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Original article

Surface Quality Forming under Parts Finishing and Strengthening Treatment with an Eccentric Hardener

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Abstract

Introduction. The formation of the quality parameters of the surface layer and the operational properties of the parts occurs throughout all stages of their manufacture. However, the decisive impact is most often exerted by the stages of finishing. Therefore, in modern digital engineering, the task of process support of high quality of the surface layer of the part is one of the challenges in solving the problem of improving the quality and reliability and increasing the life cycle of manufactured machines. Surface plastic deformation treatment is instrumental in improving the performance characteristics of machine parts. Its essence is that the required quality parameters of parts are obtained not by removing a layer of material, but by plastic deformation. During the processing, both the dimensions of the parts and the physical and mechanical properties of the surface layers are changed. In this case, the technologist has the opportunity to significantly increase the life cycle of the manufactured products through controlling the process. These studies are aimed at providing the required quality parameters of the surface layer under processing with an eccentric hardener.

Materials and Methods. The article presents the results of research on a new method of surface plastic deformation treatment — with an oscillating eccentric hardener. The considered processing method enables to obtain high quality of the treated surface, to process large-sized parts in places that are stress concentrators, to process welds, small areas of surfaces, whose hardening is needed for the part to fulfill its intended service. A set of theoretical studies was carried out; their results provided determining the parameters of a single interaction of the indenter and the surface of the part, the diameter of the plastic imprint and its depth.

Results. Dependences for determining the surface roughness, the depth of the hardened layer and the degree of deformation were obtained. The resulting formulas were tested for adequacy by experimental studies.

Discussion and Conclusion. The obtained research results can be used in the technological design of surface plastic deformation treatment processes. Further tasks for the study of the considered processing method are determined.

Keywords: oscillating tool, eccentric hardener, surface roughness, hardened layer depth, degree of deformation

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Научная статья

Формирование качества поверхностного слоя при отделочно-упрочняющей обработке деталей эксцентриковым упрочнителем

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Аннотация
Введение. Формирование параметров качества поверхностного слоя и эксплуатационных свойств деталей происходит на протяжении всех этапов их изготовления. Однако решающее влияние чаще всего оказывают этапы финишной обработки. Поэтому в современном цифровом машиностроении задача технологического обеспечения высокого качества поверхностного слоя детали является одной из важнейших при решении проблемы повышения качества, надежности и увеличения жизненного цикла производимых машин. Ведущую роль в повышении эксплуатационных характеристик деталей машин играет обработка поверхностным пластическим деформированием, сущность которой заключается в том, что требуемые параметры качества деталей достигаются не удалением слоя материала, а его пластическим деформированием. В процессе обработки производится изменение как размеров деталей, так и физико-механических характеристик поверхностных слоев, управляя которыми технолог имеет возможность значительно увеличивать жизненный цикл производимой продукции. Целью настоящих исследований является обеспечение необходимых параметров качества поверхностного слоя при обработке эксцентриковым упрочнителем.

Материалы и методы. В статье представлены результаты исследований нового метода обработки поверхностным пластическим деформированием — осциллирующим эксцентриковым упрочнителем. Рассматриваемый метод обработки позволяет получать высокое качество обработанной поверхности, осуществлять обработку крупногабаритных деталей в местах, являющихся концентраторами напряжений, обрабатывать сварные швы, небольшие участки поверхностей, упрочнение которых необходимо для выполнения деталью своего служебного назначения. Выполнен комплекс теоретических исследований, по результатам которых определены параметры единичного взаимодействия индентора с поверхностью детали, диаметр пластического отпечатка и его глубина.

Результаты исследования. Получены зависимости для определения шероховатости поверхности, глубины упрочненного слоя и степени деформации. Полученные формулы прошли проверку адекватности экспериментальными исследованиями.

Обсуждение и заключение. Полученные результаты исследований могут быть использованы при технологическом проектировании процессов обработки поверхностным пластическим деформированием. Определены дальнейшие задачи по исследованию рассматриваемого метода обработки.

Ключевые слова: осциллирующий инструмент, эксцентриковый упрочнитель, шероховатость поверхности, глубина упрочненного слоя, степень деформации

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Introduction. The reliability and durability of machine parts largely depend on the quality of their surface layer. From numerous works on mechanical engineering technology, it is known that the formation of the quality parameters of the surface layer occurs at all stages of their manufacture. However, the dramatic impact is most often exerted by the stages of finishing. Therefore, in modern digital engineering, increased attention is paid to the production design of highly efficient finishing operations of parts, which enables to respond to a challenge of increasing their life cycle. Surface plastic deformation (SPD) treatment is critical in improving the performance of machine parts carried out under finishing operations. In contrast to traditional cutting methods, the quality parameters of the surface layer in SPD are obtained through performing plastic deformation with special tools or working media. In the course of processing, simultaneously with the change in the size of the processed parts, the physical and mechanical properties of the surface layers are changed. In this case, the technologist has the opportunity to significantly increase the life cycle of the manufactured products through controlling the process.

