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INVESTIGATION OF RADIAL DEFORMATION OF NON-RIGID PARTS DURING ULTRASONIC BURNISHING WITH PRELIMINARY CLEARANCE

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The article considers the process of ultrasonic burnishing of non-rigid parts with preliminary clearance and investigates the influence of processing parameters on the quality of the surface layer. The relevance of the study is обусловлена the need to improve the accuracy, wear resistance, and durability of machine parts while simultaneously reducing material consumption and manufacturing labor intensity. It is shown that conventional machining methods are inefficient for manufacturing parts of complex geometry and components made of difficult-to-machine materials; therefore, the application of ultrasonic surface plastic deformation methods is considered a promising approach.

The study examines the process of radial displacement of a part under the action of the ultrasonic burnishing force. Existing theoretical relationships for determining part displacement were analyzed, and it was established that the known calculation models do not accurately describe the actual deformation process. A refined relationship for determining part displacement based on the average burnishing force over the vibration period is proposed.

Experimental studies were carried out on specimens made of steel 45, bronze BrOF 6.5–0.15, and aluminum alloy D16T, which have different values of elastic modulus and rigidity. Burnishing was performed using a carbide spherical tool with ultrasonic vibrations. To measure part displacement, a special experimental setup equipped with a capacitive sensor and a dynamic displacement recording system was developed. Experimental values of part displacement were obtained and compared with theoretical calculations.

It was established that during ultrasonic burnishing with preliminary clearance, the magnitude of part displacement significantly depends on the rigidity of the workpiece material and the tool penetration depth. It was proven that, in order to ensure the required surface roughness and machining accuracy, the penetration depth should not exceed 7 μm, especially for parts made of materials with a low elastic modulus. The proposed ultrasonic burnishing method makes it possible to effectively process non-rigid parts while ensuring high surface layer quality parameters.

Keywords: *ultrasonic burnishing, surface plastic deformation, radial deformation, preliminary clearance, machining accuracy, surface layer, non-rigid parts, burnishing force, ultrasonic machining, elastic modulus, surface quality.*

Eq. 4. Fig. 1. Table. 1. Ref. 12.

1. Problem formulation

The modern development of mechanical engineering is characterized by increasing requirements for the accuracy, reliability, and durability of machine parts and mechanisms [1–3]. One of the key directions in improving manufacturing processes is ensuring high-quality parameters of the surface layer of parts, since the surface condition largely determines the operational characteristics of products, including wear resistance, fatigue strength, corrosion resistance, and fitting accuracy. At the same time, industry faces the task of reducing material consumption, saving raw materials, and improving production efficiency, which requires the implementation of new high-performance machining technologies [4, 5].

Traditional machining methods do not always ensure the required surface quality when manufacturing parts with complex geometry, thin-walled or non-rigid structural elements, as well as components made of difficult-to-machine materials. In addition, the use of modern materials with special physical and mechanical

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properties requires the development of new surface-forming methods that combine high productivity with the ability to create a favorable stress–strain state in the surface layer [6].

A promising approach to solving these problems is the application of surface plastic deformation methods, in particular ultrasonic burnishing [3–5]. The use of ultrasonic vibrations during machining makes it possible to significantly reduce surface roughness, increase the hardness and wear resistance of the surface layer, generate compressive residual stresses, and improve the operational characteristics of parts. Ultrasonic burnishing is especially effective in the machining of non-rigid parts, where conventional surface strengthening methods often fail to ensure process stability because of significant elastic deformations of the workpiece.

One of the important issues in ultrasonic burnishing is the radial displacement of the part under the action of the processing force, which leads to variations in the tool penetration depth into the surface and, consequently, to reduced machining accuracy and non-uniform roughness parameters. This effect is particularly pronounced when machining parts made of materials with a low elastic modulus. Therefore, investigating the deformation behavior of parts during ultrasonic burnishing and determining rational processing parameters that ensure the required surface layer quality are highly relevant tasks.

2. Analysis of recent research and publications

Recent scientific studies in the field of surface treatment of machine parts indicate a steady trend toward the development of ultrasonic surface plastic deformation technologies, particularly ultrasonic burnishing, as one of the most promising methods for improving surface layer quality [7, 8]. A considerable number of studies are devoted to investigating the physical and mechanical processes occurring in the contact zone between the tool and the machined surface, as well as modeling the influence of ultrasonic vibrations on the formation of surface microrelief and the stress–strain state of the surface layer.

