A REVIEW ON MAGNETIC ABRASIVE MACHINING

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ABSTRACT: The magnetic abrasive machining is a machining method based on the use of the magnetic field to generate a flexible abrasive brush from abrasive and/or ferromagnetic particles. The possibility of obtaining low values for the *Ra* surface roughness parameter led to the use of this machining method, especially as an abrasive finishing method. Over the time, various versions of machining techniques were proposed and some of them were in detail investigated and applied in industry. When the problem of selection or application of a certain magnetic abrasive machining technique is formulated, information concerning the magnetic abrasive machining methods and techniques and their characteristics could be necessary. The documentary research activity allowed to the authors of this paper elaboration of a review on the magnetic abrasive machining/finishing, by taking into considerations information found in the accessible specialty literature. As a result, a synthetic presentation concerning some machining/finishing magnetic abrasive techniques, principles of this machining method, its applications and major research areas was elaborated.
KEYWORDS: magnetic abrasive machining, finishing, work principle, applications, research areas.

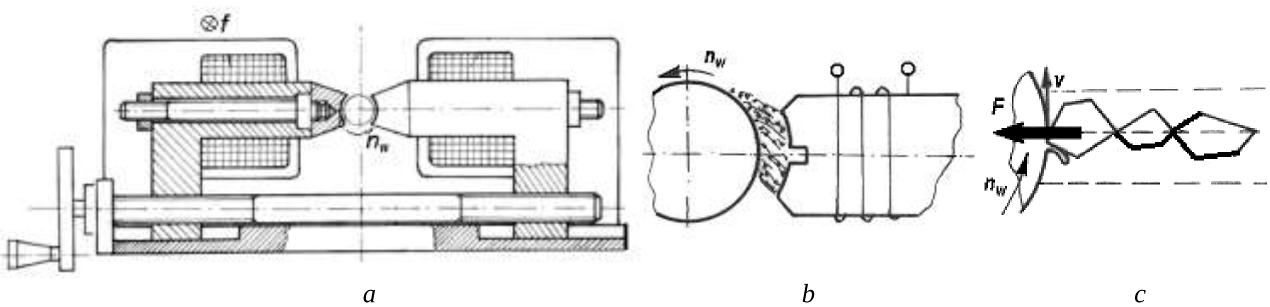
1. INTRODUCTION

The magnetic abrasive machining is included in a larger group of non-traditional machining processes that use a magnetic field to develop manufacturing processes with or without material removal from the workpiece. There are researchers which classify the magnetic abrasive finishing processes in proper magnetic abrasive finishing processes, magnetorhelogical finishing processes, magnetorheological abrasive flow finishing processes and magnetic float polishing [20].

The proper magnetic abrasive machining/finishing or the machining/finishing using magnetic abrasive particles is based on the effects generated as a consequence of the movements and pressures exerted between the workpiece surface to be machined and the abrasive particles having the role of the cutting tool (fig. 1, *b* and *c*). The abrasive particles are held in the work zone by means of a magnetic field; the process develops usually in air.

First mentions of a magnetic abrasive machining techniques seem to be made by the American Coats [9, 51] and the Russian Karlov [8] or Kargalov [41, 82]. Harry P. Coats patented a method and apparatus for polishing containers using magnetic abrasive material [9]. Kargalov proposed the use of an alternative magnetic field to finish tubes internal surfaces by means of magnetic abrasive powders. Researches concerning the magnetic abrasive finishing were mentioned in 1940 in the United States of America [8]. In the period 1950-1967, patents concerning the magnetic abrasive machining have been granted in U.S.A. and France. Ample researches were developed in Soviet Union, Japan, China, Taiwan, Republic of Correa, India, Bulgaria, Romania etc.

