DOI 10.52209/2706-977X_2022_4_37 **UDC 669.094(075.8)**

Features of Magnetic Field Modeling for Magnetic-Abrasive Treatment of Complex-Profile Surfaces

Akulovich L.M. [1], L. E. Sergeev LE.[1], Mendaliyeva S.I[2], Sherov K.T.[2]
[1] Belarusian State Agrarian and Technical University, Minsk, Belarus
[2] Seifullin Kazakh Agrarian and Technical University, Astana, Kazakhstan

Abstract. The process of modeling a magnetic field under magnetic abrasive machining of complex surfaces of engineering products is considered. Spherical shapes and surfaces of small-modular gears are considered as complex-profile surfaces. The intensity and magnetic induction of the magnetic field are determined, by which the effectiveness of the magnetic abrasive processing method is evaluated. The optimal values of the angle α in the processing zone have been identified, affecting the surface quality of the products with the magnetic abrasive processing method. The results of the dependence of the relative induction β on the value of the angle α are presented.

Keywords: magnetic abrasive machining, ferro-abrasive powder, surface, quality, magnetic induction, hardness.

Introduction

One of the most common forms of composite surfaces is a spherical shape. It is known that the technology of finishing spherical parts, in particular finishing, is based on the contact interaction of the tool and the part by their mutual wear. The kinematics of the process consists in the simultaneous rotation of the leading link in the form of a part and the driven link or lapping elastically pressed against it through a ball joint. In this case, the lapping axis passes through the axis of rotation of the part and is inclined to the axis of the formed sphere at a certain angle [1]. This process is characterized by the complexity of the mutual influence of the main technological factors, which are amenable only to indirect control.

The complexity of processing such a surface is due to the lack of guaranteed three-axis rotation of the parts, which does not make it possible to obtain a high percentage of uniformity of surface treatment. Other problems are the variability of the free rotation speed of the tool, the high gradient of the cutting speed vector and the uneven contact pressure between the tool and the part due to the presence of so-called loops and return points of the trajectory. The result of this effect is the absence of the same thickness of the removed allowance, which leads to a decrease in quality and accuracy. This problem can be solved by using magnetic abrasive treatment (MAO) of the surface, where a change in the magnitude and direction of the magnetic flux in the processing zone creates a magnetic field that changes the position of the axis of rotation of the ball and informs the ferroabrasive tool planetary motion around the product [2]. This ensures the uniformity of metal removal and the accuracy of the geometric shape of the workpiece.

1. Research methods

The calculation of the electromagnetic field in any electrical device is determined by the shape of the surface that separates media with different physical and mechanical characteristics in the field of its existence. The complexity increases when it is necessary to take into account the nonlinearity of the media, depending on the values characterizing the electromagnetic field such as the magnetic permeability of the medium and the field strength. With MAO, the movement of media, i.e. the tool and the ball, should also be added. Therefore, it is necessary to present calculations of electromagnetic field studies in an analytical form. It is known that there is a certain feature of the calculation associated with the physical modeling of the field and consisting in the implementation of the assumption condition. An example of this is that the displacement current inside the conductors can be neglected, unlike the conduction current. The expediency of choosing a coordinate system, since the differential equations for vector quantities H and B also depend on time, is determined by the nature of the problem. This is due to the minimization of funds and costs for solving extremely complex boundary-value problems. Another problem in choosing a determinant is the identification of the sign when considering the increment or decrease of the function on elementary sites. However, the need to get an idea of the MAO process of spherical surfaces requires the establishment of a research method and a model in which the phenomena are completely or mostly of the same physical nature as the original. This greatly facilitates obtaining the necessary results due to the choice of the most acceptable ranges of changes in the physical quantities and geometric dimensions of the machined parts.

A sample for physical modeling is a sphere rotating with a frequency of n and located in a magnetic field. The task is to determine the magnetic field strength, considering the field on the axis of the circular current to be known, by its direct integration.

