The Geometrical Model of Calculation of Metal Removal and Roughness in Magnetical-Abrasive Machining

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Abstract. The geometrical model of interaction between abrasive particle and the surface in magnetic-abrasive machining is offered. The theoretical research of metal removal is made. The dependences for determination of metal removal and maximum depth of particle introduction are received.

Introduction. The increasing quality requirements for manufactured products cause need for improving existing technologies and creating new ones of finishing with abrasive on a flexible binder (machining with free abrasive condensed with inertial forces, jet-shock, vibro-abrasive machining and a number of other types). The most productive way of abrasive machining on the flexible binder is magnetical-abrasive machining (MAM). The metal removal, here with, is made with the cutting tool created by magnetic field of magnetic-abrasive powder. The cutting tool is defined by increased elasticity [1, 4, 5, 6]. By means of MAM it is possible not only to provide low roughness and polish different forms of details surfaces, but also mechanize such operations, as sharp edges rounding and deburring, descaling and thin oxidic films removing. Thus there take place reinforcing and surface hardening increase.

Theory. While researching the main regularities of formation of surfaces that are machined with abrasives, one of the major questions is the question of theoretical modeling of interaction process between abrasive particles and workpiece surface. In the considered model MAM process is described by the following scheme: an abrasive particle having specific size r (circumscribed circle radius) and moving on the surface, inculcates into the material h depth and takes off chips La length (fig. 1). While calculating next assumptions are made: powder grains have a ball form of one size; working gap is filled with the powder-like environment of density and magnetic properties homogeneity.
Fig. 1 The scheme of single grain material removal in MAM

On the basis of the adopted design scheme and the above assumptions, the amount of material removed

\[ V_a = k_c S * L_a = k_c \left[ r^2 \arccos\left(\frac{r-h}{r}\right) - (r-h)\sqrt{h(2r-h)} \right] L_a \]  

(1)

where \( k_c \) –chips coefficient, which is equal to the actual area of removed metal considering elastic-plastic deformation of machined material to geometric area, \( L_a \) chips length.

The depth of grain forcing into the metal [2, 3, 6]

\[ h = r - \sqrt{r^2 - \frac{F_n}{\pi H_v}} \]  

(2)

where \( F_n \) -normal force, \( H_v \) - BHN.

Normal force is equal to \( P \) magnetic pressure multiplied by the grain cross sectional area:

\[ F_n = p Pr^2 \]  

(3)

\( L_a \) chip length in mm is determined by \( n \) inductor rotation frequency (rpm), \( t_n \) (c) polishing time and the width of inductor and workpiece contact zone.

Supposing that the magnets are disposed along the generatrix of the inductor, and the width of contact zone is equal to B core width (Fig. 3), the total chip length for one grain is determined by:

\[ L_a = \frac{nB}{60} t_n \]  

(4)

where \( n \) -the frequency of rotation (rev / min).
To determine the amount of grains involved in cutting we denote the diameter of magnetic abrasive particles $\delta_a$, and core area $F_p = B \cdot H \cdot n_M$, where $n_M$ – core number. Then the number of working magnetic-abrasive particles is determined by the formula:

$$N_M = \frac{4BHn_M}{\pi \cdot \delta_a^2}.$$  \hspace{1cm} (5)

Supposing, that $n_a$ cutting abrasive particles are attached to one magnetic particle we get the total amount of cutting grains:

$$N_M = \frac{4BH}{\pi \cdot \delta_a^2} n_a n_M.$$  \hspace{1cm} (6)

The total amount of removed material

$$V_M = N_M \ast V_a.$$  \hspace{1cm} (7)

To consider the dynamic phenomena during machining we offer the additional coefficient $k_d$. It allows to consider the deformation in the tool and workpiece contact zone. This is due to the fact that during the extensive flat surface machining cutting force causes a considerable deformation of both the tool and the magnetic-abrasive powder.
And the metal removal is reduced.
The coefficient \( k \) is always less than 1, but it approaches 1 when the surface significantly smaller than core width \( B \) is processed.
This coefficient depends on a large number of factors.
Therefore for it empiric dependence is offered.
Over time, the cutting properties of grains go down because of their bluntness and destruction.
So, we propose to use one more empirical coefficient \( k_I(\tau) \) in the formula .
To consider the process of blunting the following empirical dependence is used.

\[
k_I = e^{-C_I\tau}
\]  

(8)

Where \( C_I \) considers the change of powder cutting properties in time; \( \tau \) - the total powder working time (c).
If, for example, during \( \tau = 120 \) c time the powder cutting properties reduce to 20%, then

\[
k_I = 0.8 = e^{-120C_I}.
\]

(9)

Hence, \( C_I = 0.00186 \).
So,

\[
V_M = \frac{B^2Hnkckdk_Ina_nM}{15\pi \cdot 3^2a} \left[ r^2 \arccos\left(\frac{r-h}{r}\right) - (r-h)\sqrt{h(2r-h)}\right]
\]

(10)

After preliminary cutting marks on the prepared surface look like Fig.3.
Since the profile is periodic, the surface roughness parameters are actually determined by the area
\( x \in [0; S_z/2] \).

