

Improving Technology and Equipment for Chamber Machining of Parts by an Unfixed Grinding Material

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Abstract—The technological features of the chamber method for processing surfaces of parts with the use of unfixed grinding material are described. Manufacturing methods and ways for improving technological equipment the models of abrasive grains to actualize them, as well as mathematical dependencies that make it possible to predict the process efficiency are considered.

Keywords: surface treatment of parts using an unfixed grinding material, technological equipment, abrasive particle model, mathematical dependences, prediction of processing efficiency

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INTRODUCTION

In the course of the finishing treatment of such parts as bodies of rotation with a complicated surface contour with the use of finely dispersed unfixed abrasive particles, during the compaction by compressed air through an elastic shell in a special chamber, quite a large number of abrasive grains are involved in the metal removal.

The density of contacting between the working medium and the surface of the part in the course of processing with the use of statically compacted abrasive particles is rather high. The method for a finishing abrasive treatment with the use of statically compacted

abrasive suspensions in the developed facility based on a vertical drilling or radial drilling machine is implemented in accordance with Figs. 1a and 1b.

According to Fig. 1a, cylindrical workpieces 1 are secured to an axis 2 and placed in an abrasive suspension 3, housed in a special container 4, wherein a cylindrical shell 5 made of a special nitrile rubber.

The working suspension is compressed through applying compressed air onto the shell perimeter. The machining occurs as the axis with the workpieces rotates at a velocity of V_w . Figure 1a shows that the flat workpiece moves at a velocity of V_w in the course of machining.

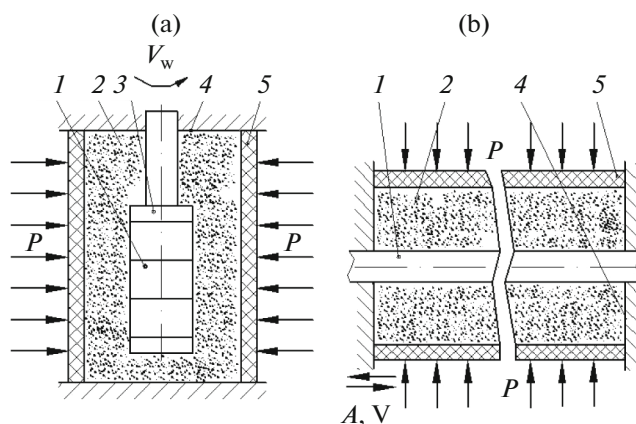


Fig. 1. Processing of parts with the use of a statically compacted abrasive: (a) processing of cylindrical parts; (b) processing of flat parts; (1) cylindrical products; (2) an axle; (3) abrasive suspension; (4) container; (5) cylindrical shell.

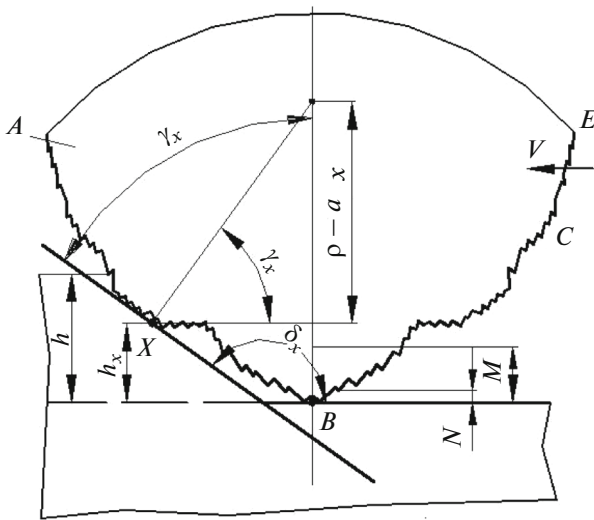


Fig. 2. Material removal by means of an abrasive grain: M are the microprotrusions of the abrasive grain tip; N is the submicroprotrusions located on the microprotrusions of the abrasive grain tips; h is the abrasive grain penetration depth into the workpiece surface; V is the travelling velocity of an abrasive grain; γ_x is the front angle of the abrasive grain; δ_x is the cutting angle.

