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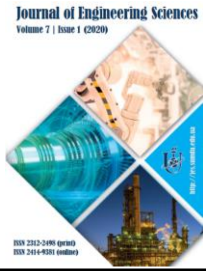

AISI 1045 Steel Flat Surfaces Machining Using the Magneto-Abrasive Method

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Abstract. The results of the study of using the end-type heads based on permanent magnets for polishing flat surfaces of ferromagnetic parts on standard metal-working equipment are presented in the work. The possibility of a highly efficient achievement of the roughness of flat surfaces up to Ra < 0.05 μm with the initial Ra > 1–2 μm with removing of the heredity of the machining in the form of microwaves obtained in the face milling operation was shown. Based on the results of the analysis of the process of dispergation of the material was analyzed the influence of the magnetic field gradient the intensity of the magneto-abrasive machining of flat ferromagnetic surfaces by heads, which form a magneto-abrasive tool in the shape of a "brush" and "half of torus". The influence of technological process parameters: the rotation speed of the working heads, the sizes of the working gap, the technological feed on the character of the change in the microgeometry of the machined surface were investigated. The machining conditions, under which occur the preferential machining of micro peaks or micro valleys on a rough surface, were identified. It was determined that the rational conditions of the magneto-abrasive machining of flat ferromagnetic surfaces are: the rotation speed of the working heads 900 rpm, the gap size between the machined surface and the working surface of the head 2.5–4.0 mm and the working feed 10–15 mm/min.

Keywords: finishing, roughness, polishing, permanent magnet, magneto-abrasive tool.

1 Introduction

Finish machining of flat surfaces and surfaces with a small curvature is a critically important task up to date, specifically when it comes to large areas. Obtaining a uniform roughness with a value of Ra < 0.1 μm on the flat surfaces in the industry as rule is achieved by using special machine tools with various types of abrasive tools both rigidly bonded and loose. Herewith appear problems connected with processing tool wear and the loss of its necessary operating form, with the requirement of ensuring a constant and uniform pressing of abrasive to the surface. To achieve a low roughness, it is necessary to carry out dead-stop grinding, which takes a lot of time. Industrial methods, traditionally used in industry, for finish machining of large-sized surfaces require an individual approach to each machined part, especially when it comes to the quality component of machining, which does not admit forming unwanted stress state in the surface layer, the formation of microdefects during machining and abrasive elements penetration into the surface.

Methods, which use movably coordinated abrasive tools for machining, are new and perspective, which successfully allow solving the above problems. To such methods can be included magneto rheological and magneto-abrasive machining (MAM), which use magnetic field energy to form the processing tool. The relative simplicity of creating such a tool opens up wide possibilities of its use on CNC machines to obtain very clean, almost mirror surfaces. However, at the same time, the main problem hindering the widespread use of these methods in the industry is the shaping of an abrasive tool, which is realized by creating a certain gradient of the magnetic field in the machining zone.

The aim of this work was the creation of an end-type tool head based on permanent magnets for machining flat surfaces of ferromagnetic products and studying the influence of machining conditions on the change in roughness and individual characteristics of the microprofile of the machined surface.

2 Literature Review

In [1] were carried out investigations and presented experimental-production equipment for the machining of flat surfaces. Despite the positive results for the implementation of the MAM process, they mainly used machines with electro-mechanical systems, which can be used in specific conditions for a particular type of part and are not mobile and easily readjustable. The results of the magneto-rheological machining of flat surfaces from electrical alloys of copper [2], silicon [3] are presented. In these studies, as a binder to form a magneto-abrasive tool were used mixtures of carbonyl iron with SiC abrasive particles, which tend to segregate, which leads to an uncontrolled decrease in processing efficiency. The carried-out calculations of magnetic fields in the working heads were unfortunately not agreed with the efficiency of the machining process. Similar questions about the use of calculation results arise in the analysis of studies on the machining of flat surfaces by end-type heads [4] and by the periphery of a round inductor [5].

