Qualification of the Machining and Fitting Precision of YBCO Bulks and Rings Joined Together via the Examination of the Trapped Flux

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***Abstract*—The quality of the drilled YBCO bulks and rings and the precision of the fitting of the YBCO rings joined together can be deduced with the elaborated method. In the case of concerted magnetization of tightly fitted rings and bulk the measured maximum flux density is approximately the same as it was prior to machining unless the material got damaged during machining. It is also a convenient method to test the material before the application of bulks and rings.**

***Index Terms*—Superconductors, magnetization processes, machining**

I. INTRODUCTION

THERE is a growing demand for machining ceramic based superconducting materials. The brittleness and hardness of the material and the need to eliminate the dust make its cutting and drilling rather complicated. Earlier we developed a new technology at the Budapest University of Technology and Economics, Hungary [1], so we are able to drill the YBCO bulk fast and this technology is of low cost. The two machining methods are as follows:

- Glass drilling method with minimal water lubricant
- Glass drilling method with liquid nitrogen: an environmentally friendly technology.

A year later we designed an economical magnetizer for the rapid pretesting of the cracks of YBCO bulks before application, and for testing cracks of YBCO bulks after their economic machining. By using this magnetizer, the quality of these machining methods can be checked via this economical magnetization. With this magnetizer, we can produce 2 T of flux density, without refrigeration of exciter coil at 2650 W in the centre of an 18.4 mm air gap [2]. This solution is of low maintenance, because there is no need for a secondary cooling system.

In Fig. 1 we can see different holes in the YBCO bulk of 8 mm height. Machining only lasted some minutes.

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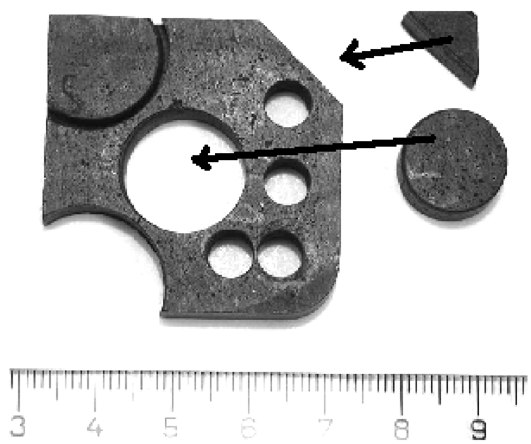

Fig. 1. Short time machining of YBCO bulk.

In Fig. 2 we can see one bulk and two rings drilled from the same bulk.

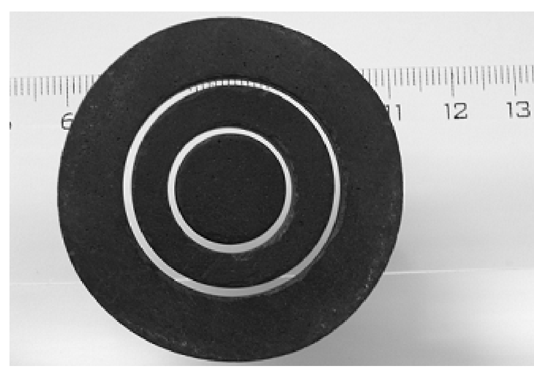

Fig. 2. The result of the economical machining.

The results of the material test after machining were the following:

- This material has not cracked.
- There is no dust.
- The phase composition of the material remains unchanged.

The composition was analyzed with electron-microscope and X-ray at Pannon University, Hungary.

The machining of the bulk in Fig. 3 was carried out in liquid nitrogen at 77 K. The sample was of 15 mm height. During machining neither the tool nor the material cracked.

Moreover, the dry superconductor dust is available within 10 minutes after machining. This is why we call it an environmentally friendly method. The experiment could be applied even in space research.