Some of the magnetic abrasive machining techniques *advantages* are: *a)* Possibility of obtaining high accuracy and low values for surface



a *b* *c*

Figure 1. Generation of the abrasive brush (*a*) and action way of abrasive particles (*b*, *c*) (n_w – workpiece rotation, *f* – feed movement, *v* –tangential cutting speed, *F* – radial cutting force) (adapted from [2, 3, 4, 76, 77])

roughness parameters; *2)* Little or no surface damage (cracks, for example) due to low cutting forces; *3)* High material removal rate (sometimes); *4)* Possibility of using both specialized machine tools or equipment adapted on universal machine tools; *5)* A certain regeneration of the cutting capacity of magnetic abrasive flexible brush, due to the change of the abrasive particles positions during the machining process; *6)* A low pressure exerted by the abrasive particles on the workpiece surface, facilitating inclusively the finishing of parts characterized by low rigidity; *7)* A relatively simple control of hardness and stiffness of the magnetic abrasive brush, acting on the parameters of the electromagnetic field (for example, on the parameters of the electric current) [14, 76, 80]; *8)* Self-adaptability for finishing distinct geometric shapes [19]; *9)* Possibility of finishing workpieces made of hard to machine materials [40]; *10)* Small diameter holes could be finished by using fine powders [12].

As less convenient aspects of the magnetic abrasive machining, the followings could be mentioned: *1)* Possibility of a remanent magnetism existence; *2*) Some difficulties in obtaining abrasive ferromagnetic particles; 3) Difficulties in finishing high dimensions workpieces [12].

The objective of the research presented in this paper was to obtain a general image concerning the evolution and the main research directions of magnetic abrasive machining processes. An analysis of the research achievements in this field was published in 2013 by Kumar et al. [35]. Reviews concerning the magnetic abrasive finishing were also elaborated by Liu et al. [40] and by Houshi [19].

2. WORKING PRINCIPLE OF MAGNETIC ABRASIVE MACHINING

As above-mentioned, the magnetic abrasive machining firstly involves the contact of the abrasive particles with the workpiece surface [67]. The abrasive particle must have ferromagnetic properties. To be maintained in contact with the workpiece surface, inclusively when there are movements achieved by the abrasive particles and/or workpiece, a high enough intense magnetic field is necessary. Essentially, the ferromagnetic abrasive particle will have such a position that the maximum dimension of the ferromagnetic component of the abrasive particle is placed along the magnetic field force lines (fig. 1, *c*). The abrasive particles practically constitute *a magnetic flexible brush* that could be also considered as an extension of the magnetic pole [48].

Three types of magnetic abrasive particles are used in the magnetic abrasive machining: *a)* unbonded type, that is a mixture of abrasive particles and ferromagnetic particles; b) bonded type, when the abrasive particles are incorporated in a ferromagnetic matrix obtained usually by a sintering process [21]; *c)* hard enough ferromagnetic particles.

When the abrasive particles have sharp edges and adequate positions, under the action of the force generated by the electromagnetic field, they succeed to remove small chips from the workpiece asperities peaks (fig. 1, *c*), determining a diminishing of the values corresponding to the surface roughness parameters.

In order to materialize the characteristics of the magnetic field, both permanent magnets and electromagnetic coils were preferred. Under the action of the magnetic field, and due to the tendency of the ferromagnetic particles to have their long axes along the force lines of magnetic field, a structure similar to that of the brush wires (1-3 mm length) is thus generated. If there are movements between the brush wires and the workpiece surface, a process of *microcutting* and *ploughing* develops, when the