In the work [6] according to the research results, a qualitative influence of such technological parameters as the machining speed and the size of the working gap was determined. However, there are no recommendations for the selection of rational magneto-abrasive powders, MAM time, and the possibility of using different types of coolant as in [1]. The importance of the problem of determining the shape of the working surfaces of magnetic heads, the presence of magnetic field concentrators and elements on them that create the conditions for the formation of zones with increased machining efficiency in a magneto-abrasive tool was shown. Carried out a detailed analysis of superfinishing methods for machining steel surfaces in [7] showed the promise of using compact heads based on high-power permanent magnets for MAM. Similar recommendations are given in [8]. However, the presented volume of carried out studies and recommendations does not contain clear information that necessary to create such mobile magnetic heads, areas and conditions for their use.

The work [9] presents studies of machining by end heads with permanent magnets of steel parts. The influence of machining speed, feeds, amount of abrasive and its size on the change in the machining productivity was analyzed. The need for a clearer analysis of the influence of the characteristics of magneto-abrasive powders of various types and compositions on the effectiveness of MAM was noted.

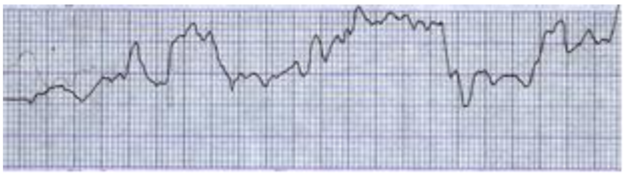
The subject of [10] is the machining of parts after the SLM process of forming workpieces from Al alloys by end heads from Nb-Fe-B magnets with the magneto-abrasive method. The possibility of achieving a surface roughness with Ra < 0.15 μm was shown. As in the above studies, mechanical mixtures were used to form a magneto-abrasive tool, the effectiveness of which decreases sharply with increasing time of continuous operation.

3 Research Methodology

3.1 Sample preparation

Preliminary preparation of flat surfaces from AISI 1045 steel before MAM was performed by face milling with the 200 mm diameter mills. The surface appearance after face milling is shown in Fig. 1 a. The presence of waviness on the surface arising after machining with the end mill is shown. Surface profilogram (Figure 1 b) in the direction of the milling feed. Measurements of the parameter Ra were taken on the profilograph-profilometer Caliber and it showed that it varies in the range of 1–2 μm.

a



b

Figure 1 – A sample surface after milling:
a – magnification X20; b – surface profilogram in the direction of the milling feed, horizontal magnification 200 and vertical magnification 5,000

Were performed the analysis of change of the relative reference profile length of surface – t_p at the profile section level p (Figure 2), obtained after milling.

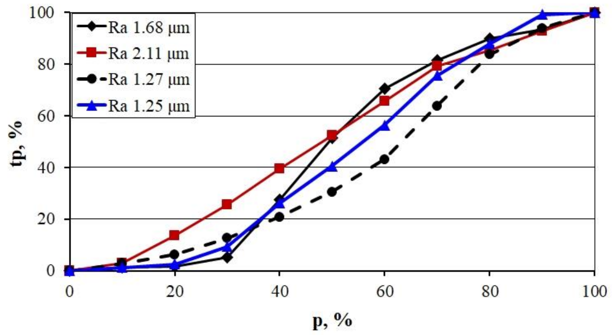


Figure 2 – Change of the relative reference profile length t_p at the profile section level p

3.2 Developing and manufacturing of tool construction using permanent magnets

When developing the design of the head, the following requirements were considered:

– should be compact, readjustable, easy-to-install in clamping devices of universal metalworking equipment;

– should provide a sufficient value of the magnetic field, which is necessary for the formation of an effective magneto abrasive tool (MAT) in the machining zone;

– should provide the most uniform distribution of magneto abrasive powder on the working surface of the head and its effective holding in the machining zone.

Considering the above requirements end head design with permanent magnets was developed and manufactured (Figure 3), which consists of three main elements.