The magnetic field strength on the axis of rotation at the point M (Figure 1), due to the current dI, is equal to:

$$dH = dH_z = dI\frac{\sin^3\beta}{2r}.$$

According to Figure 1, the relations follow:

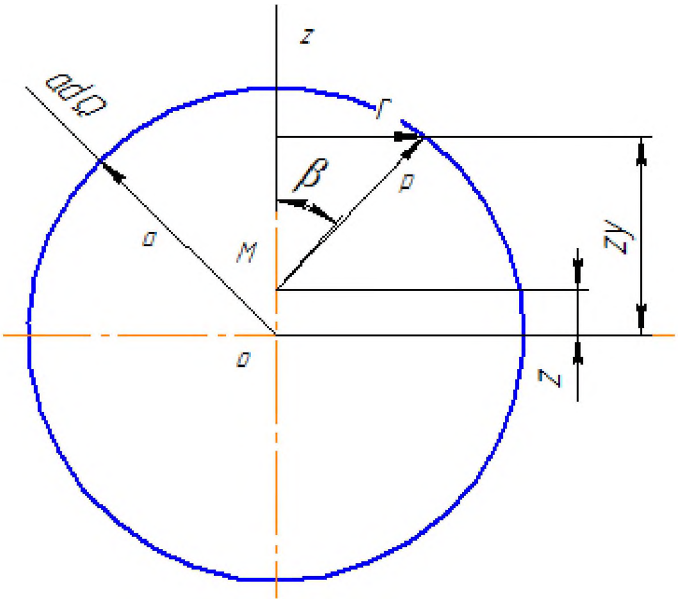
$$\sin\beta = \frac{r}{\rho};\quad r^2 = a^2 - z^2;\quad \rho^2 = z^2 + a^2 - z_{\text{э}}z.$$

Therefore, $d\Theta = -\frac{dz_{\text{э}}}{z}$ and $z_{\text{э}}dz = -\rho \cdot d\rho,$

$$d = \frac{-\rho^4 + 2\rho^2(z^2 + a^2) - (a^2 - z^2)}{\rho^2}dS.$$

Substituting these values into expressions for dH, we get:

$$d = -\frac{I}{16az^3}\cdot\frac{\rho^4 + 2\rho^2(z^2 + a^2) - (a^2 - z^2)}{\rho^2}dS.$$



z - is the distance from the center of the ball to the point of determining the intensity of MF, m; a - is the radius of the ball, m; β - is the angle between the Z axis at the point of determining the intensity of MF

Fig. 1. - Diagram for determining the magnetic field strength when using MAP

Integrating this expression by ρ, we get:

$$H = -\frac{I}{16az^3}\cdot\left[\frac{\rho^3}{3} - 2(z^2+a^2)\rho - (a^2-z^2)\frac{1}{\rho}\right].$$

The field outside the sphere defining the z coordinate, which varies from $-\infty$ to $-a$ and from a to $+\infty$, is found as:

$$H = \frac{Ia^2}{3z^3}.$$

3. Results and discussion

Thus, analyzing the obtained expression, we can conclude that the most optimal range of processed ball sizes are diameters of 2-10 mm. This is due to the fact that the required magnitude of the magnetic field strength at MAP is represented by a numerical value equal to 100-500 $A\bullet m^{-1}$. The maximum theoretically possible for MAP is the size of the ball d = 15 mm.

Another common form of complex-profile surfaces is the surface of small-modulus gears, one of the methods of obtaining which is cold rolling, providing an accurate tooth profile [3,4].