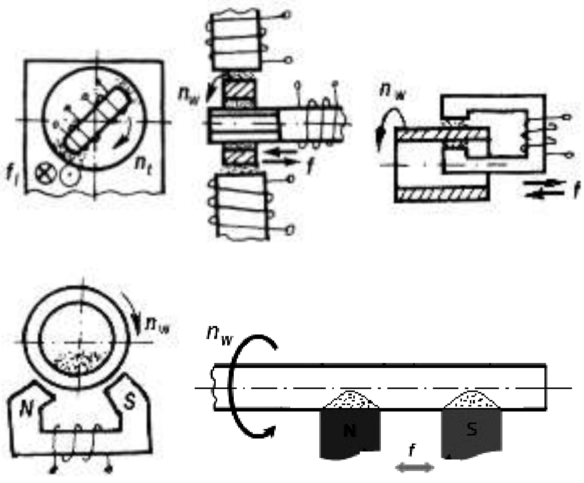


Figure 2. Magnetic abrasive machining of internal revolution surfaces (n_w – workpiece rotation, f – feed movement, n_t – rotation of a so-called tool) (adapted from [2, 3, 4, 8, 29, 64, 76])

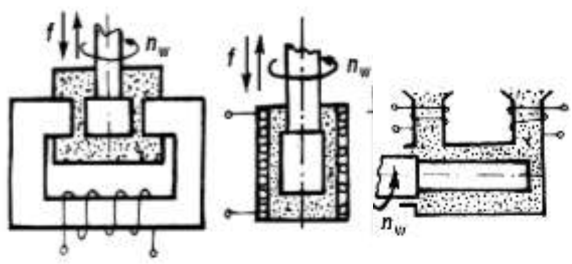


Figure 3. Magnetic abrasive finishing of external revolution surfaces (n_w – workpiece rotation, f – feed movement) (adapted from [2, 3, 4, 8, 76])

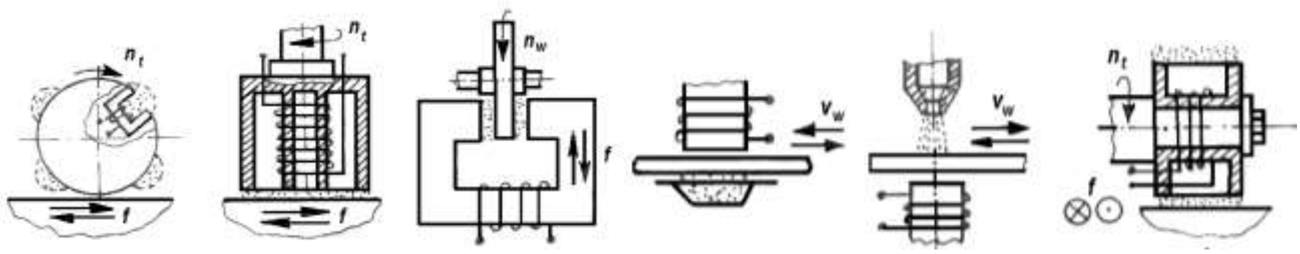


Figure 4. Magnetic abrasive machining of plane surfaces (adapted from [2, 3, 4, 8, 76])

abrasive particle edges are sharp enough, and a *microdeformation* process when the abrasive particles are not sharp enough. The abrasive particles must have also a high enough hardness. The abrasive particles are held in the work zone if there is at least a ferromagnetic component. To fulfill these conditions (high hardness, sharp edges and ferromagnetism), hard enough ferromagnetic particles could be used, but also complex particles could be met, including both an abrasive component and a ferromagnetic component.

The main machining movements could be rotary movement achieved by the workpiece (n_w, rev/min) and/or by the flexible magnetic abrasive brush, a feed movement *f* achieved with a low speed, various vibratory movements aiming to increase the complexity of relative motions between workpiece and abrasive brush surfaces [2, 76, 79 etc.].

The force which acts on a magnetic particle is given by Maxwell's relation [4]:

$$F_M = \frac{1}{\mu_0} \oint \left[(\overline{B}\overline{n})\overline{B} - \frac{1}{2} B^2 \overline{n} \right] dS \qquad (1)$$

where *B* is the vector of the magnetic induction developed on an elementary surface *dS*, $\overline{n}$ – the unitary vector perpendicular on the surface element *dS*, μ_0 – a magnetic constant, corresponding to the vacuum magnetic permeability (μ_0=4π·10^{-7} H/m). If the vector of magnetic induction is perpendicular on the surface *dS*, the following relation is valid:

$$\overline{B} \cdot \overline{n} = Bn \cos(\overline{B} \cdot \overline{n}) = Bn \qquad (2)$$

The magnetic induction *B* is proportional to the intensity *H* of the magnetic field:

$$B = \mu_n H, \qquad (3)$$

where μ_n is the magnetic permeability of the powder for an induction *B* valid in a certain point of the work zone.

