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journal or publication title	Journal of Physics: Conference Series
volume	1590
page range	012023-1-012023-5
year	2020-07-31
URL	http://hdl.handle.net/10228/00008026

doi: https://doi.org/10.1088/1742-6596/1590/1/012023

Journal of Physics: Conference Series

PAPER • OPEN ACCESS

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To cite this article: Y Kinoshita *et al* 2020 *J. Phys.: Conf. Ser.* **1590** 012023

Evaluation of superconductor assisted machining (SUAM) with superconducting coated conductors using the finite element method

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Abstract. In the present study, we numerically calculated the magnetic levitation force for superconductor assisted machining (SUAM) using the finite element method. Although we usually use bulk superconductors for magnetic levitation in SUAM, we herein considered magnetic levitation using superconductor-coated conductors. We were able to explain the experimental results on the forces of the coated conductors as well as bulk theoretically. For both bulk and coated conductor, the repulsive force was found to increase as the distance from the permanent magnet became shorter. For the coated materials, both the repulsive and attractive forces were lower than in the case of bulk superconductors. This is because the volume of superconducting material was smaller than in the case of bulk superconductors, since the overall size of both materials was the same. However, we believe that greater forces can be obtained by increasing the number of coated conductors.

1. Introduction

Both industrial products and their constituent parts are becoming increasing complex, and require manufacturing techniques such as lathe processing and magnetic polishing. However, there are restrictions due to tool interference when machining, making it difficult to apply the hollow machining method to complex shapes. In order to solve these problems, we have devised a superconductor assisted machining (SUAM) method based on flux pinning in superconductors [1]. The SUAM system uses a single-sided four-pole permanent magnet and four bulk superconductors, and magnetic levitation occurs when the permanent magnet is held in the air and cooled in a magnetic field (i.e., field cooled: FC). This permanent magnet rotates together with the superconductors. Therefore, the material can be polished from the inside by pressing the fixed permanent magnet using the bottom surface of the permanent magnet. Moreover, it is possible to restore the displacement in the horizontal direction. Using this restoring force, the SUAM system can perform cutting as well as polishing. Since the magnetic levitation tool attempts to return to its initial position, we focus on the repulsive and attractive forces. Devices that apply SUAM using bulk superconductors have been developed [2]. However, more recently, devices have been designed that use normal conductors with a superconducting coating. A magnetic field exceeding 30 T can be generated by coiled superconducting wire or tape [3], and laminated coated conductors can act as a bulk material and trap a magnetic field of 7.9 T at 4.2 K by magnetizing 130 double layers of coated conductors [4]. Therefore, it is interesting to examine the use of coated conductors for SUAM.

In the present study, we carry out numerical (finite element method, FEM) and experimental investigations into the performance of bulk superconductors and superconductor-coated wires.

2. Experimental methods

For both the bulk and coating superconductors, the material used was $GdBa_2Cu_3O_{7-\delta}$. In the case of the bulk superconductor, the sample was a square prism with a width of 35 mm and a thickness of 10 mm. We placed six superconductor-coated conductors with a width of 5 mm and a thickness of 0.13 mm side by side, stacked 20 of these layers in the thickness direction, and bonded them together. This produced a sample with a size similar to that of the bulk superconductor, to allow easy comparison. The thickness of the superconducting layer of the used coated conductor is 2 μm, and the thickness of the substrate is 100 μm. The magnet was a 450 mT single-sided four-pole magnet with an inner diameter of 19 mm, an outer diameter of 59 mm, and a thickness of 10 mm, as shown in Fig. 1. This allows the permanent magnet to rotate to follow the rotation of the superconductors that fix the permanent magnet. To achieve this, it was first necessary to magnetize the superconductors in their normal conducting state, and then cool them to the FC state. After magnetization, the repulsive and attractive forces were measured three times, and the average was taken.

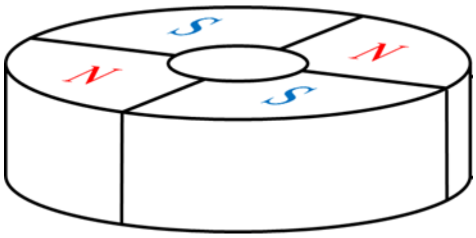

Figure 1. Four-pole permanent magnet used for SUAM.