During the rolling process, the processed gear wheel and the knurling tool, which has the shape of a cylindrical gear wheel, are in a non–locking engagement. As a result of the relative sliding of the profiles of the teeth of the workpiece and the tool on opposite sides of the wheel tooth, the allowance material flows in different directions. On the driven side of the wheel tooth profile, the metal moves from the head and leg of the tooth to the dividing circle. As a result, the metal is covered on the dividing circle – a protrusion is formed. On the opposite side of the tooth profile, the metal moves from the dividing circle to the head and leg of the tooth, which is why a depression appears in the zone of the dividing circle. Due to the flow of metal towards the tooth head, the outer diameter of the processed wheel increases (a horn-shaped growth is formed). The different nature of deformations and metal flows on both sides of the teeth create difficulties in obtaining a symmetrical profile of the wheel tooth. In order to obtain satisfactory results, a different correction is introduced on each side of the knurler tooth, but it is impossible to completely eliminate the horn-shaped influx.

In practice, the optimal way to solve this problem is grinding along the outer diameter of the gear wheel after quenching. As a result of grinding, a lot of burrs and burns are formed, which requires subsequent finishing. To date, for this purpose, the following are used: lapping, tooth honing, electrochemical treatment. However, these methods have a number of characteristic disadvantages. These include: high duration of the processing process, low tool life, environmental harmfulness of production, constant installation and dismantling of the lapping system (drive, relative location), frequent lapping mass, the need for disposal of spent abrasive, high qualification of the worker and the cost of the tool.

The removal of metal at MAP is carried out as a result of the force action of the powder on the surface of the part and the specified relative movements. The processed part 1 is placed between the pole tips 2 of the electromagnetic system with an established gap δ, in which the FAP is fed (Figure 2).

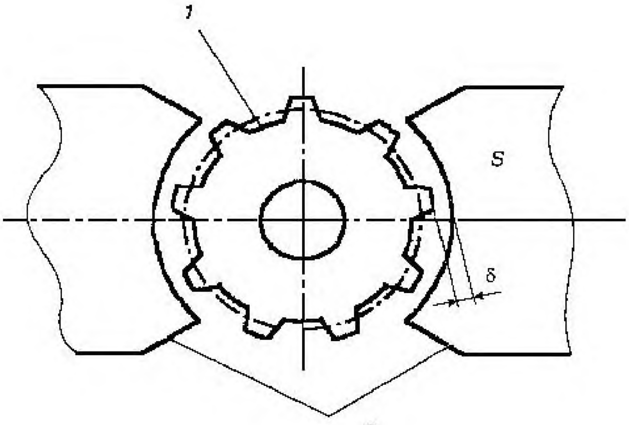


Fig.2. - Diagram of magnetic abrasive treatment of gears

For a discontinuous surface, the distribution of the magnetic flux is largely in the nature of uncertainty. This is due to the desire of the magnetic flux to carry out its passage through an energetically advantageous section of the magnetic circuit. The problem of the MAP of gears is the complexity of processing the variable diameter of the circles of their protrusions and depressions. This is due to the fact that as you move away from a conductor with a current around which, according to Ampere's law, there is a field, the latter weakens. A drop in the field strength, which is its power characteristic, leads, respectively, to a decrease in the pressure of the ferroabrasive powder (FAP) on the treated surface, and ultimately to a decrease in the removal of the material. In connection with the above, the problem arises of the optimal application of this method in order to fully utilize the technological capabilities of MAP. As mentioned above, it is the presence of a module $m \leq 2.5$ mm that practically limits the finishing treatment of gears by the tooth-honing method, and according to the data, the magnetic field penetrating into the groove attenuates at a depth approximately equal to its width. Consequently, the smaller the gear module, the more efficient the process of removing the material of the processed product is, despite the variability of the diameters of the protrusions and depressions when using MAP [5]. In addition, a positive factor in this process is the presence of an involute profile of the tooth contour (it can be conditionally considered trapezoidal), which increases the efficiency of FAP access to the treatment area and improves its quality. The second important condition is that the sharp edge is a magnetic flux concentrator and it is here that the greatest density of this flux will be.

