DOI https://doi.org/10.30525/978-9934-26-207-4-15

MODELING OF THE COMPOSITE PARTS' SURFACE MICRORELIEF FOR PRINTING EQUIPMENT AFTER MAGNETIC ABRASIVE PROCESSING

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INTRODUCTION

Printing equipment has specific operating conditions, such as high rotation speeds of massive drums, shafts, aggressive environment of paint and glued chemical products, etc., which leads to intensive wear of support units. That's why antifriction parts (sliding bearings) and support bushings of friction pairs installed in offset, printing and plate cylinders of printing equipment are widely used in printing machines[1,2].

The need for modern printing equipment is increasing every year, but at the same time, the need for repair, improvement and equipment restoration is increasing at a much faster pace. One of the main reasons for the printing machines failure is the wear of the friction units, which is due to contact parts' unsatisfactory quality parameters. This situation gives rise to the repair problem for this equipment in the shortest possible time and with minimal investment[3,4]. When repairing or designing such friction units, much attention is paid not only to the materials from which they are made, but also to the accuracy of manufacturing antifriction bushings and the working surfaces' quality parameters. Providing design and technological

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[1] Нові технології фінішного оброблення композиційних підшипників ковзання для жорстких умов експлуатації : монографія / А. П. Гавриш, О. О. Мельник, Т. А. Роїк, М. Г. Аскеров, О. А. Гавриш. Київ: «КПІ». 2012. 196 с. URL: https://scholar.google.com.ua/citations?view_op=view_citation&hl=en&user=RhLFfMwAAAAJ&citation_for_view=RhLFfMwAAAAJ:u5HHmVD_uO8C

[2] Шліфування і доводка зносостійких антифрикційних композитних деталей друкарських машин : монографія / А. П. Гавриш, Т. А. Роїк, О. А. Гавриш, П. О. Киричок, Ю. Ю. Віцюк, В. Г. Олійник. Ч. 3. Київ : Видавничий дім «АртЕк», 2021. 202 с., ISBN 978-617-7814-80-0. URL: https://ela.kpi.ua/handle/123456789/41909

[3] Ibidem.

[4] Ibidem. Нові технології фінішного оброблення композиційних підшипників ковзання для жорстких умов експлуатації. Op. cit, 196 с.

quality parameters allows to ensure the improved operating conditions of plain bearings and increase the equipment' service life[5,6,7,8].

In printing equipment, self-lubricating bearings are increasingly used in friction units, for example, based on the new antifriction composite based on powder Ni-alloy CrNi56WMoCoAl (KhN56VMKU) with 6% CaF_2 solid lubricant. New antifriction composite's metal matrix consist of following main elements, wt.%: Cr– 8.5-10.5; W– 6.0-7.5; Mo – 6.5-8.0; Co – 11.0-13.0; Al – 5.4-6.2; Ni–basis. This composite's industrial approbation showed positive results at high rotational speeds of printing machines' offset cylinders[9].

When using self-lubricating composite materials, there is no need for additional lubrication with liquid oil, and this is the direction of modern research in materials science[10,11].

The technology of contact surfaces' mechanical finishing and relevant quality parameters cause a direct influence on the wear resistance of printing equipment' antifriction parts[12,13,14].

Unfortunately, now the regularities of purposeful and stable formation of the working surfaces' quality parameters of the printing machines' hard-loaded composite antifriction parts remain unclear. This leads to their rapid wear, failure of the printing equipment and requires the spare parts large number.

So according to experts, the service life of antifriction parts in the printing machines' friction units, such as KBA Rapida-105 (Germany),

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[5] Ibidem.

[6] Гавриш А.П., Мельник О.О., Гавриш О.А. Сучасні можливості магніто-абразивним обробленням важкооброблюваних матеріалів. *Вісник Київського Національного університету технології та дизайну.* № 3(41). 2008. С. 22–28. URL: https://knutd.edu.ua/files/Visnyk/Visnyk%20KNUTD_2008_3.pdf

[7] Гавриш А.П., Мельничук П.П. Фінішна алмазно-абразивна обробка магнітних матеріалів : монографія. Житомир: Житомир. держ. технол. ун-т.. 2004. 551 с. ISBN 966-683-069-8, http://www.ukrbook.net/litopys/Knigki/2005/Lk_9_05.pdf

[8] Новітні композиційні матеріали деталей тертя поліграфічних машин : монографія / П.О. Киричок, Т.А. Роїк, А.П. Гавриш, А.В. Шевчук, Ю.Ю. Віцюк. Київ: НТУУ КПІ. 2015, 428 с. ISBN 978-066-622-692-4. URL: https://scholar.google.com.ua/scholar?hl=uk&as_sdt=0,5&cluster=6673344392320605039

[9] Ibidem

[10] Ibidem

[11] Ibidem. Нові технології фінішного оброблення композиційних підшипників ковзання для жорстких умов експлуатації. Op. cit, 196 с.

[12] Ibidem

[13] Ibidem. Шліфування і доводка зносостійких антифрикційних композитних деталей друкарських машин. Op. cit. 202 с.

[14] Ibidem. Новітні композиційні матеріали деталей тертя поліграфічних машин. Op. cit. 428 с.

Heidelberg Speedmaster SM 102 FPL (Germany), Star Binder 1509 (Switzerland), Sitma C80 750i (Italy) is only from 0.5 to 1 year, which is a consequence not only of manufacturing technology, but also imperfect technology of working contact surfaces finishing processes.

Based on the needs of the printing industry, the problem of improving the quality, durability, wear resistance, both in the creation of new and in the restoration of printing equipment' existing antifriction parts, is relevant.

Today, there is an urgent need to consistently ensure high quality parameters of the antifriction composite parts' working surfaces, which has a direct impact on reliability and durability of the individual part and the friction unit as a whole.

Also, there is still no mathematical apparatus for predicting the microrelief pattern of the antifriction part's working surface, which limits the technological parameters of finishing, in particular, one of the promising methods of fine processing such as magnetic abrasive processing (MAP). This does not allow obtaining the predicted level of parts' surface quality parameters.

Therefore, the development of mathematical apparatus and appropriate software for modelling and forecasting the possible pattern of the antifriction composites' surface microrelief after magnetic abrasive processing (MAP) is a very important task, taking into account technological factors and the preliminary analysis of possible roughness parameters of the part's surfaces.

The solution of this problem will make it possible to ensure the predictable quality parameters of the antifriction parts' contact surfaces made from new antifriction high-alloy composites and processed with MAP for printing equipment' severe operating conditions.