Shinmura et al. established the following relation for the pressure *p* exerted in the machining process [8, 68]:

$$p = \frac{B^2}{4\mu_0} \cdot \frac{3\pi(\mu_s - 1)V}{3(2 + \mu_s) + \pi(\mu_s - 1)V}, \qquad (4)$$

where μ_s is the magnetic permeability of pure iron and *V* – the volume of the magnetic abrasive material.

Another relation concerning the mean size of the force F_m which presses the magnetic abrasive brush on the workpiece surface is [12]:

$$F_m = \frac{\Phi^2}{4\mu_0 \mu_{rme} S}, \qquad (5)$$

where *Φ* is the maximum flux in the gap, μ_0 – magnetic permeability of vacuum (μ_0=4π·10^{-7} H/m= =1.256·10^{-6} N/A^2), μ_{rme} – relative magnetic permeability of the machining environment.

Makedonski and Nikolov appreciated that under the action of the force generated by the magnetic field, the abrasive particle could penetrate into the workpiece material up to a depth *h* [8, 42]:

$$h = C_h \frac{F_y^m}{\rho^r (K_m H)^s}, \qquad (6)$$

where C_h is a constant taking into consideration the change of the surface layer strength in comparison with the strength of base material, *H* – machined material hardness, K_m – constant whose value depends on the hardness change under the action of magnetic field, F_y – component of the main cutting force, acting perpendicularly on the workpiece surface, *ρ* – radius of spherical surface approximating the particle zone that penetrates the workpiece surface layer, and *m*, *r* and *s* are constant exponents.

As phenomena specific to the magnetic abrasive machining, essentially we could take into consideration the microcutting and plastic

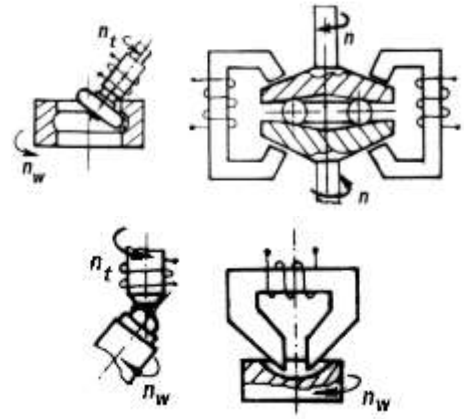


Figure 5. Magnetic abrasive finishing of shaped surfaces (adapted from [2, 3, 4, 8, 76])

microdeformations. Other observed phenomena could be the generation of inducted electric microcurrents, swirling currents, microcapillarity, magnetostriction, changes in the workpiece material microstructure (for example, diminishing the quantity of residual austenite in certain steels), diminishing of residual stresses etc.

Singh et al. considered that the micro-cutting and scratching are mechanisms able to generate the magnetic abrasive machining process [73].

Theoretical models concerning the evolution of the surface roughness in magnetic abrasive finishing processes were developed by Jain et al. [21], Jayswal et al. [22], Judal and Yadava [24], Kala et al. [28], Wani et al. [84] etc.

3. APPLICATIONS

There are various magnetic abrasive finishing techniques, adapted to distinct surfaces shapes and finishing requirements. Thus, there are adequate machining schemes that could be applied in the case of external revolution surfaces (fig. 2), internal revolution surfaces (fig. 3), plane surfaces (fig. 4), profiled surfaces (fig. 5) or other categories of surfaces and parts (fig. 6). The thickness of removed layer has values of few micrometers.

