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Evaluation of trapped magnetic field properties in superconducting MgB_2 bulk magnets of various shapes by finite element method

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Abstract

The trapped magnetic field properties of superconducting MgB_2 bulk magnets with various shapes such as a triangular, a quadrangular, a hexangular bulk were calculated by the Finite Elements Method (FEM). The effect for the combination of several numbers of bulks was also investigated for several kinds of shapes to obtain large area of bulk surface in spite of one large bulk. In this calculation, the simple magnetization process replaced by the field-cool magnetization was used to obtain the equivalent distribution of the magnetic field, and the thermal equation in FEM was omitted. The trapped magnetic field for the triangular bulk by FEM was compared with the experimental result. It was found that the calculated results agreed well with the experimental result. The maximum trapped magnetic field was obtained in the cylindrical shape among several kinds of shapes. The trapped magnetic field was increased by the combination of multi-bulks. It was confirmed that the trapped magnetic field of the multi-bulks was larger than that of the single bulk. The trapped magnetic field increases with increasing the number of the bulks.

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Keywords: MgB_2; superconducting bulk magnet; finite element method; trapped magnetic field

1. Introduction

MgB_2 has been investigated, since the transition temperature is the highest among the metallic superconductors, and the manufacturing processing is easy compared with oxide superconductors [1]. The maximum trapped magnetic

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field in MgB_2 bulk was reported to be 5.4 T at 12 K [2]. Due to these advantages, the various applications such as the drug delivery system [3], the generator systems [4] and the magnetic resonance imaging (MRI) [5] have been investigated. It is confirmed that FEM calculation is effective for the evaluation of the magnetic field distribution of MgB_2 bulks. In our previous work, the trapped magnetic field properties in the superconducting MgB_2 cylindrical bulk magnets were calculated by FEM [6]. The simple method to magnetize in comparison with the field-cool magnetization (FCM) is used in this calculation. It is reported that the increase of temperature in the magnetization process is small enough [7]. Hence the temperature dependence is safely negligible in the calculation. And the good agreement between FEM calculation and experimental result was obtained.

One of the advantages using MgB_2 is simple manufacturing process. And it is easy to obtain various shapes of bulk such as a triangular or a quadrangular bulk. In the present paper, we performed the numerical simulation of the trapped field properties for superconducting MgB_2 bulks with various shapes. The trapped field of triangular bulk by FEM was compared with that of the experimental result [8], and the trapped field distributions of the other shapes were calculated and compared with each other. We also evaluated the effect of the combination of the various bulks to obtain large trapped magnetic field at the surface in comparison with one large bulk.

2. Theoretical calculation

Trapped magnetic field distributions of several kinds of bulks were calculated by using FEM. First, the triangular bulk which thickness is 10 mm and the length of side is 10 mm shown in Fig. 1(a) was calculated to compare with the experimental result. It is compared with the bulks of different shapes. They are a triangular bulk, a quadrangular bulk, a hexangular bulk and a cylindrical bulk, respectively. Their thickness is 10 mm and lengths from the gravity point to the vertex are 10 mm. Schematic illustration of bulks is shown in Fig. 1(b)—(e). In experiment, MgB_2 is magnetized by the field-cooled magnetization (FCM). It is necessary to solve the thermal equation for simulating FCM in final decreasing magnetic field process, since the temperature is considered to increase. However, temperature dependence of magnetization can be neglected, because the thermal effect by changing the magnetic field in FCM is 0.5 K and is enough small [7]. Therefore, in the present work, another magnetization process is used for simplicity. In the magnetization, the magnetic field, which is larger enough than twice of the penetration field, is applied to MgB_2 bulk magnet in the constant temperature. The maximum field is 10 T. Then, the external field is reduced to zero. In this magnetization method, the equivalent magnetic field distribution with FCM can be realized [6]. The magnetic field dependence of the critical current density of the MgB_2 bulk at 20 K was measured by SQUID magnetometer, and it is used in this FEM calculation [9]. In this paper, the effect of the combination of the triangular bulks shown in Fig. 1(a)

