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Influence of multiple holes on the magnetic properties of YBCO superconductor

W. S. Oh[1], S. K. Oh[1], G. E. Jang[1,*], C. J. Kim[2], Y. H. Han[3], S. Y. Jung[3], T. H. Sung[3]

[1]Department of Advanced Materials Engineering, Chungbuk National University, Cheongju, Korea
[2]Korea Atomic Energy Research Institute Superconductor Laboratory, Daejeon, Korea
[3]Korea Electric Power Research Institute, Daejeon, Korea

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***Abstract*-- Bulk $YBa_2Cu_3O_{7-\delta}$(YBCO) superconductor was manufactured with the top-seeded melt grown method. The 9, 16, and 25 holes, as small as 0.7 mm in diameter, parallel to the c-axis were mechanically drilled. Magnetic flux mapping and levitation force were measured and compared to estimate the influence of multiple holes on the magnetic properties of YBCO superconductor at 77 K. According to the measurements, the maximum magnetic flux density obtained from the plain sample was 2.48 kG, while the maximum magnetic flux density of the sample with 25 holes was low as around 2.29 kG. The levitation force measured on the sample with 9 holes increased from 91 N to 105 N. The levitation force measured on the samples with 9 holes is relatively higher than the plain sample without any holes. In this case, increase of the levitation force in the perforated samples could be explained by enhancement of the cooling efficiency more effectively. We investigated that the magnetic properties of YBCO superconductor were strongly influenced by the artificial holes.**

1. INTRODUCTION

Single grain $YBa_2Cu_3O_{7-\delta}$ (YBCO) bulk is an attractive material as a bearing part of superconducting flywheel energy storage system (SFES) due to the high levitation force and the trapped magnetic field properties. To obtain good performance in applications, the YBCO superconductors have to be mechanically resistant to withstand large thermal stresses during cooling/heating cycles and magnetization [1-3]. However, bulk YBCO is brittle materials containing internal defects such as gas holes and cracks. It has been reported that such flaws have caused bulk superconductors to fail owing to the electromagnetic force induced when a magnetic field was trapped, and so a number of researches have been carried out to improve the mechanical properties of melt textured YBCO [3-6]. Tomita *et al.* reported that resin impregnation has been found to be one of effective ways in improving the mechanical properties of bulk superconductor. Resin permeated into bulk YBCO along the micro-cracks having openings on the surface [5].

* Corresponding author: gejang@chungbuk.ac.kr

Recently, it has been proposed to drill array of columnar holes inside high temperature superconducting magnets in order to improve their thermal properties. The larger exchange surface increases the heat transfer with the environment and is thus beneficial for the cooling of the superconductor [7]. Oxygenation was easily carried out on the superconductor monolith by drilling a hole in order to suppress the crack formation during oxygenation process. The magnetic trapped value of perforated pallet is 32% higher than the plain one [8]. Also our previous report indicates that reinforcement and artificial hole has significant influence on magnetic and mechanical properties [9]. However, so far not many works have been undertaken to study the effect of the number of holes on the magnetic properties of YBCO.

In this paper, the YBCO bulk containing the number of 9, 16 and 25 holes with 0.7 mm, which was mechanically drilled on parallel to the c-axis was investigated. The trapped flux distribution and the levitation force of YBCO with 9, 16, and 25 holes have been systematically investigated and compared before and after holes formation respectively.

2. EXPERIMENTS

Single-grain YBCO bulk sample with a c-orientation was fabricated by top-seeded melt process through a synthesis process detailed elsewhere [10]. In order to elucidate the effect of the number of defects on the trap field distribution at 77 K, 2 each different samples were selected and cut into the dimension of $40 \times 40 \times 3.1$ mm^3 from the melt-textured pellets parallel to the (100) and (001) planes. And then the 9, 16, and 25 artificial holes with 0.7 mm diameter were made by mechanical drilling on the surface along c-axis. The distance between holes was adjusted to same depending on holes arrangement. The Hall scans of the trapped flux distribution were made using Hall probe Lake shore model (HGCT 3020) with an active area of 0.2 mm^2 and the sweep rate was 0.2 mm/s. The scans were performed via an x-y positioning system and the active area of the Hall sensor was located 0.1 mm from the samples. To measure the trapped magnetic field distribution, samples were cooled down to liquid nitrogen (LN_2) temperature with a permanent magnet of a surface field of 3300 G and a dimension of $40 \times 25 \times 10$ mm^3. Magnetic levitation forces at 77 K were estimated from force-distance hysteresis curves of melt-textured YBCO samples under the field cooling condition using Nd-B-Fe permanent magnet with a surface field of 5500 G and a diameter of 30 mm.