Kumar et al. [35] took into consideration three main groups of magnetic abrasive processes: with permanent magnets, with direct current, with alternating current.

Up to now, the magnetic abrasive machining was applied in finishing of bearings, of bearing balls [10], aerospace components, electronics components with micro meter or submicrometer ranges [58], cutting tools [5, 18, 28, 32, 87], rollers [14], brass tubes [59], aluminium and aluminum alloys tubes [60, 74, 83], ball screw [46], capillary tubes [29], needles for biopsy [57], mechanical bushes [49], catheter shafts [18], ultra-lightweight and high-resolution mems X-ray micro-pore optics [61], in edge finishing [66], in micro-deburring processes using permanent magnet [20], in micro deburring [33], in deburring, polishing or removing the recasting layers produced by electrical discharge machining [7].

The parts and test samples affected by magnetic abrasive machining were made of non-ferromagnetic materials like stainless steel, nonmagnetic materials [31], nonferrous materials [36], brass [23], aluminium, ferromagnetic materials like steels, magnesium [36] and magnesium alloy [38], cast iron [23], paramagnetic materials [25].

As abrasive materials, in the industrial applications and in experimental researches, *ferromagnetic abrasive particles* sintered with fine abrasive particles (magnetic abrasive particles) there were frequently used [20]. Essentially, two groups of abrasive powders could be used:

a) Ferro-magnetic abrasive particles, having both abrasive and magnetic properties (ferro-boron, ferro-tungsten, hard cast iron etc.);

b) Composite particles, including a matrix with ferromagnetic properties and abrasive particles [10].

Materials for abrasive particles could be aluminium oxide (Al_2O_3), titanium carbide (TiC), tungsten carbide (WC), chromium carbide (Cr_2C_3), zirconium carbide (ZrC), silicon carbide (SiC), cubic boron nitride (CBN), diamond, alumina powder [1], ferrite particles [23], carbon nanotube [37], composite materials [15] etc.

Various specialized machine tools and devices

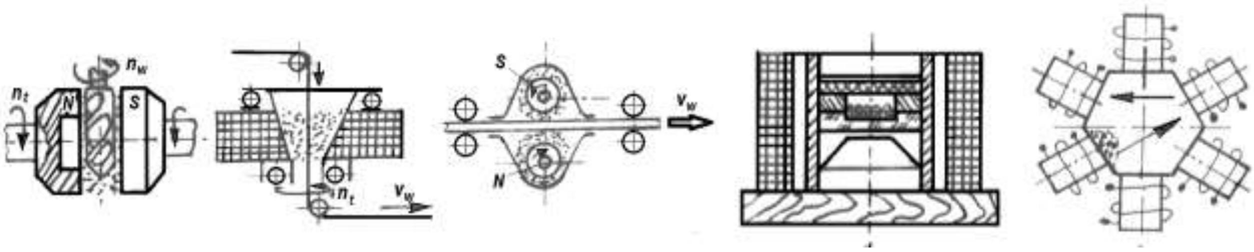


Figure 6. Magnetic abrasive finishing of other categories of surfaces (adapted from [2, 3, 4, 8, 34]

adapted to universal machine tools in order to develop magnetic abrasive machining processes are presented in [2, 3, 8, 62 etc.].

4. MAJOR AREAS OF MAM RESEARCH

A special attention was directed to the study of influence exerted by the magnetic abrasive process input factors of the magnetic abrasive machining process on the parameters of technological or service interest.