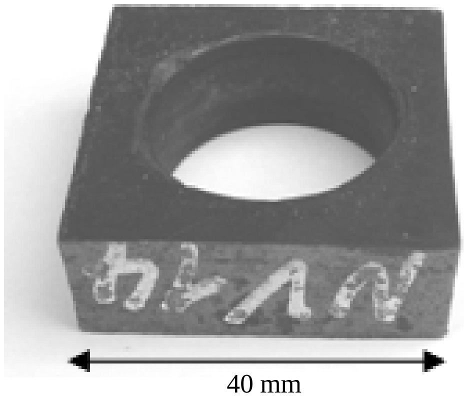

Fig. 3. Drilling in liquid nitrogen.

In Fig. 4 we can see the trapped flux of our YBCO bulk drilled in liquid nitrogen. The trapped flux was measured in IPHT Research Institute in Jena, Germany. It was magnetized in 1 T of flux density with FC method. The magnetization graph shows that there are no cracks in the material.

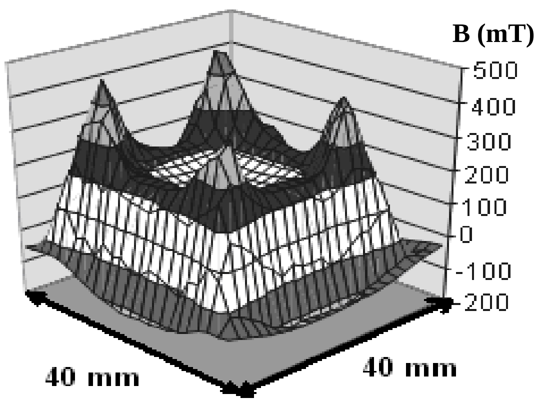

Fig. 4. Trapped flux (B_{max} = 0.4 T).

II. PRODUCING JOINT RINGS

Possessing the results described above we produced a joint system of rings, which contained an YBCO bulk, and two YBCO rings. Superconductor bulks were produced at IPHT in Jena, Germany. The goal of the experiment is to increase the size of YBCO bulks by adding concentric rings and to increase the trapped flux density. We have built a system for the experiment that contains a cylinder shaped bulk fitted into the ring with minimal air gap without welding. In the center of this system consisting of two pieces, the measured flux density has almost the same value as in a single bulk with the same the size as in our system. In the case when we need a system of bigger size and higher flux density we could use a ring welded from segments because the size of the single YBCO bulks are restricted. The advantage of the system is that the joint rings need not to be welded. Our plan for the future is to increase the value of trapped flux by surrounding a bulk with a superconductor ring composed of welded segments. The schema of this procedure can be seen in Fig. 5.

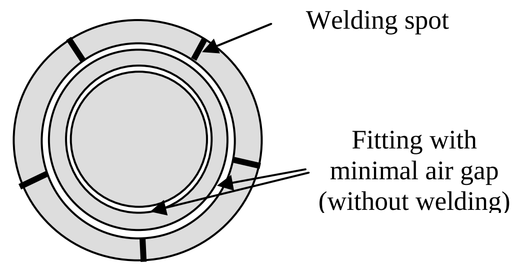

Fig. 5. Schema of the procedure.

There have already been attempts to work out the reproducible welding of YBCO superconductors but without reliable results. The technology for welding is not a new topic [3]–[5], but it remains irreproducible. At present, the reproducible welding of YBCO superconductor bulks is still a worldwide problem to be solved.

The advantage of the experiment is that with this method we can produce large bulks from tightly fitted rings for magnetization. We only need to weld rings from ring segments. These rings could be used for larger bulks to trap flux. We should cut the ring segments from the good superconducting parts of the YBCO bulk. With joining rings and bulks, we can check the quality of machining as well.

III. MAGNETIZATION RESULTS WITH FC METHOD

Applying the two systems with rings we have created a tighter unit (Fig. 6) The sizes of the rings and of the bulks are shown in Tables I and II.