The object of the study is to develop a mathematical model of the surface microrelief formation during magnetic-abrasive processing of self-lubricating parts based on a new antifriction composite KhN56VMKU + 6% CaF_2. This is a necessary task for the real possibility of obtaining predictable high surface quality parameters, taking into account technological processing factors.

1. Preconditions for the problem and problem statement

1.1. Features of magnetic abrasive processing

Among the existing finishing methods one of the effective methods of the parts' surfaces fine machining is the technology of magnetic abrasive processing (MAP)[15,16,17,18,19,20].

MAP is a process of parts fine machining in the environment of abrasive ferromagnetic powder, held by the forces of a magnetic field in the working area (working gap). The magnetic-abrasive material is placed between the poles of electromagnets, creating a cutting tool («brushes»), the density of which can be varied over a wide range by changing the magnetic field strength in the gaps[21,22,23].

The use of magnetic field energy during abrasive processing makes it possible to increase the productivity and working surfaces' quality of the composite bearings for printing machines, for example, made from the antifriction composite KhN56VMKU + 6% CaF_2.

A schematic diagram of the cylindrical friction part (bearing) processing in a magnetic field with ferromagnetic powders has been shown in fig. 1[24].

During the bearing movement through the working area, the abrasive powder covers the part, exerting pressure on it at every point on the surface.

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[15] Барон Ю.М. Магнитно-абразивная и магнитная обработка изделий и режущих инструментов. Ленинград : Машиностроение, 1986. 176 с. URL: https://www.chipmaker.ru/files/file/14966/

[16] Скворчевский Н.Я., Федорович Э.Н., Ящерицын П.И. Эффективность магнитно-абразивной обработки. Навука і тэхніка, Минск, 1991. С. 192–195.

[17] Финишная обработка деталей сферической формы с наложением магнитных полей / Л.Е. Сергеев, А.П. Ракомсин, М.И. Сидоренко, В.Е. Бабич. *Технология машиностроения*. № 12(66). 2007. С. 25–27. URL: https://www.twirpx.com/file/1014557/

[18] Акулович Л.М., Сергеев Л.Е., Лебедев В.Я. Основы магнитно-абразивной обработки металлических поверхностей : монография. Минск: БГАТУ, 2012. 316 с. ISBN 978-985-519-544-4. URL: https://dokumen.pub/9789855195444.html

[19] Гавриш А.П., Мельник О.О. Дослідження динаміки магнітно-абразивної обробки спеціальних матеріалів. *Вісник Житом. Держ. Технолог. ун-ту.* № 1(44). 2008. С. 15–20. URL: http://vtn.ztu.edu.ua/article/view/81824, https://doi.org/10.26642/tn-2008-1(44)-15-20

[20] Магнітно-абразивна обробка в важкодоступних місцях важконавантажених підшипників ковзання / А.П. Гавриш, Т.А. Роїк, В.А. Ковальов, О.О. Мельник, Ю.Ю. Віцюк. *Технологія і техніка друкарства*. Київ : НТУУ «КПІ» ВПІ. №3 (25). 2009. С. 4–7. URL: http://ttdruk.vpi.kpi.ua/article/view/57881. https://doi.org/10.20535/2077-7264.3(25).2009.57881

[21] Ibidem. Магнитно-абразивная и магнитная обработка изделий и режущих инструментов. Op. cit. 176 с.

[22] Ibidem. Эффективность магнитно-абразивной обработки. Op. cit. С. 192 – 195.

[23] Ibidem. Дослідження динаміки магнітно-абразивної обробки спеціальних матеріалів. Op. cit. С. 15-20.

[24] Ibidem. Нові технології фінішного оброблення композиційних підшипників ковзання для жорстких умов експлуатації. Op. cit. 196 с.

The presence of pressure leads to metal cutting and smoothing of microroughnesses on the part's surface, acting on the bearing from the side of the powder along the normal (magnetic) and tangential components.

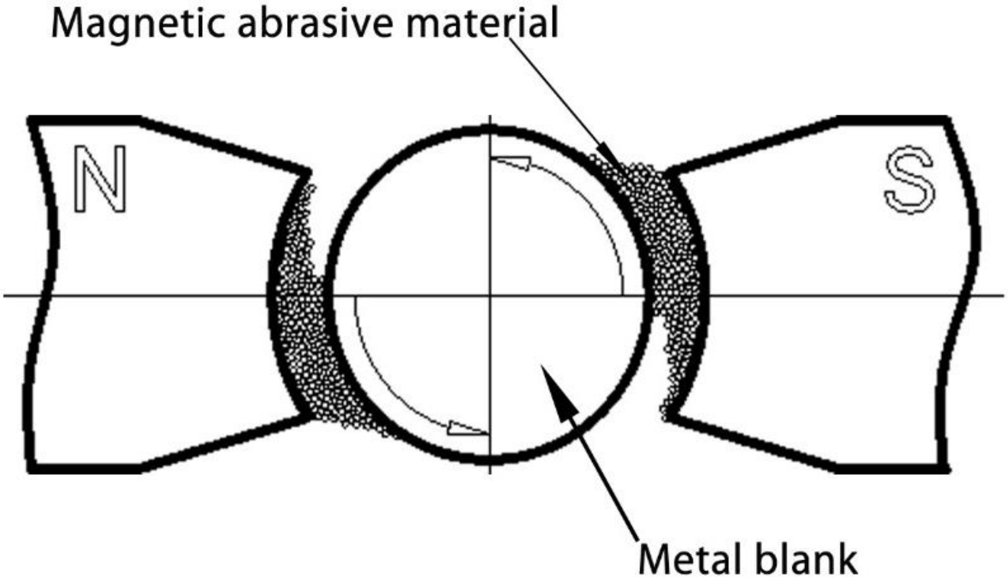

Fig. 1. Schematic MAP diagram

Features of the MAP method are[25,26,27,28,29]:

– continuous contact of the abrasive with the part's surface, which reduces the cyclic loads on the system machine − device − tool − part (MDTP) and improves the geometric dimensions accuracy and the machined surface's shape;

– the absence of the abrasive grain rigid fastening in the bond, which eliminates the probability of critical pressure and temperature in the cutting zone, increases the stability of the grain, and increases the surface layer's physical and mechanical properties;

– the ability to control the abrasive tool rigidity in the axial and longitudinal directions, and a combination of roughing and finishing without changing the technological bases and reinstalling the part;

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[25] Ibidem. Шліфування і доводка зносостійких антифрикційних композитних деталей друкарських машин. Op. cit. 202 с.

