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Evaluation of Magnetic Cutting and Polishing with Superconducting Bulks

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Abstract. In this paper, magnetic levitation tool with superconducting bulks is introduced as a new hollow machining technology. Magnetic levitation tool is the machine that magnet levitates above superconducting bulks and driving force of rotating magnet shaves the object. This tool is expected to use for a grinding machine and machining device because of hollow machining and micromachining by strong fixing. For using magnetic levitation tool, the attractive force, the repulsive force and rotating torque are important for grinding machine, machining outer surface and both, respectively. These forces are calculated by FEM, and compared with experimental results. The experimental results are agreed well with calculated results. However, the attractive force is one order smaller than that required in chemical mechanical polishing.

1. Introduction

Processing technologies are important for creating various metal parts, for example, automobiles, aircrafts and medical applications. To create metal parts, there are various hollow machining technologies, including multi-axis processing machines. Magnetic processing is one of those techniques and is actually used [1 – 3]. In this magnetic processing, magnetic abrasive grains inside the object polishes by attractive force of permanent magnet outside the object. This magnetic polishing has a disadvantage that it is hard to deal with complicated processing, since adjusting the magnetic force is difficult. In other hollow machining process, there is lathe machining. This is a method of processing the object polished by rotating lathe. In this method, although more delicate processing is possible, processing is limited by arm. In order to deal with the disadvantages of these machining methods, a magnetic levitation tool using flux pinning of superconductor is proposed. The magnetic levitation tool is the tool that fixes a permanent magnet in the air and shaves the object by rotating the permanent magnet. By stabilizing the permanent magnet, it is possible to take stability on the left and right balance, and it is expected to process detailed compared with conventional magnetic processing. Here, this magnetic levitation tool is named SUAM (SUperconductive Assisted Machine).

SUAM is expected to apply to cutting and polishing. For cutting, a strong force is required to shave the object roughly, whereas for polishing, it is required a stable force for finer processing. In the case of cutting, a stainless steel blade is attached to the levitated magnet. In the case of polishing, an abrasive or a slurry is used.

In this research, in order to clarify the behavior of the superconductor in SUAM, attractive force, repulsive force and torque were measured by basic method, and experimental results are compared with the calculated result by Finite Element Method (FEM). Furthermore, the influence on the attractive force and the repulsive force due to the initial magnetization distance of the magnet was calculated. Discussion is given for the possibility of SUAM for hollow machining process.

2. Experiment

Figure 1 shows experimental setup of SUAM. In this study, we used four quadrangular superconducting bulks and ring magnet for SUAM. $GdBa_2Cu_3O_{7-\delta}$ was used for a quadrangular superconducting bulk, which side is 35 mm and thickness is 10 mm. In experiment, the single-sided, four-pole type magnet was used in which N and S poles are alternately arranged in the azimuthal direction as shown in figure 2. This is because the one-sided, single-pole type magnet cannot prevent movement in the azimuth direction due to the azimuthal isotropy and cannot rotate itself following the rotation of the bulks. The surface magnetic flux density of this quadrangular ring magnet was 450 mT, the inner diameter was 20 mm, the outer diameter was 58 mm, and weight was 186 g. In this experiment, first, the magnet was placed at appropriate height above the bulks. Then, the superconducting bulks were cooled by liquid nitrogen and the magnetic field was trapped into the bulk. The magnet levitated above the superconductor. After trapped, the magnet moved to vertical direction and rotational direction, and the attractive force, repulsive force and rotational torque were measured by spring scale. The results of this experiment are average of experiment values performed three times.