We assume that in this area the mark profile is set by the equation \( y = ax^b \).
Then the surface roughness parameters is determined by coefficients \( a \) and \( b \). The mark height corresponds to \( R_{max} \) parameter.
Herewith

\[
R_{max} = a(S_z/2)^b.
\]

(11)

Ra parameter is determined by the formula

\[
R_a = \frac{2}{S_z} \int_{0}^{S_z/2} |y - W| \, dx
\]

(12)
Figure 3 – The shape roughness after cutting.

During processing from workpiece surface having the profile of Fig.3, allowance is removed. Herewith, the volume of the material that is removed can be calculated taking into account the expression (9).

Metal is removed from mark tops. Herewith, after some time they take the form shown in Fig. 4.

Figure 4 – Mark profile during machining.

Since the profile of original mark is described by degree dependence, parameters $S_x$ and $b_p$ are related by:

$$\Delta = a\left[\left(\frac{S_z}{2}\right)^b - \left(\frac{S_z}{2} - b_p\right)^b\right]$$

or

$$b_p = \frac{S_z}{2} - \left[\left(\frac{S_z}{2}\right)^b - \frac{\Delta}{a}\right]^{1/b}$$

(13)

Dimensions $\Delta$ and $b_p$ are determined by metal removal process.
The inductor will go the \( b_p \) distance for
\[ t_1 = \frac{b_p}{V_p} \] time, where \( V_p \) – the feed rate in mm/ s.

Since \( V_p = \frac{S}{n} \), then
\[ t_1 = \frac{60b_p}{Sn}, \quad (14) \]

where \( S \) - feed in mm / rev, \( n \) - inductor rotational speed in rev /min.

The volume of removed metal in the first pass
\[ V_{M1} = \int_{S_z/2-b_p}^{S_z/2} ax^b dx - (R_{max} - \Delta)b_p = \]
\[ = \frac{a}{b+1} \left[ \left( \frac{S_z}{2} \right)^{b+1} - \left( \frac{S_z}{2} - b_p \right)^{b+1} \right] - (R_{max} - \Delta)b_p \quad (15) \]

On the other hand, this amount is determined by dependence (10) \( t_p \), calculated with the formula (15):

\[ \frac{B^2 H_{nk} k_j k_i n_a n_M}{15 \pi D_M^2} \left[ r^2 \arccos \left( \frac{r-h}{r} \right) - (r-h)\sqrt{h(2r-h)} \right] t_1 = \]
\[ = \frac{a}{b+1} \left[ \left( \frac{S_z}{2} \right)^{b+1} - \left( \frac{S_z}{2} - b_p \right)^{b+1} \right] - (R_{max} - \Delta)b_p \]

or
\[ \frac{4B^2 H_i k_j k_i n_a n_M}{\pi D_M^2} \left[ r^2 \arccos \left( \frac{r-h}{r} \right) - (r-h)\sqrt{h(2r-h)} \right] b_p = \]
\[ = \frac{a}{b+1} \left[ \left( \frac{S_z}{2} \right)^{b+1} - \left( \frac{S_z}{2} - b_p \right)^{b+1} \right] + (R_{max} - \Delta)b_p = 0 \quad (16) \]

where \( \Delta \) is calculated with the formula (16).

Equation (14) can be solved for \( b_p \) only numerically, excluding trivial solution \( b_p = 0 \).

Fig. 5 shows the dynamics of roughness parameter changes \( Ra \) from pass to pass when feeding \( S = 0.05 \text{mm / rev} \).
The program for performing calculations is designed in VBA in MS Excel. The calculation time on modern computers is less than 1 second.

**Results and discussion.** The proposed program allows to calculate the metal removal and the surface roughness in magnetic-abrasive machining, depending on the chosen parameter of machining.

**Conclusions.** The dependences derived from modeling can help to accomplish some vital engineering tasks dealing with the workpiece finishing process. They can be used to determine optimal sizes of abrasive powder portions participating in the process of magnetic abrasive machining, an appropriate technical rate setting, the most effective trajectory and operation modes. Using the obtained results a production manager can assess a potential effect of some process related parameters (e.g. an inductor radius, the radius of the powder portion, the machine table feed, the rate of the inductor rotation, etc.) on the production efficiency. The model presented above is of great scientific value because it can be used for parameter prediction for machining sophisticated flat workpieces when machining conditions are not constant and have to be readjusted due to the peculiarities of technical characteristics of the magnetic abrasive machining process.

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