Mech. Adv. Technol. Vol. 7, No. 1, 2023, pp. 61–67

DOI: 10.20535/2521-1943.2023.7.1.271548

UDC 621.923

Analysis of the forces acting from the side of the magneto-abrasive tool on parts being machined during magneto-abrasive machining in conditions of the annular bath with large working gaps

V.S. Maiboroda[1] • **D.Yu. Dzhulii**[1] • **K.O. Zastavskyi**[1]

Received: 10 January 2023 / Revised 20 March 2023 / Accepted: 24 March 2023

Background. *For effective magneto-abrasive machining (MAM) of complex-shaped parts, comprehensive information is needed on the processes that occur when the magneto-abrasive tool (MAT) contacts with the surfaces being machined. Effective magneto-abrasive machining occurs in the presence of sufficient values of the normal and tangential components of the interaction forces between the MAT and the machined surfaces and the powder mixing during machining. Previously carried out analytical studies of dynamic parameters did not take into account the real conditions of the interaction of grains and their groups with machined surfaces.*

Objective. *Complex analysis of the processes that occur during magneto-abrasive machining of parts made from different types of materials, based on the results of the study of the friction forces between the magneto-abrasive tool and the surface being machined and the drag forces during the movement of parts in the working zone of the machine.*

Methods. *To achieve the set goal, the forces acting on the samples during their magneto-abrasive machining were measured with subsequent analytical analysis.*

Results. *The complex analysis of the processes occurring during MAM in conditions of the annular working zone with large working gaps of parts made of various materials was carried out based on the results of the study of the friction and drag forces that occur when the part moves relative to the magneto-abrasive tool.*

Conclusions. *It has been determined that when machining non-magnetic samples at the constant value of the magnetic field in the working zone, the specific drag forces are practically independent of the shape of the used powder. According to the analytical representation of the friction and drag forces, their ratio between their specific values was calculated. By the nature of the change in this ratio, it was found that it decreases with an increase in the velocity of samples movement along the working zone, and with an increase in the angular velocity of rotation of the samples around its axis, this value increases in the studied velocity range. It has been determined that at the velocity of movement along the working zone of 2.2 m/s, there is a slight increase in the ratio between the specific forces of friction and drag, which is associated with the action of ponderomotive forces that appear near the surface of the machined parts and lead to an increase in local magnetic forces in these zones.*

Keywords: *Magneto-abrasive machining, friction force, drag force, magneto-abrasive tool, magnetic induction.*

Introduction

The implementation of a high-performance finishing process of magneto-abrasive machining (MAM), especially parts of complex spatial configuration, such as an end and axial cutting tools, carbide inserts, blades of gas turbine engines is impossible without comprehensive information about the cutting magneto-abrasive tool (MAT), which is formed in the working zones of machines during the MAM process. Herewith, an important aspect is compliance with the three main conditions, the fulfillment of which is necessary to ensure an effective MAM process [1]. Due to this, the necessary information is data on the normal and tangential forces that arise in the zones of direct contact of the MAT with the surfaces being machined. Analytical analysis of these forces makes it possible to evaluate them based on the kinematic and dynamic features of the MAM process, but does not take into account the specifics of the MAT formation, which are largely determined by such characteristics as the shape and size of particles of ferroabrasive powders, magnetic properties, both of the part itself and of MAT, factors associated with adhesive interaction, which appears itself in the pair of MAT-material of the workpiece, specific processes occurring during

✉ *D.Yu. Dzhulii*
dmytro.dzhulii@gmail.com

[1] *Igor Sikorsky Kyiv Polytechnic Institute, Kyiv, Ukraine*

the structuring of MAT, its movement and reshaping occurring in the process of MAM.

The **aim of the work** was the conducting a comprehensive analysis of the processes occurring during MAM under conditions of large working gaps of the annular type of parts made of various materials, carried out on the basis of the results of the study of friction forces in a pair of MAT-machined surfaces and drag forces of MAT on the moving in the working zones of parts.

