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The Mechanism of Orientation of Ferro-abrasive Grains in the Working Gap During Magnetic Abrasive Treatment

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Abstract: The purpose of the article is to study the orientation of ferro-abrasive grains in the working space at MAT to determine the possibility of controlling this process.The article examines the behavior of ferro-abrasive grains in the working space during magnetic abrasive processing. Theoretical studies have been carried out to identify the parameters that affect the effectiveness of surface treatment of the part. The modeling of the cutting process by ferro-abrasive grain of the treated surface is based on the shape of a triaxial ellipsoid. The cutting scheme and the acting forces in the working space of the MAT are given. The expediency of oriented cutting and control of the angle of inclination of ferro-abrasive grains to intensify the cutting of the allowance for MAT is substantiated. The influence of the angle of inclination of ferro-abrasive grains on the cutting process is considered from the standpoint of the basic provisions of the cutting theory.

Keywords: magnetic abrasive treatment, ferro abrasive grain, ferro-abrasive powder, triaxial ellipsoid, microhardness, friction force, coefficient of friction, angle of inclination, cutting force.

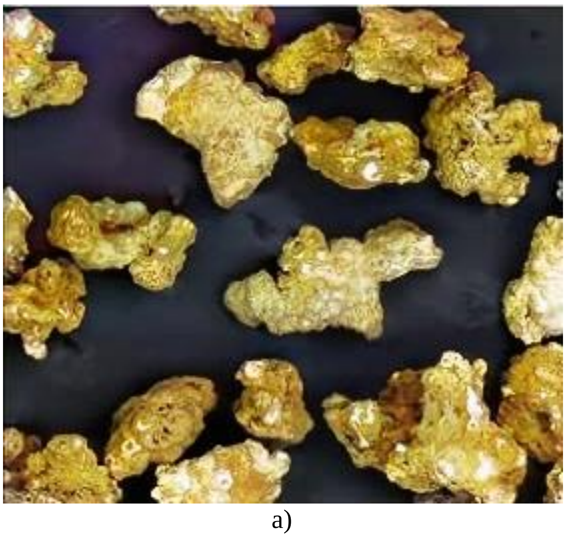
Introduction

The cutting process under MAT is influenced by the shape of the ferro-abrasive grains FAG [1]. The geometric parameters of ferro-abrasive grains determine its cutting ability, which depends on the number of cutting edges, on the corners at the vertices and the radii of rounding of the vertices.

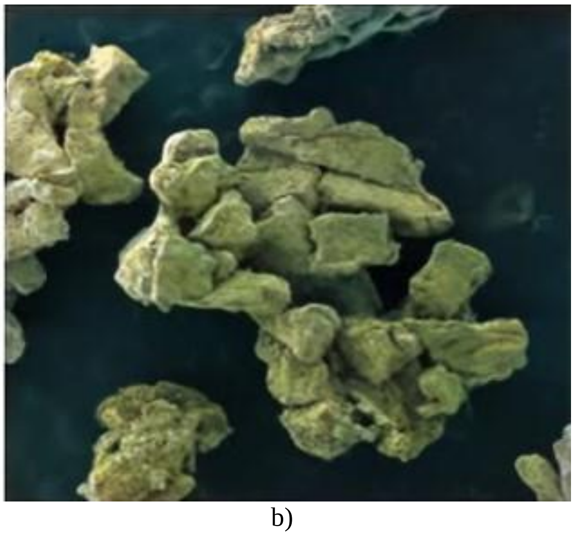
The shape of ferro-abrasive grains depends on the powder manufacturing technology, materials of magnetic and abrasive components and has, as a rule, an irregular geometric shape. Depending on the method of manufacturing powders, two typical forms of phases can be distinguished:

– fragmentation (Fig.1), obtained after grinding granular materials based on amorphous iron (powders of the POLYMER-T type) [1];

– rounded (Fig. 2), obtained from a melt without subsequent grinding (powders of type P6M5, POLYMER-M) [1].

