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Study on performance improvement of superconductive-assisted machining (SUAM) with superconducting tape

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Abstract. In this study, we calculated the repulsive force of magnetic levitation for superconductive-assisted machining (SUAM) using the finite element method. Conventionally, SUAM utilizes bulk superconductors; here, we propose a magnetic levitation tool using superconducting tape. To obtain a stronger repulsive force, we fabricated various SUAM models and performed calculations. The results showed that we could obtain a strong repulsive force by arranging six superconducting tape pieces radially at equal intervals from the center of the SUAM tool, shortening the distance between the layers, and making the tape trapezoidal in shape. By increasing the number of layers, we can expect to achieve a greater repulsive force than that obtained with bulk superconductors.

1. Introduction

With the progress in industrial product development, the parts used in these products are becoming more complicated. Hollow processing technology is used to process such complex parts. There are two types of hollow processing technologies, one that processes a part before molding and one that processes after molding. When hollow processing is carried out after molding, it can be difficult to internally process an object with a complicated shape. Therefore, superconductive-assisted machining (SUAM) has been proposed in which a permanent magnet is levitated on bulk superconductors to process an object by utilizing the magnetic flux-pinning phenomenon of superconductors [1, 2]. The permanent magnet is a single-sided 4-pole magnet and is levitated by using bulk superconductors. The levitation of the magnet occurs because the magnet is held in the air and cooled in a magnetic field, i.e., field-cooled (FC). Then, the permanent magnet rotates when the superconducting part rotates due to the pinning effect. Therefore, a material can be polished from the inside by the surface of the permanent magnet.

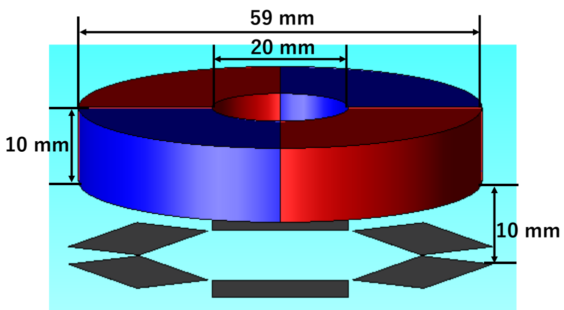
While improving the performance of bulk superconductors [3], research on the fabrication of superconducting tape has progressed, and high-performance tapes are currently being developed [4]. Superconducting tape can work in the same way as bulk superconductors, and by stacking superconducting tape pieces having 130 layers each and then magnetizing them, a magnetic field of 7.9 T could be obtained at 4.2 K [5]. Tape is easy to cut and combine. To design a SUAM tool using superconducting tape, it is necessary to evaluate the parameters affecting the force required to levitate the permanent magnet. In our previous work [6], it was shown that SUAM with superconducting tape shows comparable performance to SUAM with bulk superconductors. For real applications, it is necessary to improve the levitation performance of SUAM with superconducting tape.

In this study, we perform electromagnetic field analysis using a simple model consisting of only permanent magnet and superconducting tape using the finite element method (FEM), and search for a method to obtain stronger repulsive force with various shapes of superconducting tape pieces and configurations of SUAM. Finally, a comparison of the results for bulk superconductors and superconducting tape is given.

