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# Research on the Mechanism of High Precision Planar Magnetic Grinding

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***Abstract:*** *Magnetic grinding is a machining technique that utilizes the action of a magnetic field to remove materials and polish the surface of workpieces. Magnetic abrasive particles, as grinding tools in magnetic grinding, have a crucial impact on the grinding performance. At present, magnetic grinding particles are mainly composite particles, composed of iron-based phase and grinding phase, which have much better performance than ordinary grinding particles. Magnetic abrasive particles, due to the effect of magnetic field force, accumulate in large quantities on the magnetic poles and form magnetic strings in the machining gap. Magnetic abrasive particles attract each other along the direction of the magnetic field to form magnetic brushes. Magnetic brushes have good flexibility and elasticity, strong adaptability to machining objects, and can grind the inner and outer surfaces of flat, curved, and complex shaped parts. The grinding trajectory has an impact on the results, and under the same processing conditions, the surface uniformity after using a circular curve trajectory is better than that of a sine curve trajectory and a spiral curve trajectory.*

***Keywords:*** *High Precision; Magnetic Grinding; Mechanism; Grinding Particles; Force Analysis; Grinding Trajectory*

## 1. Introduction

With the development of modern manufacturing technology, the requirements for surface finishing and edge precision machining of parts are becoming increasingly high. The finishing technology is based on improving the surface quality of parts. After finishing, the surface of parts exhibits low surface roughness and good surface micro geometric morphology. It not only has good appearance quality, but also has characteristics such as wear resistance, corrosion resistance, and fatigue resistance. Magnetic grinding is an advanced processing technology that applies magnetic field energy to traditional grinding. The magnetic field force generated by the magnetic pole acts on the magnetic abrasive, and the magnetic brush exerts relative motion with the workpiece to grind the surface of the workpiece[1]. Magnetic brushes have good flexibility and elasticity, strong adaptability to machining objects, and can grind the inner and outer surfaces of flat, curved, and complex shaped parts[2]. Magnetic grinding is an effective finishing method with the characteristics of high efficiency, high precision, and high surface quality. It is suitable for processing flat, spherical, cylindrical, and other complex shaped parts, and can control grinding efficiency and precision. Magnetic grinding technology can also be well combined with CNC machine tools, machining centers, and robot technology to achieve automation in finishing machining.

Magnetic grinding has conducted extensive research both domestically and internationally, and has achieved many excellent results. Singh Dhirendra K designed a resistance type force sensor to measure the magnetic force generated in magnetic grinding and the cutting force of abrasive brushes, and simulated a linear regression model for the surface roughness, magnetic force, and cutting force of the workpiece after magnetic grinding [3]. Jayswal SC conducted theoretical research on the magnetic grinding process by establishing a finite element model of the magnetic force distribution on the surface of the workpiece, and constructed a theoretical model for material removal and surface roughness in precision grinding [4]. Singh R K studied the changes in surface temperature of workpiece samples during magnetic abrasive machining and verified the correctness of the model through experiments on aluminum alloys [5]. Domestic scholar Wu Guoxiang studied the magnetic field distribution between the magnetic pole head and the specimen during magnetic grinding of cylindrical non-ferromagnetic and ferromagnetic specimens. During the magnetic grinding process, the ferromagnetic sample will be magnetized and the magnetic induction strength of the machining gap will be strengthened. At this point, due to the magnetic abrasive particles in the machining gap being subjected to a magnetic field force pointing towards the center of the sample, the magnetic abrasive is adsorbed on the surface of the sample, thus preventing the splashing of magnetic abrasive particles when the sample rotates. However, due to the inability of non ferromagnetic samples to be magnetized, the magnetic force on the surface of the magnetic abrasive particles cannot provide sufficient grinding force. The method of adding a magnetic source at the processing position to strengthen the magnetic field strength between the magnetic pole head and the sample has achieved good results.

## 2. The Mechanism of Magnetic Grinding

The magnetic abrasive brush used in magnetic grinding technology is different from traditional rigid tools. It is formed by free magnetic abrasive particles through the action of a magnetic field, and has a certain degree of flexibility and viscoelasticity. In the process of magnetic abrasive machining, the magnetic abrasive brush can change with the shape of the workpiece, so it can not only process outer circles, spherical surfaces, and flat surfaces, but also free form surfaces. Magnetic grinding is a new process technology that combines magnetic field effects with traditional grinding techniques. Using a magnetic field to distribute magnetic abrasive particles in the direction of magnetic field lines to form a magnetic abrasive brush, which is applied to the relative motion between the workpiece and the magnetic abrasive brush, achieving the grinding technology of material removal. Magnetic abrasive particles are placed in the magnetic field between the magnetic pole and the workpiece. The magnetic abrasive particles fill the machining gap, and due to the effect of the magnetic field, the magnetic abrasive particles are magnetized and arranged in an orderly manner into magnetic brushes. The magnetic abrasive particles press on the surface of the workpiece, generating a vertical force with a pressure of:

$$P = \frac{B^2}{2\mu_0}\left(1 - \frac{1}{\mu_m}\right) \tag{1}$$

In the above equation, *B* represents the magnetic flux density of the processing area, $\mu_0$ represents the vacuum magnetic permeability coefficient, and $\mu_m$ represents the relative magnetic permeability coefficient of the magnetic abrasive particles.