Upon machining, microscopic chips are generated, according whose characteristics it is rather difficult to assess the productivity of the machining process [1, 2].

MATERIALS AND METHODS

Figure 2 shows an example for removing material from the surface of a workpiece using various cutting elements of abrasive grain. The character of contact between the compacted layer and the workpiece surface is to a great extent determined by the shape of the abrasive grains and their cutting elements, which is rather diverse.

However, the studies on numerous shadow prints have shown that they all can fit within an ellipse [2–4]. Taking this into account, as well as the results of scanning microscope studies on the grain topography [2–4], their shape can be simulated, to a first approximation, by an ellipsoid of revolution, on the surface of which there are microroughnesses in the form of discontinuous annular protrusions with submicroroughnesses located therein (Fig. 3).

The number of microroughnesses and submicroroughnesses on the surface of the abrasive grain can be determined in accordance with Fig. 4, based on analytical relationships derived for the first time:

$$N_m = \sum_{i=1}^{n_m} \pi c_i K_d, \quad (1)$$

where i is the number of circles in the cross-section of the ellipsoid that simulates the shape of an abrasive grain, on which microprofile protrusions with a given

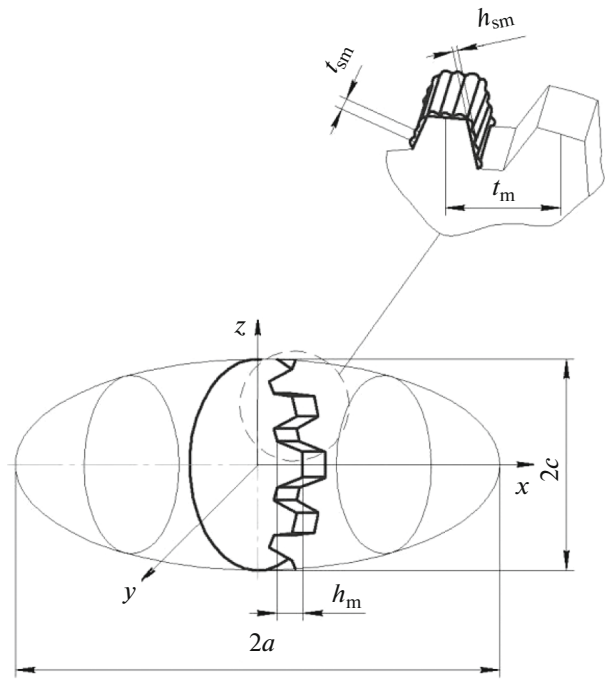


Fig. 3. Abrasive grain model: a , c are the semi-axes of the ellipsoid of revolution; h_m is the height of the microrelief protrusion; h_{sm} is the height of the submicrorelief protrusion; t_m is the average pitch of the microrelief protrusions; t_{sm} is the average pitch of the submicrorelief protrusions.

pitch t_m are located; K_d is the coefficient taking into account the discontinuity of microroughnesses (in accordance with the law of equal probability $K_d = 0.5$); n_m is the number of contact traces of microprofile protrusions with an average pitch t_m and length l_i , within the ellipse of the imprint of an unfixed abrasive particle that participate in the workpiece processing.

The total number of submicroroughnesses located on the microprofile protrusions of the abrasive grain surface can be determined according to the following analytical relationship (see Fig. 4):

$$N_{sm} = 2 \frac{h_{st} - f}{b_{sm} \cos \gamma} + \frac{\pi \rho_m \alpha'}{180 b_{sm}}, \quad (2)$$

where h_{st} static depth of submicroroughness penetration; f is the protrusion parameter for the abrasive particle microrelief $f = \rho_m \left(1 - \cos \frac{\alpha'}{2}\right)$; b_{sm} is the width of

a single submicroroughness; γ is the front angle of a single microroughness; ρ_m is the rounding radius of the abrasive grain microprofile protrusion; rounding α' is the central angle of the microrelief protrusion.

One of the most important parameters of the finishing process consists in material removal [1–5] that can be represented by a specific mathematical model.