[26] Ibidem. Сучасні можливості магніто-абразивним обробленням важкооброблюваних матеріалів. Op. cit. С. 22–28.

[27] Ibidem. Магнитно-абразивная и магнитная обработка изделий и режущих инструментов. Op. cit. 176 с.

[28] Ibidem. Эффективность магнитно-абразивной обработки. Op. cit. С. 192–195.

[29] Ibidem. Финишная обработка деталей сферической формы с наложением магнитных полей. Op. cit. С. 25-27.

– no friction of the bond on the part’s surface, which significantly reduces the abrasive processing temperature;

– the ability to cut always by the abrasive grain’s sharpest edge, when there is no need for periodic abrasive tool re-sharpening;

– penetration of metal chips between abrasive grains, which eliminates the possibility of the abrasive tool clogging;

– ensuring the metal cutting during the entire processing period, which allows grinding the high-alloy and hard-to-process materials;

– the possibility of strengthening the material’s surface layer, decrease of the residual tensile stresses from pre-treatment with their conversion into compressive stresses;

– realization of dimensional or dimensionless (decorative) processing, providing metal cutting within 0.002-0.5 mm per diameter in 10-120 s; a decrease in roughness from Ra = 1.25–0.32 µm to Ra = 0.08–0.01 µm or Ra = 10.0–2.5 µm to Ra = 0.32–0.08 µm; maintaining geometric dimensions within permissible variations.

Features of the equipment that implements the process are:

– possibility of several parts simultaneous processing that allows to reduce polishing time by 8-10 times;

– continuity of the polishing process;

– full process automation;

– abrasive cutting properties maximum use;

– wide universalization and fast readjustment from one part to another;

– rapid change of the abrasive tool after its complete wear.

The part rotates, oscillates or is stationary during abrasive processing in a magnetic field.

The magnet’s poles are stationary, oscillate or make relative movements. The magnetic field is generated from a permanent electromagnet or obtained by rectifying an alternating current.

Classical technological operations during MAP are performed in the following sequence[30,31,32,33,34]: 1) loading the part into the processing zone manually or using a transport rotor or a robotic arm; 2) supply of the

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[30] Ibidem. Нові технології фінішного оброблення композиційних підшипників ковзання для жорстких умов експлуатації. Op. cit.196 с.

[31] Ibidem. Шліфування і доводка зносостійких антифрикційних композитних деталей друкарських машин. Op. cit. 202 с.

[32] Ibidem. Магнитно-абразивная и магнитная обработка изделий и режущих инструментов. Op. cit. 176 с.

[33] Ibidem. Эффективность магнитно-абразивной обработки. Op. cit. С. 192 – 195.

[34] Ibidem. Финишная обработка деталей сферической формы с наложением магнитных полей. Op. cit. С. 25-27.

abrasive powder required portion from the automatic dosing hopper to the cutting zone; 3) giving the part (or the magnet poles) relative movements; 4) supply of coolant to the cutting area; 5) demagnetization, washing and drying of the part.

1.2. Magnetic abrasive processing of bearing's cylindrical surfaces

During MAP of external cylindrical surfaces, the scheme proposed by G. S. Shulev in the 60s of the twentieth century (Fig. 2.), received the widest practical use, which is still relevant today[35].

According to this scheme, the workpiece is mounted in the centers or cantilevered in a chuck, placed between the electromagnet poles. If the processed surface length does not exceed 80 mm, it is advisable to choose the length of the poles equal to the workpiece's length[36,37,38,39,40,41,42]. The working movements are the rotation of the workpiece (main cutting movement) and oscillation (additional movement), which can be given to both the workpiece and the inductor's poles. This scheme is effectively used for grinding magnetically conductive workpieces with a surface diameter of 15 to 200 mm and a length *L* not more than 200−250 mm, as well as thin-walled non-magnetic bushings that are mounted on a magnetically conductive mandrel.

An increase in the area of the poles' working surface leads to a simultaneous increase in the dimensions of the electromagnet windings, the torque on the spindle, and the magnetic abrasive powder consumption.

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[35] Акулович Л.М., Сергеев Л.Е., Лебедев В.Я.. Основы магнитно-абразивной обработки металлических поверхностей : монографія. Минск: БГАТУ. 2012. 316 с., ISBN 978-985-519-544-4. URL: https://dokumen.pub/9789855195444.html

[36] Ibidem

[37] Ibidem. Магнитно-абразивная и магнитная обработка изделий и режущих инструментов. Op. cit. 176 с.

[38] Ibidem. Финишная обработка деталей сферической формы с наложением магнитных полей. Op. cit. С. 25-27.

[39] Ibidem . Эффективность магнитно-абразивной обработки. Op. cit. С. 192 – 195.

[40] Ibidem. Дослідження динаміки магнітно-абразивної обробки спеціальних матеріалів. Op. cit. С. 15-20

[41] Ibidem. Дослідження динаміки магнітно-абразивної обробки спеціальних матеріалів. Op. cit. С. 15-20.

[42] Спосіб фінішної магнітно-абразивної обробки поверхонь циліндричних отворів деталей з високолегованих композитів: пат. на винахід 94657 Україна № 200911005; заявл. 30.10.2009, опубл. 25.05.2011, Бюл. № 10. URL: https://base.uipv.org/searchBul/search.php?action=viewbul&dbname= inv&section=all&page=10

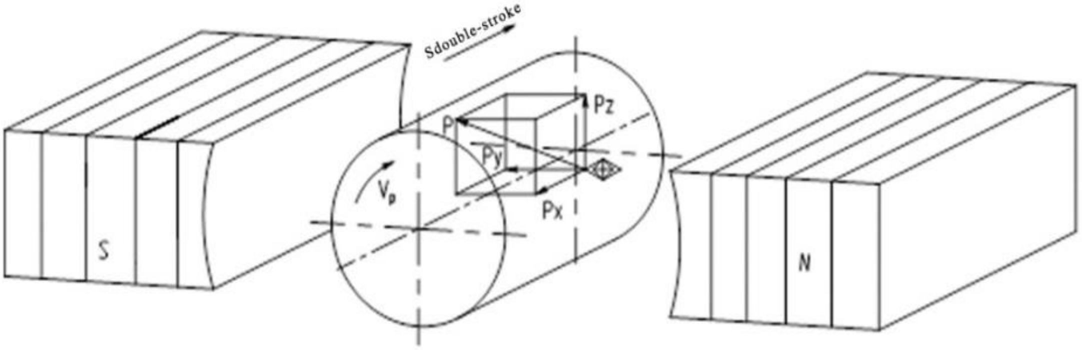

Fig. 2. Scheme of cylindrical parts processing in a magnetic field with ferromagnetic powders

The energy intensity of the process increases both due to an increase in the torque on the spindle, and due to an increase in the magnetic force in the electromagnet windings. The attraction force of the poles to the part is proportional to the square of the area of the poles' working surface.