It should be noted that the widespread use of many SPD methods in industry is hindered by poor knowledge of their basic laws, difficulties arising in the process of designing optimal combinations of processing modes, and design parameters of the tooling. On numerous occasions, treatment modes are assigned on the assumption of the results of private experimental studies, which provides low processing efficiency [1–6].

The objective of these studies is to provide the required quality parameters of the surface layer during processing with an eccentric hardener.

Materials and Methods. The need for applying SPD under the conditions of modern machine-building industries results in the creation of new processing methods. One of such methods is the processing of SPD with an oscillating tool — with an eccentric hardener.

Figure 1 shows a kinematic diagram of an eccentric hardener consisting of vibrating body 1 suspended on flat springs 2. Vibrations of vibrating body 1, acting normally to the treated surface, are excited by the rotation of eccentric mass (unbalance) 3 around the vertical axis. The rotation axis of the eccentric mass is restricted from moving relative to vibrating housing 1. The rotational motion is transmitted to the eccentric from electric motor 5 through flexible shaft 6. Tool head 4 with an instrument of the appropriate geometric form is attached to housing 1. The motion of tool 4 is limited by limiter 7 (a workpiece). In this case, the tool is an indenter with a spherical sharpening. It can be made in the form of a roller or a ball. The vibration system in the eccentric hardeners can be represented as a single-mass system with two degrees of freedom, which is under the action of a force varying according to the harmonic law. To study the system dynamics, we consider the features of its free oscillation under the action of centrifugal vibration excitation and the nature of the movement of the system hitting the limiter (a part).

Under free oscillation, the vibrating system fixed at the end of flat springs 2 (Fig. 1) performs harmonic oscillations, which are excited by the rotation of eccentric 3 with a constant angular velocity.

The proposed device can be effective when processing formed parts of not the most complex profile, and in some cases — when processing simple surfaces, such as planes or bodies of rotation.

First, it is required to check the possibility of providing a wide range of the energy of the impact of the tool head on the surface of the workpiece in combination with relatively low altitude characteristics of surface roughness.

Due to the lower rigidity of a flat spring (in our case, two springs) in the X direction, in comparison to the stiffness in the Y direction, the system describes a trajectory close to an ellipse with a larger semi-axis in the X direction. To analyze the law of motion of the system, we decompose the trajectories along the X and Y axes.

The equation of motion of the center of gravity is nothing more than a mathematical expression of Newton's second law.