The most preferable is the mathematical way of solving the problem. This gives general formulas for calculating the magnetic field in the processing zone and the possibility of obtaining a picture of this field, which leads to an assessment of the potential of the MAP process [6, 7]. This study is carried out in the area between the surfaces of the EMS (electromagnetic system) pole and the gear surface of the Z-plane wheel. It can be represented as a quadrilateral ABCD (Figure 3).

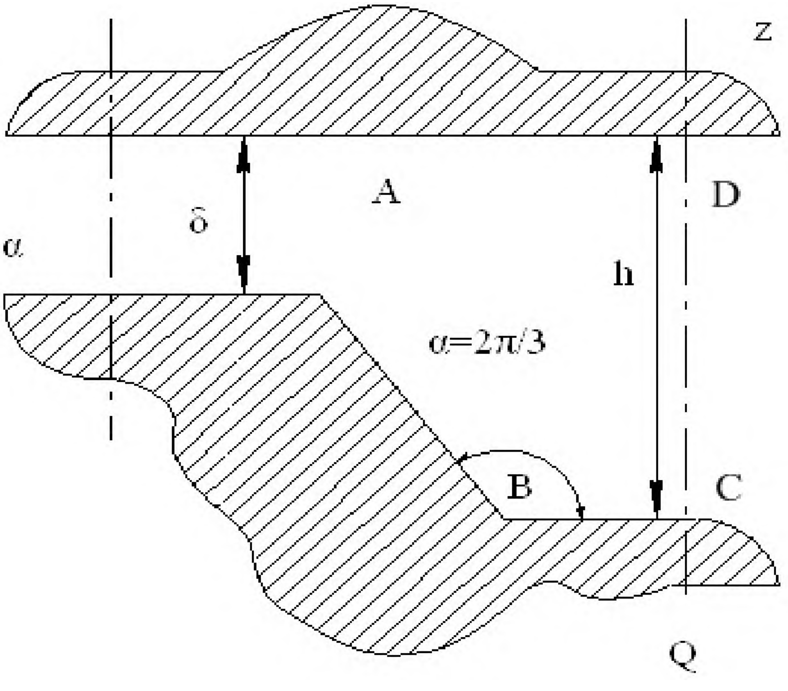


Fig.3. - The working area of the gear contour of the wheel at MAO with the condition α=2π/3

The mapping of this quadrilateral to the half-plane Q using the Christoffel-Schwartz integral in general looks like this:

$$Q = C \int_{Q_0}^{Q} (Q-a)^{\alpha_1 - 1}(Q-b)^{\alpha_2 - 1}(Q-c)^{\alpha_3 - 1}(Q-d)^{\alpha_4 - 1} + C_1,$$

where a, b, c, d are the coordinates of the vertices of the quadrilateral ABCD;

C, C1,Q_0 are arbitrary constants;

α1, α2, α3, α4 are angles at the vertices of the quadrilateral ABCD (in fractions of π).

The solution of this case after a number of transformations has the form:

$$\frac{P}{2\delta}=\frac{1}{\delta}\left\{\begin{array}{c}\ln(1-\beta)-\alpha\ln(\alpha\beta-1)+\\ +\frac{1}{2}\begin{bmatrix}\alpha\ln(1+\alpha\beta+\alpha^{2}\beta^{2})-\\ -\ln(1+\beta+\beta^{2})\end{bmatrix}+\\ +\sqrt{3}\cdot\left(\operatorname{arctg}\frac{2+\alpha\beta}{\sqrt{3}\alpha\beta}-\operatorname{arctg}\frac{2+\alpha\beta}{\sqrt{3}\beta}\right)\end{array}\right\}+\frac{\sqrt{3}}{2}(1-\alpha),$$

where P - is the gear pitch, mm;

δ - is the gap between the EMC pole and the diameter of the gear tops, mm;

h - is the depth of the groove, mm.