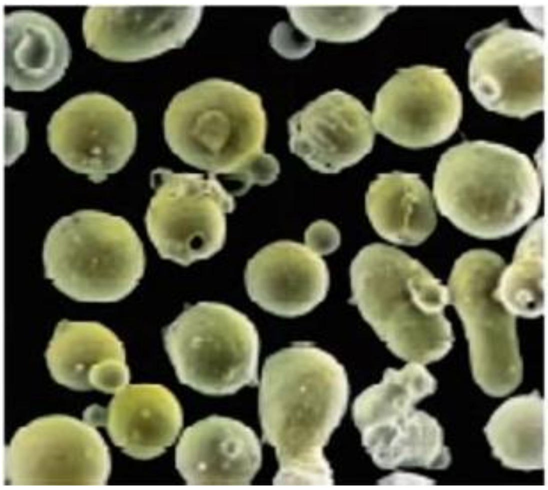


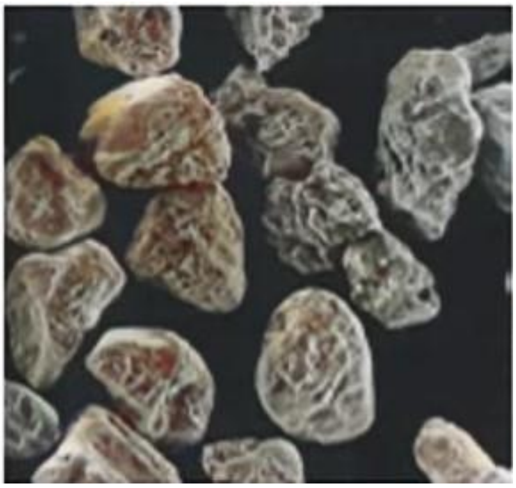
a)



b)

Fig. 1. - Photos of splinter-shaped FAP (×500): a) FeTiC; b) diamond-based powder





a) b)

Fig. 2. - Photographs of rounded FAP (×400) a – powder R6M5; b – powder TSARAMAM

FAP of the same composition can have different geometric shapes, which is due to the method of their manufacture, the type of additional processing, the size of the fraction and other factors [1].

The ability of the FAP to seal in the working gap at MAT depends on the shape of the ferro-abrasive grains. The shape of ferro-abrasive grains also affects their ability to rotate relative to the treated surface under the influence of a magnetic field during the MAT process.

According to [2], it is preferable that the shape of ferro-abrasive grains approach the shape of regular geometric shapes. This is due to the fact that rounded particles provide increased polishing ability due to the care of the treated surface of the parts, unlike the shapes of fragmented grains and conglomerate grains.

Each ferro-abrasive grain has, as a rule, several vertices formed by faces (chips) with certain radii of their rounding. The number of vertices in the abrasive grain, the angles at the vertices and the radii of rounding depend on the grade of the FAP, its grain size and the manufacturing method. According to [3], the magnitude of the angles at the vertices is in the range from 30° to 130°.

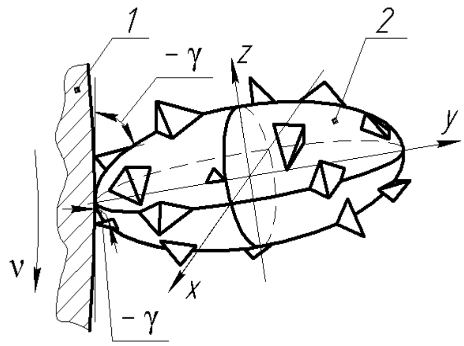
1. Methodology

The efficiency of MAT depends on the shape and size of the ferro-abrasive grains, their granulometric composition, the chemical activity of the processed material, and the microhardness of the abrasive component. Since when a grain enters a magnetic field, its largest axis is oriented in the direction of the field lines, it is preferable to use a stretched or fragmented grain shape, which facilitates the process of their reorientation during processing.

From the analysis of the geometry of the ferro-abrasive grains, it follows that they are granules of irregular angular shape with many protrusions and depressions. The morphology of the ferro-abrasive grains determines the options of their ordered packing, aggregation in the colony when forming an abrasive brush.

When modeling the contour of a cutting tool with different profile surfaces, it is convenient to represent the shape of the phase in the form of a regular geometric shape approximating oval, elliptical, spindle-shaped, lamellar.

Therefore, as a generalized model of the FAG of these shapes, it is advisable to take the form of a triaxial ellipsoid, the surface of which contains microparticles of an abrasive component. The shape of such a model is similar to a geoid, the surface of which contains abrasive particles (Fig. 3) [4].



1 – the surface to be processed; 2 – ferro-abrasivegrain;v – the speed of the main movement; γ – the front angle

Fig. 3. - A model of the shape of a ferro-abrasive grain of its location in the MAT process

In the classical MAO scheme, the front angle γ of the cutting elements of the ferro-abrasive grain has negative values.When choosing a generalized model of the ferro-abrasive grain shape, the following assumptions were introduced:

1) ferro-abrasive grain is a triaxial ellipsoid, the equation of which has the form:

$$\frac{x^2}{a^2}+\frac{y^2}{b^2}+\frac{z^2}{c^2}=1 \quad (1)$$

where *a* is the small semi-axis of the ellipsoid, mm;
b is the large semi-axis of the ellipsoid, mm;
c is the middle half-axis of the ellipsoid, mm.