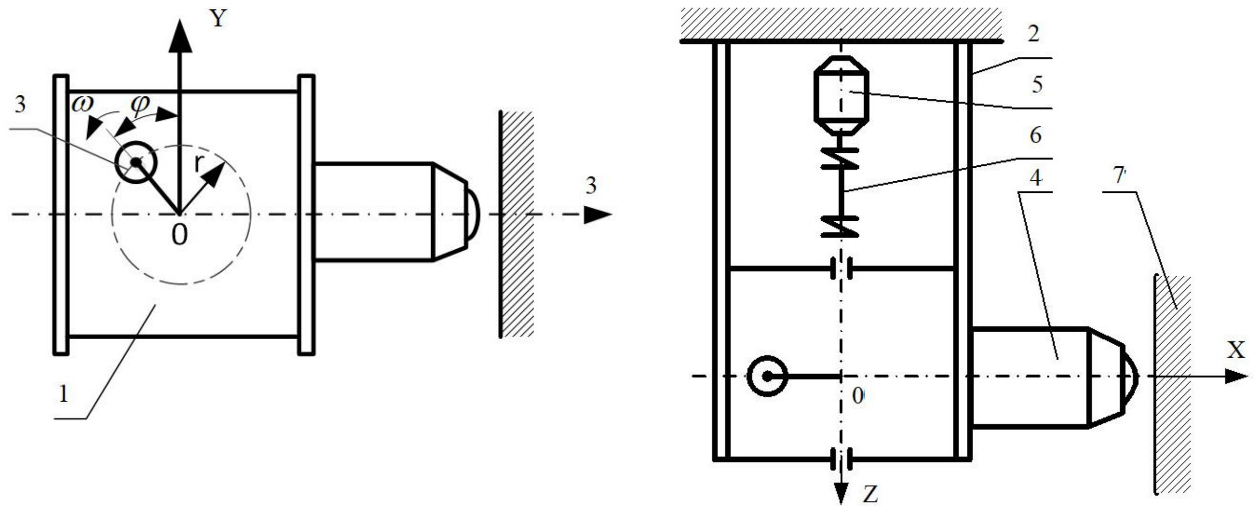


Fig. 1. Scheme of eccentric hardener: 1 — housing; 2 — flat spring; 3 — eccentric mass; 4 — tool head; 5 — electric motor; 6 — flexible shaft; 7 — limiter (workpiece)

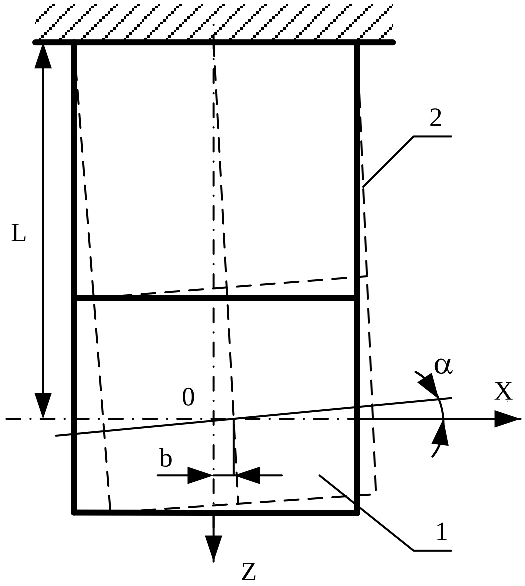


Fig. 2. Rotations of the housing of the hardener during vibrations

Research Results. To establish the main regularities of the process variables effect on the interaction of the oscillating indenter and the treated surface, it is necessary to take into account the kinetic energy of the indenter, the number of indenters, the radius of the indenter, the efficiency of the device, physical and mechanical properties of the workpiece [1–6].

Taking into account all the forces acting on the moving indenter, it is possible to write the equation of motion of the tool head in the Y direction:

$$m_c \frac{d^2 y}{dt^2} = -c_1 y - \mu \frac{dy}{dt} + m_{cam} r \omega^2 \cos \omega t - m_c g, \qquad (1)$$

in the X direction:

$$m_c \frac{d^2 x}{dt^2} = -cx - \mu \frac{dx}{dt} + m_{cam} r \omega^2 \sin \omega t, \qquad (2)$$

where $m_c \frac{d^2 y}{dt^2}$, $m_c \frac{d^2 x}{dt^2}$ — projections of the inertia forces of the system on Y and X axes, respectively; c_1, y, cx — projections of spring resistance forces on Y and X axes; $\mu \frac{dx}{dt}$, $\mu \frac{dy}{dt}$ — projections of the resistance forces of the medium on Y and X axes;; $m_{cam} r \omega^2 \cos \omega t, m_{cam} r \omega^2 \sin \omega t$ — projections of the perturbing force on Y and X axes; $m_c g$ — gravity (weight) of the vibrating system; m_c — mass of the vibrating system; c_1, c — spring stiffness in the Y and X direction; μ — resistance of the medium; m_{cam} — mass of the eccentric; r— distance from the axis of rotation of the eccentric to its center of gravity; ω — angular velocity; t — current time value; y, x — current coordinate value.

Due to the significantly greater stiffness of the springs in the Y direction relative to the stiffness in the X direction, the amplitude of the indenter movement in the Y direction is noticeably less than the amplitude in the X direction. Therefore, we assume that the system performs harmonic oscillations only in the X direction, i.e., we consider an indenter with only one degree of freedom.

If we neglect the damped oscillation, then the equation of motion will have the form:

$$x = b \sin(\omega t + \beta), \qquad (3)$$

where b — amplitude of the oscillations; β — phase difference between the exciting force and the movements of the center of gravity of the indenter.

Substituting this expression into equation (2), we find:

$$b = \frac{m_{cam} r \omega^2}{\sqrt{(c - \omega^2 m_c)^2 + \omega^2 \mu^2}}, \qquad (4)$$

$$tg\beta = \frac{\omega\mu}{c - \omega^2 m_c}. \quad (5)$$

Value μ is determined from the expressions:

$$\mu = \frac{\omega_1 m_c \delta}{2\pi}, \quad (6)$$

where ω_1 — frequency of natural oscillations; δ – logarithmic decrement of attenuation.

