DOI 10.52209/2706-977X_2025_4_86 IRSTI 55.19.03 UDC 621.923

Study of the Influence of the Angle of Inclination of the Axis of Ferroabrasive Grains on the Productivity and Surface Roughness of the Processed Part

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Abstract. The paper presents the results of experimental studies aimed at determining the patterns of influence of the inclination angle of ferro-abrasive grain (FAG) axes on the productivity and surface roughness of parts processed using the magnetic-abrasive method. New approaches to magnetic-abrasive finishing (MAF) are proposed by introducing an additional magnetic field into the working zone. The article includes the results of computer modeling of magnetic field topography achieved through the creation of an additional magnetic field. The behavior, trajectory, and cutting efficiency of ferro-abrasive grains are analyzed. The study suggests relocating the abrasive "brush" to the entry zone of the working gap, enabling a change in the rake angle toward positive values and increasing machining productivity. The experimental results allowed conclusions to be drawn regarding the effectiveness of creating additional magnetic fields and their influence on modifying the rake angle, thereby confirming theoretical principles on the impact of controlling the orientation angle of ferro-abrasive grains relative to the processed surface on improving MAF productivity.

Keywords: magnetic-abrasive finishing (MAF), ferro-abrasive grain, cutting angle, rake angle, ferro-abrasive grain axis, additional magnetic field.

Introduction

Magnetic-abrasive finishing (MAF), as one of the widely used types of finishing processes for parts, currently requires further clarification in studying the cutting process of abrasive grains on part surfaces. Previous studies [1, 2, 3, 4] have shown that the cutting force components in MAF depend on the inclination of the ferro-abrasive grain (FAG) axis relative to the processed surface, the coefficient of friction at the contact point between the FAG and the surface, the hardness of the processed material, and the thickness of the layer removed by an individual grain. The thickness of the removed material is determined by the cutting force component Py, which depends on the level of magnetic induction.

Based on the conducted research, it has also been determined that the cutting forces can be adjusted and technologically implemented by controlling the magnetic induction and the orientation angle of the ferro-abrasive grain relative to the processed surface, which influences the rake angle of the cutting edge [4,5]. Changes in magnetic induction and inclination angle can be achieved by introducing an additional magnetic field [6,7]. Positioning the source of the additional magnetic field alters the direction of magnetic field lines in the entry zone of the working gap, causing the FAG to rotate at an inclination angle $\boldsymbol{\omega}$, which creates conditions for cutting by micro-particles of the abrasive component located on the lateral surface of the ferro-abrasive powder (FAP).

Experimental studies to determine the effect of the modified rake angle of the FAP cutting edges on MAF productivity were conducted on a modernized ЭУ-6 installation equipped with an additional magnetic system. The experimental conditions were as follows: magnetic induction of the primary magnetic system B_p = 0.9 Tl; magnetic induction of the additional magnetic system B_{add} = 0.1 Ts; working gap of the primary magnetic system dp=1 mm; working gap of the additional magnetic system d_{add}=1.5 mm; particle size of ferro-abrasive powder FeTiC D=100–160 μm; main motion speed V=0.9 m/s.

The test samples were piston pins with a diameter of ϕ25 mm, made of 12XH3A steel with a surface layer hardness of 58–62 HRC. The output parameters were surface roughness Ra, μm; and productivity Q, mg/(cm^{2}min). Surface roughness measurements were performed using a Mitutoyo SJ-201P profilometer, and the weight of the samples was measured on Massa-K BK-600 scales with an accuracy of 0.01 g.

Two batches of samples were processed. The initial roughness of the samples was Ra = 1.14–0.97 μm. The first batch was processed without the additional magnetic system, while the second batch was processed with the influence of the additional magnetic field. All samples were treated with a new portion of powder. The experimental results are presented in Table 1.