A large number of researches in these areas are presented in [2–4]. However, they allowed, to a certain extent, to identify the main directions and tasks of further work. Systematic studies on the study of the frictional interaction of MAT formed from powders of different types and sizes of particles with cylindrical samples with a diameter of 16 mm, made from various materials, such as ferromagnetic steel X40Cr13, paramagnetic alloys VT8 and 2024, diamagnetic alloy Bronze during MAM in the annular working zone with working gap 35 mm wide, presented in [5], made it possible to identify the MAM conditions under which the formation of a quasi-stable MAT is ensured, and wedging zones are formed in the MAT.

The experimental results obtained for the above-mentioned materials, various MAM conditions and powders used made it possible to determine functional relationships between the specific friction force and the velocity of rotation of samples around the axis of the annular working zone and around its axis at fixed values of magnetic induction in the working zone of installation with the large annular working gap. Herewith, it was shown that the influence of the magnetic field and the frequency of rotation around the axis of the annular working zone in the studied ranges on the specific friction in the pair MAT– the surface of the part is insignificant, while the type, shape and size of the particles of the magneto-abrasive powder, as well as the velocity of rotation of the parts around its axis, are decisive, especially during MAM of ferromagnetic parts. The experimentally obtained data, presented as functions of the change in the specific value of the friction force on the velocity of rotation around the axis of the annular working zone and the velocity of rotation around its axis for various MAM conditions and for used powders, were approximated by polynomial functions of the form:

$$F_{fr} = A_{00} + A_{01}V_0 + A_{02}V_0^2 + A_{10}V_{aw} + A_{11}V_0V_{aw} + A_{12}V_{aw}V_0^2 + A_{20}V_{aw}^2 + A_{21}V_{aw}^2V_0 + A_{22}V_0^2V_{aw}^2, \qquad (1)$$

where F_{fr} – the value of the specific friction force, kPa,
V_0 – the velocity of samples rotation around their axis, m/s,
V_{aw} – the velocity of samples movement along the annular working zone, m/s,
A_{ij} – the coefficients of the approximating polynomial (Table 1).

The largest standard error of approximation did not exceed 9%.

Studies of the specific drag forces exerted by the MAT on samples moving in the annular working zone showed that, at fixed values of the magnetic field in the working zones for non-magnetic samples from various alloys, the drag forces are almost the same when using both splintered and rounded powders [6]. Therefore, further studies were carried out by comparing the results obtained on non-magnetic titanium alloy VT8 and ferromagnetic steel X40Cr13.

It was found that during the MAM of ferromagnetic samples, the velocity of their movement in the working zones does not affect the drag forces. A similar result was also obtained with MAM of non-magnetic parts when using powders with a particle size more than 300 μm for the MAT formation. The machining samples made from non-magnetic materials by powders with a particle size of 200/100 μm shows a slight increase in drag forces (up to 10%) with an increase in the MAM velocity, which can be attributed to an experimental error and requires additional, more thorough studies.

Thus, it can be argued that the determining factor influencing the magnitude of the specific drag forces in the studied ranges of conditions of the MAM process is the magnitude of the magnetic induction in the working zones of the setup, which significantly affects the coefficients of internal friction in the MAT [2]. Similar determined regularities, apparently, are associated with the peculiarities of the movement of the MAT in the mode of flow around the machined surfaces and the processes associated with the structuring of the MAT in the working zones, the formation of quasi-stable compacted formations on the frontal surfaces, which will largely affect on the drag forces exerted by the powder MAT on the moving samples in it. Thus, the drag forces obtained during MAM with the rounded Polimam-M powder are significantly higher than when machined with Ferromap powder, whose internal friction coefficient is 76.3–84.1 kPa/T, against 114.6–120.9 kPa/T for Polimam-M [2].

It was shown that in the case of MAM of non-magnetic materials, the specific drag forces are 1.2–1.45 times lower than in the case of machining samples made from ferromagnetic steel.

The experimental results obtained for various MAM conditions were presented in the form of surface topograms of changes in the specific drag forces depending on the magnetic induction and the velocity of movement of the samples along the annular working zone. Typical topograms are shown in Fig. 1 for different MAM conditions of magnetic and non-magnetic samples by Ferromap and Polimam-M powders with particle sizes of 200/100 and 400/315 μm.