Owing to the difficulties in analyzing the cutting process of the workpiece surface by the entire set of

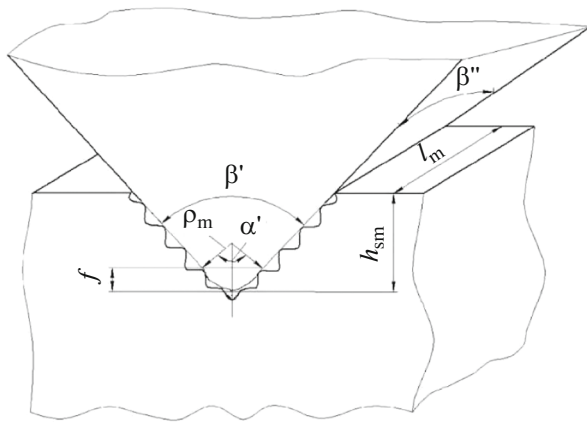


Fig. 4. Interaction between the abrasive grain and the surface of the workpiece under treatment l_m is the parameter of the abrasive particle microrelief protrusions; β' and β'' are the angles of the microrelief protrusions having the shape of a truncated regular pyramid with a rounding radius ρ_m and a total length ranging from 0 to $2c$.

abrasive grains in order to determine material removal, let us consider the mechanism of material removal by a single abrasive particle.

The fundamental studies concerning the microprofile of unfixed abrasive suspension particles are presented in [1–10], where numerical values for the width and height of the microprofile and submicroprofile of abrasive particles are determined. In the new studies, it has been established that the rounding radius of the vertices of the abrasive particle microrelief ranges from 0.1 to 0.5 μm , whereas the rounding radius of the vertices of submicroprotrusions varies in the range of 0.08–0.1 μm . It has been shown that the microrelief and submicrorelief parameters are almost not connected with the size of abrasive grains.

According to the investigation results reported in [1–5] it has been established that at the initial moment of part surface machining ($t = 0.5$ –1 min) with a total machining time of $t = 6$ –8 min, the material removal occurs primarily via submicroroughness located on the microprotrusions of the abrasive grains. As the submicroprofile depressions are filled with submicrochips, the material removal almost ceases, and the further material removal from the surface of the workpiece is accomplished with the use of the microprofile of the abrasive grains.

Numerous studies [1–5] have shown that the material removal from the surface of a part by submicroroughness amounts to 1–3%, which is negligible as to compare to the material removal owing to the microprofile of abrasive grains (97–99%). Therefore, further it can be assumed with a complete justification that the material removal from the surface of a part is carried out predominantly by the microprofile of abrasive particles. The total volume of material deformed by a single microprotrusion of an abrasive grain upon

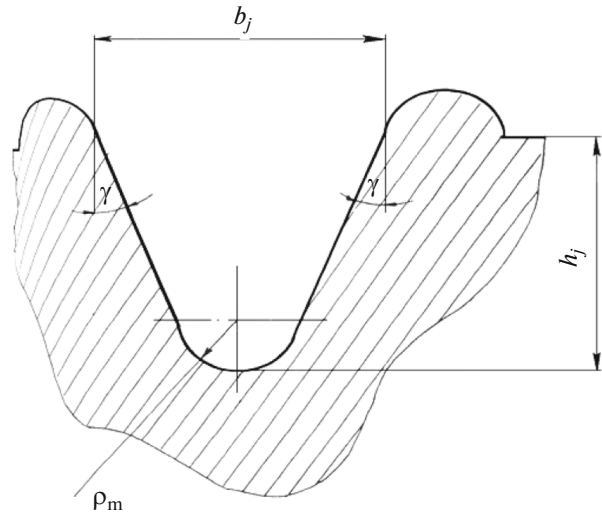


Fig. 5. Cross-section of a scratch originating from cutting a single abrasive grain by a micro-protrusion.

the machining of parts representing bodies of revolution can be determined as follows [1, 2]:

$$V_{\Sigma} = K_c V_{\text{scratch}} = 2\pi r_0 \times 0.5 \times [(b_j + 2\rho_m)(h_j - \rho_m) + \pi\rho_m^2], \quad (3)$$

where r_0 is the radius of the workpiece, m 10^{-3} ; K_c is the chip formation coefficient; $K_c = 1 - \epsilon_h$ (ϵ_h is the coefficient of deformed material heaps); ρ_m is the rounding radius of the microprofile protrusion of a single grain, m 10^{-6} ; b_j and h_j are, respectively, the width and depth of the scratch left by a single protrusion of the abrasive grain microprofile on the surface of the workpiece, m 10^{-6} (Fig. 5).