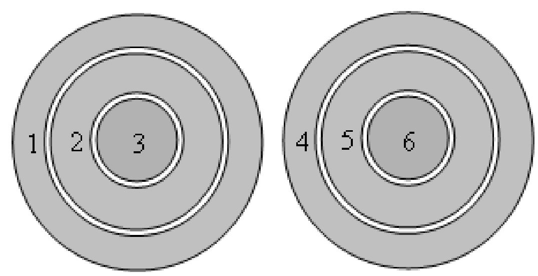

Fig. 6. The first and second ring system.

TABLE I DATA OF THE FIRST RING SYSTEM

Ring 1	**Ring 2**	**Bulk 3**
D_1 = 52 mm	D_2 = 32 mm	D_3 = 15 mm
d_1 = 35 mm	d_2 = 17.15 mm	-----------
h_1 = 8 mm	h_2 = 8 mm	h_3 = 8 mm

TABLE II DATA OF THE SECOND RING SYSTEM

Ring 4	**Ring 5**	**Bulk 6**
D_4 = 52.3 mm	D_5 = 30.5 mm	D_6 = 17 mm
d_4 = 33.3 mm	d_5 = 19.3 mm	----------
h_4 = 8 mm	h_5 = 8 mm	h_6 = 8 mm

After fitting ring No.2 and bulk No.6 we have magnetized them together with FC method.

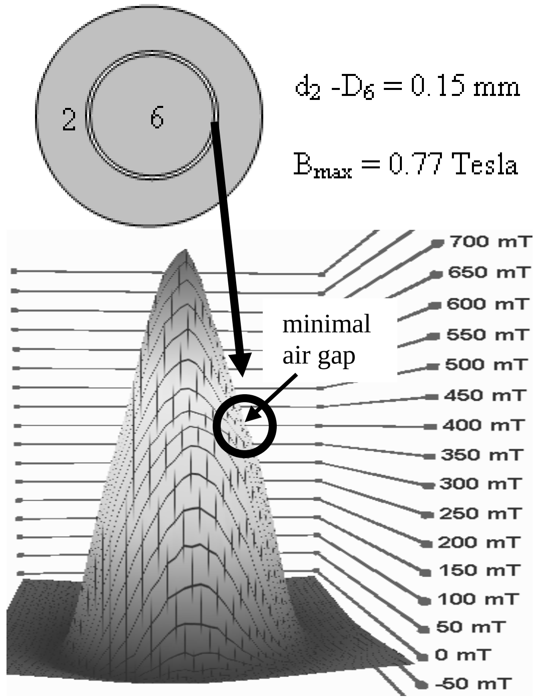

Fig.7. Magnetization with minimal gap.

We can see the joint magnetization in Fig. 7. In the next experiment we fitted bulk No.6 into ring No.5 (Fig. 8). The air gap was larger than in the previous case, 1.15 mm.

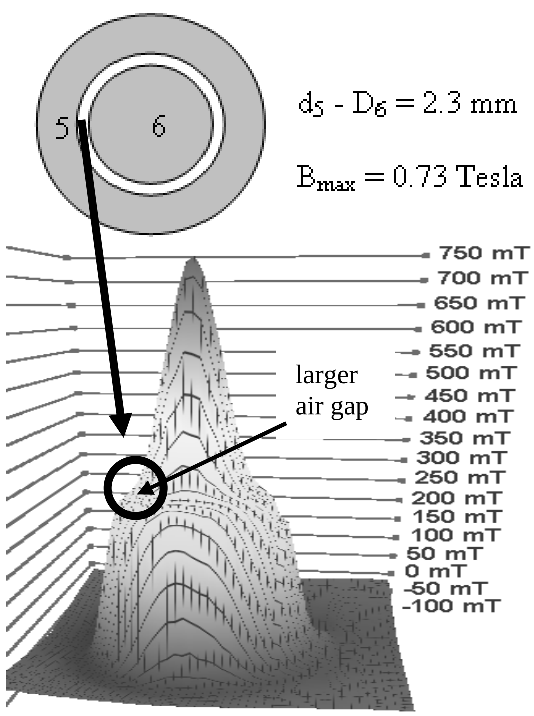

Fig. 8. Magnetization with larger gap.