Contemporary research demonstrates that the application of ultrasonic vibrations in machining and burnishing processes makes it possible to reduce processing forces, improve process stability, and significantly enhance surface quality [9]. In recent years, approaches to multiphysical modeling of ultrasonic machining processes have been actively developed, including consideration of tool oscillatory motion, contact dynamics, and the interaction of mechanical and wave effects within the material deformation zone [3, 4, 10].

A separate area of research is associated with the study of surface microtexturing and the formation of functional surfaces with specified tribological properties [10, 11]. It has been established that ultrasonic vibration promotes the formation of regular microdeformations, improves material distribution in the contact zone, and enables control over surface roughness and microgeometry parameters. At the same time, researchers note the complexity of predicting the final surface characteristics because of the nonlinear nature of the interaction between the tool and the material, as well as the presence of impulse loading conditions.

Considerable attention has also been paid to radial ultrasonic burnishing and roller strengthening processes, where the influence of vibration parameters, tool geometry, and machining conditions on microrelief formation has been investigated [5, 11]. Recent studies show that ultrasonic energy significantly affects the nature of plastic deformation in the surface layer, contributing to roughness reduction and the formation of compressive residual stresses, which positively influence the operational properties of parts.

At the same time, modern publications do not sufficiently address the issue of radial deformation of non-rigid parts during ultrasonic burnishing with preliminary clearance. In particular, the deformation behavior of parts depending on their rigidity, elastic modulus, and tool penetration depth requires further investigation. Existing models often fail to account for the real dynamic conditions of the process and the averaged character of force action over the period of ultrasonic vibrations, which leads to discrepancies between theoretical predictions and experimental results.

Thus, current research in this field is developing toward improving the physical and mathematical models of the ultrasonic burnishing process, increasing the accuracy of predicting surface quality parameters, and considering elastic deformations of non-rigid parts under real machining conditions. This determines the relevance of further experimental and theoretical studies in this area.

3. The purpose of the article

The aim of this study is to investigate the process of radial deformation of parts during ultrasonic burnishing with preliminary clearance, to analyze the influence of machining parameters on the magnitude of part displacement, and to determine the conditions required to ensure the necessary machining accuracy and surface roughness.

4. Results and discussion

The application of ultrasonic vibrations in material machining processes is one of the promising and advanced directions in the development of modern manufacturing technologies. The use of ultrasound makes it possible to significantly increase machining productivity as well as improve the operational characteristics of products, particularly the accuracy of geometric parameters and the stability of surface layer quality. An important effect is the formation of compressive residual stresses in the near-surface layers, which contributes to an increase in the fatigue strength of parts. In addition, a reduction in surface roughness and an increase in wear resistance are observed, which is especially important for parts operating under conditions of intensive friction.

Ultrasonic machining considerably expands the technological capabilities for processing difficult-to-machine materials such as high-strength steels, heat-resistant alloys, and composites. In a number of cases, this provides fundamentally new approaches to implementing technological operations that are difficult or impossible to perform using conventional methods. Thus, the scientific and technical level of manufacturing processes in modern mechanical engineering is significantly improved.

Special attention in burnishing process studies has been devoted to the influence of microdisplacements of the part under the action of force contact with the tool. Even slight displacement of the workpiece, on the order of several micrometers, in the proposed burnishing method [11, 12] leads to changes in the tool penetration depth into the surface layer. This, in turn, causes variations in the burnishing force and non-uniform formation of surface roughness along the generatrix of the part surface.

In this regard, a study of the displacement behavior of the part under the action of the burnishing force during machining was carried out. In [12], based on the differential equation of part motion under the action of an impulse radial force, a relationship describing part displacement was obtained, taking into account the elastic properties of the technological system, the mass of the part, and the parameters of impulse loading. This model makes it possible to analyze the dynamic response of the “tool–workpiece” system and to evaluate the influence of machining conditions on process stability and the quality of the formed surface.