3. Calculation methods

JMAG-Designer, developed by JSOL, was used for FEM calculations of the force on the magnetic levitation tool. The magnetic field dependence of the critical current density, and the E−J characteristics, were determined experimentally using bulk $YBa_2Cu_3O_{7-\delta}$ [5] and a $Ba_2Cu_3O_{7-\delta}$ coated conductor [6].

In the simulation, we moved the permanent magnet at a speed of 0.1 mm/s or 0.001 mm/s to determine how the force changes as the permanent magnet moves closer to or farther away from the superconducting sample. Fig. 2 shows the calculation models. The permanent magnet and the coated conductor were placed so that their centers were as shown in Fig. 2(a) and FC was performed 5 mm from the permanent magnet, as shown in Fig. 2(b). The magnet was the same permanent magnet that was used for the experiments. A similar arrangement was used for the bulk superconductor, as shown in Fig. 3. Bulk superconductors have different properties depending on the phases they contain. In the present study, a uniform structure was used for simplicity, since it was found in our previous study that the numerical calculations agreed well with the experimental results [1]. The coated sample was taken to be a laminated structure with 20 superconducting layers, each with a thickness of 2 μm, spaced at 100 μm intervals. Experiments have been conducted with higher-density laminates, such as a 6.9-mm-thick sample containing 120 layers [7] and an 8.1-mm-thick sample containing 145 layers [8]. We used 100 μm for this calculation because of the thickness of the substrate used in the present study. For each superconductor, FC was performed at a distance of 5 mm from the permanent magnet. The forces were calculated for bulk and coated models with similar dimensions. This meant that for the coated conductor, the volume of the superconducting material was about 100 times smaller than that of the bulk superconductor. The Lorentz force exerted on the superconducting samples by the permanent magnet was determined, and the force acting on the permanent magnet was indirectly evaluated. Since the purpose was to determine the magnetic levitation force acting on the superconducting samples, a finer mesh was used for the samples than for the permanent magnet. The attractive force, repulsive force, and rotational torque were then evaluated for the magnetic levitation tool.

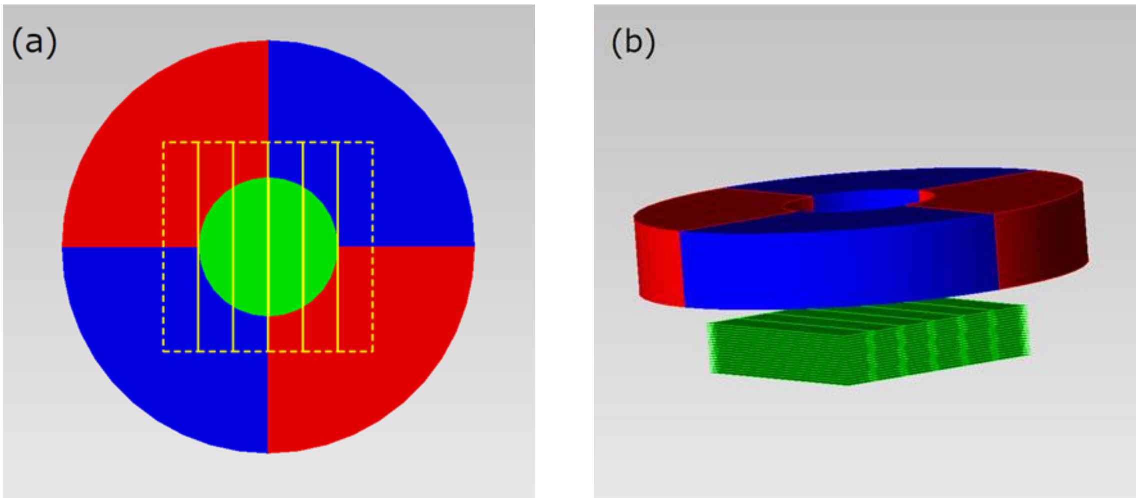

Figure 2. Calculation model for coated conductors as viewed from (a) above and (b) side.

