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

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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

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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:

\[
F_{fr} = A_{00} + A_{01}V_0 + A_{02}V_0^2 + A_{10}V_{aw} + A_{11}V_0V_{aw} + A_{20}V_{aw}^2 + A_{21}V_0V_{aw} + A_{22}V_{aw}^2V_0^2, \tag{1}
\]

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%.

Studied 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:

\[
F_{drag} = C_{00} + C_{01}B + C_{02}B^2 + C_{10}V_{aw} + C_{11}BV_{aw} + C_{12}V_{aw}B + C_{20}V_{aw}^2 + C_{21}V_{aw}^2B, \tag{2}
\]

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,
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 – \( \frac{F_{fr}}{F_{drag}} = \eta \). The value of \( \eta \) is an analog to the coefficient of friction between the machined surface and the magnetic abrasive tool formed during the MAM process. The parameter \( \eta \) 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 of friction between the machined surface and the magnetic abrasive tool formed during the MAM process.

| Part material | Powder type | Magnetic induction, T | Particle size, \( \mu m \) | \( A_{00} \) | \( A_{01} \) | \( A_{02} \) | \( A_{10} \) | \( A_{11} \) | \( A_{12} \) | \( A_{20} \) | \( A_{21} \) | \( A_{22} \) |
|---------------|-------------|----------------------|-----------------------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| VT8           | Polimam–M   | 0.2                  | 200/100                     | 210.5       | 1356.2      | -34.1       | -204.7      | -160.6      | -609.6      | 54.4         | -43.2       | 227.7       |
| X40Cr13       | Polimam–M   | 0.24                 | 200/100                     | 319.4       | 3133.1      | -4095.8     | 319.4       | 3133.1      | -4095.8     | 319.4       | 3133.1      | -4095.8     |
| F2024         | Polimam–M   | 0.2                  | 200/100                     | 67.9        | 2409.1      | -1349.5     | -47.4       | -1381.9     | 1252.5      | 11.7        | 274.1       | -303.5      |

Table 1. Values of coefficients \( A_{ij} \) in equation (1)
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 $C_i$ in equation (2)

<table>
<thead>
<tr>
<th>Part material</th>
<th>Powder type</th>
<th>Particle size, µm</th>
<th>Coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$C_{00}$</td>
</tr>
<tr>
<td>Ferromagnetic steel X40Cr13</td>
<td>200/100</td>
<td>1310.2</td>
<td>−10924.8</td>
</tr>
<tr>
<td></td>
<td>400/315</td>
<td>2287.4</td>
<td>−20796.3</td>
</tr>
<tr>
<td>Polimam–M</td>
<td>200/100</td>
<td>1162.4</td>
<td>−10051.9</td>
</tr>
<tr>
<td></td>
<td>400/315</td>
<td>1528.6</td>
<td>−13960.6</td>
</tr>
<tr>
<td>Ferromap</td>
<td>200/100</td>
<td>1052.4</td>
<td>−8849.4</td>
</tr>
<tr>
<td></td>
<td>400/315</td>
<td>791.3</td>
<td>−6667.1</td>
</tr>
</tbody>
</table>
of the change in the value of $\eta$, 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 $\eta$. 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 $\eta$ 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.

![Graphs](image-url)

**Fig. 2.** Change of the parameter $\eta$ 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 specific friction forces of 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 – $F_f/F_{drag} = \eta$. According to the nature of the change in the value of $\eta$, 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 $\eta$. 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**


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

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Проблематика. Для ефективного магнітно-абразивного оброблення (МАО) деталей складної форми необхідна вичерпна інформація про процеси, які відбуваються при контакти магнітно-абразивного інструменту (МАІ) з оброблюваною поверхнею. Ефективне магнітно-абразивне оброблення відбувається при наявності достатніх величин нормальної та тангенційно-

Висновки

при типі Результати

Методика

Верхне

ширини

Проблематика. Комплексний аналіз процесів, які виникають при магнітно-абразивному обробленні деталей висотомірних з різних типів матеріалів, за результатами дослідження сил тертя між магнітно-абразивним інструментом та оброблюваною поверхнею та за силами зовнішнього опору при русі деталей в робочій зоні верстату.

Методика реалізації. Для досягнення поставленої мети використувалось 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 з результатами дослідження сил тертя та зовнішнього опору, які виникають при русі деталі відносно магнітно-абразивного інструменту.

Висновки. Завдяки встановлено, що при обробленні немагнітних граней при постійній величині магнітного поля в робочій зоні сили тертя зовнішнього опору практично не зазнають змін залежно від форми використовуваного верстату. За аналітичним представленням сил тертя та опору розраховано їх співвідношення між ними з величиною іншими для даного типу деталей.

Ключові слова: магнітно-абразивне оброблення, сила тертя, сила зовнішнього опору, магнітно-абразивний інструмент, магнітна індукція.