In the course of preliminary calculations the authors of [11, 12], have succeeded in establishing the fact that the relative error in the calculation of total volume according to relationship (3) does not exceed 5% as to compare to the previously presented experimental studies, where the weight of the obtained microchips has been determined using special micro-analytical scales with an accuracy of up to 0.0001 g.

This indicates a sufficient accuracy of the proposed method for calculating scratch volume originating from a single microprotrusion of an abrasive grain, taking into account the chip formation coefficient.

The scratch area (see Fig. 5) and parameter b_0 can be determined as follows:

$$S_{\text{scratch}} = 0.5[(b_j + 2\rho_m)(h_j - \rho_m) + \pi\rho_m^2]; \quad (4)$$

$$b_0 = 2\rho_m + 2(h_j - \rho_m)\sin\gamma = 2h_j\sin\gamma, \quad (5)$$

where γ is the front angle of the microrelief protrusion, the average value of which is approximately 50° ; b_0 is the scratch width originating from a single microprotrusion of an abrasive grain in the middle part of the abrasive layer.

Based on the known parameters of the microcutting process with different abrasive grain elements, one can estimate the value of material removal by multiple unfixed abrasive particles.

Under the finishing treatment of the outer surfaces of cylindrical parts processed in a statically compacted abrasive suspension, knowing the scratch area, the material removal rate can be determined using the following mathematical relationship. This relationship multiplies the density of the material under removal, taking into account the coefficient of chip formation, by the scratch volume, the circumference of the workpiece diameter, its rotational frequency, and the processing time t . This mathematical relationship also includes a number of coefficients taking into account specific processing conditions.

The total number of abrasive grains N_Σ on the surface contacting with the workpiece can be determined using the following relationship [1–3]:

$$N_\Sigma = 2\pi r_0 B_w (\sqrt[3]{n_1 \rho_h})^2,$$

where r_0 is the radius of the workpiece; B_w is the length (width) of the workpiece; n_1 is the number of grains per unit weight of the compacted abrasive layer; and ρ_h is the abrasive density.

When abrasive grains penetrate the workpiece surface and under their relative motion, cutting forces occur, which determine the character of the relative position of the abrasive grains. If the cutting force exceeds the normal pressure of the abrasive grain on the workpiece, it turns with its other edge or vertex toward the workpiece.

The rotation of abrasive particles provides an increase in metal removal in the course of machining, which is taken into account by rotation coefficient K_r .

The investigations have shown that in the course of machining, the cutting ability of abrasive particles exhibit a 30% increase owing to the finest chips of the microrelief. This is taken into account by coefficient K_i . In the course of the investigations we have succeeded to reveal that depending on the machining conditions, on the composition of the abrasive suspension, and on the material of workpiece surface, the values of coefficient K_L responsible for the effect of the abrasive suspension liquid component, range from 1.2 to 1.5, whereas the values of rotation coefficient K_r range from 1.2 to 1.3.

The conducted investigations also revealed that, depending on the roughness of the surface under machining, the K_{Ra} coefficient varies within the range of 1.15–1.5.

In this case, the calculated dependence for determining the amount of metal removed upon machining the external surfaces of parts in the form of bodies of