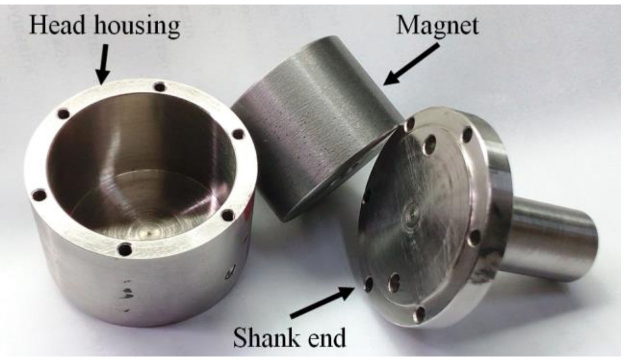
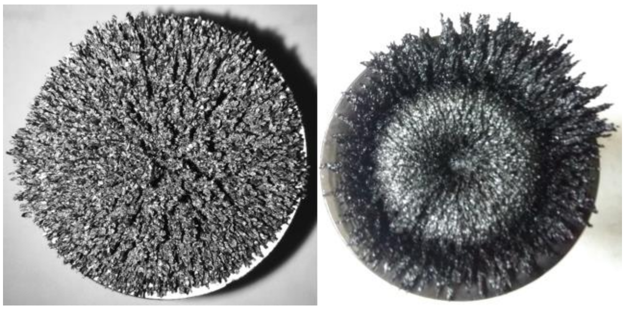


Figure 3 – Appearance of the head

To ensure the formation of MAT of various shapes, two types of end heads were manufactured (Figure 4). The first type allows creating the shape of the MAT in the shape of a “brush” (Figure 4 a) when the magneto abrasive powder is uniformly located over the end surface. For this was used the cylindrical magnet with a diameter of 40 mm, located in the non-magnetic housing. The second type is “half of the torus” (Figure 4 b) when a magneto abrasive tool is formed on the end surface of the head in the shape of half of the torus. For this were used two ring-shaped magnets, inserted coaxial one in one with a non-magnetic ring-shaped sleeve.



a b

Figure 4 – Appearance of the working surfaces of the heads: a – “brush”; b – “half of the torus”

3.3 Conditions of magneto-abrasive machining and evaluation of the obtained results

In the assembled working state, the end head is installed in the spindle of a vertical milling machine or any other equipment that provides adjustable spindle rotation and movement along three axes (Figure 5). The machined surface of the workpiece should be located parallel to the working surface of the head.

The influence of the head rotation speed in the range of 580–1,440 rpm, the cross-feed in the range of 10–50 mm/min and the working gap between the end face of the magnet and the machined surface in the range of 2.1–4.6 mm were investigated.

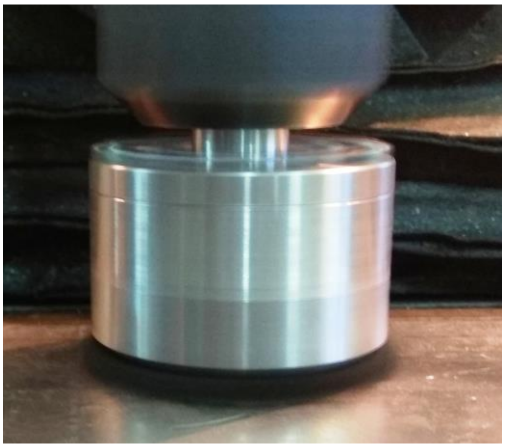


Figure 5 – The end head in working condition on the machine during machining of the flat workpiece

For the formation of MAT, a magneto abrasive powder obtained by the method of water atomization of melt – Ferromap with a particle size of 630–400 μm was used. This powder has a particle irregular shape with sharp edges and with an equiaxial coefficient equal to $k_f = 1.4$ [11, 12].

The MAM process was carried out for 5 minutes with different sizes of the working gap.

