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Technique of Comparison and Optimization of Conditions for Magnetic Abrasive Finishing

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Abstract. In this paper, the new technique involving comparison and optimization of conditions for Magnetic Abrasive Finishing (MAF) is suggested, taking into account the basic laws stated for process MAF. The formulas for the calculation of the criteria for optimization are created when the process MAF is used for polishing, removal of burrs, and other purposes. The application of the technique is shown in an experiment on the optimization conditions for the removal of burrs after drilling using the MAF method. The technique can be used after standards for this process are developed.

Introduction

Magnetic Abrasive Finishing (MAF) is used for different purposes: polishing, deburring, edge finishing, defect layer removal from a surface, etc. In most cases, magnetic abrasive powder (further – powder) is the abrasive instrument used in this technological method. The results of MAF depend on the lump conditions for the performance of the technological operation: the design of the equipment and the magnetic inductor, the characteristics of the magnetic abrasive powder, and the used regime [1]. To develop a concrete MAF operation, it is necessary to compare some variations of the inductor construction, composition, and grain of the magnetic abrasive powder, and the values of the regime parameters, using an experiment in a working environment. To make the experiment shorter, it is necessary to create and prove the determined impartial criteria so as to compare the results of the MAF operations using different conditions. Attempts to perform this task have already been undertaken [2]. This paper is a continuation of the investigation that gave ground to the new complex criteria for comparing magnetic abrasive powders, MAF conditions, and designers' equipment decisions.

Technique of Comparison of MAF Operations Results

MAF Process Base Regularities. A comparison of MAF conditions will be objective if they are received with the use of base regularities of the MAF process. During MAF, an allowance is removed through magnetic abrasive powder impact. MAF is a non-linear process. The longer its duration is, the less is the intensity of a removed allowance [See the curve $q(\tau)$ in Fig. 1]. The reasons for this are a decrease in the cutting behavior of the powder and a decrease in its amount in the working gap or zone. The dependence of the removed allowance mass on the MAF duration is a powerful dependence, as shown below:

$$q = q_1 \tau^m, \tag{1}$$

in which q, mg/cm^2 is a removed mass from a 1-cm^2 area of the work surface in time τ; q_1, mg/(cm^2·min) is a removed mass from a 1-cm^2 area in the first minute (1 second or 1 hour can also be chosen as the time unit); and $m < 1$ is an exponent describing a productivity reduction of the MAF process during a MAF operation.

When the target of MAF is the rounding of workpiece edges, the base regularity of the rounding radius ρ from the MAF duration $\rho = f(\tau)$ is similar to Eq. 1:

$$r_e = r_{e1}\tau^z, \tag{2}$$

in which r_e, mm is the radius of the edge after τ mins. of MAF; r_{e1}, mm is the radius after the first minute of MAF; and z is an exponent.

Concurrently with the allowance removal or the edge rounding, there is a decrease in the roughness (polishing) of a work surface during MAF. The base regularity $R_a = f(\tau)$ seems to be dependence (Fig. 1):

$$R_a = R_{a\text{-}in} - k_r\,\tau^y, \tag{3}$$

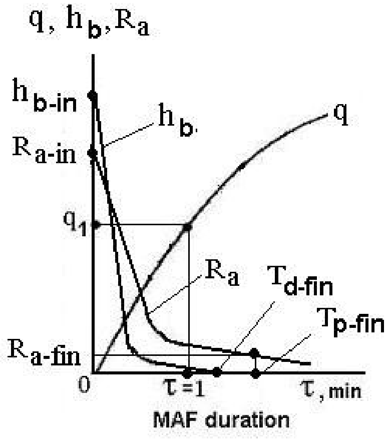

Fig. 1. Diagrams of base regularities of the MAF process

in which R_a refers to the roughness of a work surface after τ minutes of polishing; $R_{a\text{-}in}$ is the parameter R_a of the initial roughness before MAF; and k_r, µm/min and y are the parameters of the dependence.