Table 1. Indicators of productivity and surface roughness when controlling the angle of inclination of ferroabrasive grains and without control

Time processing τ, sec.	*Ra* after MAF, mkm		Efficiency of MAF*Q*, mg/(sm^2×min)	
	Without additional MS	With additional MS	Without additional MS	With additional MS
15	0,75	0,68	25,5	26,2
30	0,4	0,36	17,8	23,3
45	0,25	0,20	14,2	19,7
60	0,2	0,24	11,5	16,1

The MAF setup with an additional magnetic system maintains the initial productivity of the FAP batch for an extended period due to oriented cutting (Fig. 1).

An analysis of the experimental data (Fig. 1) shows that, in the classical MAF scheme, productivity drops sharply after 15 seconds of processing, and by 30 seconds, productivity decreases by 30%–40% compared to the level during the first 15 seconds of processing. In contrast, with MAF utilizing a controlled inclination angle of FAG in the working gap, the productivity decline is more gradual, amounting to only 10%–14% of the productivity observed during the first 15 seconds of processing.

The lowest surface roughness, when controlling the inclination angle of ferro-abrasive grains, is achieved after 45 seconds of processing, whereas with the classical processing scheme, the lowest surface roughness is attained after 60 seconds (Fig. 1).

The results of the experimental studies confirm the theoretical principles regarding the influence of controlling the orientation angle of ferro-abrasive grains (FAGs) relative to the processed surface on improving MAF productivity.

To determine the shape and dimensions of the pole tips, it is necessary to understand the distribution of magnetic field lines in the working gap for various gap geometries. As the amount of ferro-abrasive powder supplied increases, the number of grains in contact with the processed surface also rises, which slows down the rotation of the workpiece. At the same time, as the gap is filled with ferro-abrasive powder, its magnetic permeability increases, leading to a redistribution of the magnetic flux across the gap's cross-section and a reduction in the magnetic induction gradient [8,9].

Let us consider the effect of magnetic field focusing in the working gap on the gradient of magnetic induction. To analyze this, we modeled the operation of the magnetic system using the FEMM 4.2 software.

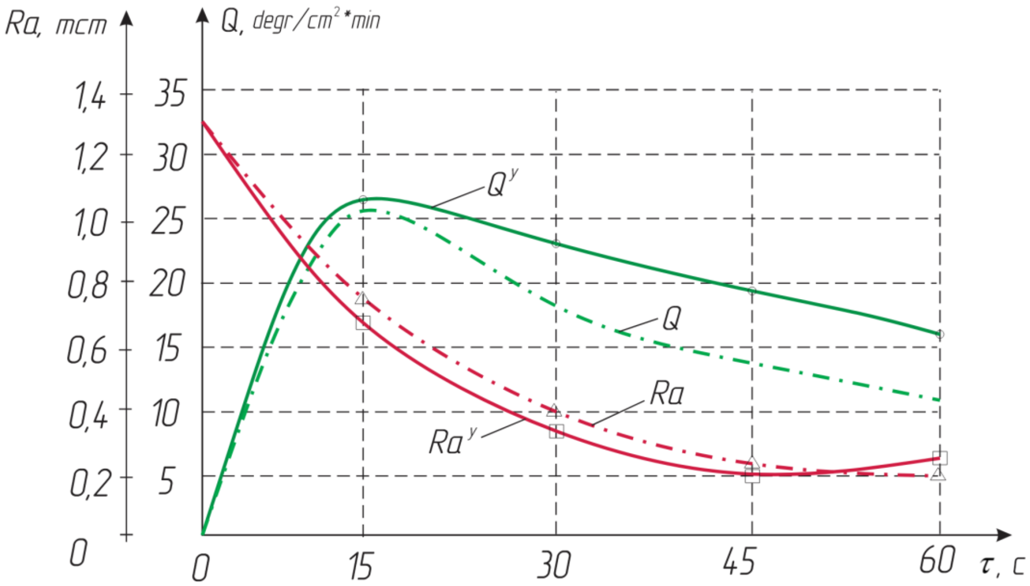


Fig. 1 - Graph of the dependence of Ra roughness and productivity Q from the processing time t. Q and Ra are the MAF performance and surface roughness, respectively, under the classical scheme; Q and Ra are the MAF performance and surface roughness, respectively, when controlling the phase orientation angle