The results obtained are approximated by polynomial functions of the form:

$$F_{drag} = C_{00} + C_{01}B + C_{02}B^2 + C_{10}V_{aw} + C_{11}BV_{aw} + C_{12}V_{aw}B^2 + C_{20}V_{aw}^2 + C_{21}V_{aw}^2B, \qquad (2)$$

where F_{drag} is the value of the specific drag force from the side of the MAT to the samples moving in the annular working zone, kPa,

B – the value of magnetic induction in the working gaps of the machine, T,

C_{ij} – the coefficients of the approximating polynomial (Table 2).

The largest standard error of approximation did not exceed 18%.

Having the analytical representation of the functions of changes in the values of the specific friction forces in the pair MAT-surface of the part and the drag forces exerted by the MAT on the moving parts, it is possible to calculate the ratio between the specific forces of friction and drag – $F_{fr}/F_{drag}=\eta$. The value of η is an analog to the coefficient of friction between the machined surface and the magnetic abrasive tool formed during the MAM process. The parameter η will depend on the physical characteristics of the machined surfaces and the material of the magneto-abrasive powder, the shape and size of the particles, their tribotechnical characteristics and, to a large extent, the conditions of movement and the features of the contact interaction of the MAT particles with the machined surfaces, which are associated with the specifics of the formation and movement of individual groups of particles – representative volumes formed in the MAT during MAM, especially near the machined surfaces. According to the nature

Table 1. Values of coefficients A_{ij} in equation (1)

Part material	Powder type	Magnetic induction, T	Particle size, μm	Coefficients								
				A_{00}	A_{01}	A_{02}	A_{10}	A_{11}	A_{12}	A_{20}	A_{21}	A_{22}
X40Cr13	Polimam–M	0.2	200/100	210.5	1356.2	–34.1	–204.7	–160.6	–609.6	54.4	–43.2	227.7
			400/315	319.4	3133.1	–4095.8	–304.5	–1009.4	2090.7	73.1	120.9	–347.1
		0.24	200/100	69.7	2409.1	–1349.3	–47.4	–1381.9	1252.5	11.7	274.1	–303.5
			400/315	218.5	4929.3	–6760.1	–187.5	–2375.9	4266.0	40.8	390.7	–782.3
	Ferromap	0.2	200/100	78.8	1753.3	–226.9	–77.0	–1454.2	705.1	19.7	365.0	–252.1
			400/315	14.6	1033.0	49.6	–18.7	–634.2	330.2	10.5	157.9	–118.6
		0.24	200/100	9.2	1208.7	904.2	4.0	–766.5	–417.8	–1.9	171.4	32.6
			400/315	–20.5	1162.3	–96.1	31.0	–654.0	497.1	–2.6	145.8	–150.8
VT8	Polimam–M	0.2	200/100	61.5	1111.1	–1719.5	–64.2	–120.6	492.5	14.3	23.0	–72.4
			400/315	173.0	1052.2	–1811.0	–126.8	451.6	–199.4	26.5	–140.3	154.8
		0.24	200/100	73.5	1386.6	–2471.2	–67.4	–86.2	921.2	13.4	–20.6	–124.8
			400/315	188.2	901.8	–1637.2	–143.6	942.7	–837.7	30.1	–276.2	334.7
	Ferromap	0.2	200/100	78.5	1114.8	–1652.7	–51.0	–226.4	603.7	9.8	–5.1	–46.4
			400/315	70.8	1507.5	–2382.6	–26.0	–558.4	1548.0	5.4	78.7	–285.0
		0.24	200/100	101.8	1435.1	–2287.4	–86.8	–583.8	1389.5	19.9	91.0	–250.5
			400/315	103.7	1782.0	–2015.7	–64.2	–800.8	1051.5	16.9	138.2	–141.2
Bronze	Polimam–M	0.2	200/100	123.9	1322.5	–2386.3	–106.4	369.8	268.8	21.9	–181.9	95.4
			400/315	322.0	969.7	–1905.2	–271.1	984.0	–695.8	61.5	–270.9	286.7
		0.24	200/100	107.3	3126.7	–4963.4	–102.8	–1146.4	2479.2	22.3	168.2	–405.3
			400/315	188.7	2243.1	–3860.4	–118.3	–65.6	1013.4	21.5	–71.9	–42.9
	Ferromap	0.2	200/100	124.9	1355.3	–1965.5	–101.8	–633.8	1100.6	21.7	124.8	–201.1
			400/315	414.8	2662.3	–4507.8	–367.2	–1531.3	3350.8	87.7	294.3	–718.9
		0.24	200/100	112.0	1556.9	–2452.8	–100.5	–726.3	1502.0	23.2	130.9	–274.5
			400/315	237.2	2871.2	–3890.3	–185.8	–1617.9	2436.7	42.7	292.8	–433.0
2024	Polimam–M	0.2	200/100	141.1	2019.4	–2975.3	–129.2	–669.6	1381.0	29.0	95.5	–194.6
			400/315	142.7	1275.1	–1821.6	–134.9	–222.3	584.2	30.5	32.9	–82.1
		0.24	200/100	97.8	2289.4	–3594.3	–73.5	–755.0	1848.8	13.9	103.6	–285.9
			400/315	120.6	1495.0	–2392.9	–89.6	–249.2	891.5	17.0	34.1	–133.2
	Ferromap	0.2	200/100	138.4	1341.3	–2200.1	–120.6	–463.5	1150.8	26.6	67.1	–181.6
			400/315	136.0	1310.3	–1863.7	–104.4	56.1	206.9	27.9	–94.2	113.5
		0.24	200/100	76.8	1601.3	–2417.1	–72.5	–700.6	1395.1	18.0	116.3	–233.6
			400/315	94.1	2171.4	–3352.8	–56.3	–739.9	1706.0	15.3	117.5	–281.3