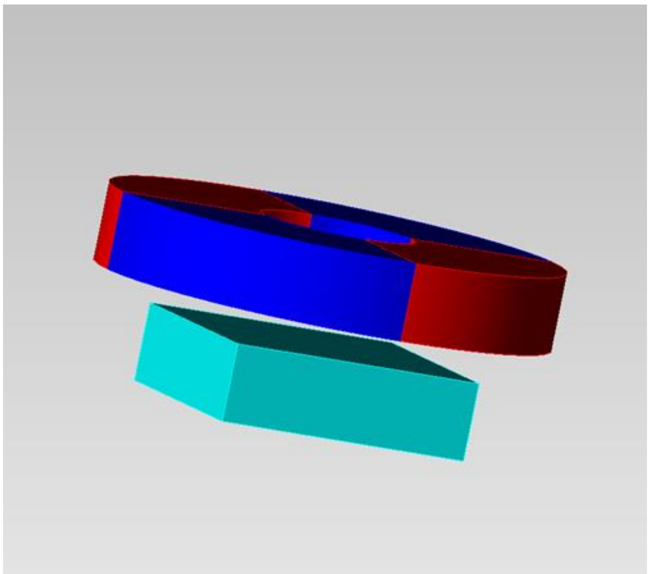

Figure 3. Calculation model for bulk superconductor.

4. Results and discussion

Fig. 4 shows the experimental and calculated results for the force as a function of the distance between the coated conductor and the permanent magnet when the initial magnetization position is 5 mm. The repulsive force increases as the distance from the permanent magnet decreases to the initial magnetization position. When the distance between the permanent magnet and the coated conductor is 1.0 mm, the maximum repulsive force is 3.94 N. In contrast, the attractive force increases as the distance from the initial magnetization position increases. At a distance of 6 mm from the initial magnetization position, the attractive force is at a maximum. At smaller distances, the experimental and calculated force values are similar. However, they diverge at larger distances because the attractive force reaches a peak and decreases. This is because the permanent magnet does not move away at a constant speed during the experiment. The experimental values approach the calculated values by moving away at a constant speed. Also, the calculated values do not change smoothly. This is because the mesh for the coated conductor has a larger aspect ratio than that for the bulk superconductor. The calculation error increases with increasing aspect ratio, so it is larger for the coated conductor.

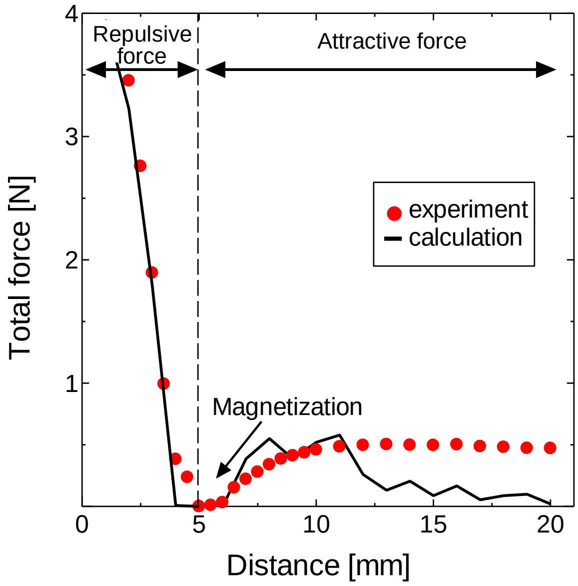

Figure 4. Repulsive and attractive forces for coated conductors.

Fig. 5(a) shows the calculated attractive force for the bulk and coated samples. When the distance to the permanent magnet is 1 mm, the force generated by the bulk superconductor is 8.67 N, whereas for the coated conductor it is 3.94 N. Fig. 5(b) shows the results for the repulsive force. For the bulk superconductor, the force is 1.20 N when the distance from the initial magnetization position is 3 mm, whereas for the coated conductor, it is 0.58 N when the distance from the initial magnetization position is 6 mm. For all distances, the values are approximately two times lower for the coated conductors. This is due to the lower volume of superconducting material in the coated conductor, and could be improved by increasing the number of layers or reducing the distance between layers. Compared with the bulk superconductor, the coated conductor has a more complicated model, so precise calculation is difficult. Moreover, since the superconducting part is thin, the amount of force change in each mesh element is large. Since the attractive force is about an order of magnitude smaller than the repulsive force, the attractive force curve for the coated conductor is not smooth. This could be improved by the use of a finer mesh.