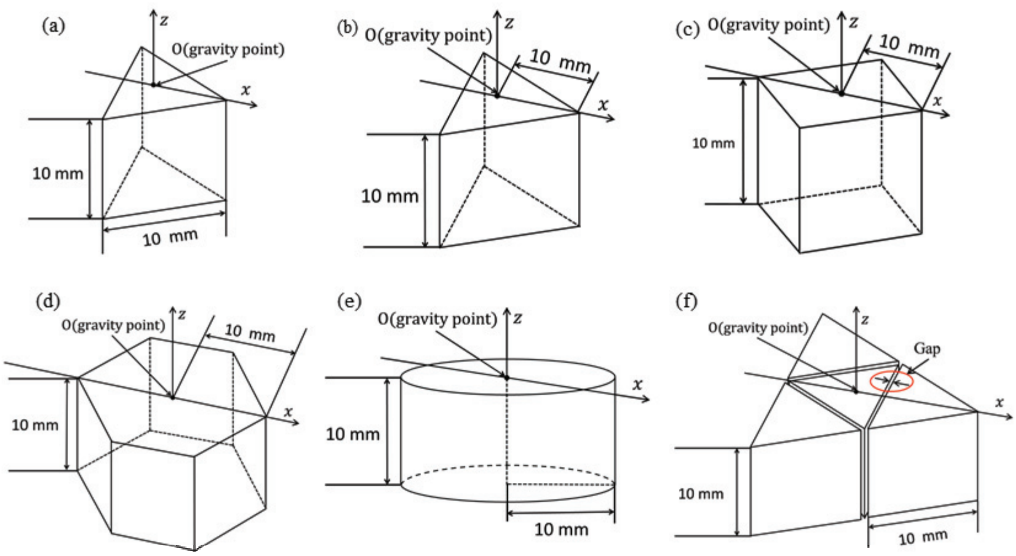

Fig. 1. Bulk models which calculated by FEM. x indicates distance from gravity point to vertex, and z indicates position from bulk surface.

was investigated. The multi-bulks formed a large triangular bulk as shown in Fig. 1(f). The numbers of triangular bulks are 4, 9, and 16.

3. Results and discussion

Fig. 2 shows the experimental result of the trapped magnetic field distributions of the triangular bulk as shown in Fig. 1(a) by FCM and the calculated result by FEM. x indicates the position from the gravity point of the triangular bulk, and z indicates the position from the bulk surface. The FEM result agrees well with the experimental results. Therefore, the present calculation method using simple magnetization process is effective. The trapped magnetic field distribution is asymmetry for the shape effect. The shape effect of the position far from the bulk surface is small.

Fig. 3 shows the comparison with the calculation results of the trapped magnetic field distributions of the triangular, the quadrangular, the hexangular, and the cylindrical bulk by FEM. From this result, it is confirmed that the trapped magnetic field is increased due to multipolarization of the bulks. The trapped magnetic fields on 5.0 mm above the bulk top surface at the center of the bulk are 0.45 T, 0.52 T, 0.65 T, and 0.70 T, respectively. The difference with the triangular and the cylindrical bulk is 0.25 T. In contrary, the difference with the hexangular and the cylindrical bulk is not large. Therefore, though the cylindrical bulk is effective for single bulk, the hexangular bulk is more effective for combination of the bulks because of available for multi-bulks without gap between small bulks.

Fig. 4 shows the maximum field of 4 bulks which gap between two adjacent bulks is 0.01—1.0 mm. The result of trapped field of 0.01 mm is higher than the result of 1.0 mm. The maximum field of 1.0 mm gap is 0.26 T and 0.11 T, and 0.01 mm gap is 0.35 T and 0.19 T for $z = 5$ mm and 10 mm, respectively. Therefore, the trapped magnetic field of multi-bulks is depended on the gap of two equivalent bulks. In practical case, the bulk is processed by resin processing, and there is a gap between two bulks. Therefore, it is desired that the gap between the bulks is reduced as much as possible in the case of using the multi-bulks to obtain the high trapped magnetic field.

Fig. 5 shows the trapped magnetic field distribution of the single bulk and the multi-bulks with 4, 9 and 16 bulks above 10 mm from the bulk top surface. The gap between two adjacent bulks is 0.1 mm. The result of the trapped field of the multi-bulks is improved compared with the result of the single bulk. The maximum field increases with increasing the number of the bulks, and the maximum trapped magnetic field of 16 bulks is 0.25 T. The trapped magnetic field of the position away from the bulk surface is largely influenced by the combination of the multi-bulks. In present study, the triangular bulks are used to combine the multi-bulks. The trapped magnetic field can be improved by the shape of single bulk such as the quadrangular, the hexangular bulk.