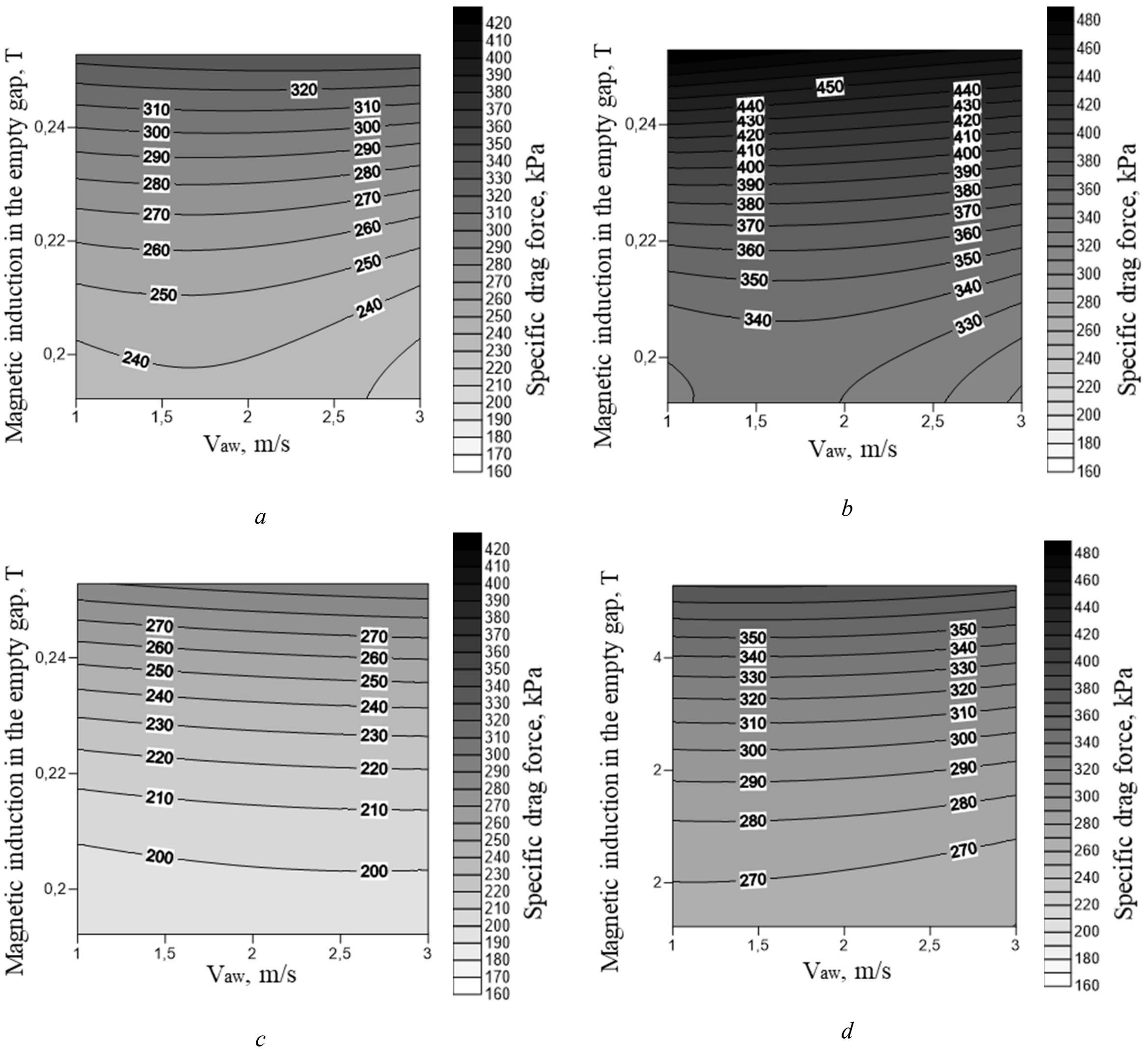