As process input factors, the followings were used: mesh number (600-1200), abrasive powders percentage weight *w*% of abrasive in the blend of abrasive and ferromagnetic particles (having values of 20-30 %), voltage *U* (60-80 V), magnetic flux density *Φ* [59], rotation speed *n* or natural logarithm of electromagnet number of revolutions per minute *ln RPM*, dimensions of the test piece, presence or absence of slots in magnet [20, 53, 63], presence of an alternating magnetic field [86], characteristics corresponding to the electromagnetic field (voltage *U* applied to electromagnet, magnetic induction *B*, magnetic flux density), characteristics of the movements between workpiece and abrasive particles (rotation sped *n* or peripheral speed *v* [13], amplitude and frequency of the eventual additional vibratory motion), the working gap (clearance) *δ* between workpiece surface and magnetic poles [13] (δ=0.9-3 mm), magnetic pole arrangement [90], duration *t* of the machining process, initial value of *Ra* surface roughness parameter [58], workpiece material properties [64], various interaction effects etc.

There were used as values for the magnetic abrasive process input factors: peripheral speed: v=0.9-2 m/s, longitudinal feed f=0.12-0.2 m/s, magnetic induction B=0.3-1.2 T [12], pressure p=0.09-0.50 MPa [2].

The working liquid applicable in the case of magnetic abrasive machining has the composition in accordance with the type of workpiece material [2].

As *output factors*, one used arithmetic mean deviation of surface profile *Ra* [28, 36, 39, 65, 78, 81, etc.], percentage change in surface roughness *ΔRa*, surface texture [34, 73], normal and tangential components of cutting force F_c [16, 31, 43, 53, 55, 59, 72 etc.], material removal rate (mg/min) [13, 23, 53, 90 etc.], workpiece-brush interface temperature [45, 52, 53].

Some values of the output parameters could be: material removal rate Q=10-20 mg/min, Ra=0.01-0.08 μm, machining duration t=10-20 min [12].

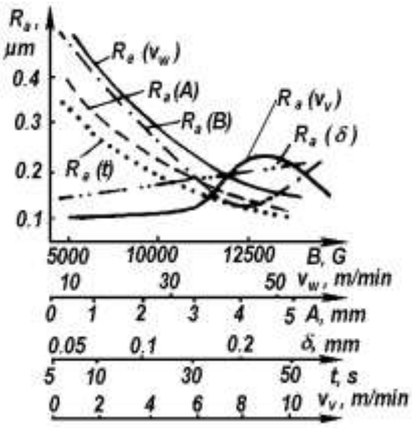


Figure 7. Influence exerted by some factors on the size of the Ra surface roughness parameter (adapted from [8, 76])

The minimum value of the surface roughness parameter obtained during the experimental investigation of magnetic abrasive machining process seems to be Ra=0.0076 μm, in the case of finishing of stainless steel rollers [20]. An image concerning the general influence exerted by some process input factors on the size of the *Ra* surface roughness parameter could be seen in figure 7. As expected, the increase of the abrasive particles dimensions determines an increase of the *Ra* surface parameter size. Essentially, the increase of process duration *t* and vibratory motion amplitude *A* determines decrease of the *Ra* surface roughness parameter, while the increase of the clearance *δ* leads to an increase of the *Ra* value. The curve *Ra=f(v)* could have a maximum for a certain value of the cutting speed, while a minimum of the *Ra* surface roughness parameter could be observed for a certain value of magnetic induction *B*.

Mulik and Pandey [53] found that in the case of plane magnetic abrasive finishing of hardened AISI 52100 steel, the percentage contributions of distinct input factors on the surface roughness is the following: mesh number – 26%, natural logarithm of electromagnet rotation speed in rev/min – 22 %, percentage weight of abrasive in the blend of abrasive and ferromagnetic particles %*wt* – 21 %, voltage *U* x logarithm of electromagnet rotation speed in rev/min – 7 %, mesh number x percentage %*wt* – 6 %, *ln RPM* x %*wr* – 11 % (7 % being the error).

The main research methods applied in investigation of the magnetic abrasive machining/finishing were: planned factorial experiments with independent variables with up to 4 levels, adaptive neuro-fuzzy inference system (ANFIS) [1, 47], analysis of variance (ANOVA) [50, 53, 58], Ishikawa cause and effect diagram [13, 45], response surface methodology [17, 75], finite element method [24], fuzzy logic [30] etc.