2) the dependence of the magnitude of the semi-axes of a triaxial ellipsoid on the grain size of the FAP is described by the expression

$$c=(a+b)/\,2 \quad (2)$$

2. Results and Discussions

Let's consider the general scheme of cutting with a single ferro-abrasive grain, the location of which relative to the treated surface is shown in Fig. 4 [4].

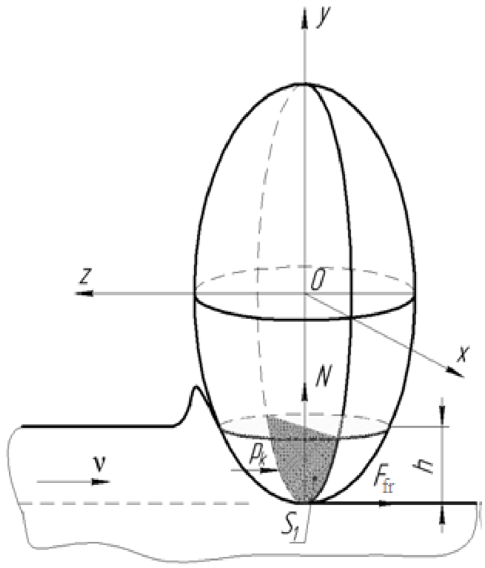


Fig. 4. - Cutting scheme with a single ferro-abrasive grain at MAT

The following forces act on the FAG:
--the reaction force of the treated surface N, equal to the value of the normal component of the magnetic field strength F_m (ΔB_1);
-the friction force F_{fr} between the FAG and the treated surface, which is set by the ratio:

$$F_{fr}=\mu N=\mu F_m(\Delta B_1), \quad (3)$$

where μ - coefficient of friction on the contact surface;

N - total normal pressure p_k, along the contact surface acting on the area located in the normal phase section and enclosed between the contact spot of the ferro-abrasive grain with the treated surface and the plane determining the value of the layer to be removed *h* by a single grain of FAP at a given time.

With respect to the parameters acting on a single FAG, the following assumptions are made:

1) The stress distribution over the surface of the FAG in the cutting area is uniform;

2) The stress on the surface of the cutting zone is proportional to the hardness of the material being processed.
3. The coefficient of frictionμ does not change over the entire surface of the contact between the phases and the workpiece.

Thus, the projection components of the cutting force acting on the FAG at MAT in the direction of the *z* and *y* axes can be expressed by dependencies [4]:

$$P_z = p_k S_1 + F_{fr}, \tag{4}$$

where S_1 - value of the cross-sectional area, which is affected by the total voltage across the contact surface, mcm^2.

$$P_y = N, \tag{5}$$

The size of the cross-sectional area can be calculated using the formula [4]

$$S_1 = \int_{-b}^{-b+h} dy \int_{-a\sqrt{1-\frac{y^2}{b^2}}}^{a\sqrt{1-\frac{y^2}{b^2}}} dx \tag{6}$$

where *b* and *a* are the major and minor semi-axes of a triaxial ellipsoid, microns.

Given the symmetry of the ellipse with respect to both axes, we can write:

$$S_1 = \int_{-b}^{-b+h} dy \int_{-a\sqrt{1-\frac{y^2}{b^2}}}^{a\sqrt{1-\frac{y^2}{b^2}}} dx = 2\int_{b-h}^{b} dy \int_{0}^{a\sqrt{1-\frac{y^2}{b^2}}} dx = 2\int_{b-h}^{b} dy\,(x)\Big|_0^{a\sqrt{1-\frac{y^2}{b^2}}} =$$

$$= 2\int_{b-h}^{b} a\sqrt{1-\frac{y^2}{b^2}}dy = 2\int_{b-h}^{b} \frac{a}{b}\sqrt{b^2-y^2}dy =$$

$$= \left| \begin{array}{c} y = b\sin t \\ dy = b\cos t dt \\ y = b \Rightarrow t = \frac{\pi}{2} \\ y = b-h \Rightarrow t = \arcsin\frac{b-h}{b} \end{array} \right| =$$

$$= 2\int_{\arcsin\frac{b-h}{b}}^{\frac{\pi}{2}} \frac{a}{b}\sqrt{b^2-b^2\sin^2 t}\, b\cos t\, dt =$$

$$= 2\int_{\arcsin\frac{b-h}{b}}^{\frac{\pi}{2}} \frac{a}{b} b^2\cos^2 t\, dt = 2ab\int_{\arcsin\frac{b-h}{b}}^{\frac{\pi}{2}} \cos^2 t\, dt =$$