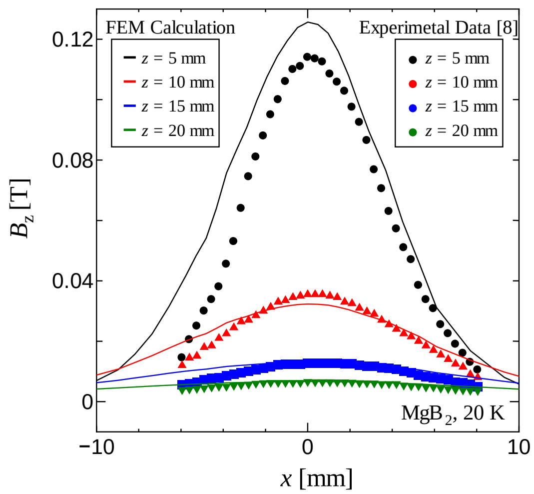

Fig. 2. Comparison between FEM calculation and experimental results of trapped magnetic field for single triangular bulk.

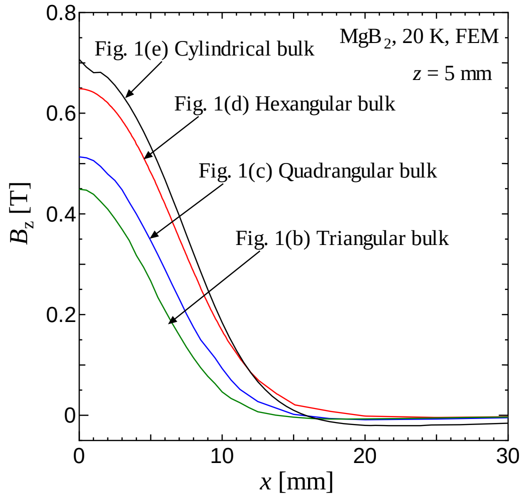

Fig. 3. Comparison of trapped magnetic field in triangular, quadrangular, hexangular and cylindrical bulk.

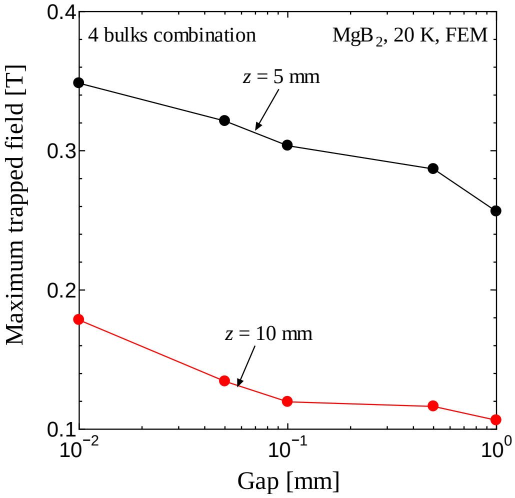

Fig. 4. Maximum trapped magnetic field for multi-bulks with different gap between bulks.

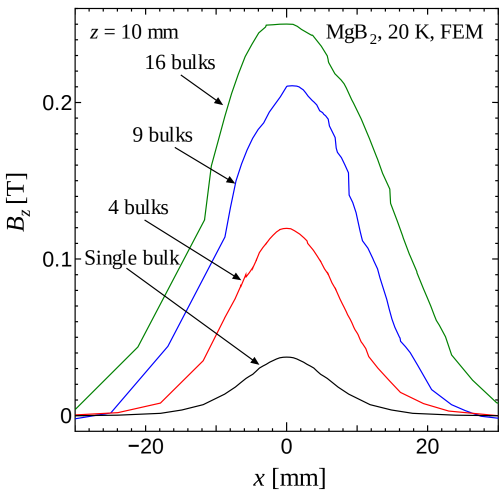

Fig. 5. Trapped magnetic field distribution for single triangular bulk and multi-bulks.

4. Conclusion

The trapped magnetic field of bulks with various shapes such as the triangular, the quadrangular bulk can be calculated by FEM. The result of the trapped magnetic field distribution of the polygon bulk is inferior to the result of the cylindrical bulk. The hexangular bulk is effective for using multi-bulks, since the gap between bulks can be small compared with cylindrical bulk. The trapped magnetic field of the combination of the triangular bulk was calculated. As a result, it was confirmed that the trapped magnetic field of the multi-bulks was larger than that of the single bulk. The trapped magnetic field increases with increasing the number of the bulks. The distance between the adjacent bulks of the multi-bulks should be small to obtain the larger trapped magnetic field. These results are useful to achieve the generation of the higher magnetic field by using the small bulks. The trapped magnetic field of multi-bulks can be improved by the shape of bulks. It is necessary to evaluate the trapped magnetic field of multi-bulks with different shapes of bulk in addition of triangular bulk.

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