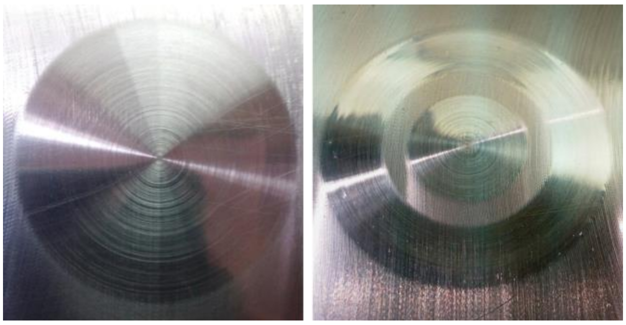
After machining, the surfaces were measured on a profilometer by tracing the probe from the center to the periphery of the machined zone. Five measurements of each track were made in different radial directions and the obtained results were averaged.

The MAM results evaluation was made by the changing of Ra parameter both along the milling direction and in the perpendicular direction, as well as by the analyzing of the dependences of the change in the value of the relative reference profile length depending on the profile section level according to the described in [13] procedure. The proposed approach allows determining the position of inflection points on the dependencies $t_p = f(p)$, in other words, to identify the conditions for the change of micro peaks of the obtained profile to the micro valleys. As well as to identify the conditions for the possible removing of technological heredity of the machining, which was formed during the preparatory milling operation in the form of microwaves.

4 Results and Discussion

After MAM of parts by different types of heads without cross-feed, the following markings were obtained from the interaction of MAT with the machined surface (Figure 6).

Typical views of the deviations of the macroprofile from a flat shape of surface – from the center of machining to the periphery after MAM by different heads, without cross-feed and at a rotation speed of 900 rpm are shown in Figure 7.



a b

Figure 6 – The marking from the interaction of the MAT with the surface of the part when using the head of the type “brush” (a) and “half of the torus” (b)

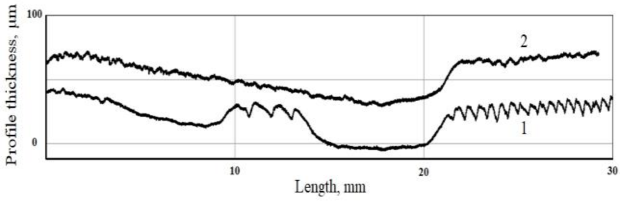


Figure 7 – The shape of macroprofile of the machined area of the flat surface obtained after MAM by heads: 1 – “half of the torus”; 2 – “brush”

The cross-sectional area of the deviation of the macroprofile from the horizontal surface that was machined by different heads can be used as a characteristic of the efficiency of their work for different sizes of the working gap – the distance from the end face of the magnet to the machined surface. Obtained results are presented in the form of histograms in Figure 8.

Markings of the interaction of individual powder particles with the machined surface have appeared especially actively at a small working gap of 2 mm. In these conditions occurs the active formation of locking zones the MAT, in which individual particles are pressed into the surface of the part. With an increase in the working gap by 0.6–1.0 mm or more, when the conditions for locking the MAT are significantly nullified, plastic deformation and smoothing of the micro peaks without removing them occurs in the working gap. That is, surface microroughness obtained at the milling stage – microwaves are not removed, but only slightly reduced.

Changes of the roughness parameter Ra for different sizes of the working gap and different values of the initial roughness are shown in Figure 9.

Rational variation of the size of the working gap allows controlling the process of dispergation of the material from the surface.

In the next step of the investigations, the influence of various rotational speeds of the working heads on the changes in the parameter Ra was analyzed. The results of the change of parameter Ra after machining with using Ferromap powder (particle size of 630–400 µm), with the working gap of 4.6 mm and a cross-feed of 10 mm/min are shown in Figure 10.

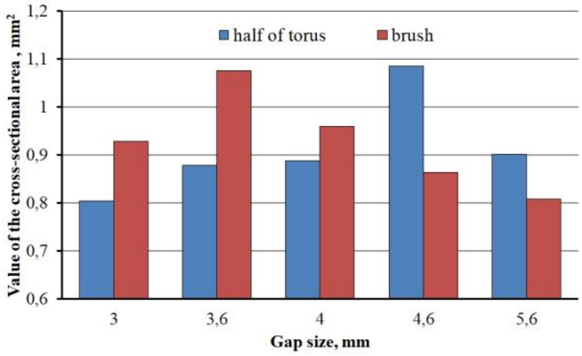


Figure 8 – Value of the cross-sectional area of the marking of the machined flat surface after MAM by types of head