When MAF is used for deburring, the base regularity of a burr h_b high from the MAF duration $h_b = f(\tau)$ looks like the following equation:

$$h_b = h_{b\text{-}in} - k_h \cdot \tau^x, \tag{4}$$

in which h_b, µm is the height of burrs after MAF with the duration τ; $h_{b\text{-}in}$ and µm is the initial height of the burrs; k_h and x are parameters describing the durability of the burrs and the deburring conditions.

Comparison of Criteria. The task of allowance removal may be included in the technological operations of the removal of a defect layer, a paint, or a calx. The height of a removal layer is usually in the range of 1-10 µm. This is why it is comfortable to measure the removed allowance as a removed mass, especially when workpieces (or experimental samples) have small dimensions. Eq. 1 is derived at the time of an experiment in which only one MAF condition is changing, but the rest of the conditions are permanent. The structure of a magnetic inductor can also be a changing condition of the experiment.

Parameter q_1 of Eq. 1 labels the initial productivity, and the exponent $m < 1$ labels the decrease in productivity when the MAF duration is increasing. This can be seen in the following derivative:

$$\frac{dq}{d\tau} = q_1 m \tau_i^{m-1} = \frac{q_1 m}{\tau_i^{1-m}} = q_i'. \tag{5}$$

The magnitude q_i' refers to the allowance mass removed in one minute with #i. It can be seen that the actual specific productivity q_i' is less than the exponent m. So both parameters, q_1 and m, can be used as indirect criteria for comparing a variable condition of MAF.
More exact comparison and optimization can be performed using the following technique, applied on an example of MAF, i.e., on a shaft cylindrical surface. The rotation frequency n of the shaft was changed during the experiment, and Eq. 1 was derived for each value of n. Thus, both dependences, $q_1(n)$ and m(n), can be derived. The time needed to remove the same allowance specific mass q as that in Eq. 1 may be determined as follows:

$$\tau(n) = \sqrt[m(n)]{\frac{q}{q_1(n)}}\ . \tag{6}$$

It is necessary to make use of the well-known mathematical method of determining the rotation frequency by providing a minimal period of time in which to remove the allowance with the specific mass q, so as to determine the partial derivative and to equate it with zero:

$$\frac{\partial \tau(n)}{\partial n} = 0. \tag{7}$$

Then it is necessary to solve Eq. 7, concerning the rotation frequency n.
The application of Eq. 1 for choosing a more effective magnetic abrasive powder is shown in the article “Characterization of the Magnetic Abrasive Finishing Method and Its Application to Deburring” by the authors of this book.

Comparison Criterion for Polishing by MAF. In this case, the criterion for the comparison, the duration of MAF, $\tau = T_{R\text{-}fin}$ (Fig. 1) for the desired roughness $R_a = R_{a\text{-}fin}$, can be derived from Eq. 2, as shown below:

$$T_{R-fin} = \sqrt[y]{\frac{R_{a-in} - R_{a-fin}}{k_r}}\ . \tag{8}$$

Comparison criterion for deburring by MAF. The criterion is the time needed for complete deburring, $T_{d\text{-}fin}$, which can be obtained by substituting $h_b = 0$ in Eq. 1, as in the following equation (See Fig. 1):

$$\tau = T_{d-fin} = \sqrt[x]{\frac{h_{b-in}}{k_h}}\ . \tag{9}$$

The technique described above has been checked in an experiment with removal burrs after drilling on steel samples.

Optimization of Deburring Conditions. The experiment was completed with a vertical milling machine. The face electromagnetic inductor was fixed in the machine spindle and used as the source of the magnet field in the working gap δ, which was filled with magnetic abrasive powder (Fig. 2). The steel samples were fixed on the vibrating table. Lastly, the oscillation motion for the samples was imposed during MAF. The vibrating table was placed