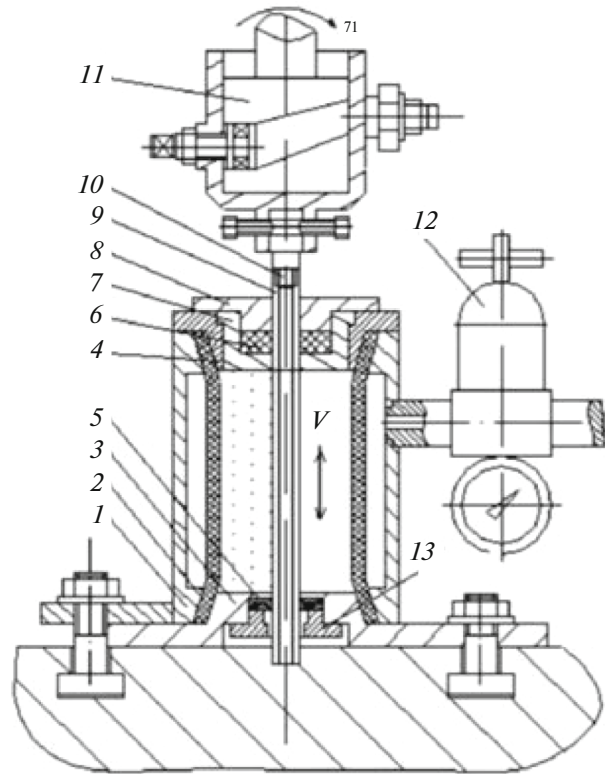


Fig. 6. Schematic diagram of the installation for processing flat surfaces of parts with compacted abrasive material: (1) casing; (2) elastic cylindrical shell; (3, 4) two covers for fastening the elastic shell; (5, 6) the seals of the input/output windows of the parts; (7) a cup; (8) pressure cover; (9) mandrel for installing a part; (10) fastening; (11) a cam mechanism; (12) pressure-reducing valve with a pressure gauge; (13) pressure cover.

rotation with the use of a compacted abrasive medium is as follows:

$$Q_\Sigma = \rho(1 - \varepsilon_h) 2\pi n_0 r_0 t \times 0.5[(b_j + 2\rho_m) \times (h_j - \rho_m) + \pi \rho_m^2] N_\Sigma K_r K_i K_{Ra} K_L. \quad (6)$$

The design of a new installation used for processing flat part surfaces with the use of a compacted abrasive material makes it possible to adjust double stroke time via changing the rotational frequency of the cam that is rigidly connected to the machine spindle. This provides an improvement of the surface quality of the parts and the productivity of the process. Figure 6 shows a schematic diagram of the installation. The installation includes a casing 1, an elastic cylindrical shell 2, two covers 3 and 4 for fastening the elastic shell, seals 5 and 6 for the input/output windows for parts, a cup 7, wherein the seals are placed, two pressure covers 8 and 13, a pressure-reducing pneumatic valve 12 with a pressure gauge connected to the supply pneumatic network, a mandrel for installing a part 9 with a fastener 10 and a cam mechanism 11 that sets a reciprocating motion of the part with stopping at the end of each stroke. The

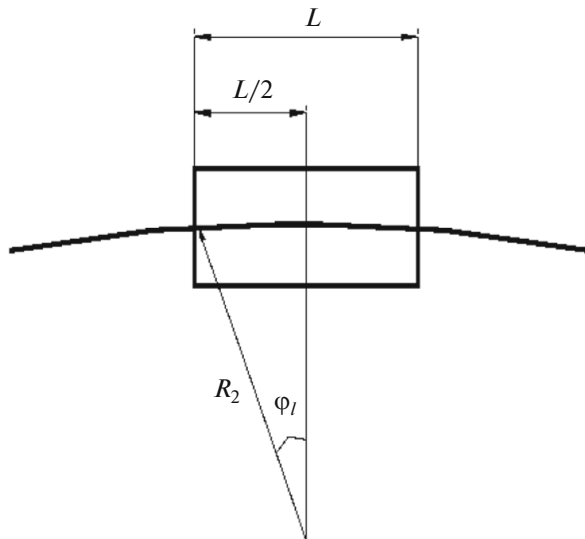


Fig. 7. Workpiece profile.

entire installation is rigidly fixed on the table of a vertical drilling machine and connected to its spindle.

The output shaft rotational frequency of the machine motor amounts up to 1000 min^{-1} .