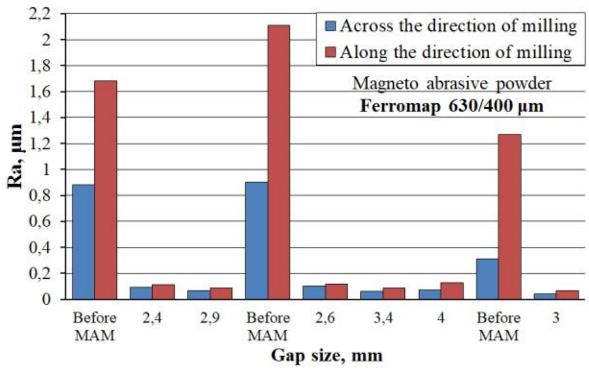


Figure 9 – Changes of Ra at different sizes of the working gap

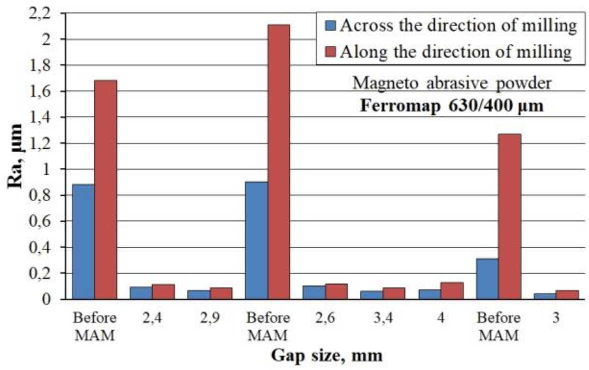


Figure 10 – Ra parameter of the flat surface machined by the MAM method at different rotational speeds of the end head

The appearance of machined surfaces at twenty-fold and four-fold magnification and surface profilograms after MAM with the head rotation speed of 900 rpm are presented in Figure 11.

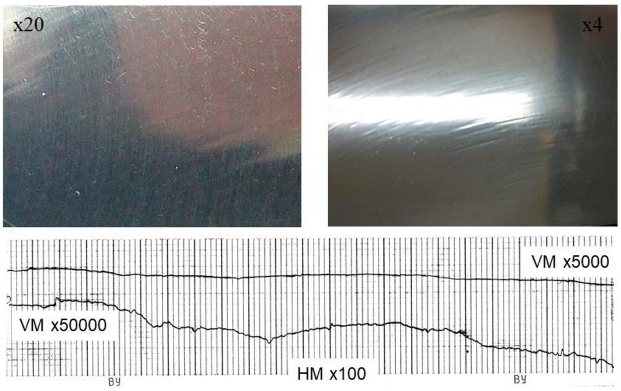


Figure 11 – Appearance and profilograms of the surface after MAM with end head: VM – vertical magnification; HM – horizontal magnification

It should be emphasized that under the specified MAM conditions the removal of microwaves occurs almost completely and only markings of microroughness from MAT are identified on the machined surface. The presence of an extreme decrease in Ra at a rotation speed of 900 rpm is explained by the rational ratio of the normal and tangential components of the interaction forces of the MAT with the machined surface. At the rotation speed of 580 rpm, the value of the tangential component of the forces, which responsible for the dispersion of the material from the surface, is not sufficient. While at rotation speeds of 1,120 rpm and higher, there will appealingly be active sliding and rotation of the particles of the ferro-abrasive powder over the surface, which does not provide favorable conditions for the running of micro-cutting processes.

The influence of the feed rate of the head during the MAM process on the change of surface roughness is studied. In this series of experiments, the working gap was h = 4 mm, the head rotation speed was 900 rpm. The obtained results are shown in the form of histograms in Figure 12.

It was shown that at feed speeds of more than 25 mm/min, the MAM process is stabilized, and at lower speeds occurs the process of “smoothing” of microroughness, which helps to remove the microwaves obtained at the stage of surface preparation during milling.