Therefore, with an increase in the poles' working surface, it is necessary to increase the rigidity of magnetic system and part. The part's large dimensions and its large inertial mass make it difficult to oscillate. In this case, it is necessary to provide oscillating movements to the pole pieces.

3. Results and discussion

Prediction of the ferroabrasive grain trajectory in the working gap depending on the processing parameters

Taking into account that magnetic-abrasive processing is related to finishing operations, it is extremely necessary to have a mathematical apparatus for predicting the microrelief pattern of the antifriction part's working surface after MAP.

To solve this problem, it is necessary to analyze the principles and geometric prerequisites for the formation of microrelief pattern, both individual ferroabrasive grains and their totality.

Obtaining mathematical dependences of the ferroabrasive grain movement relative to the processed surface can be divided into three stages:

1) Drawing up an equation on a plane;
2) Deformation of the plane into a cylinder;
3) Coordinates transformation.

Drawing up an equation on a plane.

Let us consider the movement of a point along the two axes x and y (Fig. 3). In this case, the parameters x and y are the coordinates of the grain movement, accordingly, along the axis of rotation V_s and in the direction perpendicular to it V_n.

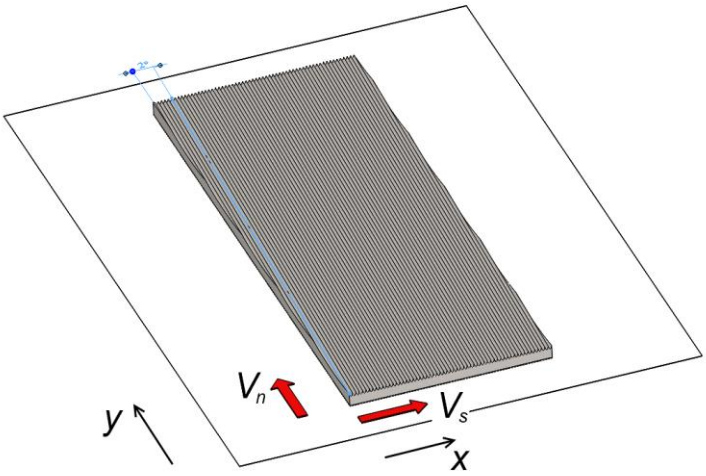

Fig. 3. The movement trajectory of a single grain on a plane

As it is known from geometry, the equation of such motion can be written as:

$$\begin{cases} x = x_0 + at \\ y = y_0 + bt \end{cases} \tag{1}$$

where t is the parameter responsible for the length of the segment (in our case it can be interpreted as time), a and b are the plane's geometric parameters.

Relation (2) is the tangent of the inclination angle of the line (Fig. 3).

$$tg(\alpha) = \frac{b}{a} \tag{2}$$

If the movement starts from the zero point of the coordinate system, then x_0 and y_0 are equal to 0. The x_0 parameter will be nonzero when the grain movement trajectories are shifted along the rotation axis.

The angle of inclination depends on the feed ratio (V_n and V_s). Since the feed rates are given in one dimension, we can write:

$$tg(\alpha) = \frac{b}{a} = \frac{V_n}{V_S} \tag{3}$$

Thus, formula (1) for the partial case can be written:

$$\begin{cases} x = V_S \cdot t \\ y = V_n \cdot t \end{cases} \tag{4}$$

Deformation of the plane into a cylinder. Since the processed surface geometry is cylindrical, it is necessary to «wrap» the plane into a cylinder (Fig. 4):

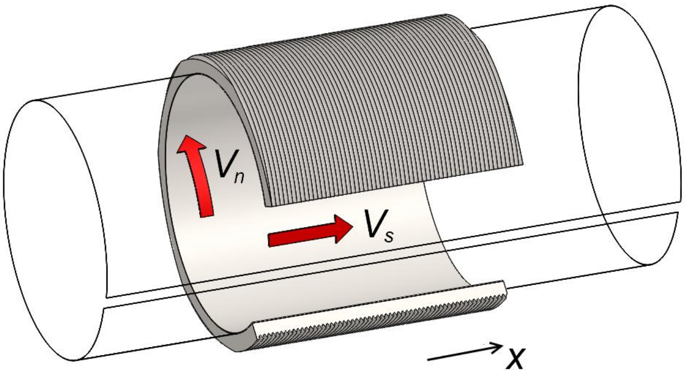

Fig. 4. Transformation of the grain motion plane into a cylinder

To do this, we write down the formulas of such a transformation.

If you select the *x*-axis of the plane as the rotation axis, then this coordinate remains unchanged. In this case, the elementary segment Δy on the plane will turn into an arc on a cylindrical surface, the length of which is calculated by the well-known formula:

$$\Delta y = L = 2\pi R \times \alpha \qquad (5)$$

where α is the central angle, rad;

R is the radius of the cylinder.

Thus, equation (1) is written as follows in the cylindrical coordinate system:

$$\begin{cases} x_c = x = x_0 + at \\ \alpha = \dfrac{y}{2\pi R} = \dfrac{y_0 + bt}{2\pi R} \end{cases} \qquad (6)$$

Taking into account (3) and (4), equation (6) will take the following form:

$$\begin{cases} x_c = V_S \cdot t \\ \alpha = \dfrac{V_n \cdot t}{2\pi R} \end{cases} \qquad (7)$$

Coordinates transformation. This stage must be performed for reasons of convenience in plotting graphs, therefore, we perform the transition to a cylindrical coordinate system using the known formulas[43]:

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[43] Цилиндрическая система координат. URL: https://portal.tpu.ru/SHARED/k/KONVAL/ Sites/Russian_sites/T_field/manual/35.htm

$$\begin{cases} x_d = x_c = x_0 + at \\ y_d = R \cdot \cos\alpha = R \cdot \cos\left(\dfrac{y_0 + bt}{2\pi R}\right) \\ z_d = R \cdot \sin\alpha = R \cdot \sin\left(\dfrac{y_0 + bt}{2\pi R}\right) \end{cases} \tag{8}$$

or

$$\begin{cases} x_d = V_S \cdot t \\ y_d = R \cdot \cos\left(\dfrac{V_n \cdot t}{2\pi R}\right) \\ z_d = R \cdot \sin\left(\dfrac{V_n \cdot t}{2\pi R}\right) \end{cases} \tag{9}$$

To obtain a graphical representation of the abrasive grain trajectory, we use the Python programming language and the Matplotlib library.