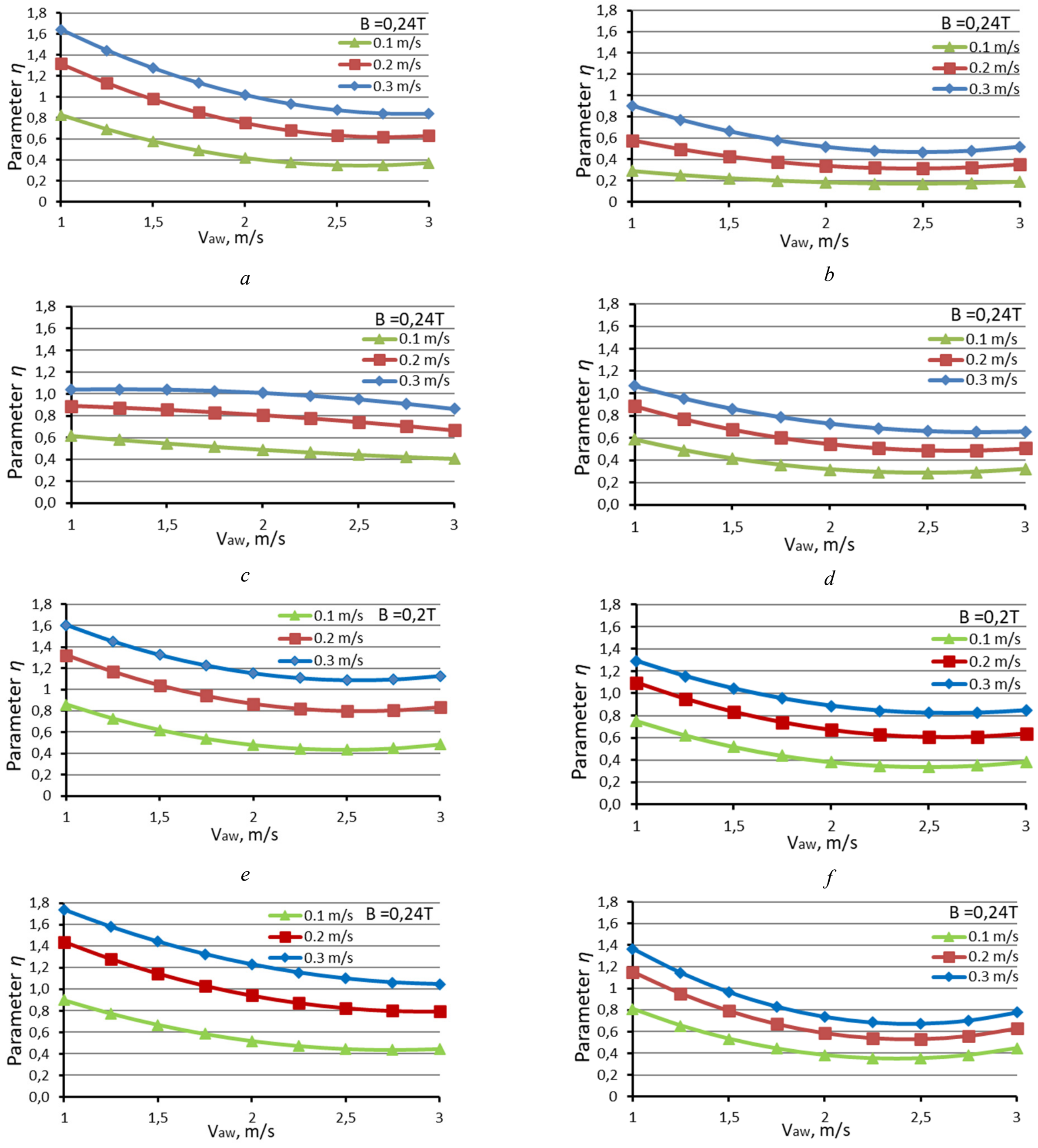