In [12], based on the differential equation of the motion of a part subjected to an impulse radial force, the following relationship describing part displacement was obtained:

$$x = \frac{t_{\text{к}} N}{k_d T} + \sum_{n=1}^{\infty} \frac{\frac{N}{k_d} \cdot \frac{2}{\pi} sin\left(n \frac{t_{\text{к}}}{T} \pi\right)}{\sqrt{\left(1 - n^2 \frac{\omega^2}{\omega_{\text{д}}^2}\right)^2 + 4n^2 \nu^2 \frac{\omega^2}{\omega_d^2}}} sin(n\omega \cdot t + \phi_n) \tag{1}$$

where $\phi = arctg \frac{1 - n^2 \left(\frac{\omega^2}{\omega_d}\right)}{2n\nu\left(\frac{\omega}{\omega_d}\right)}$; where ($k_d$) is the stiffness of the part in the horizontal direction; (ω_d) is the angular frequency of part vibrations; ($v = c/c_0$), where (c) is the viscous damping coefficient and (c_0) is its critical value.

The same study also showed that at ($\omega/\omega_0 > 3$) (which is observed during ultrasonic burnishing), the displacement of the part under the action of impulse forces is characterized only by the static term of relationship (1), i.e.

$$x = \frac{t_k}{T} \frac{N}{k_{\text{д}}} \tag{2}$$

Substituting the values of (t_k) and (T), we obtain:

$$x = \frac{arccos \frac{\delta}{\zeta + arcsin \frac{h_{prp}}{\zeta}}}{2\pi} \frac{N}{k_d} \tag{3}$$

Experimental investigations of part displacement were carried out on specimens made of C 45 steel, aluminum alloy D16T, and bronze BrOF 6.5–0.15. The selection of these materials was обусловлена by the fact that they possess different elastic moduli and, consequently, parts made from these materials with identical dimensions exhibit different stiffness values. The specimen length was 100 mm and the diameter was 10 mm. During machining, the specimens were mounted between centers.

Burnishing was performed under the following conditions: vibration amplitude ξ= 15 µm, preliminary clearance δ varied from 0 to 15 µm, feed rate S = 0.02 mm/rev, and cutting speed V = 100 m/min. A carbide spherical tip made of VK15 hard alloy with a sphere radius R = 2 mm was used as the burnishing tool. During burnishing, the vibration amplitude and frequency, the tool–workpiece contact time, and the burnishing force averaged over the vibration period were measured according to the procedures described above. The horizontal stiffness of the parts was calculated using the relationship presented in [12]. For steel specimens, it was 4.95 mN/m; for duralumin specimens, 1.67 mN/m; and for bronze specimens, 2.59 mN/m.

For comparison of displacement values, conventional burnishing (without ultrasound) was additionally performed. In this case, the tool penetration depth was equal to that used during ultrasonic burnishing. The experiments showed that conventional burnishing of parts with such stiffness values is impossible because the displacement of the parts under the action of the radial force exceeds the tool penetration depth, causing the tool to slide over the surface without producing plastic deformation.

During the experiments, the maximum displacement of the parts was measured in the plane located at an equal distance from the specimen ends. The measurement of part displacement under the action of the radial burnishing force was carried out according to the procedure developed by the authors. The measurement scheme is shown in Fig. 1.

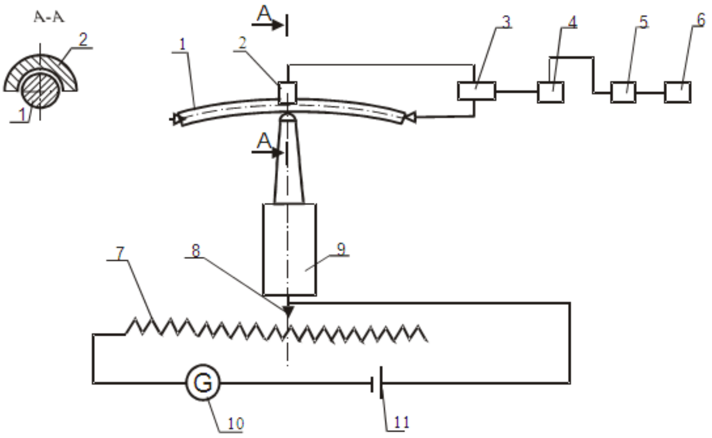

Fig. 1. Scheme for measuring part deflection:

1 – workpiece; 2 – sensor; 3 – E12-1 measuring device; 4 – S8-12 oscilloscope; 5 – amplitude rectifier; 6 – N115 strip-chart oscilloscope; 7 – position sensor; 8 – slider; 10 – galvanometer; 11 – DC power supply

The workpiece 1 is mounted between the machine centers. To eliminate radial runout, the workpiece is предварительно turned. A capacitive sensor 2 is positioned near the workpiece, and a specified capacitance between sensor 2 and workpiece 1 is set using the E12-1 measuring device 3. Sensor 2 is a semi-ring made of 12Kh18N10T steel mounted on a holder. Using a micrometric screw, the semi-ring can be displaced in the radial direction to set the required capacitance between the sensor and the workpiece. The sensor holder is electrically insulated from the machine-tool carriage and moves together with the tool during machining.