The machine operates as follows. A prototype of the part is placed inside the machine working chamber, after which it is filled with an abrasive medium, a cup with seal is installed, and the machine is closed by a top cover 8. The workpiece is then connected to the replaceable cam mechanism, and the required air pressure, supplied from the pneumatic network, is set with the use of a pneumatic pressure-reducing valve. The air pressure is registered using a pressure gauge. Machining occurs under the workpiece reciprocating motion. The cylindrical cam groove is profiled in such a way that the dwell time at the end of each stroke is $0.15T_{ds}$, where T_{ds} is the double stroke time of the part. The machine design makes it possible to adjust the double stroke time through varying the rotational frequency of the cam that is rigidly connected to the machine spindle.

At the same time, the quality of the machined surface of the parts and the processing productivity exhibit an increase. The pressure of supplied compressed air was changed using a 122-12-U4 pneumatic pressure reducing valve corresponding to GOST (State Standard) 18468-79. The pressure was registered using a MVTPSd-00-OM-2 corresponding to GOST (State Standard) 12733-79 with a scale-division value of 0.005 MPa . Flat surfaces of rectangular or square parts $200\text{--}300 \text{ mm}$ long made of 50G2 grade steel with a hardness of $45\text{--}50 \text{ HRC}$ were processed with the use of the installation prototype. The initial surface roughness of the samples R_a ranged from 0.63 to $1.25 \mu\text{m}$.

As the working media we used 14A grade electrocorundum abrasives with a grain size of $Z = 0.40\text{--}0.63 \text{ mm}$ and a volumetric humidity of 20% . A 2%

aqueous solution of trisodium phosphate was used as the liquid component of the medium. The processing was carried out at the following operating parameters: the velocity of workpiece reciprocating motion (cutting velocity) $V = 0.1\text{--}0.25 \text{ m/s}$; the pressure of the compacted abrasive medium on the surface of the workpiece $p = 0.1\text{--}0.15 \text{ MPa}$; polishing time $t = 5 \text{ min}$. The roughness after processing with the use of compacted abrasive amounted to $R_a = 0.16\text{--}0.24 \mu\text{m}$. The velocity of the workpiece reciprocating motion can be determined according to the following relationship:

$$V = \frac{2n_{\text{doub.stroke}}(l_1 + l_2)}{60 \times 1000}, \quad (7)$$

where $n_{\text{doub.stroke}}$ is the number of workpiece double strokes per minute with respect to the compacted cutting medium; l_1 and l_2 are, respectively, the length of the workpiece surface and the stroke reserve under the motion of the workpiece in the working medium. At $l_1 = 200\text{--}300 \text{ mm}$ and $l_2 = 50 \text{ mm}$, and at $n_{\text{doub.stroke}} = 15\text{--}25 \text{ (doub.stroke/min)}$ the cutting velocity varies in the range of $V = 0.1\text{--}0.25 \text{ m/s}$.

If the surface of a part has a flat section, or the entire part consists of flat sections, then the profile of the workpiece can be represented, to a first approximation, as a part of a circular arc having sufficiently large radius R_2 (Fig. 7).

Radius R_2 is determined according to the following relationship:

$$R_2 = \frac{L}{2 \sin \phi_l}, \quad (8)$$

where L is the length of the flat section of the part, m; ϕ_l is the geometric angle, degrees.

According to reference data available from [11, 12]:

$$R_2 = \frac{1}{K_c},$$

where K_c is the curvature of the flat section (ranging within $0.05\text{--}0.001$).

At that, the relationship for determining the amount of metal removed upon machining flat outer surfaces of parts with length L_i with the use of an unfixed grinding material can be represented as follows:

$$Q_\Sigma = \rho(1 - \varepsilon_h) \sum_{i=1}^m L_i n_{\text{doub.stroke}} t \times 0.5[(b_j + 2\rho_m) \times (h_j - \rho_m) + \pi \rho_m^2] N_\Sigma K_r K_i K_{Ra} K_L. \quad (9)$$

In this case, the total number of abrasive grains N_Σ on the surface contacting with the workpiece can be determined as:

$$N_\Sigma = \sum_{i=1}^m L_i B_{wi} (\sqrt[3]{n_l \rho_h})^2,$$

where where $\sum_{i=1}^m L_i B_{wi}$ is the total length and total width of the machined surfaces of a flat part.

It should be noted that the specific material removal rate can be determined according to the following relationship:

$$q = \frac{Q_{\Sigma}}{S}, \text{ mg/cm}^2,$$

where S is the surface area of the workpiece under machining.