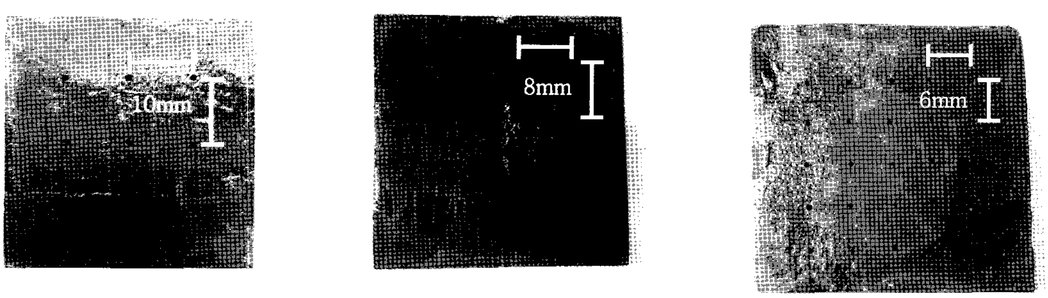
3. RESULTS AND DISCUSSION

The top surfaces of the YBCO samples with 9, 16, and 25 holes as small as 0.7 mm in diameter are shown in Fig. 1. Fig. 2 represents the 2 and 3 dimensional surface magnetic field distributions taken on the plain and drilled samples after being field-cooled in 3300 G at 77 K. Generally most of field profile and contour of the plain sample without any holes show more likely rounded than ones with any artificial holes. The 2 and 3D representation of field mapping indicates the single corn pattern corresponding to a signature of a single domain. The additional corn shape was observed at the right edge on trapped field profile in the plain sample (Fig. 2(e)) and this is presumably related with other single grain formed at the stage of the crystal growth.

However the flux contour of plain sample became heavily deformed with increasing the number of holes on the surface of YBCO. The maximum trapped fields of YBCO without hole in Fig. 2(a) ~ (d), were 1.98 ~ 2.31 kG in the completely penetrated state. As compared with the samples with 9 and 16 holes (Fig. 2(a)-(d)), the maximum trapped fields obtained from the plain samples were higher only by a few percent and reveal not much significant variation between them, despite the fact that the bulk volume decreases macroscopically by the presence of many holes. The maximum remnant trapped fields in the samples with 9 and 16 holes were around 2.21 ~ 2.2 and 1.95 ~ 2.2 kG respectively. In the present case, it seems that the cooling efficiency is well enhanced by increasing surface area through mechanical drilling. Generally drilled samples would always have lower performances than plain samples, mainly due to a reduction in effective area of super-current path.

However, it can be found that the maximum trapped field shows the tendency of decrease with increasing the number of holes. As seen in Fig. 2, the holes themselves cannot be distinguished clearly in remnant flux profiles, but some indentations can be noticed. The shape of the induction profile is also different and the multiple peaks are visible. Obviously the volume of contour decreased systematically with increasing the number of holes. Moreover mechanical drilling possibly induces the micro-cracks and other defects near the holes. This implies that the trapped field capacity shows a tendency to decrease after holes and defects generation. The trapped field, being generated by superconducting currents flowing in the sample, combines local values of the critical current J_c with the current loops size. The size of the current loops depends on the quality of the crystal growth and on the absence of cracks and defects while the J_c depends on the local pinning properties of the material. The current did not seem to flow in the whole sample. These cracks and defects directly impede the current flowing and may explain the lower trapped field.