The grinding pressure generated by magnetic abrasive particles is related to the magnetic flux density in the processing area and the relative magnetic permeability of the particles themselves, always pressing towards the surface of the workpiece. When the magnetic pole rotates, the magnetic particle brush will move relative friction with the workpiece surface along with the rotation of the magnetic field, and perform grinding processing under the action of pressure. When the magnetic abrasive brush rotates during machining, the magnetic abrasive particles will be subjected to centrifugal force, resulting in a tendency to fly away along the tangent direction of the rotational motion. At this point, the magnetic field will have a holding force that binds the magnetic abrasive within the processing area to ensure smooth grinding processing. The main factors affecting the effectiveness of magnetic abrasive machining include magnetic field strength, machining clearance, relative velocity between magnetic particle brush and workpiece surface, magnetic pole shape, magnetic properties of magnetic abrasive particles, and abrasive particle diameter.

## 3. Force Analysis of Magnetic Grinding Particles

During magnetic abrasive finishing, the force exerted on the grinding particles under the action of the magnetic field is F, which is mainly the magnetic field force. The force between the grinding particles is relatively small and therefore ignored. The magnetic field force is decomposed into forces along the direction of the magnetic induction line and forces perpendicular to the direction of the magnetic induction line [6].

Force in the direction of magnetic induction line:

$$F_x = V_0 \chi H \frac{\partial H}{\partial x} \tag{2}$$

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Force in the direction of vertical magnetic induction line:

$$F_y = V_0 \chi H \frac{\partial H}{\partial y} \tag{3}$$

The force received under the action of a magnetic field:

$$F = \sqrt{F_x{}^2 + F_y{}^2} = V_0 \chi H \sqrt{\frac{\partial H^2}{\partial x} + \frac{\partial H^2}{\partial y}} \tag{4}$$

In the above equation, $V_0$ is the volume of a magnetic abrasive particle, in units of $\mu m^3$; $\chi$ is the magnetic susceptibility of magnetic abrasive particles; *H* is the magnetic flux density, i.e. the magnetic induction intensity, in units of $A/m$; $\frac{\partial H}{\partial x}$ is the rate of change in magnetic induction intensity in the *X* direction, and $\frac{\partial H}{\partial y}$ is the rate of change in magnetic induction intensity in the *Y* direction. If the shape of the grinding particles is regarded as a sphere, it can be obtained that:

$$F \propto = D^3 \chi H \left(\partial H / \partial x\right) / \left(\partial H / \partial y\right) \tag{5}$$

In the above formula, *D* is the diameter of the grinding particle, and the magnetic field force is directly proportional to the diameter of the grinding particle. The larger the particle diameter is, the larger the magnetic field force is, and it is related to the magnetic induction intensity, the magnetic susceptibility of the particle and the change rate of the magnetic induction intensity.

## 4. Grinding Particle Ratio

In magnetic abrasive finishing technology, magnetic abrasive particles are aggregated into magnetic abrasive brushes under the action of an external magnetic field, which serve as grinding and cutting tools, affecting the efficiency and effectiveness of the magnetic abrasive finishing process. Therefore, the research on the preparation process of magnetic abrasive particles and the required materials plays a crucial role in the development of magnetic abrasive finishing technology. At present, magnetic grinding particles are mainly composite particles, composed of iron-based phase and grinding phase, which have much better performance than ordinary grinding particles. After adding magnetic abrasive particles to the magnetic needle, the cutting edge that plays a grinding role changes from the original end face of the magnetic needle to the grinding phase of the magnetic abrasive particles, improving the material removal amount; Magnetic needles can squeeze magnetic abrasive particles into small grooves, achieving grinding processing of small grooves and improving the uniformity of grinding. The best grinding effect is achieved when the mass ratio of the magnetic needle and magnetic grinding particles is 1:2. The magnetic needle magnetic grinding process has a wide range of applicability for complex and micro workpieces, and has unique advantages compared to traditional finishing processes [7].

