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Magnetic Finishing Model Using a Halbach Plate with A Circulatory System

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ABSTRACT: *By generating a magnetic field generated by a Halbach array in combination with a polishing system, we established a highly efficient polishing model using a magnetic polishing material. This study is an application of a magnetorheological fluid polishing machine (MRF) immersed in a solution of magnetic abrasive particles, enhanced by a Halbach magnet array for a magnitude value of about 0.6-1T. A simulation setup was created to evaluate the surface polishing efficiency and material removal behaviors. The simulation results show that the predicted machined surface can achieve very good roughness without generating surface damage. In addition, the mechanisms governing material removal were analyzed and discussed. These findings highlight the potential of the model. complete Surface polishing with magnetic abrasive particles as a technique for efficient high precision polishing on a variety of difficult-to-machine materials.*

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I. INTRODUCTION

With the advances and requirements in science and technology today , the importance of the quality or surface roughness of parts is becoming increasingly important in many fields [1, 2]. This directly affects the operation of the part , as well as its durability and mechanical properties. Improving the surface quality brings many advantages in the operation or operation of the part , such as reducing friction and increasing its lifespan. and notably improve the performance of the detail [3, 4] . Among them, magnetorheological fluid polishing (MRF) is known as one of the most effective methods to achieve surface quality that even surpasses the parameters that are difficult to achieve by conventional or traditional methods . This model uses the interaction between the magnetic field array and the solution containing magnetic abrasive particles to machine the workpiece surface , effectively removing the excess residue. [5, 6] . The effectiveness of this established model is based on the effect of the magnetic field array on the magnetic polishing solution when in contact [7] .

In recent years , Halbach magnetic arrays have attracted considerable interest from scientific researchers due to their unique ability to optimize the distribution and magnitude of magnetic fields in magnetic field installations. [8] . This Halbach array consists of permanent magnets that can be arranged in many configurations such as linear or concentric arrangement [9] . The outstanding feature of the Halbach array is its ability to generate a strong magnetic field , evenly distributed within the operating range [10] . In the magnetic polishing method proposed here , the Halbach array plays a very important role in enhancing the magnetic force in the machining area. [11, 12] . By enhancing the magnetic field within the range machining , which significantly improves surface polishing efficiency [13] .

II. METHOD OF SETTING UP POLISHING MODEL.

2.1. Schematic diagram of equipment and method for removing excess material.

Figure 1 below Explain the principle and operation and polishing mechanism of the model is established . When the process is started, the driving wheel (wheel number 1) is driven by the servo motor and transmitted to the conveyor system, then the driven wheel (wheel number 2) rotates. This third wheel is a Halbach array arranged in a concentric circular profile. Which acts as a magnetic field source during the machining process. The polishing liquid is pumped up from the solution tank and adhered to the conveyor surface. The workpiece is mounted on a specialized fixture and rotated by the servo motor, then the abrasive solution is moved on the machined surface . After completing a cycle , the magnetic polishing solution is collected back into the tank . This cycle is repeated continuously until the surface reaches the required roughness.

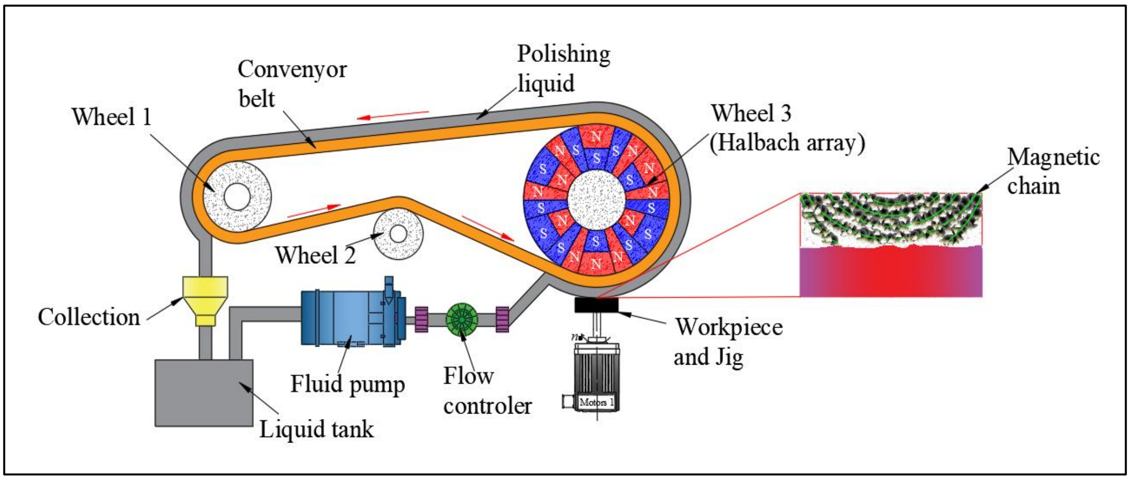

Figure 1 Working principle of magnetic polishing model.