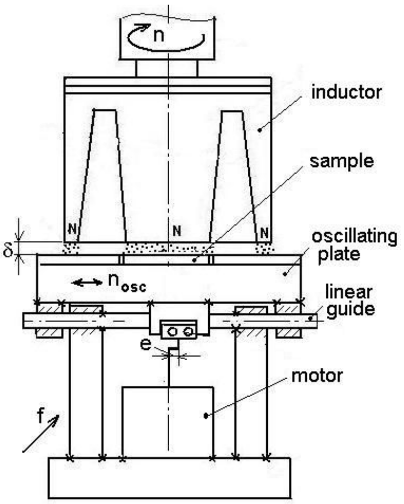

Fig. 2. Scheme of experiment

Table 1. Conditions for the Experiments

Condition	Numerical Value
Electromagnetic inductor, EMI-1	
External diameter of the pole N, D_{ext}	110 mm
Procedure of MAF: rpm n, rev/min	95~380
feed f, mm/min	61~342
table stroke number	1~8
current I, A	1.0~1.6
Height of the working gap δ, mm	2
Magnetic induction in the gap δ, T	0.47~0.72
Volume of the powder V_p, cm^3	13
Coolant	3% oil in water
Procedure of drilling:	
hole diameter, mm	3
rpm, rev/min	3000
feed, mm/min	25, 30, 45
Material of samples	Steel SM45C

on the machine table and fed in a perpendicular direction to the oscillation. The powder Fe-TiC was used in the experiment with a composition grain of 400/300 μm, and

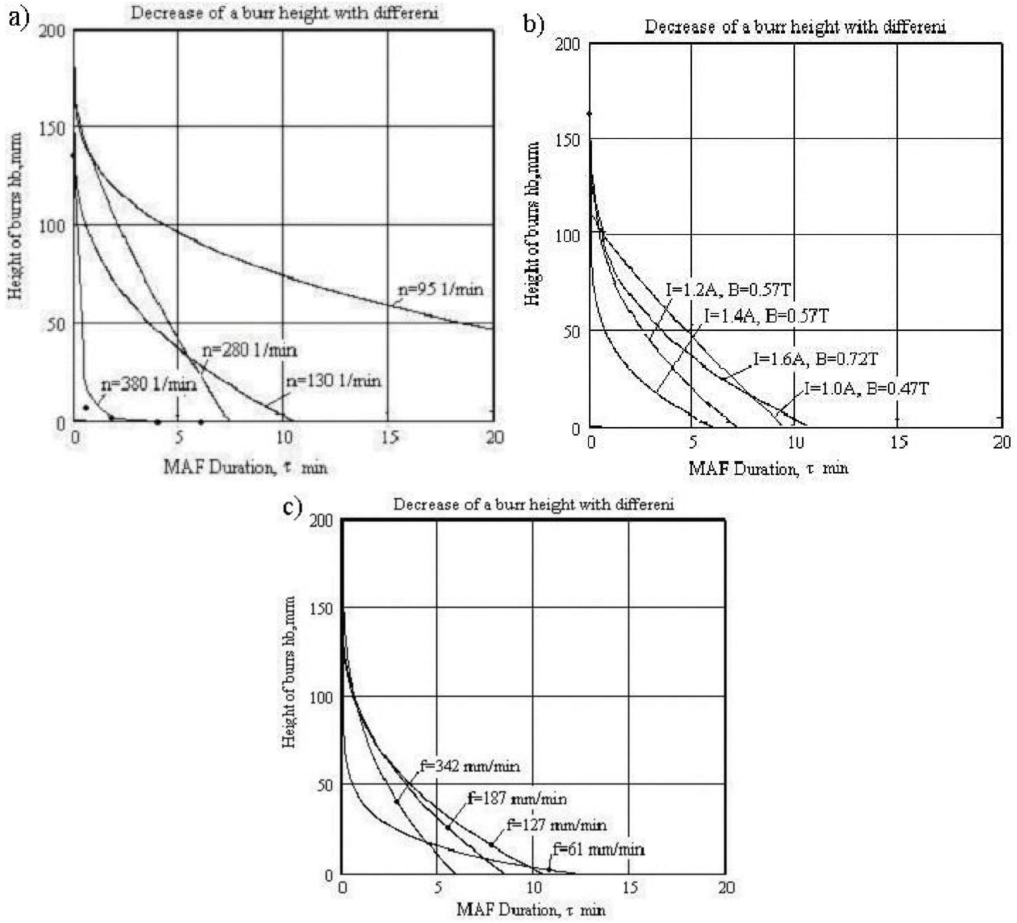

Fig. 3. Family of curves $h_b = f(t)$ received with a different rpm (a), coil current (b), feed (c)