The results of applying the magnetic abrasive machining process were evaluated by means of atomic force microscopy, scanning electron microscopy, measuring the surface roughness parameters, optical profiler, measuring the cutting force components etc.

A research direction in the field of magnetic abrasive machining concerned the identification of the process input values able to ensure optimized values for the values corresponding to the parameters of technological interest. Thus, the researchers developed planned factorial experiments in accordance with the requirements of Taguchi method and used also the analysis of variance [1].

As an objective function valid in the optimization process, Kim and Choi took into consideration the difference ΔRa between the values of initial and final surface roughness parameter [21] Ra:

$$\Delta Ra = Ra^0 - Ra(t_f) = \left[\frac{9\cdot 10^3 K_{maf} K_3^2 A_{air} I_M \mu_0}{8\pi H_w L_w^2 \tan\theta}\right] \cdot \quad (7)$$

$$\cdot \left(\frac{v_{ma} t_f}{d_{ma}}\right)\left(\frac{w_f I^2}{K_2 + w_f}\right), \quad [\mu m]$$

where:

$$K_2 = \frac{3(\mu_{rf} + 2)}{\pi(\mu_{rf} - 1)}, \quad (8)$$

$$K_3 = \frac{n_c}{A_{air}\left(\frac{l_{air}}{A_{air}} + \frac{1}{\mu_{em}}\frac{l_M}{A_M}\right)}, \quad (9)$$

$$K_{maf} = \frac{C' C_0 C_1 C_2 C_3 C_4}{C_5 C_6}, \quad (10)$$

where Ra^0 – value of initial surface roughness parameter (μm), $Ra(t_f)$ – value of surface roughness parameter after finishing operation for the time t_f (μm), l_f – length of the workpiece finished surface, K_{maf} – a constant of proportionality, determined by considering some other constants C', C_0, C_1, C_2, C_3, C_4, C_5, C_6, A_{air} – cross-sectional area of air-gap (mm2), μ_0 – magnetic permeability in vacuum ($4\pi\cdot 10^{-7}$ H/m or N/A^2), H – Brinell hardness number (MPa or N/mm^2), L_w – length of workpiece (mm), θ – half of mean angle of abrasive cutting edges (degrees), v_{ma} – relative velocity between magnetic abrasive particles and workpiece (mm/s), t_f - finishing time, d_{ma} – mean diameter of abrasive particles (mm), d_m=15.24M_a^{-1}, M_a – mesh size of abrasive particles, w_f – volume ratio of ferromagnetic material in the magnetic abrasive particles (ratio of the volume of ferromagnetic material and the volume of the abrasive particles), I – current intensity (A), μ_{rf} – relative magnetic permeability of ferromagnetic material, l_{air} – length of air-gap (mm), l_M – length of magnet (mm), A_M – cross-sectional area of magnet (mm^2), μ_{em} – relative magnetic permeability of electromagnets, A_{air} – cross-sectional area of magnet (mm^2).

Some aspects concerning the optimization of magnetic abrasive machining processes were addressed by Nguyen [56, 75].

The problem of identifying a correlation between the surface roughness and the forces involved by the magnetic abrasive finishing process was investigated by Singh et al. [72].

Another research direction addressed in order to improve the performances of the magnetic abrasive machining was the combination of this process with other nonconventional or conventional machining processes; thus, the so-called *hybrid processes* were proposed.

For example, in the electrochemical magnetic abrasive machining process, the material is removed from the workpiece surface layer, as a result, both of abrasive effects and electrochemical dissolution [3, 15, 24, 39]; in such a case, the following relation was proposed to estimate the Ra value of the arithmetic mean deviation of the profile [24]:

$$Ra = Ra^0 - \sqrt{\frac{k_c Ra^0 V_w}{4\pi d_w l_w}}, \quad (11)$$

where k_c is a constant which considers the actual contribution of material removal in surface roughness reduction, V_w – total volume of material removed from the workpiece during the process, d_w – diameter of the cylindrical workpiece surface, l_w – length of workpiece machined portion.