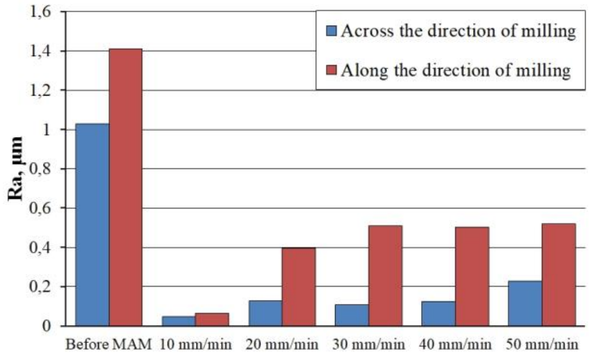


Figure 12 – Changes for Ra at the different value of tool cross-feeds

More detailed analysis of the formed after MAM surface roughness was carried out according to the results of the study of changes of the relative reference profile length from the profile section level. Typical dependencies of change of the reference profile length for surfaces obtained after MAM with Ferromap powder 630–400 μm (Figure 9) for different initial surfaces obtained after milling are presented in Figure 13. An analysis of the obtained results made it possible to identify the machining conditions under which the preferential machining of micro peaks on a rough surface or micro valleys is possible. The typical curves, which show the preferential machining of micro peaks at different initial surfaces, were obtained after MAM with the end head with a working gap of more than 2.2 mm. In the case when the gap size $h \leq 2.4$ mm, the micro valleys are preferentially polished.

The typical values of the positions of the points of inflection on the curves of the reference profile length obtained after MAM with 630/400 μm Ferromap powder at various initial surfaces formed after milling are presented in the form of histograms for various gaps (Figure 14). For the indicated values, machining was carried out at a rotational speed of the working head of 900 rpm.

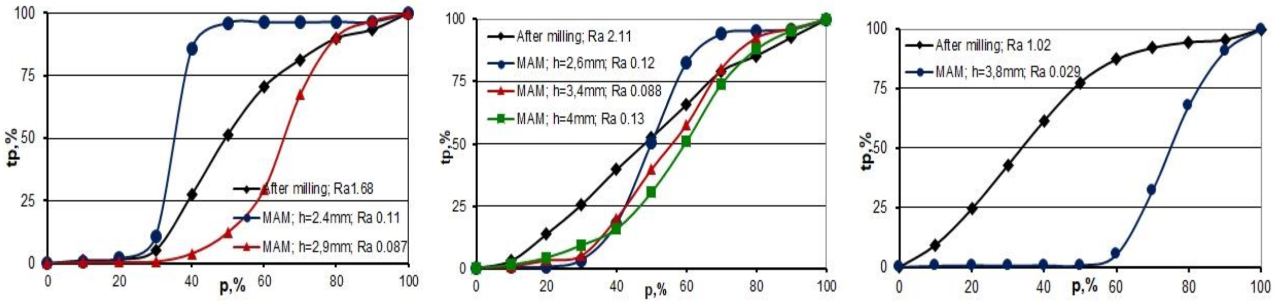


Figure 13 – The behavior of the relative reference profile length from the profile section level

An analysis of the position of the transition zones from peaks to valleys, and the above data about changing of the parameter Ra as a result of MAM, showed that a shift in the transition zone from micro peaks to micro valleys in the region of values greater than $p = 0.5$ indicates an active decrease in the waviness of the machined surface obtained at the milling stage.

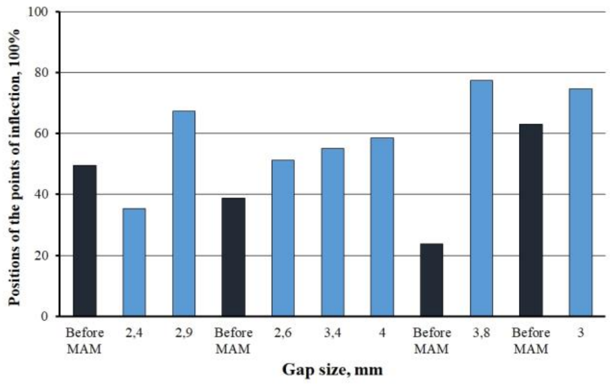


Figure 14 – Positions of the points of inflection on the curves of the reference profile length