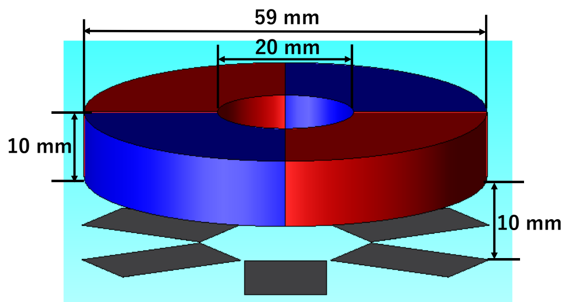
2. Calculation Methods

In this study, the finite element method (FEM) was used to analyze the electromagnetic field of the superconductive-assisted machining (SUAM) tool. For this purpose, JMAG manufactured by JSOL was utilized for the finite element method calculation. For the magnetic field dependence of the critical current density and *E-J* characteristics used in the calculation, the experimental results of $GdBa_2Cu_3O_{7-\delta}$ superconducting tape [7] were used. The critical current of the superconducting tape is 1.7×10^{10} A/m2 at 77.3 K and 0 T. The critical temperature of the tape is 93 K. The size of the $GdBa_2Cu_3O_{7-\delta}$ superconducting tape pieces was 20 mm long, 12 mm wide, and 1 μm thick for the superconducting layer. Six pieces were employed in each model, and models with two different configurations were fabricated. The arrangement of the superconducting tape pieces and permanent magnet is shown in figure 1. The model with six tape pieces placed azimuthally at equal intervals from the center of the SUAM is designated Type A, and the model with six tape pieces placed radially is designated Type R. In addition, we created up to four layers similar to the upper layer at intervals of 50 μm, and analyzed repulsive force for Type A and Type R. In order to investigate the change in repulsive force as a function of the distance between the upper and lower layers, four layers similar to the upper layer were created using the Type A model at intervals of 50 μm, 100 μm, 300 μm, and 500 μm. In addition, the size of the superconducting tape in Type A was changed to a trapezoidal shape with an upper base of 20 mm and a lower base of 34 mm to try to reduce the gap between the tape pieces. The arrangement using the trapezoid-shaped superconducting tape pieces is shown in figure 2. The 4-pole permanent magnet was placed so that the center of the permanent magnet coincided with the center of the tape pieces. We used a permanent magnet with an inner diameter of 20 mm, outer diameter of 59 mm, thickness of 10 mm, and a magnetic field of 450 mT at the magnet surface. These values are the same as the 4-pole permanent magnet used in reference [1].

The superconducting tape pieces were magnetized with field-cooled magnetization (FC) at the magnetizing position of 10 mm between the upper part of the tape and the 4-pole permanent magnet. The cooling temperature is 77.3 K of liquid nitrogen. Then, the repulsive force on the permanent magnet



(a) Type Azimuthal (Type A)



(b) Type Radial (Type R)

Figure 1. Superconductive-assisted machining (SUAM) with different superconducting tape configurations. The model with six pieces placed azimuthally at equal intervals from the center of the SUAM is designated Type A, and the model with six sheets placed radially is designated Type R.

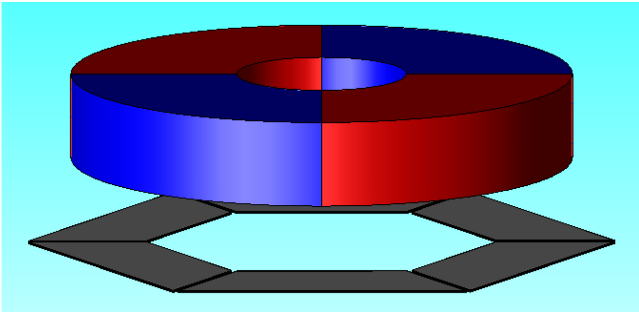


Figure 2. Superconductive-assisted machining (SUAM) with trapezoid-shaped superconducting tape. The superconducting tape pieces in Type A were changed to a trapezoidal shape with an upper base of 20 mm and a lower base of 34 mm.

generated by the superconducting tape was calculated when the permanent magnet was moved perpendicularly to the superconducting tape pieces at a speed of 0.1 mm/s. The distance between the permanent magnet and the superconducting tape pieces was decreased from 10 mm to 1 mm. In this paper, we only focus on the repulsive force, since the attractive force and torque are almost proportional to the results for the repulsive force, and thus it is clear that if the repulsive force is improved, the attractive force and torque are also improved.

3. Results and discussion

Figure 3 shows the FEM calculation results for the two models when the number of layers of superconducting tape was increased from 1 to 4. The difference between Type A and Type R was also calculated and is shown in figure 3. As can be seen in figure 3, both repulsive forces are inversely proportional to the distance and increase with the number of layers. It was confirmed that the force is zero at a distance of 10 mm, which is the magnetizing position, and that the repulsive force emerges when the permanent magnet is brought closer to the tape from the magnetizing position, and grows larger with shorter distance. Furthermore, it can be seen that Type A has a larger repulsive force than Type R when the distance is closer than 5 mm with two or more layers. This is because Type A can obtain a larger repulsive force in the tape pieces at the boundary between the north and south poles of the permanent magnet. In addition, the area of shielding current inside the tape pieces for Type A is larger than that for Type R, since the tape pieces are located at the edge of the permanent magnet. Therefore, if the superconductive-assisted machining (SUAM) tool is configured according to Type A and the number of layers is increased, the repulsive force will increase. Thus, if we increase the number of layers, we can expect a larger repulsive force than that obtained with bulk superconductors.