The result of the program use is a graphical reproduction of the abrasive grain movement relative to the processed surface of the cylindrical part (in our case, the bearing). The results of the mathematical modelling for grain motion are given below depending on the initial data changes.

When constructing the grain movement trajectory (Fig. 5), the following initial data were taken: R=25мм, $\alpha = a \times tg(5/0.18) = 87.9°$. Obviously, this angle should be calculated based on the ratio of radial and axial feeds (V_n and V_s).

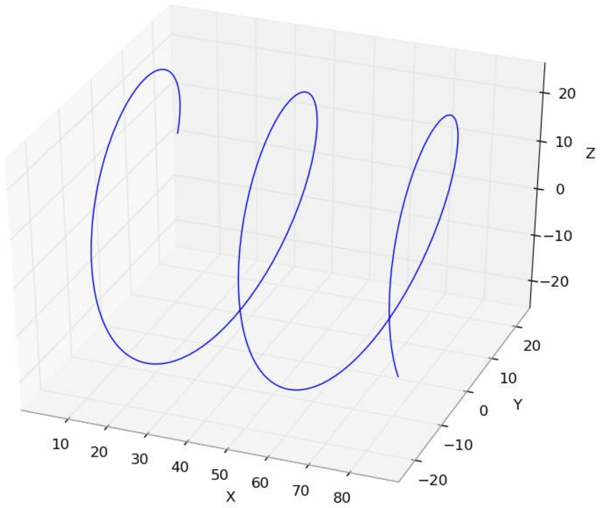


Fig. 5. Trajectory of a single abrasive grain movement

As it can be seen from Fig. 5, mathematical modeling made it possible to construct the trajectory of a single abrasive grain.

The obtained equations analysis.

1) If $a = 0$ (ie $\alpha = 90$ °), we obtain a trajectory in the form of a circle.

2) The curves family is obtained by introducing into the equation the shift value of the curve along the rotation axis $\Delta h\cdot \times k$ *(k=0,1,2…n)* (distance between grains):

$$\begin{cases} x_d = x_c = \left(x_0 + \Delta h \cdot k\right) + at \\ y_d = R\cdot\cos\alpha = R\cdot\cos\left(\dfrac{y_0 + bt}{2\pi R}\right) \\ z_d = R\cdot\sin\alpha = R\cdot\sin\left(\dfrac{y_0 + bt}{2\pi R}\right) \end{cases} \qquad (10)$$

Taking into account formulas (3) and (4), we will have:

$$\begin{cases} x_d = \Delta h\cdot k + V_S\cdot t \\ y_d = R\cdot\cos\left(\dfrac{V_n\cdot t}{2\pi R}\right) \\ z_d = R\cdot\sin\left(\dfrac{V_n\cdot t}{2\pi R}\right) \end{cases} \qquad (11)$$

Computer modeling made it possible to obtain a clear picture of the abrasive grains location (Fig. 6, 7) during the surface processing of the studied bearings based on the new composite KhN56VMKYu + 6% CaF_2.

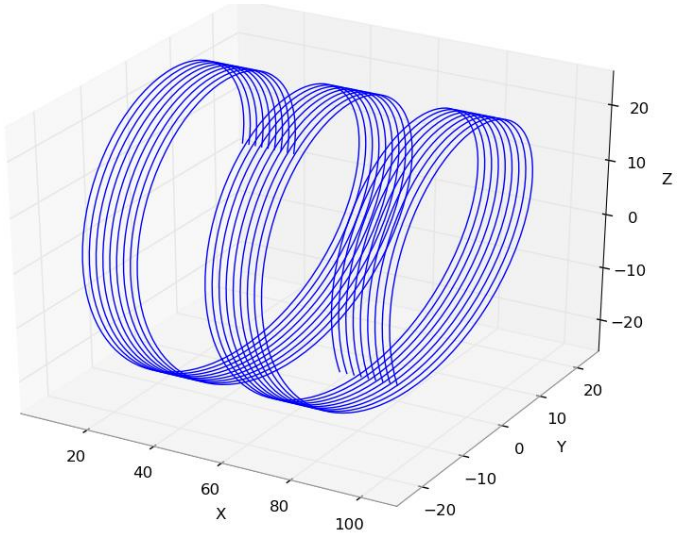


Fig. 6. The trajectory of several grains shifted relative to each other by the value of *Δh*

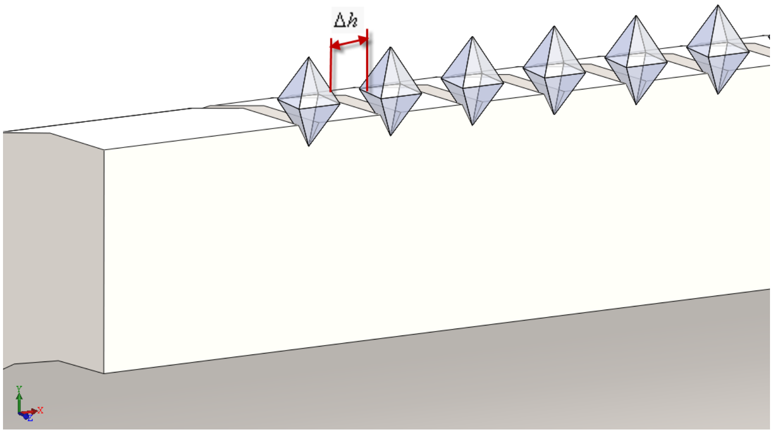


Fig. 7. Schematic representation of the grains arrangement with their displacement by the value Δh in the cutting process and the mark formation on the processed surface