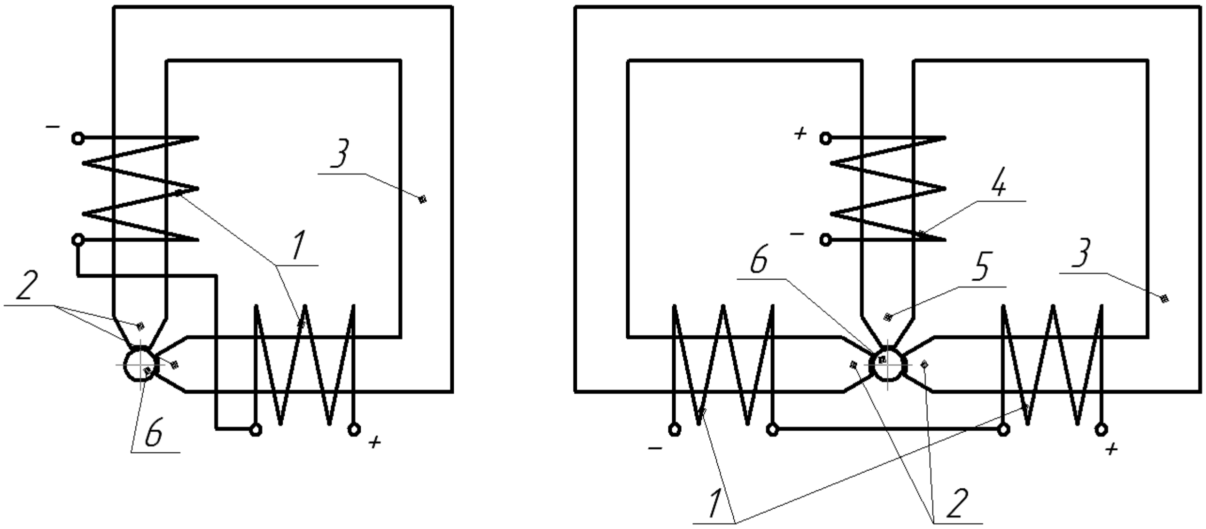
1. Experimental Studies

To achieve controlled oriented cutting, various methods for altering the direction of magnetic field lines were explored. Ferro-abrasive grains that make contact with the processed surface via their abrasive component rotate their central axis perpendicular to the processed surface. This rotation is caused by a torque generated by friction forces at the contact point between the abrasive component of the FAG and the processed surface, which are offset from the grain orientation axis. As the density of ferro-abrasive grains increases, an "expansion" of the abrasive "brush" is observed in the exit zone of the working gap, along with changes in the magnetic field topography.

In this configuration, the FAGs adopt positions where the rake angles become negative. As a result, MAF occurs at cutting angles exceeding 90°.

It is known that as the cutting angle increases, the chip removal process worsens. Furthermore, as the cutting edges of the FAG dull, the process transitions into surface burnishing, which reduces machining productivity. Therefore, to enhance MAF productivity, it is essential to adjust the inclination angle of the FAG axis relative to the processed surface.

To reduce the cutting angle of FAGs by altering the direction of the magnetic field lines, technical solutions have been proposed. These include asymmetric placement of the pole tips of the primary magnetic field relative to the processed surface (Fig. 4a) or installing a source of an additional magnetic field between the pole tips of the primary magnetic field (Fig. 2b) [10,13].



1, 4 – electromagnetic coils; 2, 5 – pole tips; 3 – magnetic core; 6 – workpiece

Fig. 2. – Schemes of MAF with asymmetrically positioned pole tips (a) and with an additional magnetic system (b)

The presence of multiple electromagnetic coils results in the superposition of the primary and additional magnetic fields in the working gap, influencing changes in the cutting angle.

Using asymmetrically positioned pole tips in MAF allows the creation of two zones within the working gap: one for micro-cutting and another for surface burnishing (Fig. 4a) [11,13].