In Figure 2 , is the cross-sectional image of the polishing block established according to the circularly arranged Halbach array theory . The circular Halbach array is made of NdFeB magnets and has an outer diameter of 80 mm, the magnet length is 2 5 mm. The North and South poles of each magnet are indicated by different colors as described in Figure 1. Furthermore , the circular Halbach array generates a magnetic field array characterized by a concentrated impact force and an impact direction set to point from the center of the magnet wheel to the outside of the conveyor.

The red lines and arrows in Figure 3 represent the magnetic induction directions , describing the trajectories of the polishing solution affected by the magnetic field lines . In the machining zone, the magnetic solution is subjected to two forces FX and FY, which are oriented along the magnetic field lines in the x and y directions. The expressions for these forces are given by the following equation [14] :

$$F_X = \theta \times V \times \lambda_0 \left[\frac{H \partial H}{\partial x} \right] \tag{1}$$

$$F_Y = \theta \times V \times \lambda_0 \left[\frac{H \partial H}{\partial y} \right] \tag{2}$$

In which: V represents the volume of the magnetic particle, θ Δ represents the magnetic susceptibility of the magnetic particle, H and λ the magnetic field density and the vacuum permeability. The slope in the x,y direction is determined by $\frac{\partial H}{\partial x}$, $\frac{\partial H}{\partial y}$. So the magnetic force acting on the solution has the formula as described below:

$$F = F_X \times \sin\left(\mu_i\right) + F_Y \times \cos\left(\mu_i\right) \tag{3}$$

In there , μ_i the angle of inclination of the magnetic field line. The magnetic force is determined by FM with the following mathematical expression:

$$F_M = \frac{3}{2} \mu_0 \times \left(\pi R^2\right) \times \left(\frac{{X_R}^2 H^2}{(3 + X_R)^2} \right) \tag{4}$$

Where : R represents the radius of the magnetic particle, XR is the specific magnetic susceptibility of the magnetic particle and m0 is the permeability of the vacuum. Through the interaction between the particles and the magnetic field, the semi -solid polishing agent adheres tightly to the conveyor belt and is transmitted. along the conveyor belt illustrated in Figure 1.

2.2. Method of generating magnetic field for magnetic polishing model.

With the aim of increasing the magnetic field strength to achieve maximum efficiency For this polishing process , a magnet pole arrangement method called Halbach array was applied. used. COMSOL multiphysics simulation software is used in this study to conduct simulation of Halbach magnet array. Figure 2 describes the characteristics of the Halbach array method used in this study. The Halbach array originates from its unique structural design, which minimizes energy loss while maximizing the magnetic field of the magnet used [15] . For this magnetic polishing method , the Halbach array is applied, which consists of different magnets arranged in a circular concentric structure with an outer diameter of 80 mm, a hole diameter of 30 mm, and a thickness of 25 mm . The findings are presented in Figure 2, which illustrates the results obtained during the simulation . Furthermore, Figure 2 also provides details on the magnitude of the magnetic field generated by the Halbach array. In addition , Figure 2 shows the magnitude of the magnetic field in the polished area and gradually increases towards the edge of the Halbach array profile . Figure 3 illustrates the distribution of the generated magnetic field lines. The simulation results give a magnetic flux magnitude of 0.6T.