Thus, it was shown that the best efficiency – the largest dimensional removal is typical at using the head of the type “brush” with a working gap of 3.6 mm, while when using the head of the type “half of the torus” the largest amount of material removed from a flat surface takes place with a gap of 4.6 mm. The largest removal is identified at the periphery of the head, where the highest speed of the relative motion of the magneto-abrasive tool relative to the machined surface and where the bulk of the magneto-abrasive powder is displaced under the influence of centrifugal forces during the MAM process. At the approach to the center of the working surface (axis) of the head, the amount of removal decreases.

It should be emphasized that the more complex topography of the magnetic field in the working gap, which is formed between the machined surface and the end face of the magnetic head of the type "half of torus", the presence of “locking” zones in the middle part of the end face of head initializes more active removal all over the working surface of the head.

It was shown that the best results - the smallest surface roughness after MAM were obtained at a head rotation speed of 900 rpm. These results are close to the optimal rotation speeds of the magnetic heads, given in [2, 14].

It is important to note that the rational ratio of the normal and tangential forces of interaction of the MAT with the surface will be depended largely on the size of the working gap, the magnetic properties of the powder magneto-abrasive material and the presence of cutting fluid in the working zone. Determination of the optimal ratios of the indicated components of forces depending on the conditions of the MAM requires additional research.

5 Conclusions

Finally, based on the results of the studies, the use of end-type heads based on permanent magnets for polishing flat surfaces of ferromagnetic parts on standard metal-working equipment was recommended. The possibility of a highly efficient achievement of the roughness of flat surfaces up to Ra < 0.05 μm with the initial Ra > 1–2 μm with removing of the heredity of the machining in the form of microwaves obtained in the face milling operation was shown. The sizes of rational gaps depending on the technological conditions of magneto-abrasive machining were determined. The carried-out analysis of the characteristics of the microprofile made it possible to determine the main paths at targeted control of the process of its formation.

References

1. Khomich, N. S. (2006). *Magneto-Abrasive Machining of Products: Monograph*. Belarusian National Technical University, Minsk, Belarus.
2. Harsh, K., Vishwas, G. (2018). Magnetorheological nano-finishing of diamagnetic material using permanent magnets tool. *Precision Engineering*, Vol. 51, pp. 30–39, doi: 10.1016/j.precisioneng.2017.07.003.
3. Jain, V. K., Ranjan, P., Suri, V. R., Komanduri, R. (2010). Chemo-mechanical magneto-rheological finishing (CMMRF) of silicon for microelectronics applications. *CIRP Annals – Manufacturing Technology*, Vol. 59(1), pp. 323–328, doi: 10.1016/j.cirp.2010.03.106.
4. Leonov, S. L., Ikonnikov, A. M, Grebenkov, R. V. (2017). Calculation of magnetic induction in the working gap during magneto-abrasive machining of flat surfaces of workpieces made of ferromagnetic and non-magnetic materials with permanent magnet inductors. *Technological Equipment, Machining Attachments and Instruments*, Vol. 4, pp. 49–54.
5. Ikonnikov, A. M, Leonov, S. L., Grebenkov, R. V., Kulavik, A. A. (2018). Analysis of magnetic forces in the working clearance with magnetic-abrasive treatment of inductors on standing magnets. *Journal of Modern Technologies*, Vol. 3(11), pp. 27–32.
6. Chaurasia, A., Wankhede, V. (2018). Magnetic abrasive finishing of inconel 718 super alloy using permanent magnet. *International Research Journal of Engineering and Technology*, Vol. 5, pp. 1165–1168.
7. Nagdeve, L., Jain, V. K., Ramkumar, J. (2018). Nanofinishing of freeform/sculptured surfaces: state-of-the-art. *Manufacturing Rev.*, Vol. 5, p.з 20, doi: https://doi.org/10.1051/mfreview/2018005.
8. Baron, Yu. M. (1986). *Magneto-Abrasive and Magnetic Machining of Products and Cutting Tools*. Mechanical Engineering, Saint-Petersburg.