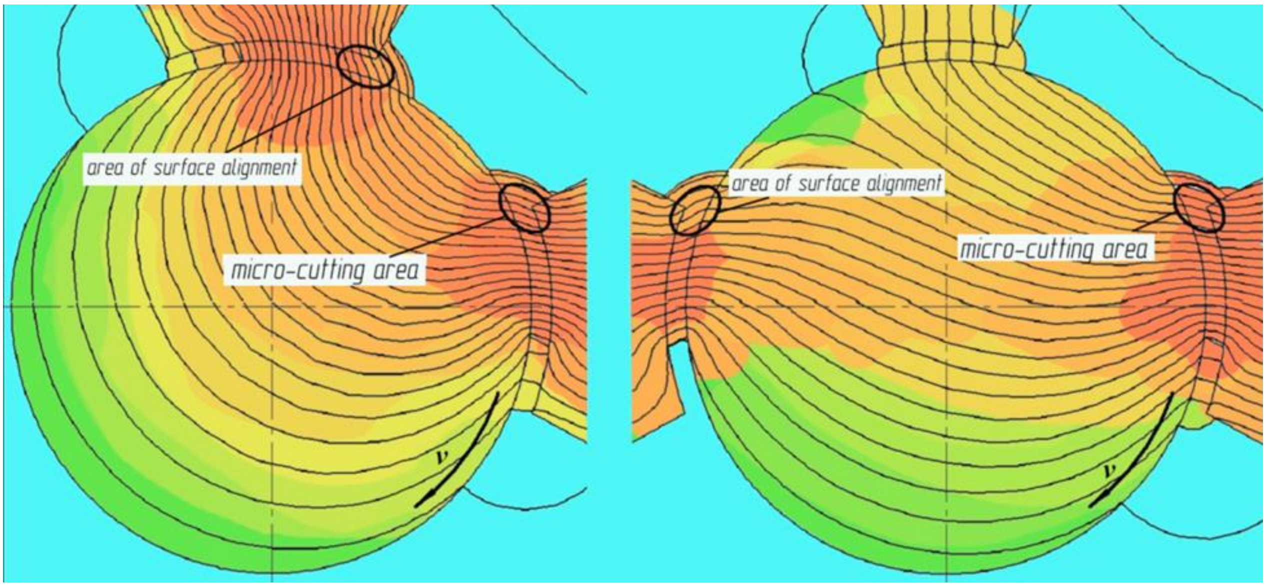


Fig. 3. – Topography of the magnetic field in the working gap with an asymmetric arrangement of the pole tips (a) and with an additional magnetic system (b) v - main motion speed

This scheme is particularly effective for small material removal tasks when the processing time does not exceed 15 seconds.

The MAF scheme with an additional magnetic field source similarly alters the magnetic field topography in the working gap (Fig. 3b). This configuration focuses magnetic field lines in the entry zone of the working gap, creating conditions for modifying the gradient of magnetic induction within that zone [13].

Positioning the additional pole tip at a 90° angle to the main magnetic core allows adjustments to the magnitude and gradient of magnetic induction in the working gap. This, in turn, alters the direction of the magnetic field lines of the primary magnetic system.

A study of the topography of the magnetic field in the working gap using computer modeling made it possible to establish that an additional magnetic system allows changing the angle of inclination of the magnetic field lines in the area of the entrance to the working gap in the range from 43° to 50° (Fig. 4).