$$= 2ab \int_{\arcsin\frac{b-h}{b}}^{\frac{\pi}{2}} \frac{1+\cos 2t}{2} dt = ab\left(t + \frac{1}{2}\sin 2t\right)\Big|_{\arcsin\frac{b-h}{b}}^{\frac{\pi}{2}} =$$

$$= ab\left(\frac{\pi}{2} - \arcsin\frac{b-h}{b} - \frac{1}{2}\sin\left(2\arcsin\frac{b-h}{b}\right)\right) =$$

$$= ab\left(\frac{\pi}{2} - \arcsin\frac{b-h}{b} - \frac{b-h}{b}\sqrt{1-\left(\frac{b-h}{b}\right)^2}\right) =$$

$$= ab\left(\arccos\frac{b-h}{b} - \frac{b-h}{b}\sqrt{1-\left(\frac{b-h}{b}\right)^2}\right) \quad (7)$$

In formula (7), the thickness of the cut layer *h* can be determined from Kick's law [5] if the ferro-abrasive grain is likened to an indenter:

$$\mathrm{h} = \sqrt{\frac{\mathrm{P_g}}{\mathrm{c_g}}} \quad (8)$$

where P_g - insertion force, it will be equal to the magnetic field strength F_m, N;

c_g - coefficient depending on the angle of FAG insertion and the elastic–plastic properties of the material into which it is pressed.

The angle of ferro-abrasive grain insertion also depends on the angle of inclination of the axis of the ferro-abrasive grain relative to the treated surface. It follows from formula (8) that the thickness of the cut layer is influenced by the angle of inclination of the axis of the ferro-abrasive grain. Consider this influence.

In the middle part of the working gap, the magnetic lines of force are directed perpendicular to the surface to be processed (Fig. 4). Accordingly, the largest axis of the ferro-abrasive grain is directed. When changing the direction of the magnetic force lines by an angle of *ω*, the abrasive grains also rotate their largest axis by the same angle (Fig. 5).

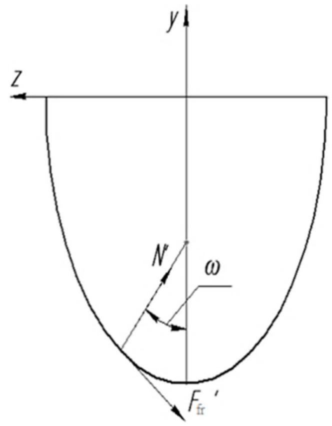


Fig. 5. - Diagram of forces acting on the lateral surface of the FAG N' is the normal reaction force acting on the ferro-abrasive grain from the side of the processed material; F_{fr}' is the friction force

Consider the effect of cutting forces on a ferroabrasive grain when its angle of inclination*ω* changes. Force projections on the Z axis:

$$\mathrm{N}_z' = \mathrm{N}' \sin\omega, \quad (9)$$

$$\mathrm{F}_{\mathrm{fr}\,z}' = \mathrm{F}_{\mathrm{fr}}' \cos\omega \quad (10)$$

Summing the vectors *N'* and F_{fr}' on the half-meter, taking into account the change in the angle *ω*, we obtain the sum of their integral absolute values [6]:

$$\left|\int_{90^\circ}^{0^\circ} N' \sin\omega d\omega\right| + \left|\int_{90^\circ}^{0^\circ} F'_{fr} \cos\omega d\omega\right| = N' + F'_{fr}. \quad (11)$$

Normal forces can be determined through the normal pressure $p_{N'z}$, and the friction force can be determined through the tangential stress $p_{F'fr}$. In turn, the normal pressure is proportional to the hardness of the processed material, as shown in the expression [6]:

$$p_{N'_z} \approx \beta \cdot H_V \quad (12)$$

where H_V - hardness of the treated surface on the Vickers scale, MPa;

β - constant expressing the ratio of the values $p_{N'z}$, and H_V.

For example, according to the literary source [7], the value β = 1÷ 1.23.We take a lower limit value, then β = 1, i.e. the normal pressure on the grain surface is equal to the hardness of the material being processed.