Fig. 9 shows the joint magnetization of rings No.4 and No.5 and bulk No.6, with B_{max} = 0.815 T. In the four corners of the figure, the flux deriving from a granular current can be well distinguished. As we can see from the results of joint magnetization, the concentric air gap decreases the trapped flux as it hinders the evolvement of granular current.

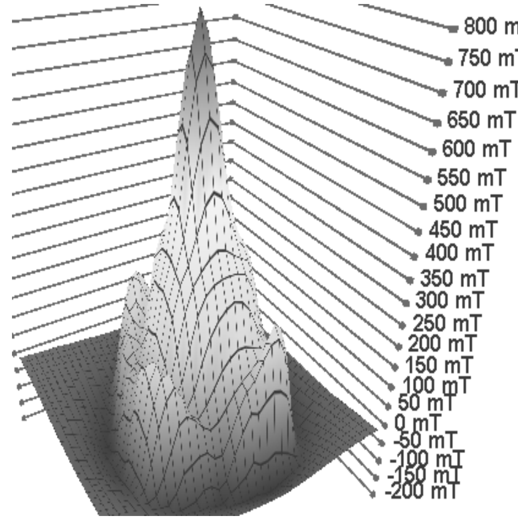

Fig. 9. Magnetization of two rings and one bulk with larger gap.

IV. Theoretical evaluation

When we accomplish the tight fitting of bulks and rings into a system, we have to use two separate pieces of YBCO bulks for drilling because of material loss during machining. This means that the two pieces do not have the same material properties. Therefore, when we analyze the trapped flux density, we get different values for dB/dr at the neighborhood of the fitting. For the magnetization of our system containing the bulk and the ring, the following equation is true:

$$\frac{dB_{bulk}}{dr} \neq \frac{dB_{ring}}{dr}$$

The cross-section of the measured flux density on the surface shows only one breakpoint in the case of faultless machining and tight fitting of the system. This can be seen in Fig. 10.

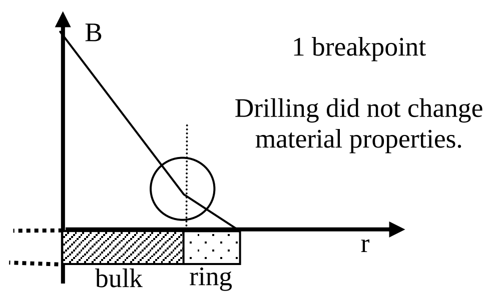

Fig. 10. Material properties after machining without changes – in principle.

If the cross-section of the measured flux density on the surface shows, not only one breakpoint, then machining was bad or changes occurred in the properties of the materials in the case of tight fitting. This is shown in Fig. 11.

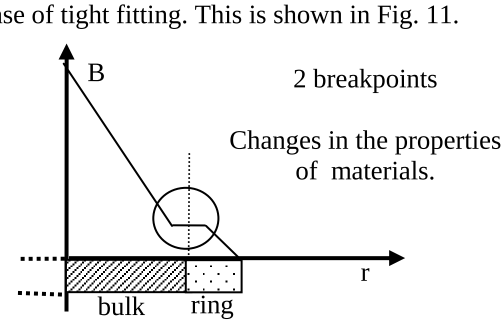

Fig. 11. Material properties after machining with changes – in principle.

V. Magnetization Results with ZFC Method

We made series of experiments to test the quality of machining. We have magnetized with ZFC method after producing the joint bulk and ring. Changes in material properties can also be demonstrated with ZFC method. The series of experiments also show gradually the process of magnetization, when we first magnetize the inner bulk before magnetizing the whole system. First, we magnetized the bulk with ZFC method in 1.5 T magnetic field. Then we fitted the ring on the magnetized bulk but the ring was not in superconducting condition yet. After this, we measured the trapped flux (Fig. 12). Next, we placed them into magnetic field. Gradually we increased the original 0.5 T magnetic field by 0.25 T up to 2 T and measured the trapped flux density. Here we show some pictures about the magnetization process (Fig. 13 to 14). In Fig. 14 the loss of symmetry in flux density is caused by the difference of air gap within the fitting.