the size of its abrasive particles was 40/28 μm. The abrasive particles were located on the grain surface. Other conditions correspond to Table 1.

Three factors were optimized: the frequency of rotation n of the magnetic inductor, feed f of the machine tool table, and coil current I. The experiments were carried out as follows. Each steel sample with the drilled holes was consistently processed using the MAF method during 1, 2, 4, 6 strokes of the table. Before MAF and after each of the specified strokes, the sample was retrieved from the machine and the heights of the burrs were measured. Experimental equations of a type of Eq. 4 were received from the averaged results of the measurements. The approximation was executed with the help of the software MathCad 2001. Then, using Eq. 8, the duration $T_{d\text{-}fin}$ necessary to complete the deburring was calculated at each new combination of conditions. The magnitude $T_{d\text{-}fin}$ was used here as a criterion for optimization. Using the calculated $T_{d\text{-}fin}$, the relations $T_{d\text{-}fin} = f(n)$, $T_{d\text{-}fin} = f(I)$, and $T_{d\text{-}fin} = f(f)$ were constructed. Based on these results, the conclusions on the optimum MAF conditions were made, while ensuring the minimal time $T_{d\text{-}fin}$ for complete deburring.

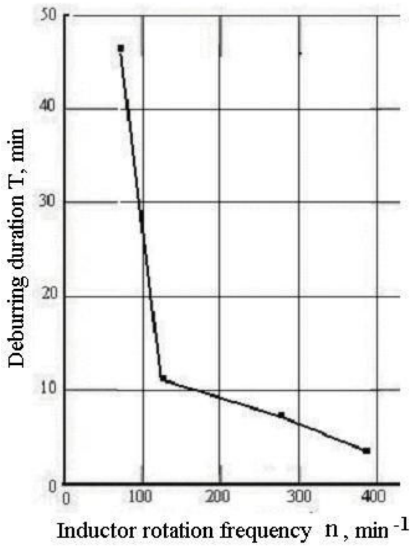

Fig. 4. Influence of the rotation frequency on the deburring duration

The approximated curves received in this experiment are shown in Fig. 3. The relationship between the deburring time and the frequency of rotation, $T_{d\text{-}fin} = f(n)$, shown in Fig. 4, can be obtained from the approximation in Fig. 3a. With the increase in the frequency n, the contacts of the abrasives with burrs in a unit of time increased, which explains the reduction in the duration $T_{b\text{-}fin}$. A further increase in the rotational frequency for greater efficiency will result in the throw-out of the powder from the working gap due to centrifugal forces, which will be the limit of the rotational frequency.

The increase in the feed in the given range resulted in the reduction of the duration of the deburring (Fig. 5). As the feed rate increased, the deburring time for completely removing the burrs became shorter. A faster feed rate means more strokes of the table in a specified time, which enables more effective deburring.