The productivity per minute can be defined as:

$$Q_{\min} = Q_{\Sigma}/t, \text{ mg/min},$$

where t is the required processing time.

RESULTS AND DISCUSSION

After 2–3 min of machining, the initial microrelief, owing to wearing abrasive particles, undergoes transforming into a smoother working microrelief that ultimately determines the amount of material removed from the surface, the set surface roughness, the precision parameters of the machining process, as well as the physical-and-mechanical properties of the surface under treatment.

The proposed patterns for the finishing abrasive machining of parts with the use of unfixed grinding material, based on which experimental equipment samples have been developed, provide expanding the technological capabilities of the equipment, making it possible, under necessary retooling, to process both bodies of rotation and flat parts, while promoting an increased productivity level and improved polishing quality.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

REFERENCES

1. Skryabin, V.A. and Pshenichnyi, O.F., *Simulation of the micro-cutting process during the machining of parts using a compacted layer of loose abrasive*, *Mashinostroenie: Respublikanskii mezhdovedstvennyi sbornik* (Mechanical Engineering: Republican Interdepartmental Compendium), Minsk: Vysheishaya Shkola, 1988, pp. 33–37.
2. Skryabin, V.A., *Osnovy protsessy submikrorezaniya pri obrabotke detalei nezakreplennym abrazivom. Monografiya* (Fundamentals of the Submicron Cutting Process in the Machining of Parts Using Unbound Abrasives: A Monograph), Penza: Penzenskoe Vysshee Artilleriiskoe Inzhenernoe Uchilishche Imeni Glavnogo Marshala Artillerii N.N. Voronova, 1992.
3. Skryabin, V.A., Process productivity in the machining of parts using a statically compacted layer of abrasive micropowder, *Izvestiya Vysshikh Uchebnykh Zavedenii. Seriya Mashinostroenie*, 1994, no. 4, pp. 128–130.
4. Martynov, A.N., *Osnovy metoda obrabotki detalei svoobodnym abrazivom, uplotnennym inertsionnymi silami* (Fundamentals of the Free Abrasive Particle Processing Method, Compacted by Inertial Forces), Saratov: Saratovskii Gosudarstvennyi Tekhnicheskii Universitet, 1981.
5. Skryabin, V.A. and Skhirtladze, A.G., *Tekhnologicheskoe obespechenie kachestva obrabotki slozhnoprofil'nykh detalei uplotnennymi melkodispersnymi sredami. Monografiya* (Technological Quality Assurance in the Machining of Complex-Shaped Parts Using Compacted Fine-Particle Media: A Monograph), Stary Oskol, Belgorod oblast: Tonkie Naukoemkie Tekhnologii, 2015.
6. Skryabin, V.A., Skhirtladze, A.G., and Rybakov, Yu.V., A new method for the final finishing of parts using free, fine-particle media, *Tekhnol. Met.*, 2003, no. 2, pp. 16–17.
7. Skryabin, V.A. and Svechnikova, G.I., Experimental studies on the performance of final abrasive finishing of parts with different profiles, *Mashinostroitel*, 2011, no. 4, pp. 18–22.
8. Martynov, A.N., Lemin, V.A., Skryabin, V.A., Fedoseev, V.M., and Sytnikov, A.V., Method for working parts, RF Patent 1803308, 1993.
9. Martynov, A.N., Fedoseev, V.M., and Skryabin, V.A., Method of abrasive working of parts, SU Inventor's Certificate 1579740, 1990.
10. Shirokov, I.B., Artemov, I.I., and Zhuravlev, N.A., Device for centrifugal processing of parts, SU Inventor's Certificate 512902, 1976.
11. Skriabin, V.A. and Fomichev, V.O., Method for abrasive processing of flat surfaces of parts, RF Patent 2748919, 2021.
12. Skryabin, V.A., Features of intricate-shaped parts by close-settled fine abrasive media, *Vestnik Mordovskogo Universiteta*, 2015, vol. 25, no. 4, pp. 72–89. <https://doi.org/10.15507/0236-2910.025.201504.072>

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