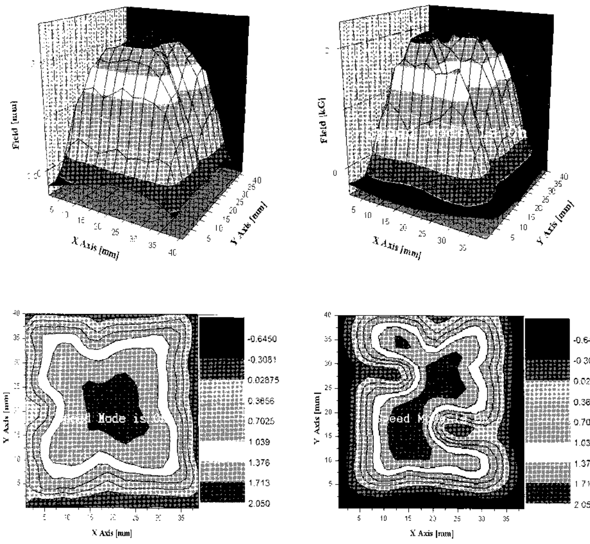
Fig. 3 demonstrates the force-distance curves in terms of a number of holes in YBCO samples measured at 77 K and 5500 G. As seen in Fig. 3, the levitation repulsive forces are somewhat dependent on the samples with a number of holes. The levitation force measured on the samples with 9 holes at Fig. 3(a) ~ (b) is relatively higher than the plain sample without any holes. The maximum repulsive force(the distance from sample to magnet : 0 mm) on the samples with 9 holes increased from 89 and 91 N to 98 and 105 N respectively. In this case, increase of the levitation force in the perforated samples could be explained by enhancement of the cooling efficiency more effectively. Because the sample with holes offers the large and favorable surface exchange into the liquid nitrogen bath [8]. But the levitation force on the samples with 16 holes decreased from 87 and 89 N to 80 and 80 N respectively.



(a) (b) (c)

Fig. 1. The photographs of YBCO sample in terms of a number of holes; (a) with 9 holes, (b) with 16 holes and (c) with 25 holes.

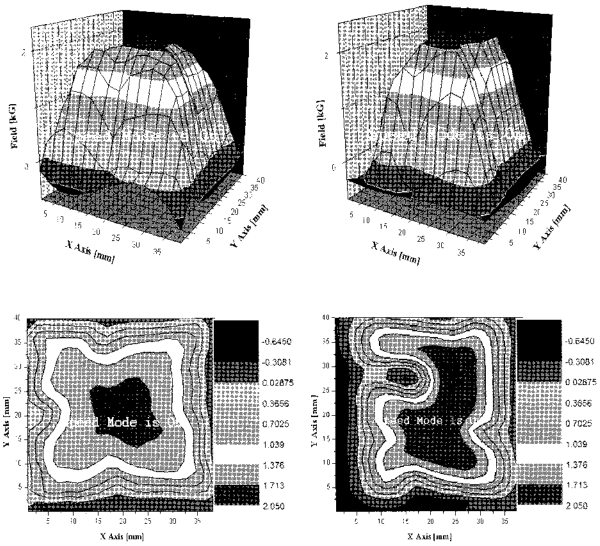
plain sample | sample with 9 holes



max. flux density: 2.2 kG | max. flux density: 2.22 kG

(a)

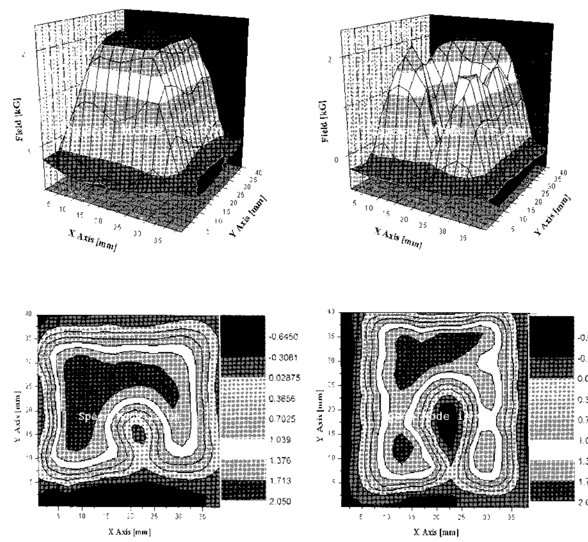
plain sample | sample with 9 holes



max. flux density: 2.1 kG | max. flux density: 2.21 kG

(b)