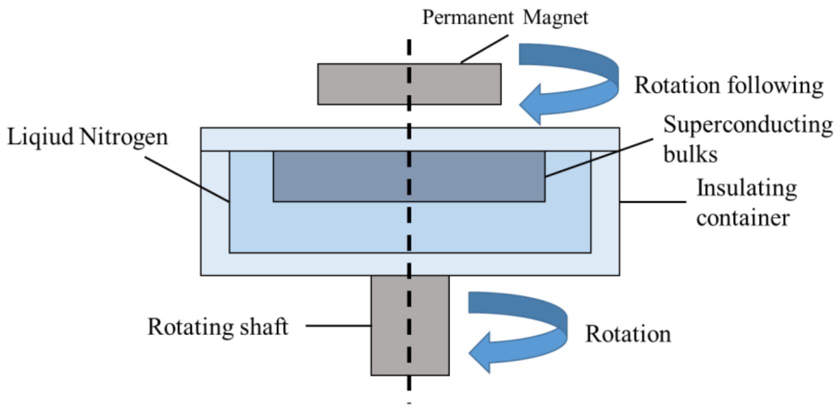

Figure 1. Schematic illustration of SUAM (SUperconductive Assisted Machine).

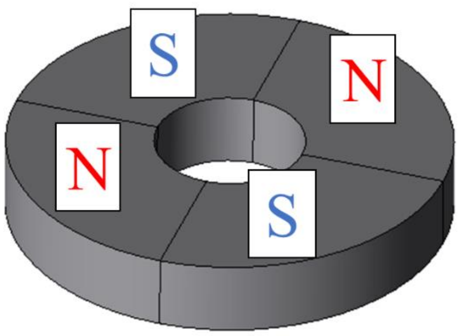

Figure 2. 4-pole magnet used in the SUAM.

3. Calculation Method

In the present study, JMAG-Designer 15.0 was used as Finite Element Method (FEM) simulation software. In this calculation, the permanent magnet was separated from the superconducting bulk by a certain distance, and the superconducting bulk was cooled to trap the magnetic field. For simplified calculation, calculation of temperature dependence of superconductivity was omitted. First, the conductor was set as normal conductor in the initial state, and a permanent magnet was placed over the superconducting bulk with distance of 10 mm. Hence, the magnetic field was penetrated into the bulk. Then, the conductor changed from normal conductor to superconductor in order to reproduce cooling magnetization in the magnetic field. In this way, the magnetic field was trapped in the bulk. Experimental values were used for J_c-B characteristics and n-value models were used for E-J characteristics [4].

4. Results and Discussion

Figure 3 shows experimental results of attractive and repulsive forces when the initial magnetization distance is 10 mm, and calculation results by FEM. The maximum repulsive force is 120 N at 1.0 mm. Here, since the gravitational force is 1.8 N (0.19 kg), the levitation distance is 9 mm which is 1 mm lower than the initial magnetization distance. The maximum attractive force due to the Lorentz force is about 1.8 N. In this study, experimental results and calculation results compare with Chemical Mechanical Polishing (CMP). CMP is the polishing technology, which is currently used as a standard technique for polishing of semiconductor [5 – 7]. Considering CMP, pressure is required 10 – 30 kPa [5 – 7]. Since the contact area of this tool is 2300 mm^2, attractive force should be 23 – 70 N. Therefore, attractive force by present apparatus of 1.8 N does not satisfy this value. In practical case, the initial magnetization distance must be optimized. Therefore, the attractive force was calculated when the initial magnetization distance is changed to 5 – 15 mm.

Figure 4 shows the maximum attractive force when the initial magnetization distance is changed. Since the magnetic field trapped by the superconductor increases, the maximum attractive force increases as decreasing initial magnetization distance. When the initial magnetization distance is 5 mm, the maximum attractive force is 5.9 N. Although it is not beyond the attraction force required in CMP as above mentioned, it is necessary to improve the apparatus such as using a stronger magnet. However, it is difficult to increase the magnetic field of permanent magnet. Hence, using a weight on the magnet seems to be useful for increasing attractive force, since the repulsive force is enough large. For example, when the weight of 1.0 kg is put on magnet, it can generate 9.8 N. Then, the levitation