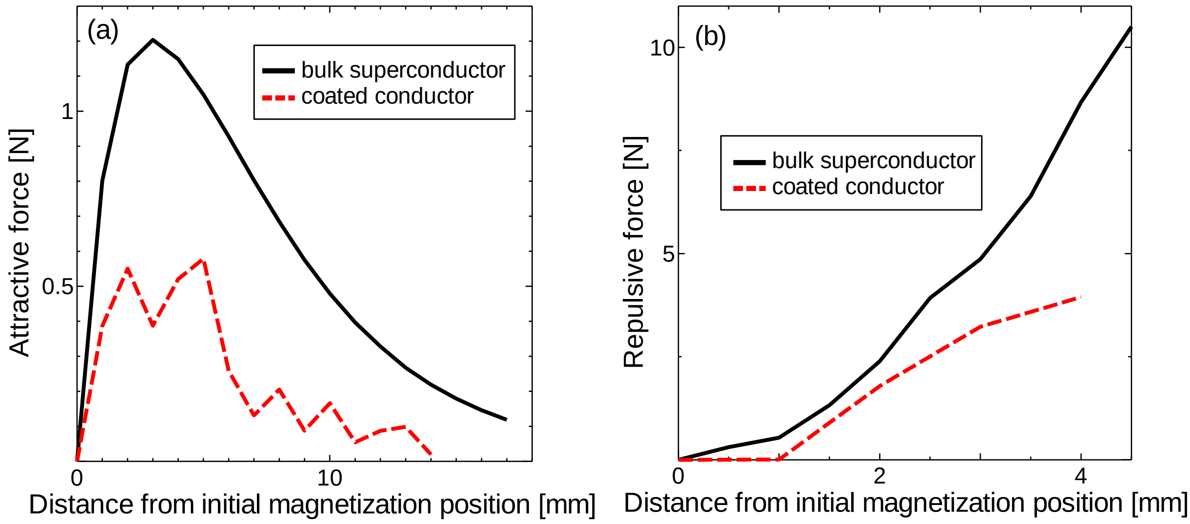

Figure 5. (a) Attractive force and (b) repulsive force for bulk superconductor and coated conductor.

Fig. 6 shows the relation between the number of layers and the repulsive force for the coated conductor, for a distance of 1 mm from the permanent magnet. The repulsive force increases as the number of layers increases. However, even for 20 layers, it is smaller than that for a bulk superconductor of the same size. An approximate calculation shows that 38 layers can produce as much force as the bulk superconductor.

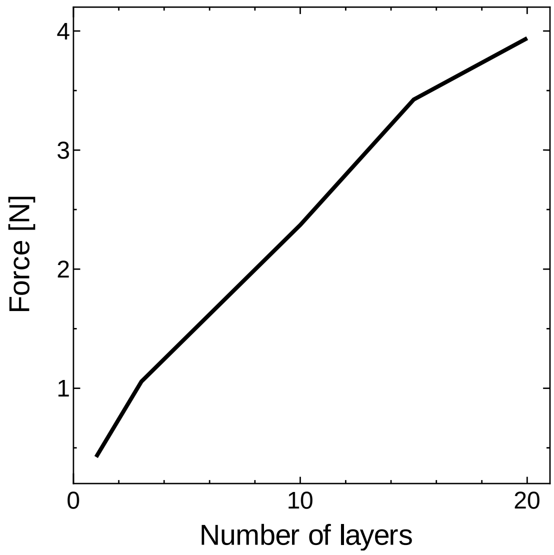

Figure 6. Relation between number of layers and repulsive force.

5. Conclusion

In the present study, the force acting on a superconductor-coated conductor was shown to be calculable using the finite element method. The calculation results were in good agreement with the experimental results. Both the repulsive and attractive forces were found to be smaller for the coated conductor than for the bulk superconductor, since the volume of superconducting material was lower in the former case. Even 20 layers of coated conductors were shown to produce less force than a bulk superconductor of the same size. However, it is thought that by further increasing the number of layers, the same force as that generated by the bulk superconductor can be obtained. Therefore, devising a technique by which to increase the density of laminated coated conductors by reducing the distance between layers is needed.

Acknowledgements
The present study was supported in part by JSPS KAKENHI Grant Number 19H00771.

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