Fig. 1. Change in the specific drag force depending on the magnetic induction in the working gaps and the velocity of samples movement along the annular working zone during MAM using Ferromap powder (400/315 µm) – *a*, *b* and Polimam–M powder (200/100 µm) – *c*, *d* samples from non–magnetic materials – *a*, *c* and ferromagnetic materials – *b*, *d*

Table 2. Values of coefficients C_{ij} in equation (2)

Part material	Powder type	Particle size, µm	Coefficients							
			C00	C01	C02	C10	C11	C12	C20	C21
Ferromagnetic steel X40Cr13	Plimam–M	200/100	1310.2	–10924.8	28566.0	–42.9	338.6	–524.7	3.5	–26.2
		400/315	2287.4	–20796.3	54488.9	–173.5	2659.4	–8138.5	–55.8	228.7
	Ferromap	200/100	643.6	–4668.2	13216.5	152.3	–1436.3	3243.8	–6.8	31.8
		400/315	2237.4	–20735.3	57579.5	–264.2	3553.5	–13566.9	–86.0	511.2
Non-magnetic alloy VT8	Plimam–M	200/100	1162.4	–10051.9	25962.6	–3.0	30.3	73.1	–1.3	0.9
		400/315	1528.6	–13960.6	37819.1	24.5	743.9	–3395.9	–46.5	188.8
	Ferromap	200/100	1052.4	–8849.4	22058.2	–56.5	239.6	298.9	16.8	–84.7
		400/315	791.3	–6667.1	19085.5	202.4	–1401.4	2551.6	–26.2	94.4

of the change in the value of η, it was found that with an increase in the velocity of samples movement along the annular working zone, basically, its monotonous decrease takes place. An increase in the velocity of samples' rotation around their axis leads in the range under study to the almost proportional increase in the value of η. It was determined that when the velocity of samples movement along the annular working zone is more than 2.2 m/s, there is a slight increase in the ratio between the specific forces of friction and drag, which, apparently, is associated with the action of ponderomotive forces [2], which occurs near the surface of the machined parts and leading to an increase in local magnetic forces in these areas. Nature of dependences of the change in the parameter η during MAM of samples from various materials depending on the velocity of their rotation around the axis of the annular working zone by powders of different types and with different particle sizes at velocities of parts rotation around their axis varying from 0.1 to 0.3 m/s are presented in fig. 2.