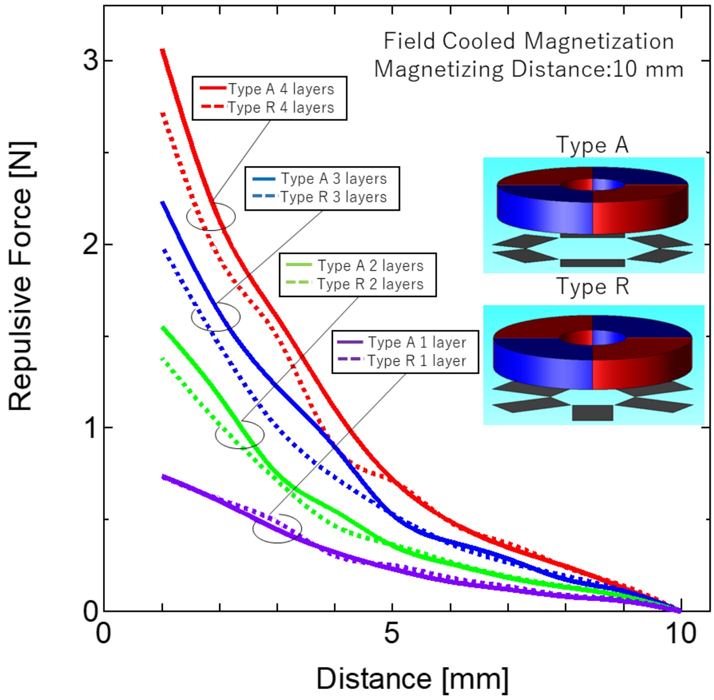


Figure 3. Repulsive force when magnetizing distance is 1 – 10 mm for Type A and Type R. Magnetizing position is 10 mm with field-cooled magnetization.

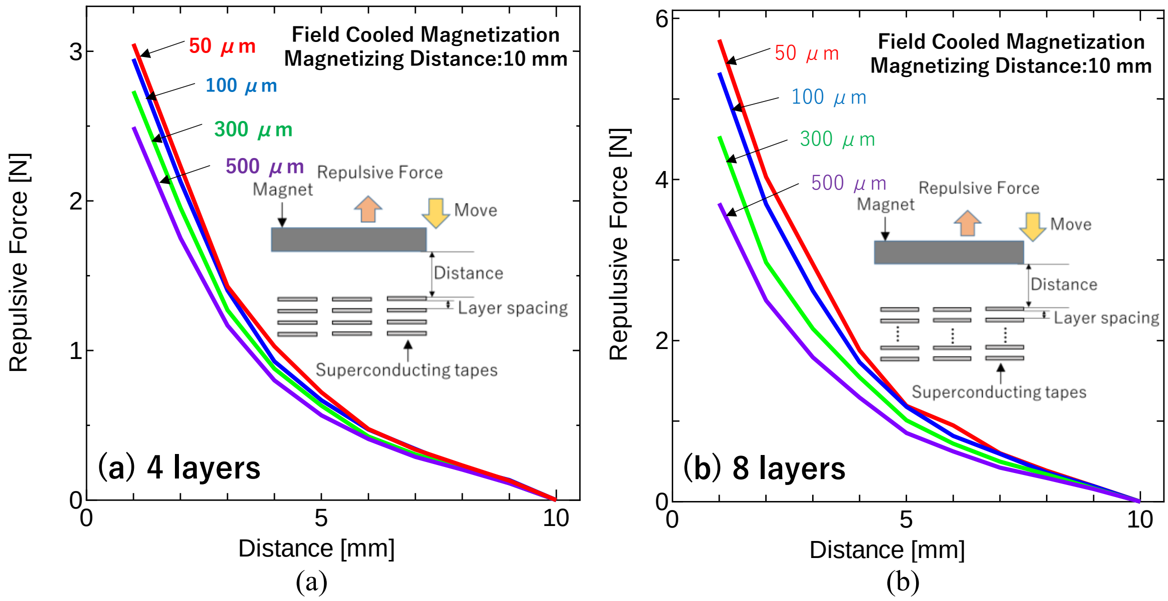


Figure 4. Repulsive force when magnetizing distance is 1 – 10 mm for various distances between layers, (a) 4 layers and (b) 8 layers of superconducting tape.