9. Uddin, M. S., Santos, V., Marian, R. (2019). Interplay of process variables in magnetic abrasive finishing of AISI 1018 steel using SiC and Al2O3 abrasives. *Journal of Manufacturing and Materials Processing*. Vol. 3(2), pp. 18, doi: https://doi.org/10.3390/jmmp3020029
10. Teng, X., Zhang, G., Zhao, Yu., Cui, Yu., Li, L., Jiang, L. (2019). Study on magnetic abrasive finishing of AlSi10Mg alloy prepared by selective laser melting. *The International Journal of Advanced Manufacturing Technology*, Vol. 105, pp. 2513–2521, doi: https://doi.org/10.1007/s00170-019-04485-5.
11. Tkachuk, I. V., Maiboroda, V. S. (2014). Geometric characteristics of magneto-abrasive powders. *Tool reliability and technological systems optimization*, Vol. 34, pp. 49–55.
12. Maiboroda, V. S. (2001). *Fundamentals of Creation and Use of Powder Magneto-Abrasive Tool for Finishing of Shaped Surfaces*. National Technical University of Ukraine "Kyiv Polytechnic Institute".
13. Ulyanenko, N. V. (2006). *Increase of Efficiency Hard-Alloy Cutting Tackle by Magneto-Abrasive Treatment Application and Wear-Resistant Coating*. National Technical University of Ukraine "Kyiv Polytechnic Institute".
14. Gusev, V. V., Kucherenko, S. V., Sukhoruchko, K. S. (2011). Magneto-abrasive machining of internal surfaces with using permanent magnets. *Mechanical Engineering and Mechanical Science*, Vol. 8(190), pp. 145–151.
15. Oliker, B. E. (1990). *Powders for Magneto-Abrasive Machining and Wear Resistant Coatings*. Metallurgy, Moscow.
16. Wang, Y. Q., Yin, S. H., Huang, H., Chen, F. J., Deng, G. J. (2015). Magnetorheological polishing using a permanent magnetic yoke with straight air gap for ultra-smooth surface planarization. *Precision Engineering*, Vol. 40, pp. 309–317, doi: https://doi.org/10.1016/j.precisioneng.2014.11.001.
17. Karpuschewski, B., Byelyayev, O., Maiboroda, V. S. (2009). Magneto-abrasive machining for the mechanical preparation of high-speed steel twist drills. *Manufacturing Technology*, Vol. 58(1), pp. 295–298, doi: https://doi.org/10.1016/j.cirp.2009.03.046.
18. Kanish, T. C., Narayanan, S., Kuppan, P., Denis Ashok, S. (2019). Experimental investigations on magnetic field assisted abrasive finishing of SS 316L. *Procedia Manufacturing*, Vol. 30, pp. 276–283, doi: 10.1016/j.promfg.2019.02.040.
19. Zou, Ya., Xie, H., Dong, Ch., Wu, Ji. (2018). Study on complex micro surface finishing of alumina ceramic by the magnetic abrasive finishing process using alternating magnetic field. *The International Journal of Advanced Manufacturing Technology*, Vol. 97, pp. 2193–2202, doi: https://doi.org/10.1007/s00170-018-2064-0.
20. Gupta, B., Jain, A., Purohit, R., Rana, R. S., Gupta, B. (2018). Effects of process parameters on the surface finish of flat surfaces in magnetic assist abrasive finishing process. *Materials Today*, Vol. 5, pp. 17725–17729, doi: https://doi.org/10.1016/j.matpr.2018.06.095.
21. Das, M., Jain, V. K., Ghoshdastidar, P. S. (2012). Nanofinishing of flat workpieces using rotational–magnetorheological abrasive flow finishing (R-MRAFF) process. *The International Journal of Advanced Manufacturing Technology*, Vol. 62, pp. 405–420, doi: https://doi.org/10.1007/s00170-011-3808-2.