After differentiating equation (4) in time and examining the function at the extremum, we obtain an expression for determining the maximum speed of the indenter:

$$V_X = \frac{m_{cam} r \omega^3}{\sqrt{(c-\omega^2 m_c)^2 + \omega^2\mu^2}}. \quad (7)$$

The largest kinetic energy of the indenter is determined from the equation:

$$T = \frac{m_c V_X^2}{2} = \frac{m_c m_{cam}^2 r^2 \omega^6}{2[(c-\omega^2 m_c)^2 + \omega^2\mu^2]}. \quad (8)$$

The analysis of the interaction of spherical indenters and a deformable half-space (the surface layer of the workpiece) is described in the classical works of I. V. Kudryavtsev [1, 2, 4, 5]. The diameter of the plastic print can be determined from the dependence

$$d = \sqrt[4]{\frac{D_i \cdot T \cdot \eta}{M \cdot HD}}. \quad (9)$$

In this case, the depth of the plastic print can be defined as:

$$h = \frac{1}{4}\sqrt{\frac{T \cdot \eta}{M \cdot D_i \cdot HD}}, \quad (10)$$

where T — kinetic energy of the tool head; HD — dynamic hardness of the part material (ratio of the impact energy of the spherical indenter to the volume of the displaced material upon impact); D_i — diameter of the indenter; η — efficiency of the device; M — number of indenters.

When processing with an eccentric hardener, the roughness parameters of the treated surface can receive a constant (steady-state) value, which is reproduced during further processing of the surface of the part. The relief of the resulting surface can be both isotropic and anisotropic and is formed by repeatedly superimposing traces of a single interaction.

When the oscillating indenter interacts with the initial protrusions of the microasperity, its height decreases with a simultaneous decrease in the depth of the cavities of the microasperity. With increasing processing time, the initial surface roughness profile is completely reshaped. As a result, a new microrelief is formed, and it has a specific character for each SPD method [7–19].

The finally formed roughness of the treated surface is called "established". As a rule, its altitude parameters do not depend on the initial one. They are formed under the specific conditions of each processing method and depend on its process variables. Based on the methodology of papers [3, 4], a dependence was obtained for determining the steady-state surface roughness during treatment with an eccentric hardener:

$$Ra = 0.0075\sqrt{\frac{T \cdot \eta}{D_i \cdot M \cdot HD}}. \quad (11)$$

The parameters of the surface layer hardening, which include the depth of the hardened layer and the degree of deformation, have a major impact on increasing the life cycle of the machined parts. As a result of theoretical studies, analytical dependences were obtained for their calculation during processing with an eccentric hardener:

$$h_n = \sqrt[8]{\frac{\left(\dfrac{T \cdot \eta}{D_i \cdot M \cdot HD}\right)^3}{D_i}}, \quad (12)$$

$$\varepsilon = 1.13\sqrt[4]{\frac{T \cdot \eta}{D_i^3 \cdot M \cdot HD}}. \quad (13)$$

The above dependences correspond to the physical meaning of the phenomena occurring under processing, and have been verified during complex experimental studies.

In the course of the experimental studies, samples from various materials often utilized for the manufacture of machine parts were used: high-quality and alloy steels (steel 45, HVG, steel 30, steel 30HGSA, etc.), aluminum alloys (AL1, AVT, D16, etc.). Flat samples were treated with an eccentric hardener under different modes. Ball and roller indenters were used.

According to the theoretical dependences, graphs of the dependences of the roughness of the treated surface, the depth of the hardened layer and the degree of deformation on the processing modes, characteristics of working media and processed materials were constructed.

In the graphs (Fig. 3–6), a solid line shows curves constructed according to theoretical formulas, and the dots show the results of experimental studies. The construction of confidence intervals with a confidence factor of 95% has been performed.

There is high convergence of the results, which indicates that the theoretical dependence reflects correctly the phenomena occurring during the processing of SPD with an oscillating tool — an eccentric hardener.