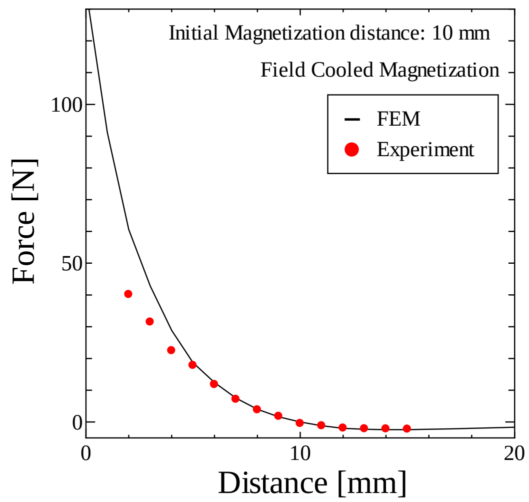

Figure 3. Repulsive force at distance below 10 mm and attractive force at distance above 10 mm.

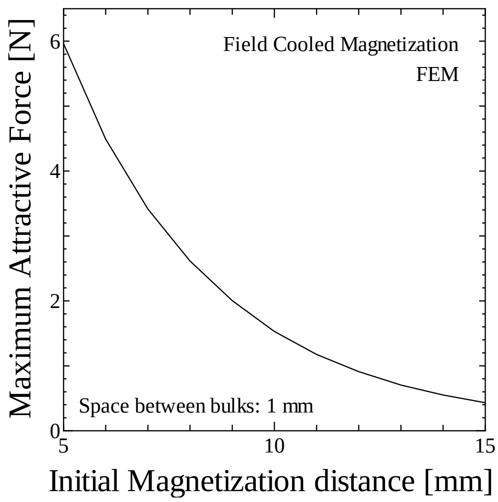

Figure 4. Maximum attractive force as a function of initial magnetization distance.

height becomes 6 mm. However, this value is not enough to use SUAM as a hollow machining process. Then, the weight is put with considering the levitation distance. It is expected that the pressure 10 kPa of a conventional CMP will be achieved by adding the weight of 2.3 kg on the permanent magnet. Furthermore, the effect of varying the distance between the bulks is considered as the factor of the change in the maximum attractive force.

Figure 5 shows the maximum attractive force as changing the space between quadrangular superconducting bulks. The initial magnetization distance is 10 mm. As shown in figure 5, the maximum attractive force decreases as increasing the space between bulks. This occurs because the trapped magnetic field decreases due to larger space between the bulks. This effect is significant, and a difference in attractive force between 1 mm and 10 mm is about 0.45 N. Hence, it is necessary to make the space between the bulks as narrow as possible. Since the superconducting bulks is subjected to resin processing in practical situation, it is necessary to make as close contact as possible in consideration of its thickness. It is found that the current bulk space of 1 mm is reasonable, since attractive force does not change largely from 0.1 to 2 mm.

Figure 6 shows experimental result and calculated results by FEM of the rotational torque when the initial magnetization distance is 10 mm. Here, φ represents the angle of movement of the magnet and the superconductor from the initial magnetization position. It is found that FEM results agree well with experimental result. Since the displacement in the superconductor becomes large, as the angle increases, the torque of the magnet becomes larger. When the angle reaches 45 degrees, the maximum torque is obtained. In the experimental results, the magnet got out at a point exceeding 45 degrees, and measurement could not be done. In FEM, the torque becomes 0 at 90 degrees, and then the torque works in the reverse direction. Torque draws a curve like a sine wave. When a torque greater than the maximum torque is worked, the position of the magnet is moved by the greater force. Therefore, it can be said that the torque at 45 degrees is the torque limit of SUAM.

Figure 7 shows calculation results by FEM for rotational torque in the case of changing initial magnetization distance from 5 – 15 mm. The maximum torque is obtained at 45 degree, regardless of initial magnetization distance. Maximum torque increases as decreasing the initial magnetization distance, and maximum torque at 5 mm is 0.48 N・m. It is found that the phase of rotational torque is not affected by initial magnetization distance.