Under the action of the burnishing force, the workpiece bends and the distance between the sensor and the workpiece decreases, while the capacitance of the “workpiece 1 – sensor 2” system increases, which is recorded by device 3.

To record dynamic displacements, an S8-12 electronic oscilloscope 4 was connected to the output of measuring device 3. An amplitude rectifier 5 was connected in parallel to the oscilloscope input, and its output was connected to an N115 strip-chart oscilloscope 6, which recorded the part displacement on paper.

Calibration of the sensor was carried out as follows. Using a micrometric screw, sensor 2 was brought close to workpiece 1 and the capacitance was measured. Then sensor 2 was successively moved toward workpiece 1 in increments of 0.5 μm. At each change in the distance between the sensor and the workpiece, the change in capacitance of the “sensor–workpiece” system was recorded using devices 3, 4, and 6. The change in the distance between the tool and the workpiece was monitored using an M217 instrument. Calibration graphs were plotted based on the obtained measurement data.

To determine the location of part deformation along its length, a position sensor 7 was used (Fig. 1). A potentiometer of type SP3-23 served as the sensor. It was mounted on the machine-tool guideways, while the potentiometer slider 8 was rigidly connected to the lower carriage of the tool post. A DC power supply 11 was included in the electrical circuit, and the sensor was connected to galvanometer 10 of the strip-chart oscilloscope 6. When slider 8 moved together with the lower carriage of the tool post, the electrical resistance of the circuit changed and, consequently, the electric current varied. The oscillogram of carriage displacement represented a straight line inclined at a certain angle, while the carriage position corresponded to the ordinate of a point located on this line.

In addition to the above-described procedure, a strain-gauge center was also used to measure part displacement. During the experimental investigations, it was established that the calculated displacement values obtained using equation (3) and the experimental values differed significantly. In our opinion, this can be explained by the fact that the author of [3] assumed that the maximum force (N) acts on the part during the entire period of tool–workpiece contact, although according to equation (1), this is not the case.

Therefore, the values of part displacement were calculated and compared with experimental data using the following relationship:

$$x = \frac{P_c}{k_d}, \tag{4}$$

where (P_c) is the average burnishing force over the vibration period, determined experimentally or by calculation.

Table 1 presents the experimental (Exp.) and calculated (Calc.), according to equations (3) and (4), values of part displacement during ultrasonic burnishing with preliminary clearance.

As can be seen from Table 1, the displacement values calculated using equation (3) differ significantly from the experimental results. Therefore, for displacement calculations, the relationship proposed in this study (equation (4)) should be used.

Table 1.

Experimental and calculated values of part displacement during ultrasonic burnishing with preliminary clearance

Depth of penetration, μm	**Displacement, μm**								
	C 45 steel			**BrOF 6.5–1.5 tin-phosphor bronze**			**D16T aluminum alloy**		
	Calc.	**Calc.**	**Exp.**	**Calc.**	**Calc.**	**Exp.**	**Calc.**	**Calc.**	**Exp.**
1	0,09	0,01	0	0,24	0,04	0	1,1	0,8	1
3	0,5	0,07	0	1	0,22	0	3,4	1,8	2
5	1,1	0,22	0	2,3	0,58	0,7	6,2	2,9	3
7	2	0,5	0,5	3,9	1	1	9,5	3,9	3,5
9	3,2	0,85	1	6	1,72	2	13,4	5,16	5,5
11	4,8	1,4	1,7	8,4	2,65	3	17,4	6,35	6,5
13	6,6	2	2	11,3	3,65	3,5	22	7,65	8
15	8,7	2,9	2,5	14,6	4,9	5,5	27,1	8,9	8,5

5. Conclusion

Based on the conducted experimental and theoretical investigations, it has been established that the proposed ultrasonic burnishing method is effective for machining non-rigid parts made of materials with different physical and mechanical properties. Its application ensures stable formation of a high-quality surface layer due to the combination of ultrasonic vibrations and a controlled surface plastic deformation process, which enables a reduction in surface roughness and an improvement in machining accuracy.