The magnetic susceptibility of magnetic abrasive particles is determined by the magnetic properties and volume fraction of the ferromagnetic and abrasive phases. When the external magnetic field reaches saturation magnetization, further increasing the magnetic field strength does not increase the magnetic force experienced by the particles. In addition, the size of the machining gap directly affects the magnetic force acting on the magnetic abrasive particles in the machining area. The smaller the machining gap, the greater the magnetic force. However, if the machining gap is too small, it will lead to a decrease in the number of magnetic abrasive particles and reduce their rolling degree, which in turn will lead to a decrease in machining efficiency and quality. Therefore, there exists an optimal value for the magnetic flux density in the machining gap under specific working conditions. According to J D. Kim's research shows that the maximum grinding pressure is obtained when the magnetic flux density in the machining gap is 1.2T. For the processing of magnetic materials, the machining gap is the distance between the grinding magnetic pole head and the workpiece. The size of the machining gap is closely related to the magnetic resistance in the magnetic circuit. As the machining gap increases, the magnetic resistance in the magnetic circuit increases, the magnetic leakage increases, the magnetic induction intensity weakens, and ultimately leads to a decrease in the machining ability of the magnetic abrasive particles, affecting the machining effect; On the other hand, it is directly related to the amount of magnetic abrasive particles filled. The selection of machining gap size directly affects the efficiency of magnetic abrasive finishing and the surface integrity after machining.

The influence of magnetic abrasives with different particle sizes on the surface quality of workpieces varies. As the particle size of magnetic grinding particles decreases, the efficiency of grinding processing shows a decreasing trend, but the surface roughness of the workpiece after grinding is inversely proportional to the abrasive particle size. The smaller the particle size, the lower the surface roughness value. Due to the small machining gap caused by the increase in abrasive particle size, on the one hand, it will increase the grinding pressure and increase the initial machining efficiency. However, the grinding particles will cause deeper scratches on the surface of the workpiece, thereby affecting the surface roughness after machining; On the other hand, if the machining gap is too small, the abrasive particle size increases, and the amount of magnetic abrasive filled in the same space decreases. The increase in grinding pressure will also increase the centrifugal force. When the magnetic pole head rotates, a large amount of abrasive will be thrown away, thereby affecting the machining effect. Excessive machining clearance can result in lower grinding pressure in the machining area, causing magnetic abrasive particles to form a sliding polishing effect in the machining area, thereby affecting machining efficiency and grinding quality.

Due to the limitation of the stator coil winding, the grinding container barrel of the electromagnetic grinding equipment is smaller than that of the permanent magnet grinding device, which limits the movement range of the magnetic needle and affects the processing effect. To improve the processing efficiency of electromagnetic needle magnetic grinding, a certain amount of magnetic grinding particles are mixed into the magnetic needle to assist in magnetic needle magnetic grinding, in order to improve the grinding efficiency and improve the grinding effect. The grinding pressure of loose abrasive increases approximately linearly with the increase of iron particle content. In the process of magnetic grinding, as the content of iron particles in loose abrasive increases, the number of abrasive particles decreases, and the number of cutting edges also decreases. As a result, the amount of metal cut is also reduced, and the original cutting marks on the workpiece cannot be completely removed quickly, resulting in unsatisfactory processing quality and efficiency. Therefore, there exists an optimal content and particle diameter for iron particles in loose abrasives.

## 5. The Impact of Grinding Trajectory on the Results

The process of magnetic grinding is actually the process of abrasive particles cutting the surface of the workpiece. The motion of the abrasive particles directly affects the machining accuracy and production efficiency of grinding. Reasonable selection of motion mode and machining trajectory is extremely important for magnetic grinding [8]. The grinding motion trajectory should ensure that each point on the machining surface of the workpiece and the surface of the tool magnetic pole has the same or similar cutting conditions and cutting conditions. The movement of the tool magnetic pole should ensure that each point on the workpiece has the same or similar grinding stroke, and avoid periodic repetition as much as possible. The grinding motion should strive to be smooth and avoid corners with excessive curvature as much as possible [9].

(1) Sinusoidal curve trajectory. This article calculates the amplitude, period, and phase of the sine curve based on the surface size of the workpiece, and then substitutes the parameters into the sine curve expression to draw the sine curve path. The expression for the sine curve trajectory function is [10]:

$$Y = A\sin\left(\omega t + \phi\right) \tag{6}$$

In the above equation, $A$ represents amplitude, $\omega$ represents period, and $\phi$ represents phase. The starting point is the origin of the $X$-axis and $Y$-axis, and the magnetic pole spindle starts from the origin and completes the magnetic machining of the workpiece along the sine curve.