The tangential stress is expressed in terms of the normal stress and the coefficient of friction according to the formula

$$p_{F'_{fr}} = \mu p_{N'_z} \quad (13)$$

Taking into account the expressions (4), (5), (11), (12) the component of the cutting force P_z acting on a single grain can be described by the dependence:

$$P_z = H_V \cdot (1+\mu) S_1 + \mu F_m(\Delta B_1), \quad (14)$$

$$P_y = F_m(\Delta B_1) \quad (15)$$

On the other hand, summing up the projections of the forces *N'* and F_{fr}' on the z axis and taking into account (3), we obtain the cutting force:

$$P'_z = N'_z + F'_{fr} = N'(\sin\omega + \mu\cos\omega) \quad (16)$$

The value of P_y'at MAT is always equal to the magnitude of the magnetic field strength. With the constant strength of the magnetic field, according to formula (12), the ferro-abrasive grain will be embedded in the treated surface to a depth determined by the elastic-plastic properties of the treated material. [8,9,10]

Thus, the expediency of oriented cutting and control of the angle of inclination of ferro-abrasive grains to intensify the cutting of the allowance at MAT is theoretically justified. Let's consider the influence of the angle of inclination of ferro-abrasive grains on thecutting process from the standpoint of the basic provisions of the cutting theory. An increase in the angle of inclination of the grains ω leads to an increase in the shear angle β_1 and a decrease in the cutting angle (Fig. 6).

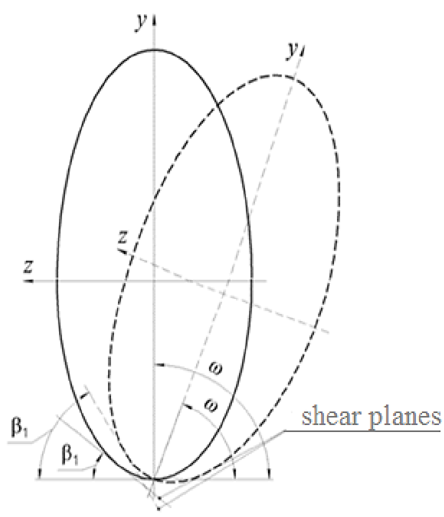


Fig. 6. - Directions of the chip shear plane when the angle of inclination of the ferro-abrasive grain changes

Reducing the cutting angle facilitates the chip removal process and reduces the cutting force P_z. However, the radius of rounding of the cutting edge must be taken into account.

The shape of the ferro-abrasive grain in the form of a triaxial ellipsoid has a different curvature along the contour. The radius of rounding has the smallest value at the intersection point of the ellipse with the largest half-axis b. The possible contact zones of the FAP grain with the treated surface are within half of the perimeter of the contact zone, which corresponds to a change in the boundary values of the angle ω from90° to 0°. The refore, it is necessary to introduce a technical restriction on the angle of inclination of the grain ω. The problem can be solved theoretically or graphically using the ellipse construction method.

In the first case, it is necessary to determine the coordinates (y_0 z_0) of the intersection point M_0 of the large and small circles approximating the ellipse curve by solving a system of equations:

$$\begin{cases}(z+z_1)^2+y^2=R_1^2\\ z^2+(y-y_2)^2=R_2^2\end{cases} \quad (17)$$

where $R_1$and R_2 - radii of the large and small circles, microns.

Then determine the equation of the tangent to the small circle at the point M_0(18) and its angle of inclination to the axis oy:

$$\begin{aligned} yy_0+zz_0&=R_1\\ yy_0+zz_0&=R_1\end{aligned} \quad (18)$$

The analysis of the above dependencies (17 and 18) shows that the boundary value of the rotation angle depends on the ratio of the semi-axes of the ellipsoid a, b and c. The accepted shape of the triaxial ellipsoid is generalized. If the half axes are equal, the ferro-abrasive grain will have a spherical shape, and if the 2 axes are equal, the ellipsoid of rotation.

Therefore, it is advisable to take the average shape of a ferro-abrasive grain in the form of a triaxial ellipsoid with a half-axis ratio b = 1 : c = (b+a)/2 : a = 0,25. With this assumption, the boundary value of the angle of inclination of the ferro-abrasive grain, equal to 58°, was determined using the graphical method.

Thus, the components of the force depend on the tilt of the axis of the ferro-abrasive grain relative to the treated surface, as well as on the coefficient of friction in contact with the treated surface, on the hardness of the processed material and the size of the layer to be removed by a single grain.

Conclusions

Based on the dependencies obtained, the following conclusions can be drawn:

– it is technologically difficult or impossible to control the amount of cutting forces by changing the coefficient of friction in contact of the ferro-abrasive grain with the surface to be processed;

– the hardness of the processed material is a constant value (specified in the design documentation);

– the value of the allowance to be removed is determined by the component of the cutting force P_y, depending on the magnitude of the magnetic induction;

– changing the cutting forces is accessible and technologically easy to implement by controlling the magnitude of magnetic induction and the angle of orientation of the ferro-abrasive grain relative to the surface to be processed, which affects the value of the leading angle of the cutting edge.

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