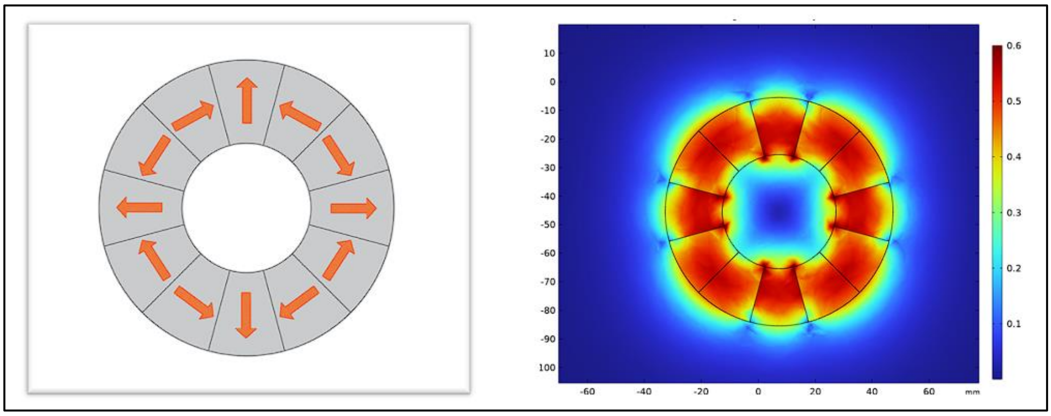

Figure 2 . Detail of the Halbach array used.

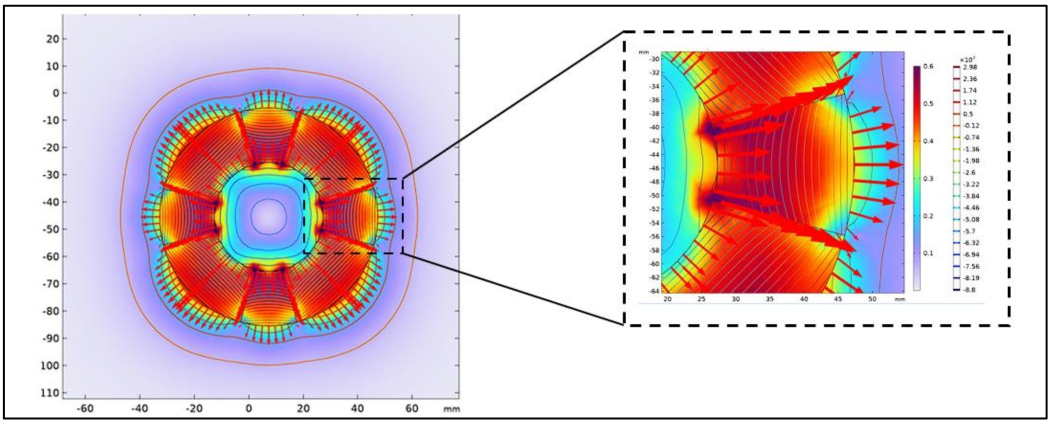

Figure 3. Magnetic field distribution

2.3. Polishing area and range.

Before examining the properties of the polishing operation and the pressure distribution in the machining zone , it is necessary to first determine the profile of the polishing zone . This zone is determined by the contact point regions between the polishing tool and the workpiece surface, forming a shape with a profile very similar to the polishing tool profile we created . Based on the magnetic field analysis information given in section 2.2 , it can be seen that the polishing zone has a shape quite similar to a perfect ellipse . However, during the polishing process During the process, the polishing solution is stretched, compressed , deformed and changes many states when acting on the surface of the workpiece, causing its shape to deviate from the perfect ellipse.

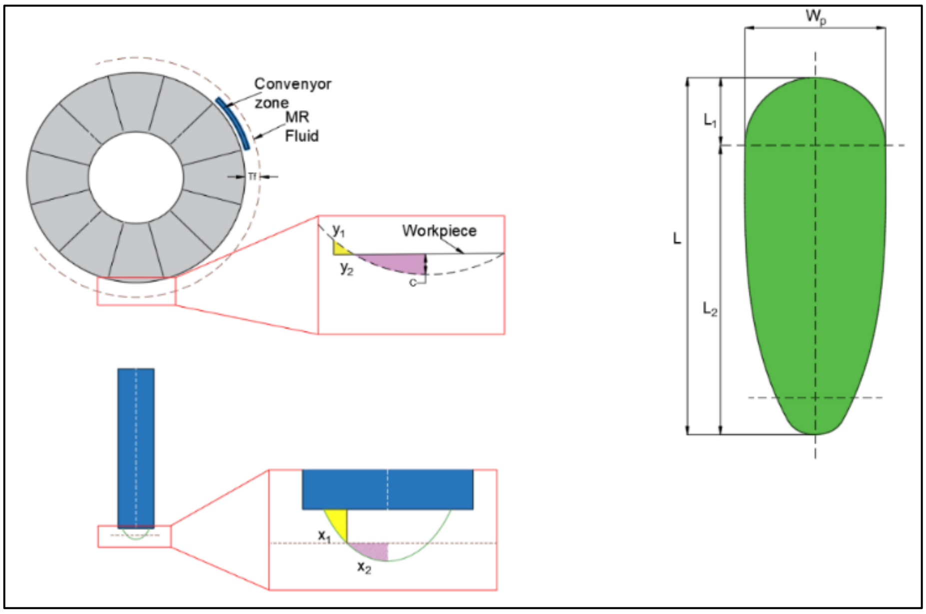

Figure 4. Schematic illustration of a) fluid compressed in the y direction, b) Fluid compressed in the x direction, c) Polished area.