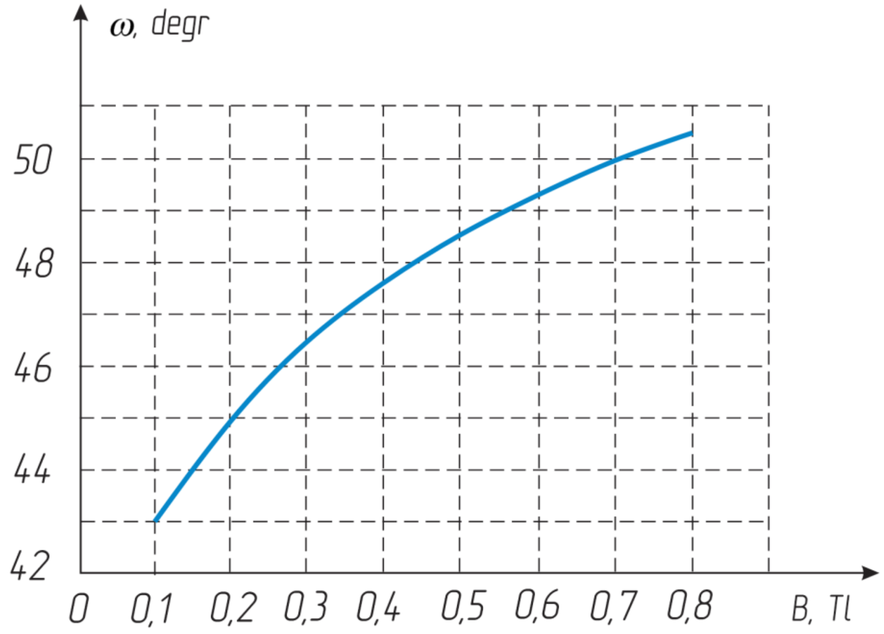


Fig 4. - Dependence of the angle of inclination of the magnetic field lines in the area of the entrance to the working gap on the magnitude of the magnetic induction of the additional magnetic system

The change in the inclination angle ω of the magnetic field lines in the working gap is described by the equation:

$$\omega = -9.8214B_a^2 + 18.804B_a + 41.615 \quad (1)$$

where B_d - is the magnetic field induction in the working gap of the additional magnetic system, measured in Tesla (Tl).

The inclination angle of the magnetic field lines varies along the perimeter of the working gap: from the entry point to the center of the gap, the angle changes from 43^o to 85^o (Figs. 5 and 6).

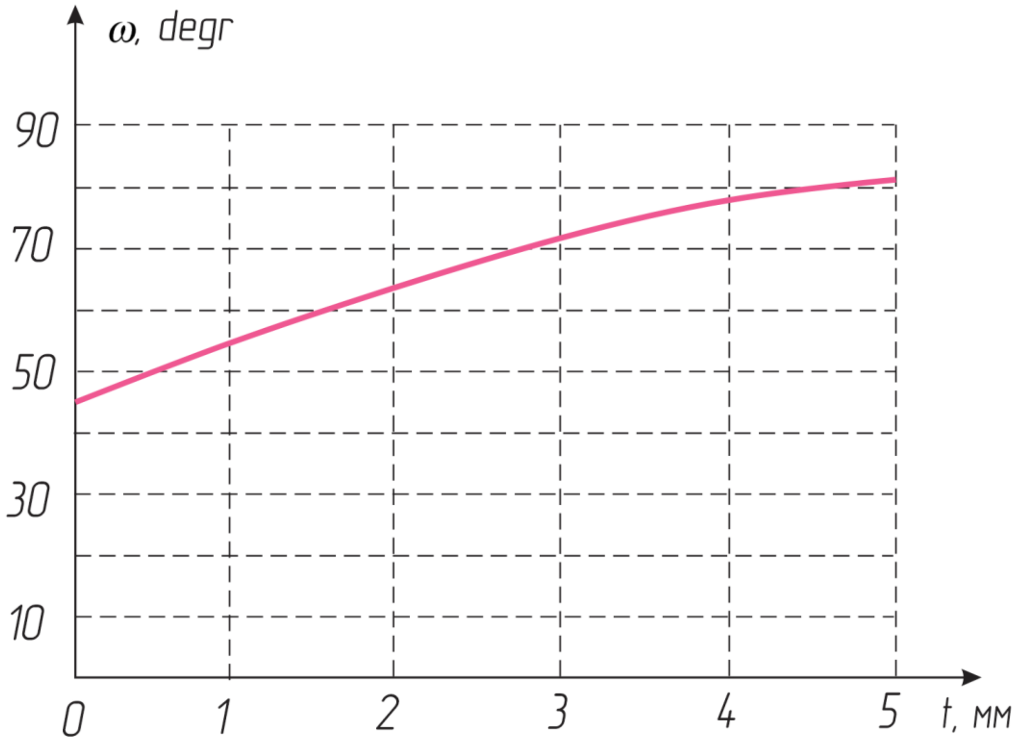


Fig 5. – Dependence of the angle of inclination of the lines of force as they move away from the point of entry into the working gap, v is the speed of rotation of the workpiece