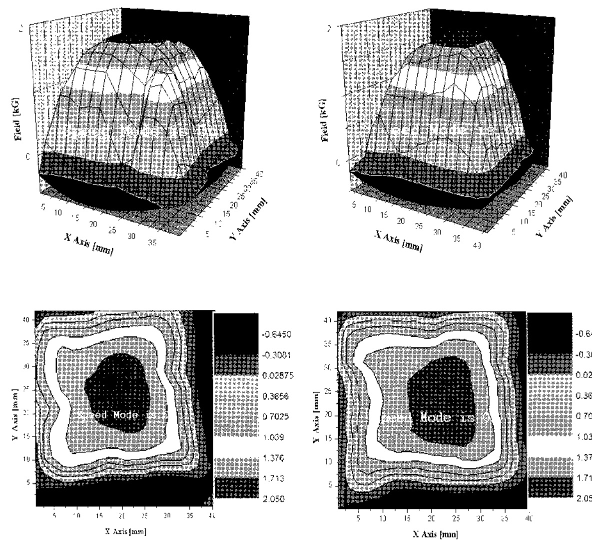
plain sample | sample with 16 holes



max. flux density: 2.31 kG | max. flux density: 2.2 kG

(c)

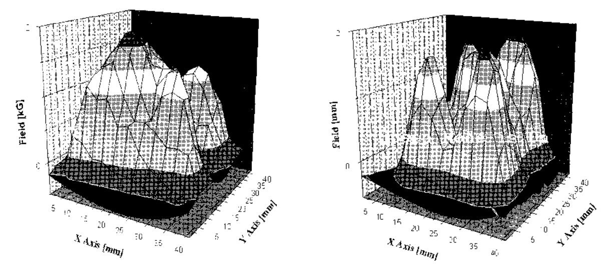
plain sample | sample with 16 holes



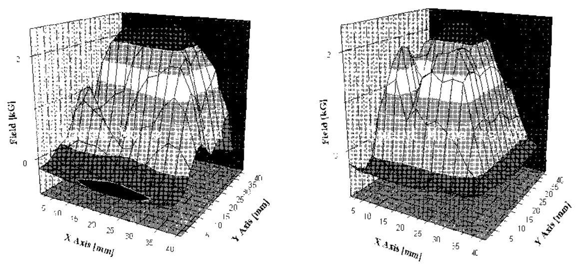
max. flux density: 1.98 kG | max. flux density: 1.95 kG

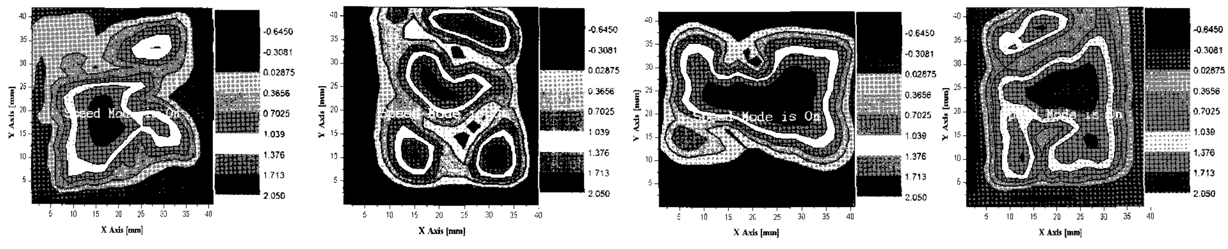
(d)

plain sample | sample with 25 holes



plain sample | sample with 25 holes

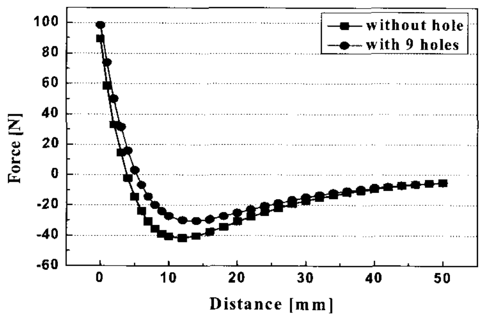




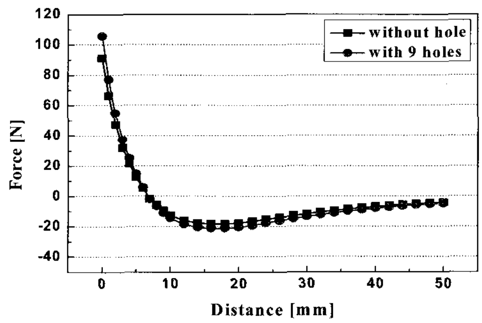
max. flux density: 1.92 kG max. flux density: 1.90 kG max. flux density: 2.48 kG max. flux density: 2.29 kG