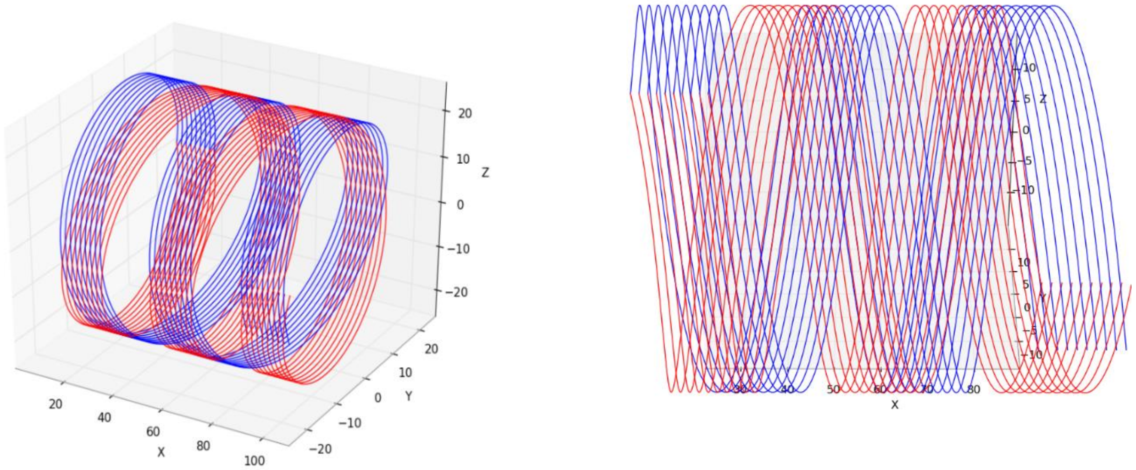
3) Changing the rotation direction is done by changing the inclination angle by the value $(2\pi-\alpha)$, which for periodic odd functions is equivalent to the introduction of the sign «-»:

$$\begin{cases} x_d = x_c = \left(x_0 + \Delta h \cdot k\right) + at \\ y_d = R \cdot \cos\left(2\pi - \alpha\right) = R \cdot \cos\left(\dfrac{y_0 + bt}{2\pi R}\right) \\ z_d = R \cdot \sin\left(2\pi - \alpha\right) = R \cdot \sin\left(\dfrac{y_0 + bt}{2\pi R}\right) \end{cases} \qquad (12)$$

or

$$\begin{cases} x_d = \Delta h \cdot k + V_S \cdot t \\ y_d = R \cdot \cos\left(\dfrac{V_n \cdot t}{2\pi R}\right) \\ z_d = -R \cdot \sin\left(\dfrac{V_n \cdot t}{2\pi R}\right) \end{cases} \qquad (13)$$

As a result, a crossed microrelief of the composite bearing's processed surfaces is formed (Fig. 8).

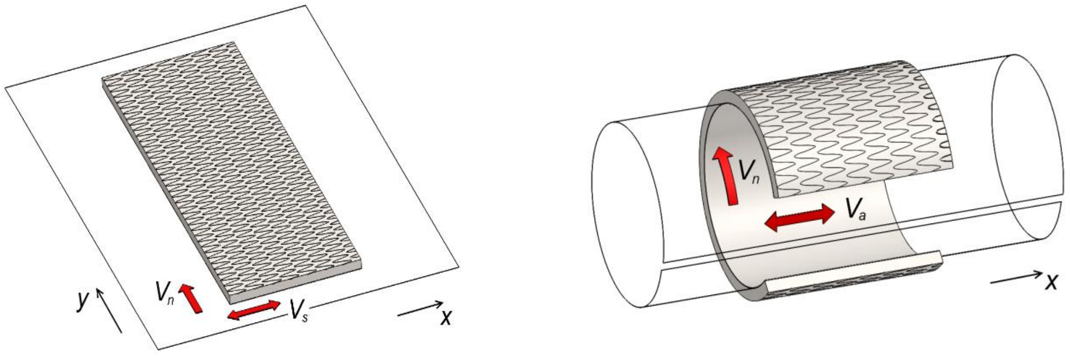


a b

Fig. 8. Formation of crossed microrelief by ferroabrasive grains: a – in three-dimensional space, b - microrelief on the plane

4) Complex motion is carried out by summing the equations of the corresponding motions, for example, the oscillations imposition.

Let us consider a case showing the formation of the ferroabrasive grain trajectory with additional oscillation (V_a) (Fig. 9).



a b

Fig. 9. Formation of the ferroabrasive grain trajectory with oscillation: a − on the plane, b − after transformation into a cylindrical shape

In this case we have two movements:
– straight-line movement along the *y*-axis

$$\begin{cases} x = 0 \\ y = y_0 + bt \end{cases} \tag{14}$$

– oscillating motion along the *x*-axis

$$\begin{cases} x = A \cdot \sin\left(f \cdot t\right) \\ y = 0 \end{cases} \tag{15}$$

where *A* is the amplitude, $f = \frac{V_S}{A}$, f -oscillation frequency

Summing (14) and (15), we obtain:

$$\begin{cases} x = A \cdot \sin\left(f \cdot t\right) \\ y = y_0 \end{cases} \tag{16}$$

Substituting (16) into (4) and (5), we obtain the resulting equation:

$$\begin{cases} x_d = A \cdot \sin\left(f \cdot t\right) \\ y_d = R \cdot \cos\left(\frac{y_0 + bt}{2\pi R}\right) \\ z_d = R \cdot \sin\left(\frac{y_0 + bt}{2\pi R}\right) \end{cases} \tag{17}$$

Taking into account technological variables (mode parameters variables) we will have:

$$\begin{cases} x_d = A \cdot \sin\left(f \cdot t\right) \\ y_d = R \cdot \cos\left(\dfrac{V_n}{2\pi R}\right) \\ z_d = R \cdot \sin\left(\dfrac{V_n}{2\pi R}\right) \end{cases} \tag{18}$$

The resulting oscillations frequency F to be obtained on a cylindrical surface will be:

$$F = \frac{\sqrt{V_S^2 + V_n^2}}{2\pi A} \tag{19}$$

The obtained results are valid for one curve, the curves family is described by the equation:

$$\begin{cases} x_d = \Delta h \cdot k + A \cdot \sin\left(f \cdot t\right) \\ y_d = R \cdot \cos\left(\dfrac{V_n \cdot t}{2\pi R}\right) \\ z_d = R \cdot \sin\left(\dfrac{V_n \cdot t}{2\pi R}\right) \end{cases} \tag{20}$$

Based on the calculations results, a model image of the abrasive grains movement in three-dimensional space was constructed (Fig. 10).