Before establishing the stress field distribution zone in the machining area , it is necessary to determine the zone. the polishing zone boundary according to different parameters. When the magnetic polishing fluid enters under the influence of a magnetic field , it changes from liquid to semi-solid and they bonded together into a strip consisting of abrasive grains . We examined the polishing profile changes due to variations in the working depth of the abrasive grain strip . The value of y2 in Figure 4 can be determined using equation (5):

$$y_2^2 = \left(\frac{D_s}{2}\right)^2 - \left(\frac{D_s}{2} - P\right)^2 \tag{5}$$

As shown in the diagram from Figure 4 , the polished region is formed from different regions. For regions y2 and y1, their magnitudes are determined through the following formula:

$$q = y_2 - y = \frac{D_s}{2} - P - \sqrt{\left(\frac{D_s}{2}\right)^2 - (y_2)^2} \tag{6}$$

$$\left(\int_{y_1}^{y_2} q dy\right) = -\left(\int_{y_2}^{0} q dy\right) \tag{7}$$

Where : D s is the diameter (mm) of the polishing tool and P is the depth of the contact area (mm). From here, the length of the polished region can be calculated as follows:

$$L = |y_2| \tag{8}$$

The width of the polished zone (W f) can be calculated similarly to the process of determining the length of the polished zone (L) in the case where the pressure outside the polished zone is equal to or approximately 0. From here, a vertical section of the polished zone on the workpiece surface can be established through a geometric method, the result of which is shown in Figure 4. This zone is divided into two parts, the back zone and the front zone determined through the following formulas (9) and (10) respectively :

$$x^2 \frac{1}{\left(\frac{W_f}{2}\right)^2} + \frac{(y+L_1)^2}{(L_1)^2} \le 1 \left\{ x \in \left[\frac{-W_f}{2}; \frac{W_f}{2}\right], y \in [-L_1; 0) \right\} \tag{9}$$

$$x^2 \frac{1}{\left(\frac{W_f}{2}\right)^2} + \frac{\left(y+L_1\right)^2}{\left(L_2\right)^2} \le 1 \left\{ x \in \left[\frac{-W_f}{2};\frac{W_f}{2}\right], y \in \left[-L_2;-L_1\right) \right\} \quad (10)$$

In which : L1 and L2 are the length from bottom to center and from center to top of the machined area respectively , W f is the width of the machined area.

2.4. Shear stress at the polished area.

For the magnetorheological solution in the polishing process, its viscosity index is not a constant but depends on other parameters: particle density, flow rate, etc. This means that the polishing solution is a kind of non-Newtonian material . In this situation , the shear stress in the polishing zone generated by the tool on the workpiece surface can be determined through the Reynolds equation [16] . The Reynolds equation is described as follows (11):

$$\frac{\partial}{\partial y}\left(\frac{G^3}{\eta}\frac{\partial p}{\partial y}\right) + \frac{\partial}{\partial x}\left(\frac{G^3}{\eta}\frac{\partial p}{\partial y}\right) = 6V\frac{\partial G}{\partial y} \quad (11)$$

In which : G is the working distance (mm), V is the relative speed of the conveyor (rpm), p is the shear stress in the area.