(e) (f)

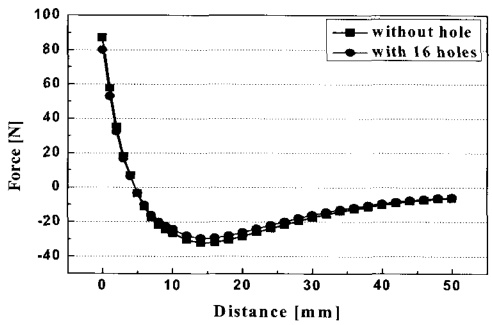
Fig. 2. The 2 and 3 dimensional surface magnetic field distributions taken on the plain and drilled samples after being field-cooled in 3300 G at 77 K; (a) the plain and sample with 9 holes (volume: 40 x 40 x 3.1 mm^3), (b) the plain and sample with 9 holes (volume: $40 \times 40 \times 3.1$ mm^3), (c) the plain and sample with 16 holes (volume: $40 \times 40 \times 3.1$ mm^3), (d) the plain and sample with 16 holes (volume: $40 \times 40 \times 3.1$ mm^3), (e) the plain and sample with 25 holes (volume: $40 \times 40 \times 3.1$ mm^3) and (f) the plain and sample with 25 holes (volume: $40 \times 40 \times 3.1$ mm^3).



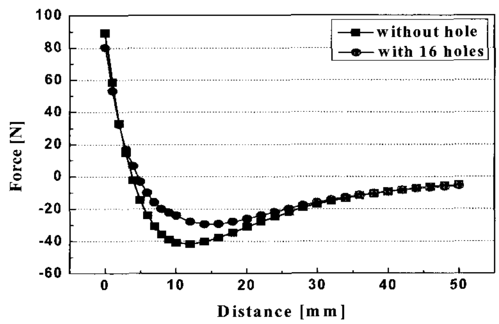
(a)



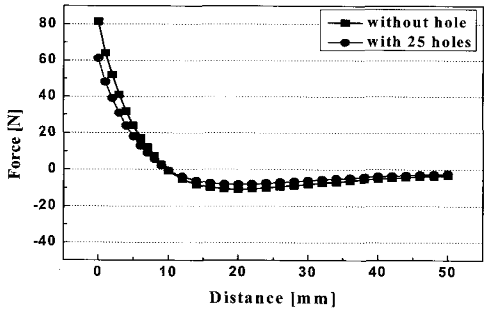
(b)



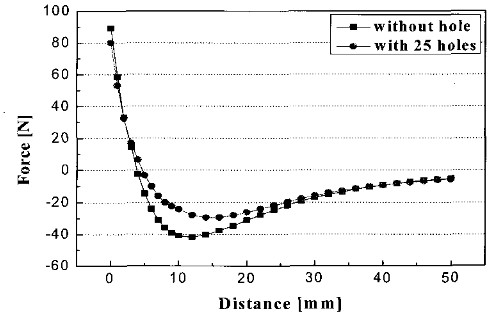
(c)



(d)



(e)



(f)

Fig. 3. The force-distance curves in terms of a number of holes in YBCO samples measured at 77 K and 5500 G; (a) sample 1, (b) sample 2, (c) sample 3, (d) sample 4, (e) sample 5 and (f) sample.