Figure 4(a) shows the results of FEM calculations for four layers of superconducting tape with different layer spacings. Figure 4(b) shows the results of FEM calculations for eight layers of superconducting tape with different layer spacings. From figure 4(a), the repulsive force increases by 10% when the distance between layers is 300 μm compared to 500 μm, and by 23% when the distance between layers is 50 μm. Furthermore, figure 4(b) shows that the repulsive force increases by 40% at

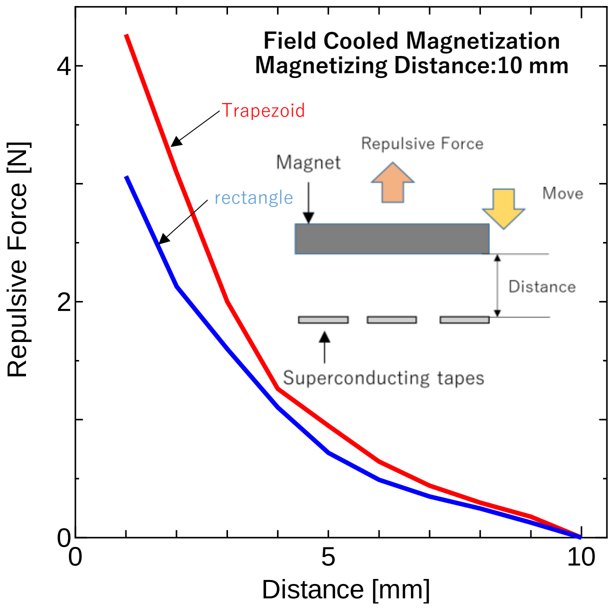


Figure 5. Repulsive force when magnetizing distance is 1 – 10 mm for Type A and model of Type A superconducting tape with the size changed to a trapezoidal shape with 20 mm upper side and 34 mm lower side.

50 µm compared to 500 µm. Therefore, it can be seen that the repulsive force is improved more when the distance between the layers is shortened and the number of layers is 8 than when the number of layers is 4. This is because as the number of layers increases, the total pinning force becomes greater. From these results, it can be concluded that the shorter the distance between layers, the greater the repulsive force.

The results of FEM calculations are shown in figure 5 for Type A and Type A with the tape shape changed to a trapezoid with an upper base of 20 mm and a lower base of 34 mm. From figure 5, the repulsive force increases by 40% when the shape of the superconducting tape is changed to a trapezoid. This large increase in repulsive force is due to the fact that the number of tape pieces between the N and S poles of the 4-pole magnet is greater than before. Then, a strong repulsive force can be obtained with the tape between the N and S poles of the 4-pole magnet. Therefore, when six superconducting tape pieces are arranged radially, a strong repulsive force can be obtained by changing the tape to have a trapezoidal shape.

In our previous work [6], it was shown that the performance of SUAM in terms of the repulsive force can be improved by increasing the number of superconducting tape pieces in the layer. Therefore, combining our previous work with the present results, we found that if the shape is tailored and the layers are properly arranged, repulsive force greater than that generated by bulk superconductors can be obtained easily and cheaply. The reason why stacked superconducting tapes perform better than bulk superconductors is that superconducting tape has a high critical current density and is thin compared with bulk superconductors.

4. Conclusion

In this study, in order to efficiently obtain a large repulsive force, various models for superconductive-assisted machining (SUAM) were fabricated and analyzed. As a result, it was found that it is possible to obtain a larger repulsive force by fabricating a SUAM tool using the Type A configuration shown in figure 1, shortening the distance between superconducting layers, and making the tape trapezoidal in shape. In addition, by increasing the number of layers, we can expect to achieve a larger repulsive force

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than that obtained in the bulk. In future work, it is necessary to develop a technology to reduce the thickness of the support layer in the superconducting tape, such as Hastelloy, in order to shorten the distance between layers.

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