(2) Spiral curve trajectory. This article designs corresponding geometric parameters based on the length and width of the workpiece, referring to the mathematical model of the helix, and then inputs the parameters into the helix curve expression to draw the helix curve path. The expression for the spiral curve function is:

$$\begin{cases} Y = r\sin\left(t\right) \\ X = r\cos\left(t\right) \end{cases} \tag{7}$$

In the above equation, $r$ is the radius of the circular surface, that is, the distance from the point to the central axis; $t$ is the angle between the projection of the line connecting the point and the origin on the $XOY$ reference plane and the $X$-axis. The magnetic pole spindle starts from the origin and completes magnetic machining of the workpiece along the spiral curve.

(3) Circular curve trajectory. The magnetic pole spindle first follows a circular trajectory along the XOY plane, and then gradually moves towards the X-axis along the length direction of the workpiece. The processed trajectory is a circular ring tightly fitted with a circular ring shape, hence it is called a circular line. The expression for the circular line function is:

$$\begin{cases} (x-a)^2 + y^2 = R^2 & 0 \le x \le 2R \\ X = x+2 & x = 0,2,4,6,\cdots \end{cases} \tag{8}$$

In the above equation, the origin of the circle is $(a,0)$ and the radius is $R$, which needs to be determined based on the length and width of the workpiece. The magnetic pole spindle starts from the origin and completes magnetic machining of the workpiece along the circular curve.

The impact of grinding trajectory on the results is as follows: under the same processing conditions, the surface uniformity after using circular curve trajectory is better than that of sine curve trajectory and spiral curve trajectory. The reason is that under the same processing conditions, the workpiece processed using circular curves has a larger processing area than sinusoidal and helical curves. Therefore, under the same conditions, circular curve processing is given priority. Under the same processing conditions, the surface roughness of the workpiece processed using circular curves is better than the other two trajectories. The reason is that the circular curve has a stronger repeatability on the same surface domain than the other two trajectories. The surface of the same surface domain is polished multiple times during the circular curve path rotation process, which improves the efficiency of the workpiece's polishing processing. When using circular curve workpieces for magnetic finishing, it is necessary to adjust the curve equation based on the length, width, and height parameters of the workpiece, in order to further convert it into a debugging machine program. Corresponding processing is carried out on the debugged machine program to ensure the universality of the processing.

The grinding motion should meet the following points: the grinding motion should ensure that the magnetic abrasive particles are in uniform contact with the workpiece, so that the surface of the workpiece is uniformly loaded, in order to improve the surface accuracy of the workpiece; The grinding path of magnetic abrasive particles on the surface of the workpiece has a significant impact on whether the surface grinding of the workpiece is uniform. Grinding should adopt parallel motion as much as possible to ensure the connection between any two points on the surface of the workpiece. It is important to maintain parallelism throughout the entire grinding motion to ensure the geometric accuracy and dimensional uniformity of the workpiece; During magnetic grinding, the motion trajectory of the grinding tool should continuously and regularly change direction, so that countless cutting marks on the surface of the workpiece are regularly interlaced with each other, and the smoother the grinding, the higher the surface accuracy of the workpiece; Select the optimal grinding speed according to different grinding process requirements; The entire grinding process should strive for smooth motion, especially for workpieces with small and slender grinding areas. It is important to pay attention to the slow change in the direction of grinding motion and avoid small bends, otherwise, due to the unstable grinding motion, problems such as uneven grinding of the workpiece surface, edge and angle loss may occur; During the grinding process, the magnetic abrasive particles should always be in a floating state with the workpiece, which can enable better contact between the abrasive particles and the surface of the workpiece.

## 6. Conclusions

Compared with traditional grinding and polishing methods, magnetic abrasive finishing has many advantages: firstly, it has good flexibility and adaptability. In a magnetic field, magnetized abrasive particles rely on the force of the magnetic field and the magnetic attraction between them to non rigidly solidify together to form an abrasive brush. The shape of the abrasive brush can change with the shape of the workpiece during processing, demonstrating excellent flexibility and adaptability. Secondly, it has good self sharpening ability. The relative motion during machining causes the abrasive particles to slide along the machining surface while rolling, and the abrasive particles constantly change positions, giving them excellent self-sharpening properties. Unlike ordinary grinding wheels, which have blockage and particle passivation, it greatly improves machining efficiency. Thirdly, the grinding pressure is highly controllable. The processing pressure of magnetic grinding can be adjusted by changing the current, making it relatively easy to control. Fourthly, it has a wide range of applications. Magnetic machining can not only be used for finishing, but also for deburring, chamfering, and rust removal. Not only can it process flat surfaces, inner and outer cylindrical surfaces, and spherical surfaces, but it can also process complex curved surfaces, and even workpieces that cannot be processed by ordinary processing methods. Fifthly, it can strengthen the surface of the workpiece. While finishing the workpiece, not only can residual tensile stress generated during mechanical processing and grinding be removed, but also a reserved compressive stress can be formed to improve the fatigue strength of the workpiece.

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