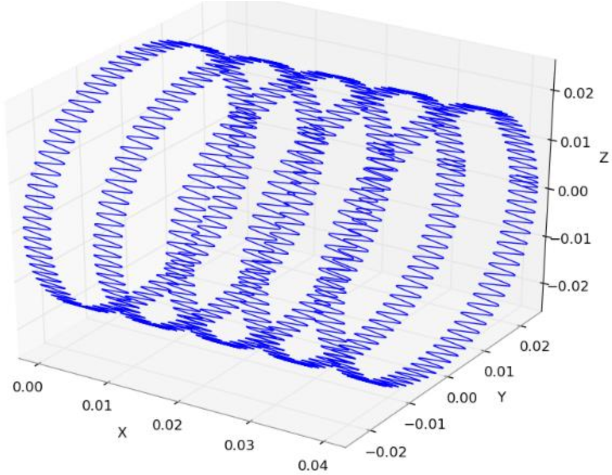


Fig. 10. Graphic representation of the ferroabrasive grain movement in three-dimensional space

The introduction of the inclination angle to formula (4) modified it as follows:

$$\begin{cases} x = x_0 + at \\ y = y_0 + bt \end{cases} \tag{21}$$

This made it possible to make an equation for the abrasive grains sinusoidal motion along a cylindrical surface with axial feed:

$$\begin{cases} x_d = x_0 + \Delta h \cdot k + A \cdot \sin\left(f \cdot t\right) \\ y_d = R \cdot \cos\left(\dfrac{y_0 + bt}{2\pi R}\right) \\ z_d = R \cdot \sin\left(\dfrac{y_0 + bt}{2\pi R}\right) \end{cases} \tag{22}$$

Accordingly, taking into account technological variables (variable operating parameters), we obtain:

$$\begin{cases} x_d = \Delta h \cdot k + A \cdot \sin\left(f \cdot t\right) + V_S \cdot t \\ y_d = R \cdot \cos\left(\dfrac{V_n \cdot t}{2\pi R}\right) \\ z_d = R \cdot \sin\left(\dfrac{V_n \cdot t}{2\pi R}\right) \end{cases} \tag{23}$$

Graphic representation of the abrasive grains movement with the addition of the inclination angle component has been shown in Fig. 11.

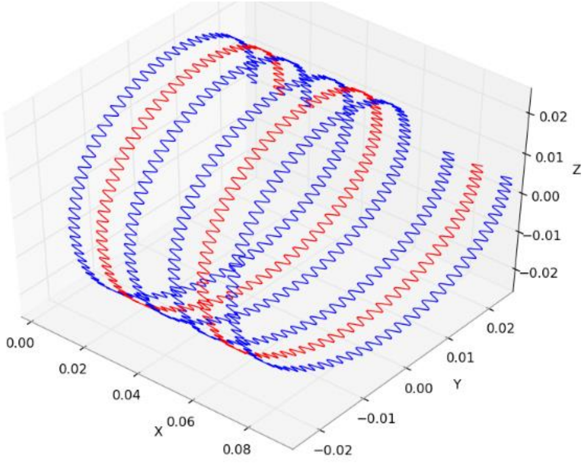


Fig. 11. Graphic representation of the ferroabrasive grains movement in three-dimensional space with the addition of the inclination angle component

Changing the rotation direction is performed similarly to equation (13) by entering a negative coordinate z_d, which made it possible to construct the corresponding trajectory of the ferroabrasive grains movement (Fig. 11).

The images of the ferroabrasive grains movement in three-dimensional space with the addition of the inclination angle component, reciprocating motion modeling, the microrelief pattern formation on the processed surface by ferroabrasive grains, taking into account all affecting factors, and the scheme of microrelief formation on the part's surface based on antifriction composite KhN56VMKYu + (4-8)% CaF_2 with ferroabrasive grains totality have been shown in fig. 12−14 accordingly.

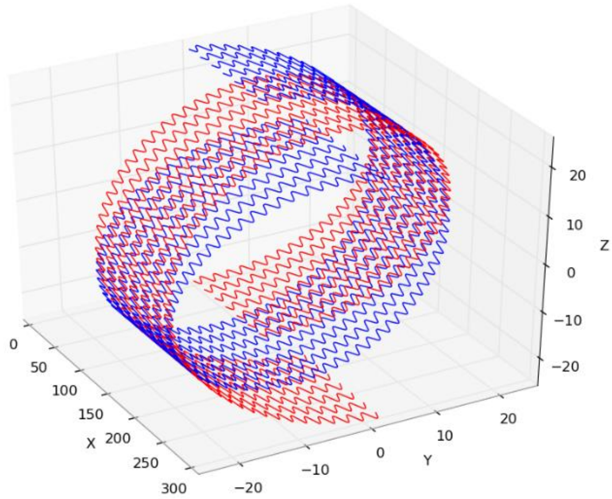


Fig. 12. Graphic representation of the ferroabrasive grains movement in three-dimensional space with the addition of the inclination angle component and reciprocating motion modeling

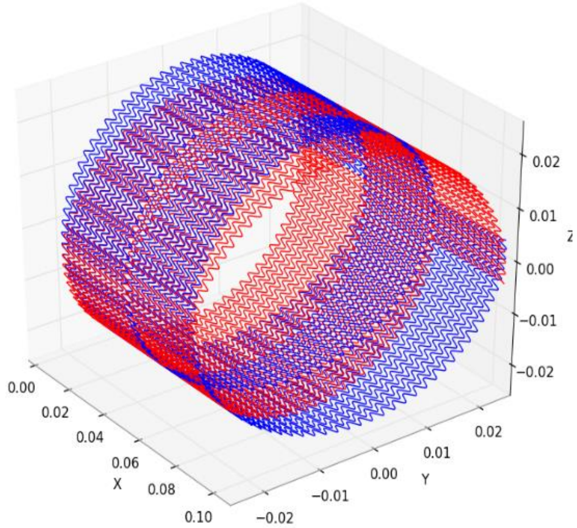


Fig. 13. The formation of the microrelief pattern on the part's processed surface by ferroabrasive grain, taking into account all influencing factors

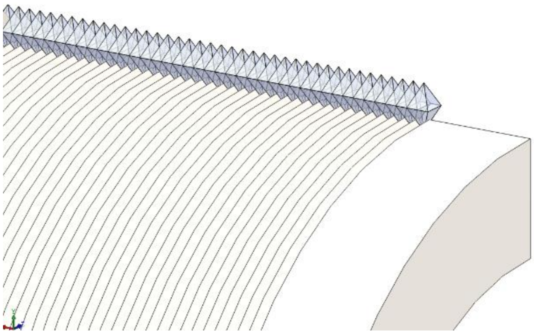


Fig. 14. Schematic image of microrelief formation by ferroabrasive grains totality

A graphical image of the two ferroabrasive grains motion in three-dimensional space and an approximate modeling with different amplitudes and movement different directions have been shown in fig. 15. Modeling of the processed surface's relief by grains totality has been shown in fig. 16.