It follows from expression (8) that the minimum value of relative induction:

$$\beta=\frac{B}{B_{\max}}=\sqrt[3]{\frac{Q+1}{Q+\alpha^{3}}},$$

$$\beta=\frac{1}{\alpha}.$$

For h = 0 (smooth cylindrical surface), β = 1, and if h ≠ 0, then the dependence βmin = f(α) has the form of a hyperbola. By setting the values of the relative induction β and substituting them into the equation, the corresponding values of P/2δ are revealed for different β. By presenting these indicators in relation to a real gear wheel (diameters of the circumference of vertices and depressions, the engagement modulus, etc.) and a magnetic field (magnetic induction), it is possible to determine the most acceptable processing conditions and establish the capabilities of the MAP process to obtain the necessary qualities and performance [8]. Figure 4 shows the dependence $\beta=f\left(\frac{P}{2\delta}\right)$ at a value of α = 120° (trapezoidal tooth), which most corresponds to the shape of the working contour of the gear wheel.

The conducted studies allowed us to determine that the maximum possible value of *α*, at which the MAP process is carried out, is the range 4-6. By converting *P/2δ* as *πm/2δ* and substituting this range, it is possible, by varying the indicators *m* and *δ*, to predict the processing of small-module gears by the MAP method.

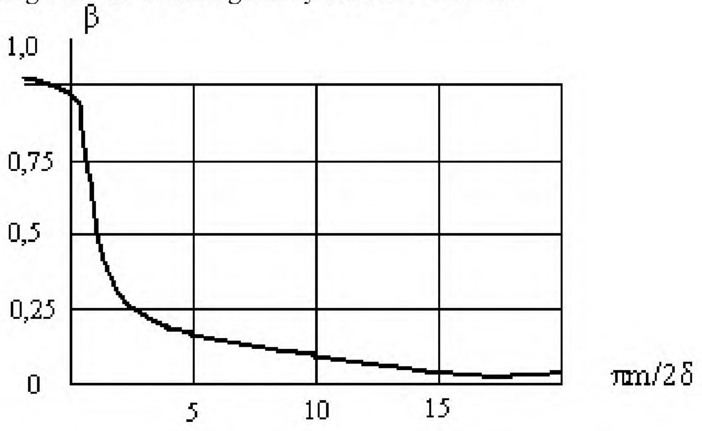


Fig. 4. - Distribution of relative induction β in the groove of the gear wheel at α=2π/3

Conclusion

Based on the above, studies were conducted aimed at assessing the technological capabilities of the MAP method in the processing of small-module wheels (m = 1.5 mm). Gears had an oblique tooth, $\beta = 12°$, material – steel 40X GOST 4543-71, 40-45 HRC, equipment – SFT 2.150.00.00.000, FAP – 15 CT TU 6-09-03-483-81. Parameters and processing modes: magnetic induction value, B = 1 Tl; cutting speed, $V_c = 0.15$ m/s; oscillation amplitude, A=1.5 mm; working gap filling factor, $K_f=1$; working gap value, $\delta=1$ mm. The main task of processing by the MAP method was to round the chamfers of the toothed contour of the wheels and eliminate the burrs formed by the previous grinding operation along the outer diameter of the parts.

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Information of the authors

Akulovich Leonid Mikhailovich, Doctor of Technical Sciences, Professor of the Metal Technologies Department of the Belarusian Agrotechnical University
E-mail: leo-akulovich@yandex.ru

Sergeev Leonid Efimofich, Candidate of Technical Sciences, Associate Professor of the Metal Technologies Department of the Belarusian Agrotechnical University
E-mail: l.sergeev.tm@bsatu.by

Mendalieva Saule Ilyinichna, Candidate of Technical Sciences, Senior Lecturer of the Department "Technological Machines and Equipment" of the Seifullin Kazakh Agrotechnical University
E-mail: saule-decanuf@mail.ru

Sherov Karibek Tagaevich, Doctor of Technical Sciences, Professor of the Department "Technological Machines and Equipment" of the Seifullin Kazakh Agrarian and Technical University
E-mail: shkt1965@mail.ru