a *b*

c *d*

e *f*

g *h*

Fig. 2. Change of the parameter η depending on the rotation velocity around the axis of the annular working zone and the rotation velocity around its axis during MAM by Polimam-M powder: *a*, *c*, *e*, *g*, Ferromap powder: *b*, *d*, *f*, *h* with particle sizes of 200/100 μm: *b*, *d*, *e*, *f*, *g* and 400/315 μm: *a*, *c*, *h*

The analysis of the obtained results showed that the highest values of the ratio between the specific forces of friction and drag take place at MAM by powders with a particle size of 200/100 μm for both splintered and rounded particles, which confirms the previously obtained results.

Conclusions

The complex analysis of the processes occurring during MAM under conditions of large working gaps of the annular type of parts made of various materials was carried out, based on the results of the study of friction forces in a pair of MAT and machined surfaces and drag forces exerted by MAT on parts moving in working areas. It was shown that at fixed values of the magnetic field in the working zone for non-magnetic samples from various alloys, the specific drag force was practically the same when using both splintered and rounded powders of various types. According to the results of the analytical representation of the functions of changes in the values of the specific friction forces in the pair MAT-surface of the part and the drag forces exerted by the MAT on moving parts, the ratio between the specific friction forces and drag forces was calculated – $F_{fr}/F_{drag} = \eta$. According to the nature of the change in the value of η, it was found that with an increase in the velocity of movement of parts around the axis of the annular working zone, basically, its monotonous decrease takes place. The increase in the velocity of parts rotation around their axis leads in the range under study to an almost proportional increase in the value of η. It was determined that when the velocity of samples movement along the annular working zone is more than 2.2 m/s, there is a slight increase in the ratio between the specific forces of friction and drag, which is associated with the action of ponderomotive forces, which occurs near the surface of the machined parts and leading to an increase in local magnetic forces in these areas.

References

[1] V.S. Maiboroda, I. V. Slobodianiuk and D. Yu. Dzhulii, *Magnitno-abrazivnaya obrabotka detaley slozhnoy formy*, Zhitomir: PP "Ruta", 2017.

[2] V.S. Maiboroda, "Osnovy stvorennya i vykorystannya poroshkovoho mahnitno-abrazyvnoho instrumentu dlya finishnoyi obrobky fasonnykh poverkhon", Dr. dissertation, Dept. Mech. Eng., National Technical University of Ukraine "Kyiv Polytechnic Institute", Kyiv, Ukraine, 2001.

[3] I.V. Tkachuk, "Formuvannya mahnitno-abrazyvnoho instrumentu zi stabilnymy vlastyvostyamy v robochykh zazorakh kiltsevoho typu", Ph.D. dissertation, Dept. Mech. Eng., National Technical University of Ukraine "Kyiv Polytechnic Institute", Kyiv, Ukraine, 2015.

[4] P. Singh and P. Kumar, "Effect of Rotation Speed and Grit Size in Magnetic Abrasive Finishing of Inner Surface of Brass (CuZn35) Pipe", *International Journal of Surface Engineering & Materials Technology*, vol. 6, no. 1. pp. 44–48, 2016.

[5] V.S. Maiboroda, K.O. Zastavskyi and R.B. Zhuk, "Osoblyvosti vzaiemodii mahnitno-abrazyvnoho instrumentu z obrobliuvanoiu poverkhneiu v umovakh kiltsevoi vanny", *Technical Engineering*, No. 2(88), pp. 3–13, 2021. doi: https://doi.org/10.26642/ten-2021-2(88)-3-13

[6] V.S. Maiboroda *et al*., "Investigation of the drag forces arising in the magneto-abrasive tool during the finishing of cylindrical parts in the annular bath", *Bulletin of the National Technical University "KhPI". Series: Techniques in a machine industry*, No. 2(6), pp. 16–22, 2022. doi: 10.20998/2079-004X.2022.2(6).03

[7] M.S. Uddin, V. Santos and R. Marian, "Interplay of process variables in magnetic abrasive finishing of AISI 1018 steel using SiC and Al_2O_3 abrasives", *Journal of Manufacturing and Materials Processing,* vol. 3(2), no. 29. pp. 1–18, 2019. doi:10.3390/jmmp3020029

[8] N.S. Khomych, *Maghnytno-abrazyvnaja obrabotka yzdelyj: monoghr*. Mynsk: BNTU, 2006.