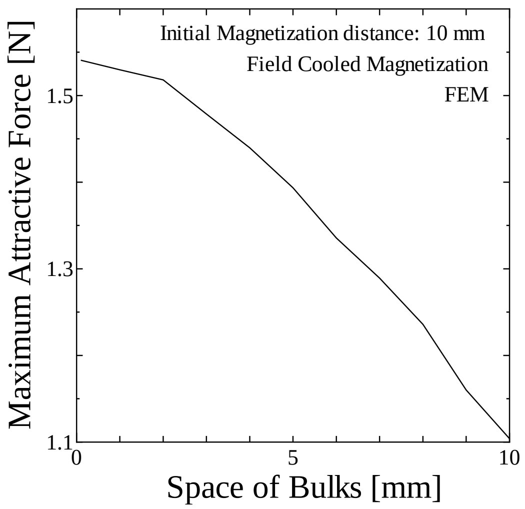

Figure 5. Maximum attractive force as a function of space between bulks.

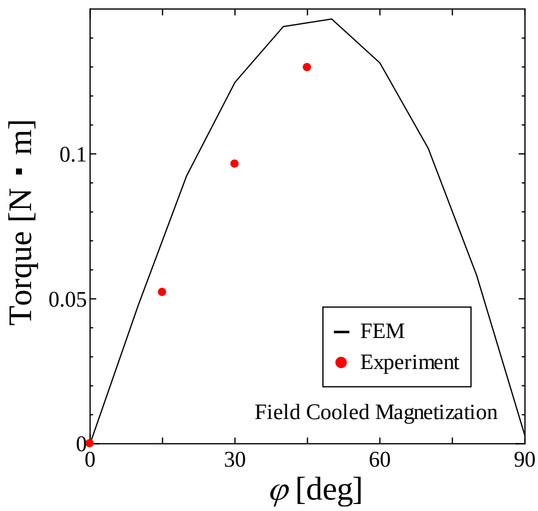

Figure 6. Rotational torque as a function of angle when initial magnetization distance is 10 mm.

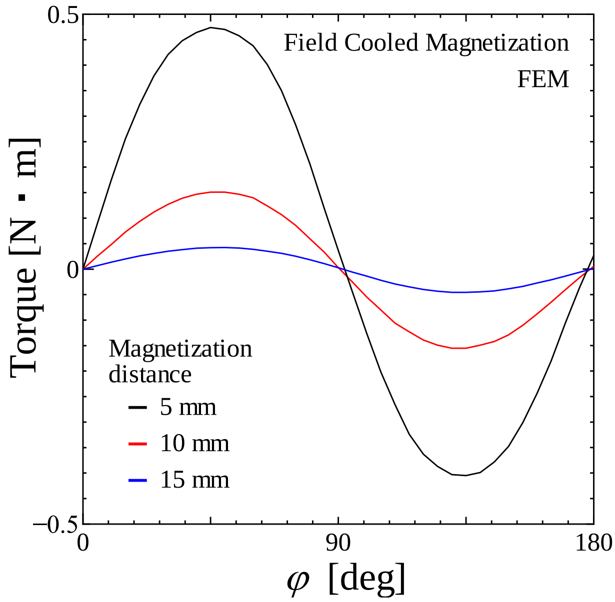

Figure 7. Rotational torque as a function of angle with various initial magnetization distance.

5. Conclusion

In this study, attractive force, repulsive force and rotational torque of SUAM were experimentally measured. The FEM results of repulsive force and attractive force agreed well with the experimental results. We also compared FEM result and experimental result of the rotational torque. The FEM result agreed well with the experimental result. The maximum attractive force in various setting is 6.0N which is one order lower than that expected in Chemical Mechanical Polishing (CMP). From these results, it is concerned that SUAM at present stage cannot provide the same polishing performance as CMP. Therefore, it is necessary to use strong magnet in order to obtain stronger pressure and put the weight on the magnet.

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