It has been found that the key parameter determining process stability and the final surface characteristics is the tool penetration depth. Exceeding the critical value leads to an increase in radial displacement of the workpiece, which is especially pronounced for materials with a low elastic modulus and, consequently, results in deterioration of the geometric accuracy of the machined surface.

It has been established that, to ensure the required surface roughness and machining accuracy, a rational limitation of the tool penetration depth is no more than 7 μm. Adhering to this technological parameter makes it possible to minimize elastic deformations of the “tool–workpiece” system, stabilize the burnishing force, and ensure reproducibility of machining results.

Thus, the developed ultrasonic burnishing method can be recommended for practical use in mechanical engineering production when machining non-rigid parts, as it ensures improved surface layer quality under rational selection of process parameters.

Future research directions are related to the improvement of physical and mathematical models of the ultrasonic burnishing process, taking into account the nonlinear elastoplastic behavior of materials and the dynamic interaction between the tool and the workpiece surface. It is also advisable to expand experimental studies to a wider range of materials, including composite materials and high-strength alloys, as well as to investigate the influence of frequency and amplitude parameters of ultrasonic vibrations on process stability. Special attention should be given to optimizing tool design and developing active control systems for penetration depth to compensate for elastic deformations of non-rigid parts in real time.

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ДОСЛІДЖЕННЯ РАДІАЛЬНОЇ ДЕФОРМАЦІЇ НЕЖОРСТКИХ ДЕТАЛЕЙ ПРИ УЛЬТРАЗВУКОВОМУ ВИГЛАДЖУВАННІ З ПОПЕРЕДНІМ ЗАЗОРОМ

У статті розглянуто процес ультразвукового вигладжування нежорстких деталей із попереднім зазором та досліджено вплив параметрів обробки на якість поверхневого шару. Актуальність роботи обумовлена необхідністю підвищення точності, зносостійкості та довговічності деталей машин при одночасному зниженні металоємності та трудомісткості виробництва. Показано, що традиційні методи механічної обробки є малоефективними при виготовленні деталей складної форми та деталей із важкооброблюваних матеріалів, тому перспективним напрямком є застосування ультразвукових методів поверхневого пластичного деформування.

У роботі досліджено процес радіального відтискування деталі під дією сили ультразвукового вигладжування. Проведено аналіз існуючих теоретичних залежностей для визначення переміщення деталі та встановлено, що відомі розрахункові моделі недостатньо точно описують реальний процес *деформації. Запропоновано уточнену залежність для визначення відтискування деталі на основі середньої сили вигладжування за період коливань.*

Експериментальні дослідження виконано на зразках зі сталі 45, бронзи БрОФ 6,5–0,15 та алюмінієвого сплаву Д16Т, які мають різні значення модуля пружності та жорсткості. Вигладжування проводили твердосплавним сферичним інструментом із використанням ультразвукових коливань. Для вимірювання переміщення деталі розроблено спеціальну експериментальну установку з ємнісним датчиком та системою реєстрації динамічних переміщень. Отримано експериментальні значення відтискування деталі та проведено їх порівняння з теоретичними розрахунками.

Встановлено, що при ультразвуковому вигладжуванні з попереднім зазором величина відтискування суттєво залежить від жорсткості матеріалу деталі та глибини впровадження інструмента. Доведено, що для забезпечення необхідної шорсткості поверхні та точності обробки глибина впровадження не повинна перевищувати 7 мкм, особливо для деталей із матеріалів із низьким модулем пружності. Запропонований спосіб ультразвукового вигладжування дозволяє ефективно обробляти нежорсткі деталі та забезпечувати високі параметри якості поверхневого шару.

Ключові слова: *ультразвукове вигладжування, поверхневе пластичне деформування, радіальна деформація, попередній зазор, точність обробки, поверхневий шар, нежорсткі деталі, сила вигладжування, ультразвукова обробка, модуль пружності, якість поверхні.*

Ф. 4. Рис. 1. Табл. 1. Літ. 12.

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