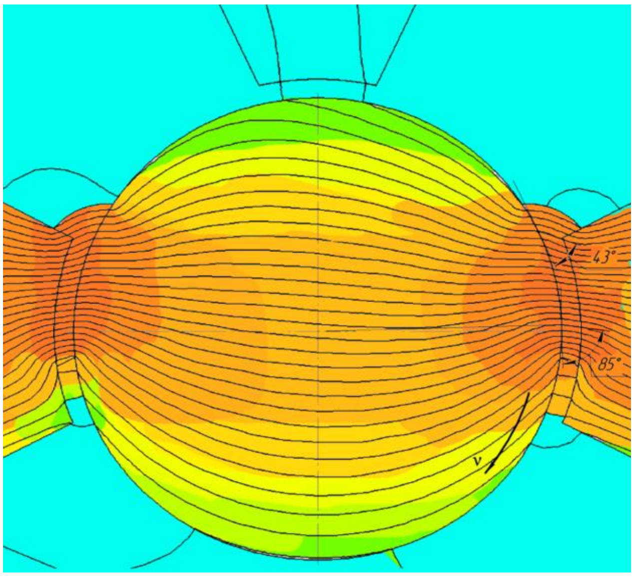


Fig 6. – Computer model of the inclination angle variation of magnetic field lines along the perimeter of the working gap

According to the principle of superposition of magnetic fields, the total change in the inclination angle of magnetic field lines across the working gap cross-section as it approaches the center of the pole tip is described by the equation:

$$\omega = -0.95t^2 + 12.387t + 42.857, \quad (2)$$

where t is the distance from the edge of the pole tip, measured in millimeters (mm).

The magnetic field at a specific point in the working gap, created by multiple sources, equals the vector sum of the fields from each source.

Computer modeling has established that the induction magnitude of the additional magnetic field is limited by the maximum induction of the primary magnetic field. If this limit is exceeded, a branch of the magnetic core at like poles is truncated, and the total magnetic flux closes through the branch with opposite poles. Therefore, the boundary condition for the magnetic induction generated by the additional magnetic system can be expressed as:

$$B_{add} < B_p, \quad (3)$$

where B_{add} and B_p are the magnetic induction magnitudes of the additional and primary magnetic systems, respectively, measured in Tesla (Tl).

The boundary value for the inclination angle of the ferro-abrasive grain (FAG) is 58° [1,13] (Fig 7).

The application of an additional magnetic system to control the inclination of the primary system's magnetic field lines allows the abrasive "brush" to shift toward the entry point of the working gap [14]. It also orients the FAGs to achieve positive inclination angles for their rake surfaces (+γ).