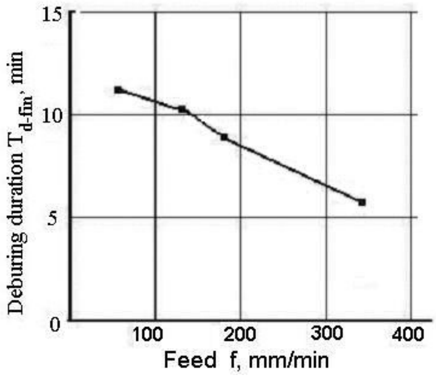

Fig. 5. Influence of the feed on the deburring duration

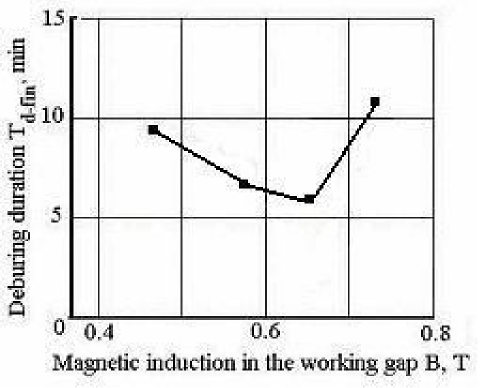

Fig. 6. Influence of magnetic induction on the deburring duration

The relationship, $T_{d\text{-}fin} = f(B)$, between the duration of the deburring and the magnetic induction in the internal working gap is shown in Fig. 6. The shortest duration of the deburring was obtained at the magnetic induction B = 0.67 T (I = 1.4 A). The increase in the coil current and the magnetic induction over specified values resulted in magnetic saturation of the powder in the working gap and the reduction of the magnetic and cutting forces.

The configurations of the edge are represented in Fig. 7 before MAF and after 3 and 7 strokes. Typical examples of burr measurement using the laser triangulation method are shown in Fig. 8 for the edge before and MAF finishing.

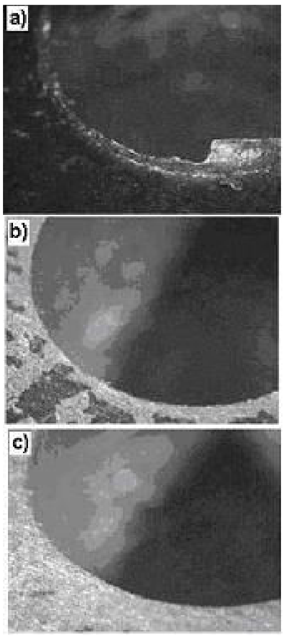

Fig. 7. View of the hole edge before MAF (a), after 3 strokes (b), and after 7 strokes (c)

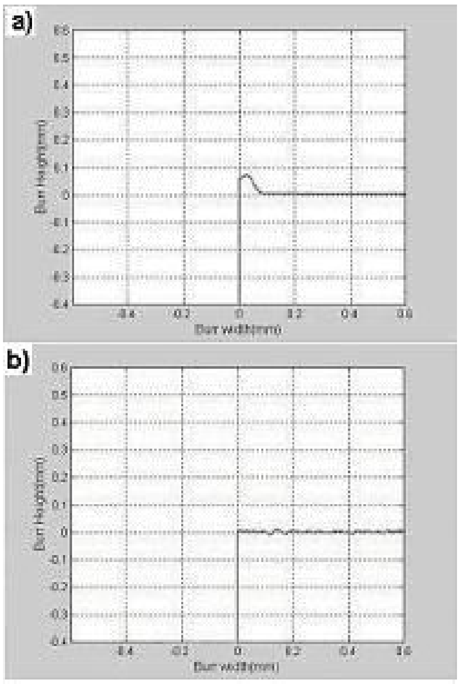

Fig. 8. Micro-burr geometry graph before (a) and after (b) MAF

Summary

The developed technique for comparison of magnetic abrasive powders and other MAF conditions allows the determination of the optimal conditions for polishing, deburring, edge rounding, etc. Besides, it allows choosing of the more effective powder and of inductor construction for the MAF operation. It uses the following criteria for comparison and optimization: the initial productivity, q_1; the exponent m for the removal allowance; time $T_{R\text{-fin}}$ for polishing; time $T_{d\text{-fin}}$ for complete deburring, etc. The results of the experimental optimization of deburring conditions after drilling on steel samples are as follows. The increase in the feed rate of the table and the frequencies of the magnetic inductor rotation resulted in the reduction of the necessary duration of the deburring time, $T_{d\text{-fin}}$. The face electromagnetic inductor applied here was sufficient for removing the burr after drilling on the steel components.

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