TABLE I
THE SUMMARIZED RESULTS OF MAGNETIC FIELD DISTRIBUTIONS AND THE MAXIMUM LEVITATION FORCE IN TERMS OF A NUMBER OF HOLES.

sample No.	maximum flux density (kG)		maximum levitation force (N)	
	before drilling	after drilling	before drilling	after drilling
1 (9 holes)	2.2	2.22	89	98
2 (9 holes)	2.1	2.21	91	105
3 (16 holes)	2.31	2.2	87	80
4 (16 holes)	1.98	1.95	89	80
5 (25 holes)	1.92	1.90	81	63
6 (25 holes)	2.48	2.29	96	80

The relative decrease of levitation repulsive force in the samples with 16 and 25 holes (Fig. 3(c)-(f)) is presumably related to the relative reduction of superconducting volume and additional defects and cracks generated during the drilling process even holes offers the favorable channel for heat conduction. As pointed out, possible mechanical damages were found earlier in some of the heavily deflected and distorted contour lines in the distribution of remnant flux mapping, especially in sample with 25 holes. Table 1 is the summarized results of magnetic field distributions and the maximum levitation force.

According to these results, no clear trend can be established between the number of hole and the magnetic properties of the YBCO. But the samples with 9 holes show the maximum trapped field values and levitation forces are somewhat higher than plain one. From the observation of the profile in field trapping capacity and levitation force it seems that 9 holes in our preliminary result did not strongly affect the superconducting properties at the large scale as compared with the plain one.

4. CONCLUSION

The 2 and 3 dimensional surface magnetic field distributions and the maximum levitation force were measured at 77 K on the samples before and after mechanical drilling with 9, 16, and 25 holes as small as 0.7 mm in diameter. From the observation of the profile, the samples without hole were conical, indicating that there is less weak link in this sample. However with 16 and 25 holes, the deviation from the Bean cone increased and lowered the maximum magnetic flux density. Also in measurement of the maximum levitation force, the repulsive force decreased with increasing the number of hole. Our preliminary results indicate that the trapped field profile and levitation force in melt-textured YBCO superconductor are strongly influenced by the number of artificial hole.

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REFERENCES

[1] N. Sakai, S. J. Seo, K. Inoue, T. Miyamoto, M. Murakami, "Mechanical properties of RE-Ba-Cu-O bulk superconductors", *Physica C* 335, pp.107, 2000.

[2] D. Isfort, X. Chaud, R. Tournier, G. Kapelski, "Cracking and oxygenation of YBaCuO bulk superconductors: application to c-axis element for current limitation", *Physica C* 390, pp.341, 2003.

[3] M. Tomita, M. Murakami, "High-temperature superconductor bulk magnets that can trap magnetic fields of over 17 tesla at 29K", Nature 421, pp.517, 2003.

[4] M. Tomita , M. Murakami , K. Katagiri, "Reliability of mechanical properties for bulk superconductors with resin impregnation" *Physica C* 378-381, pp.783, 2002.

[5] M. Tomita, M. Murakami, "Effect of resin impregnation on the prevention of crack propagation for bulk Y-Ba-Cu-O superconductors" *Physica C* 392-396, pp.562, 2003.

[6] M. Murakami, M. Morita, K. Doi and K. Miyamoto, "A New Process with the Promise of High J_c in Oxide Superconductors" *Jpn. J. Appl. Phys.* 28, pp.1189, 1989.

[7] Ph. Laurent, J-P. Mathieu, B. Mattivi, J-F. Fagnard, S. Meslin, J. G. Noudem, M. Ausloos, R. Cloots, Ph. Vanderbemden, "Study by Hall probe mapping of the trapped flux modification produced by local heating in YBCO HTS bulks for different surface/volume ratios" *Supercond. Sci. Technol.* 18, pp.1047, 2005.

[8] J. G. Noudem, S. Meslin, D. Horvath, C. Harnois, D. Chateigner, S. Eve, M. Gomina , X. Chaud, M. Murakami, "Fabrication of textured YBCO bulk with artificial holes" *Physica C* 463, pp.301, 2007.

[9] G. E. Jang, W. S. Oh, Y.H. Han, S.Y. Jung, T.H. Sung, "The effect of impregnation by resin and CNT compound on the mechanical and magnetic properties of YBCO superconductor", *Physica C* 468, pp.1444, 2008.

[10] C. J. Kim, Y. A. Jee, G. W. Hong, T. H. Sung, Y. H. Han, S. C. Han, S. J. Kim, W. Bieger, G. Fuchs, "Effects of the seed dimension on the top surface growth mode and the magnetic properties of top-seeded melt growth processed YBCO superconductors", *Physica C* 331, pp.274, 2000.