In this polishing model , the distance between the conveyor belt and the workpiece surface (G) is one of the parameters that greatly affects the polishing process, adjusting this parameter can change and improve the material removal ability [17, 18] . For areas with higher cutting pressure, it means that the material removal occurs more effective , this is also related to the polishing profile as analyzed previously . When moving gradually to the edge and out of the machining area , the abrasive grain is no longer compressed or affected by the magnetic field caused by the magnet array , leading to the cutting pressure gradually weakening and becoming almost zero at the edge . Furthermore , as G decreases, the abrasive grain is compressed more strongly , causing the cutting pressure to also increase . This is also completely reasonable compared to the previous analysis. This parameter can be determined through formula (8). In the case of a stable fluid flow , meaning that the fluid thickness (Tf) does not change, changing the working distance also means changing the depth of the polishing zone (C).

$$G = T_f - C \quad (12)$$

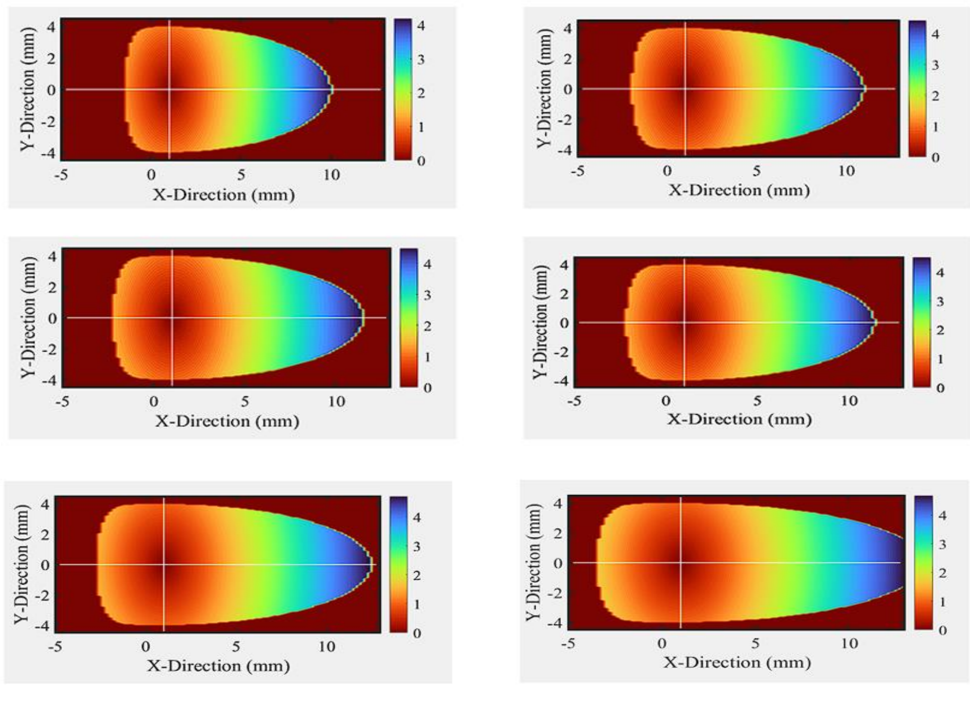

Figure 5. Polished area at working distances a) G=0.45(mm); b), G=1(mm); c) G=1.55(mm); d) G=2.0(mm); G=2.5(mm); G=3(mm).

III. CONCLUSION.

This study presents a Magnetically Controlled Finishing (MRF) process using abrasive fluid, in which the integration of Halbach magnet arrays is a prominent feature to enhance the magnetic field control. The objective of the study is to optimize the polishing process by taking advantage of the unique magnetic flux orientation properties of the Halbach arrays, thereby significantly improving the control of the force and magnetic field distribution acting on the machined surface.

Through theoretical analysis combined with numerical simulation using the finite element method with COMSOL multiphysics software, we have confirmed the important role of the Halbach array in creating a magnetic field with uniform magnitude and direction, concentrated in the machining area. The research results have allowed us to establish a process for designing and assembling the magnet array according to the Halbach principle, and at the same time determine the amplitude and distribution of the magnetic flux generated from this structure in detail.

In addition, the study also shows the shape of the impact zone (also known as the machining contour zone) that the model creates on the surface of the part. We have built mathematical expressions describing the relationship between process parameters and the geometry of the impact zone, thereby helping to accurately predict the efficiency of the polishing process under different conditions. Furthermore, mechanical factors such as stress in the cutting zone, contact force between the abrasive grain and the workpiece surface, as well as the influence of parameters such as rotation speed, gap distance, MRF fluid viscosity, etc. are all carefully analyzed and calculated.

The obtained results not only clarify the working mechanism of the Halbach array-enhanced MRF polishing method, but also open up the prospect of wide application of this method in precision machining processes, especially for difficult-to-machine materials such as technical ceramics, sapphire, or advanced optical materials. With this goal in mind, we aim to continue researching and improving equipment, conducting experimental tests, and gradually transferring technology to industrial production fields that require high precision and surface quality.

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