Sihag et al. proposed and investigated experimentally a hybrid technique including a chemical oxidation process and a magnetic abrasive machining process; such a hybrid technique could be applied especially in the case of workpieces made of hard materials, as tungsten is [71].

A combination of magnetic abrasive machining with electrophoretic deposition process was investigated by Yang et al. [88]; they appreciated that such a process contributes to the improving of the surface roughness and reducing technical and personnel training costs.

Ultrasonic assisted magnetic abrasive finishing was the object of research activity aiming the increase of material removal rate [45, 50, 54, 53, 69, 70].

Information concerning the finishing forces developed in magnetic abrasive finishing was presented in [27, 31, 55].

Chou et al. investigated the rheological effect of gel abrasives in magnetic abrasive finishing of cylindrical rods made of mold steel [7]. They noticed the better results obtained when using bean gums in comparison with those achieved when using silicone gels.

A research direction was also the increase of the complexity of movements achieved by the workpiece and/or the electromagnet/permanent magnet able to generate the electromagnetic field. In this way, for example, there were developed processes of vibration-assisted magnetic abrasive machining [89].

Investigations concerning the use of a double disk magnetic abrasive finishing process (fig. 8), inclusively in the case of paramagnetic materials, were developed by Kala et al. [25, 26, 27, 28].

Wu et al. noticed that when using the alternating magnetic field, an oily grinding in combination with magnetic particles could ensure an improvement of the surface roughness [85].

The temperature in the workpiece-brush interface was evaluated by simulation using finite element analysis based ANSYS software by Mishra et al. [44]. They predicted a temperature of 34-51 ^{o} C [44]; the experimental research validated the simulation results. Mulik et al. measured a temperature of about 33-46 ^{o} C at the interface of workpiece surface and abrasive particles, in the ultrasonic assisted magnetic abrasive finishing process [53].

5. CONCLUSIONS

The magnetic abrasive machining method is based on the use of the magnetic field in order to generate and held in the machining zone a flexible abrasive brush, able to be used especially as a finishing tool. Over the years, researchers proposed or improved new magnetic abrasive finishing techniques and investigated various aspects concerning the method working principles, versions of method application in practice and possibilities of proper applications of magnetic abrasive techniques in the industry. As process input factors, in the research activities

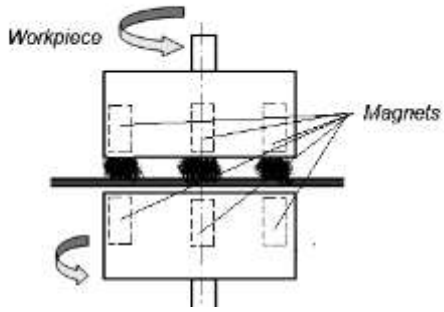


Figure 8. Double disk magnetic abrasive finishing process (adapted from [26, 28])

aiming obtaining better scientific and technical knowledge on the magnetic abrasive machining methods, the following were especially preferred: electrical parameters determining the magnetic field properties, characteristics of movements developed between the magnetic flexible abrasive brush and workpiece surface to be machined, working gap size, presence or absence of a certain working liquid etc.

As future possible research directions in the field of magnetic abrasive machining/finishing, one could mention:

- Identification of improved or new mathematical theoretical models valid for magnetic abrasive machining;

- Identification of new substances able to be used as abrasive particles or gels able to sustain the abrasive particles in the machining zone;

- Developing improved or new equipment for magnetic abrasive machining and abrasive materials;

- Extending the experimental research on parts/ test samples made of other materials;

-Applying new methods of obtaining empirical mathematical models corresponding to the experimental results;

- Developing of additional investigations concerning the optimization of the magnetic abrasive machining process.

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