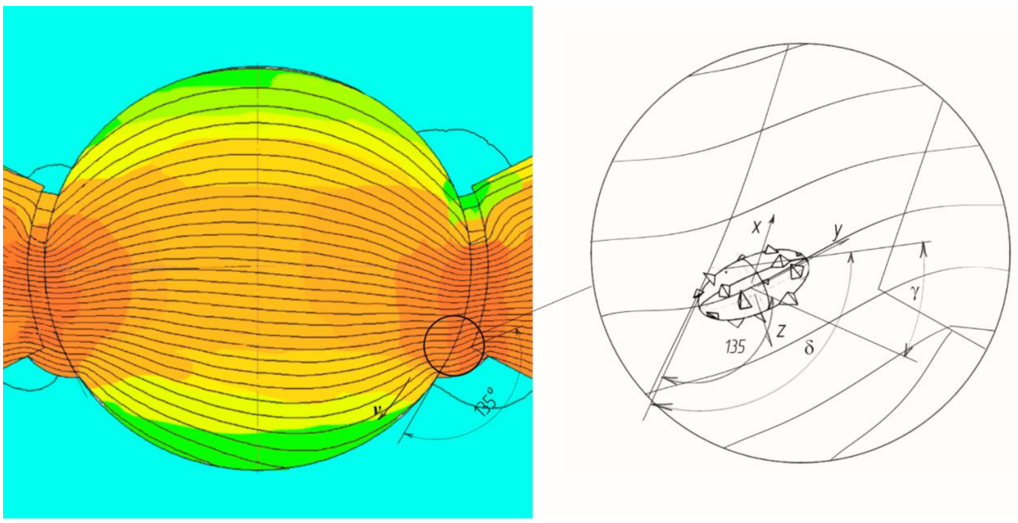
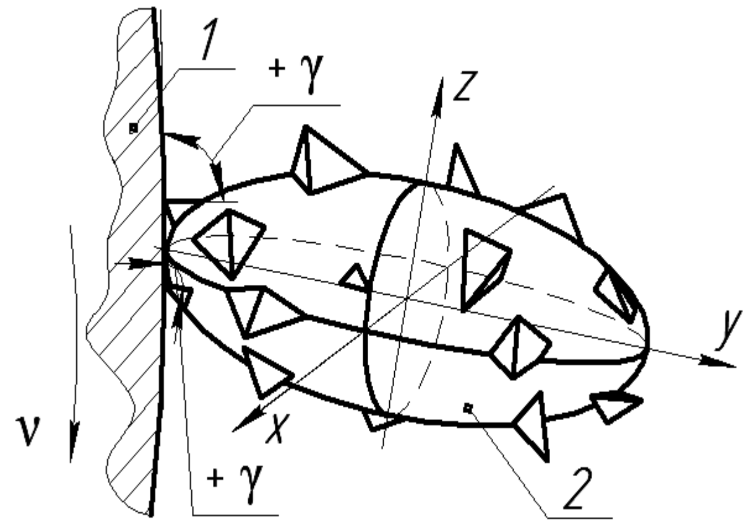


Fig 7. – Computer model of the inclination of magnetic field lines and the position of a ferro-abrasive grain v – primary motion velocity; dP – cutting angle; γ – rake angle

This arrangement of FAGs forms a cutting zone at the entry point of the working gap near one pole tip and a burnishing zone near the other pole tip of the primary magnetic system.

Smooth adjustment of the inclination angle of the magnetic field lines by varying the magnetic induction generated by the additional magnetic system allows control over the cutting intensity and the surface roughness.

Thus, modifying the magnetic field topography in the working gap during MAF of cylindrical surfaces enables the achievement of positive rake angles for the cutting edges of FAGs (Fig. 8) [13].



1 – Processed surface; 2 – Ferro-abrasive grain; v – Primary motion velocity; γ – Rake angle

Fig 8. – Micro-cutting scheme with a single ferro-abrasive grain

Thus, the investigation of the magnetic field topography has shown that the formation of the abrasive "brush" leads to a redistribution of the magnetic flux across the working gap.

The developed mathematical model of magnetic flux distribution within the volume of ferro-abrasive grains (FAG) demonstrates that the FAGs act as concentrators of magnetic induction, with the highest values located at sections adjacent to the processed surface. [11,13] As a result, the cutting zone is positioned at the exit of the working gap, and the tangential component of the cutting force moves the FAGs in the direction of the primary motion vector. This increases the rake angle towards negative values, which enhances the burnishing effect of the FAGs on the processed surface and reduces the intensity of the cutting process.

Conclusions

Based on the modeling of the magnetic field topography, it has been proposed to shift the abrasive "brush" to the entry zone of the working gap by creating an additional magnetic field in this area. This approach allows for a significant change in the rake angle toward positive values, increasing metal removal intensity by 30%–40%.

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