jin, World Scientific, Singapore, 1993, pp. 213-270
3. Lehndorff B., Kürschner H-G., and Piel H. : Mapping of magnetic force and field distribution of melt-textured Y-Ba-Cu-O. *IEEE Trans. Appl. Supercond.,* vol. 5, no.2, June 1995, pp. 1814-1817.
4. Salama K., Selvamanickam V., Gao L., and Sun K. : High current density in bulk $YBa_2Cu_3O_x$ Superconductor. *Appl. Phys. Lett.,* vol. 54, no. 23, June 1989, pp. 2352-2354.
5. Murakami M., Morita M., Doi K., and Miyamoto K. : A new process with the promise of high J_c in oxide superconductors. *Jpn. J. Appl. Phys.,* vol. 28, no. 7, July 1989, pp. 1189-1194
6. Murakami M., Oyama T., Fujimoto H., Taguchi T., Gotoh S., Shiohara Y., Koshizuka N., and Tanaka S. : Large levitation force due to flux pinning in YBaCuO superconductors fabrication by melt-powder-melt-growth process. *Jpn. J. Appl. Phys.,* vol. 29, no.11, November 1990, pp. 1991-1994.
7. Ogawa N., Yoshida M., Hirabayashi I., and Tanaka S., : Preparation of YBCO bulk superconductor by Platinum doped melt growth method. *Supercond. Sci. and Technol.,* vol. 5, 1992, p. S89.
8. Mironova M., Lee D. F., Selvamanickam V., and Salama K., : Structure and Defects at Y_2BaCuO_5-$YBa_2Cu_3O_x$ interface in melt-textured YBCO superconductors. *Interface Science* , vol. 1, 1994, p.381.
9. Weinstein R., In-Gann Chen, Liu J., Parks D., Selvamanickam V., and Salama K., : Persistent magnetic fields trapped in high T_c superconductor. *Appl. Phys. Lett.*, vol. 56, no. 15, April 1990, pp.1475-1477.