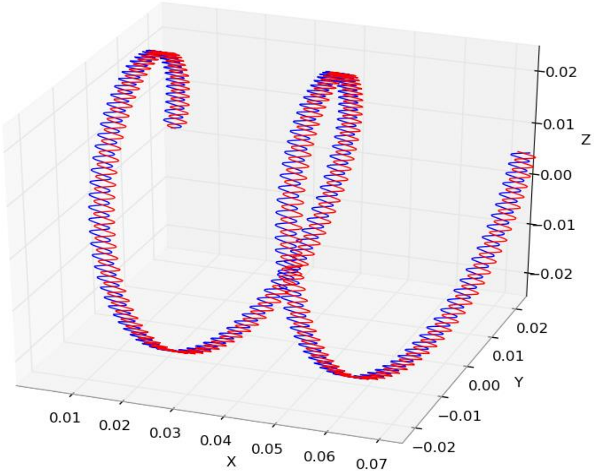


Fig. 15. Graphical image of two ferroabrasive grains movement in three-dimensional space with different amplitudes and movement direction

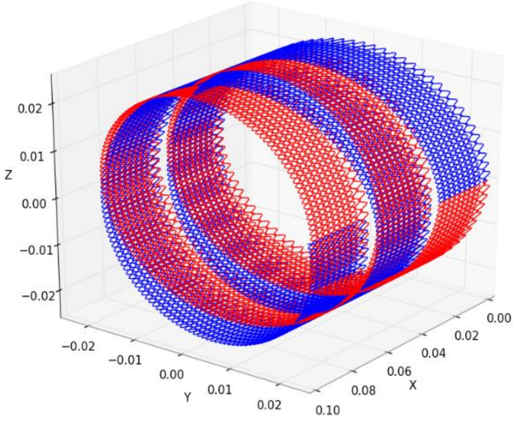


Fig. 16. Graphic representation of the ferroabrasive grains movement in three-dimensional space with grains totality

To find the points of two curves intersection, we write a parametric equations system of these curves.

$$\begin{cases} x_1 = A \cdot \sin\left(f \cdot t\right) + V_S \cdot t \\ y_1 = R \cdot \cos\left(\dfrac{V_n \cdot t}{2\pi R}\right) \\ z_1 = R \cdot \sin\left(\dfrac{V_n \cdot t}{2\pi R}\right) \end{cases} \tag{24}$$

$$\begin{cases} x_2 = \Delta h - A \cdot \sin\left(f \cdot t\right) + V_S \cdot t \\ y_2 = R \cdot \cos\left(\dfrac{V_n \cdot t}{2\pi R}\right) \\ z_2 = R \cdot \sin\left(\dfrac{V_n \cdot t}{2\pi R}\right) \end{cases} \tag{25}$$

As is known from geometry, two curves have an intersection point if the following condition is met: $\begin{cases} x_1 = x_2 \\ y_1 = y_2 \\ z_1 = z_2 \end{cases}$ (26)

In our case, taking into account (24) and (25), we have:

$$\begin{cases} A \cdot \sin\left(f \cdot t\right) + V_S \cdot t = \Delta h - A \cdot \sin\left(f \cdot t\right) + V_S \cdot t \\ R \cdot \cos\left(\dfrac{V_n \cdot t}{2\pi R}\right) = R \cdot \cos\left(\dfrac{V_n \cdot t}{2\pi R}\right) \\ R \cdot \sin\left(\dfrac{V_n \cdot t}{2\pi R}\right) = R \cdot \sin\left(\dfrac{V_n \cdot t}{2\pi R}\right) \end{cases} \tag{27}$$

In order to exclude the parameter *t* from the equations system, it suffices to solve only the first equation from (27), the other two become an identity.

Thus:

$$A \cdot \sin\left(f \cdot t\right) + V_S \cdot t = \Delta h - A \cdot \sin\left(f \cdot t\right) + V \tag{28}$$

$$2A \cdot \sin\left(f \cdot t\right) = \Delta h \tag{29}$$

$$t = \frac{\arcsin\left(\Delta h / 2A\right)}{f}, \quad \Delta h < 2A \tag{30}$$

Substituting t from equation (30) into any of equations (27), we obtain the coordinates of the curves’ intersection point.

Obviously, there will be more than one such point. Since the function is periodic, all other points will be found by adding a period of $2\pi k$, to the time parameter ($k=0,1,\ldots n$).

CONCLUSIONS

It was performed the computer modeling of complex trajectories of the ferroabrasive grains totality movement in the working gap depending on the MAP parameters at finishing of bearing’s working surfaces based on new antifriction composite KhN56VMKU + 6% CaF_2.

This allows predicting their working surfaces topography and controlling the microrelief formation by the technological modes to ensure maximum surfaces’ quality parameters, which are a prerequisite for high wear resistance of friction units in printing machines.

As a result of theoretical research the software was created to model and predict the possible surfaces’ microrelief pattern after MAP realized by a single ferroabrasive grain and ferroabrasive grains totality.

The developed software for modeling and predicting the possible microrelief pattern of the processed surfaces after MAP can be further used for a preliminary analysis of possible roughness parameters under certain technological modes of magnetic-abrasive processing.

SUMMARY

In conditions of high competition, the requirements for the quality of modern printing equipment are growing every year. At the same time, the need to repair, improve and restore used equipment is growing much faster. This is due to the specific operating conditions of printing equipment that operates at high speeds of offset, printing, form cylinders, in aggressive environments, etc., which causes the friction units intense wear. When repairing or designing such friction units, much attention is paid not only to the materials from which they are made, but also to the accuracy of manufacturing antifriction parts and their working surfaces’ quality parameters. Unfortunately, now the regularities of purposeful and stable

formation of the working surfaces' quality parameters of the printing machines' hard-loaded composite antifriction parts remain unclear. Also, there is still no mathematical apparatus for predicting the microrelief pattern of the antifriction part's working surface, which limits the technological parameters of finishing, in particular, one of the promising methods of fine processing such as magnetic abrasive processing (MAP). In a work it was carried out the mathematical modeling of the surface microrelief formation during magnetic-abrasive processing of self-lubricating parts based on a new antifriction composite KhN56VMKU + 6% CaF_2. This was a necessary task for the real possibility of obtaining predictable high surface quality parameters, taking into account technological processing factors. It was performed the computer modeling of complex trajectories of the ferroabrasive grains totality movement in the working gap depending on the MAP parameters at finishing of bearing's working surfaces. Software was created to model and predict the possible surfaces' microrelief pattern after MAP realized by a single ferroabrasive grain and ferroabrasive grains totality. The developed software can be further used for a preliminary analysis of possible roughness parameters under certain technological modes of magnetic-abrasive processing.

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