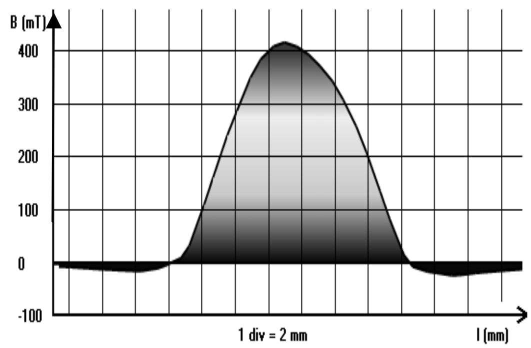

Fig. 12. Magnetized bulk + normal state ring, Bmax = 0.42 T.

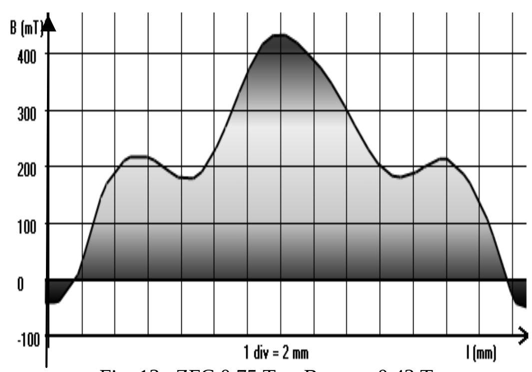

Fig. 13. ZFC 0.75 T, Bmax = 0.43 T.

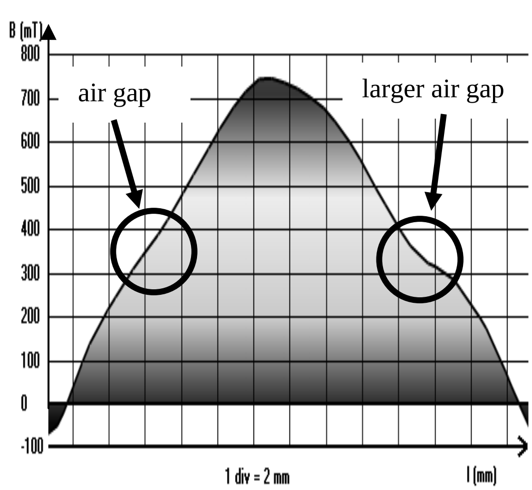

Fig. 14. ZFC 2 T, Bmax = 0.75 T.

The result of this ZFC magnetization is the same as if we magnetized the bulk and the ring together with FC method, only the way leading to magnetization differed. Thus, first we magnetized the inner part of the bulk and then the system of bulk and ring with ZFC method. In this case, also the penetration of the flux happened from the outer to the inner part through the air gap. We measured B_{max}= 0.84 T with FC method, when magnetizing the ring and the bulk together by applying 2 T.

VI. Conclusion

1) The tightly joined ring and bulk system has less trapped flux than in the case of one nonmachined (without concentric air gap) bulk of the same size. This phenomenon is due to the changes of granular current, because the air gap (no superconducting coupling) decreases the granular current.
2) In the case of tight fitting the maximal flux density of the bulk and ring system practically does not decrease, it is almost the same as if it were one bulk, because a minimal air gap does not decrease the inter-granular current.
3) Increasing the air gap of fitting decreases both the value of the trapped flux and the value of maximal flux density.
4) The trapped flux and flux density of the superconductor bulk supplemented with a tightly fitted ring can be increased due to the inter-granular current.
5) If cracks do not occur during machining, but the machined surface suffers steady phase changes, i.e. it loses its superconducting quality or it becomes worse, then there appear breaking points in the radial change (steepness) of the measured flux density.

Acknowledgment

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