[9] T.C. Kanish *et al*., "Investigations on the finishing forces in Magnetic Field Assisted Abrasive Finishing of SS316L", *Procedia Engineering,* vol. 174, pp. 611–620, 2017. doi: https://doi.org/10.1016/j.proeng.2017.01.196

[10] T.C. Kanish *et al*., "Experimental Investigations on Magnetic Field Assisted Abrasive Finishing of SS 316L", *Procedia Manufacturing*, vol. 30, pp. 276–283. 2019. doi: https://doi.org/10.1016/j.promfg.2019.02.040

[11] R. Sharma and H. Bhardwaj, "Internal Finishing of Stainless Steel Cylinder using Magnetic Abrasive Finishing Method", *International Journal of Scientific Research and Education*, 2014. Vol. 2, No. 8, pp. 1512–1521, 2014.

Аналіз сил, що діють зі сторони магнітно–абразивного інструменту на оброблювані деталі при магнітно–абразивному обробленні в умовах кільцевої ванни з великими робочими зазорами

В.С. Майборода[1], Д.Ю. Джулій[1], К.О. Заставський[1]

[1] *КПІ ім. Ігоря Сікорського, Київ, Україна*

Проблематика. *Для ефективного магнітно-абразивного оброблення (МАО) деталей складної форми необхідна вичерпна інформація про процеси, які відбуваються при контакті магнітно-абразивного інструменту (МАІ) з оброблюваними поверхнями. Ефективне магнітно-абразивне оброблення відбувається при наявності достатніх величин нормальної та тангенційної складових сил взаємодії МАІ та оброблюваних поверхонь та перемішування порошку в процесі оброблення. Виконані раніше аналітичні дослідження динамічних параметрів не враховують реальних умов взаємодії зерен та їх груп з оброблюваними поверхнями.*

Мета. *Комплексний аналіз процесів, які виникають при магнітно–абразивному обробленні деталей виготовлених з різних типів матеріалів, за результатами дослідження сил тертя між магнітно–абразивним інструментом та оброблюваною поверхнею та за силами лобового опору при русі деталей в робочій зоні верстату.*

Методика реалізації. *Для досягнення поставленої мети виконувалось вимірювання сил, що діють на зразки під час їх магнітно–абразивного оброблення з наступним їх аналітичним аналізом.*

Результати. *Виконано комплексний аналіз процесів, які відбуваються при МАО в умовах великих робочих зазорів кільцевого типу деталей, виготовлених з різних матеріалів за результатами дослідження сил тертя та лобового опору, які виникають при русі деталі відносно магнітно–абразивного інструменту.*

Висновки. *Встановлено, що при обробленні немагнітних зразків при постійній величині магнітного поля в робочій зоні сили питомого лобового опору практично не залежать від форми використовуваного порошку. За аналітичним представленням сил тертя та опору розраховано їх співвідношення між питомими їх величинами. За характером зміни цього співвідношення встановлено, що воно зменшується зі збільшенням швидкості руху зразків вздовж робочої зони, а зі збільшенням кутової швидкості обертання зразків навколо власної осі ця величина збільшується в досліджуваному діапазоні швидкостей. Встановлено, що при швидкості руху вздовж робочої зони 2.2 м/с має місце незначне зростання величини співвідношення між питомими силами тертя та опору, що пов'язано з дією пондеромоторних сил, що проявляються поблизу поверхні оброблюваних деталей і призводять до збільшення локальних магнітних сил в цих зонах.*

Ключові слова: *магнітно–абразивне оброблення, сила тертя, сила лобового опору, магнітно–абразивний інструмент, магнітна індукція.*