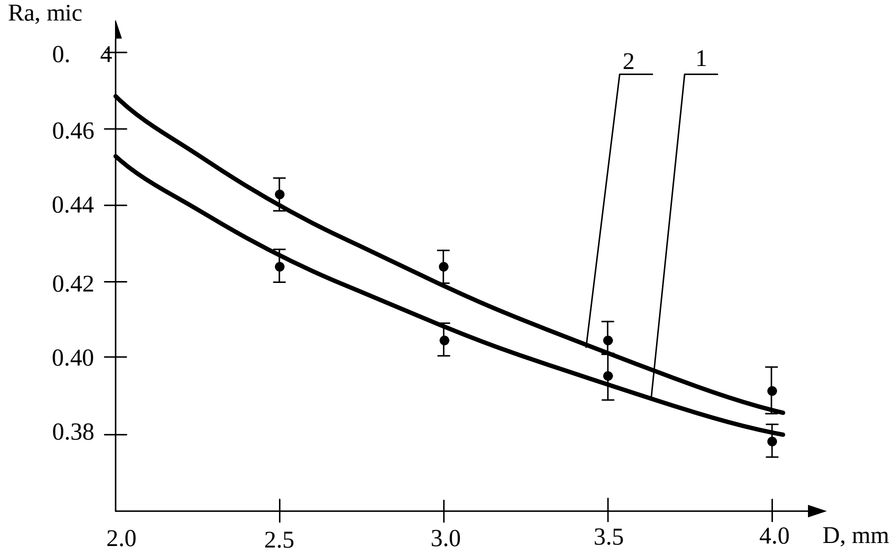


Fig. 3. Dependence of the surface roughness on the radius of the indenter:
1 — steel 45 sample material; 2 — HVG sample material

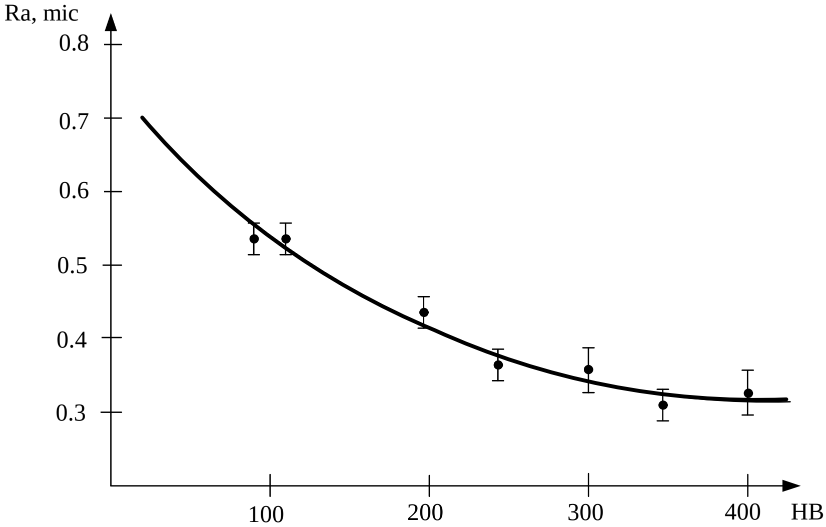
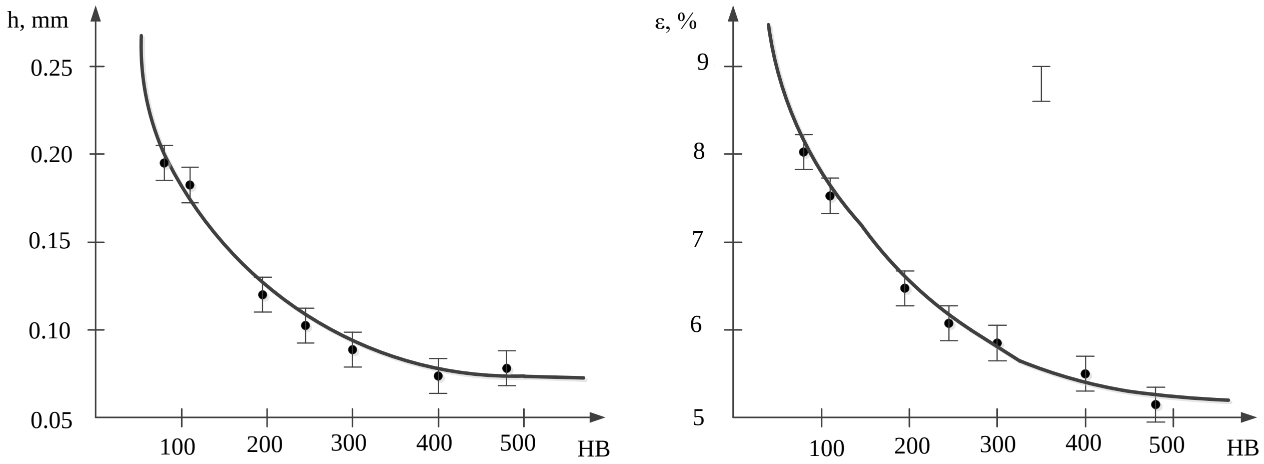
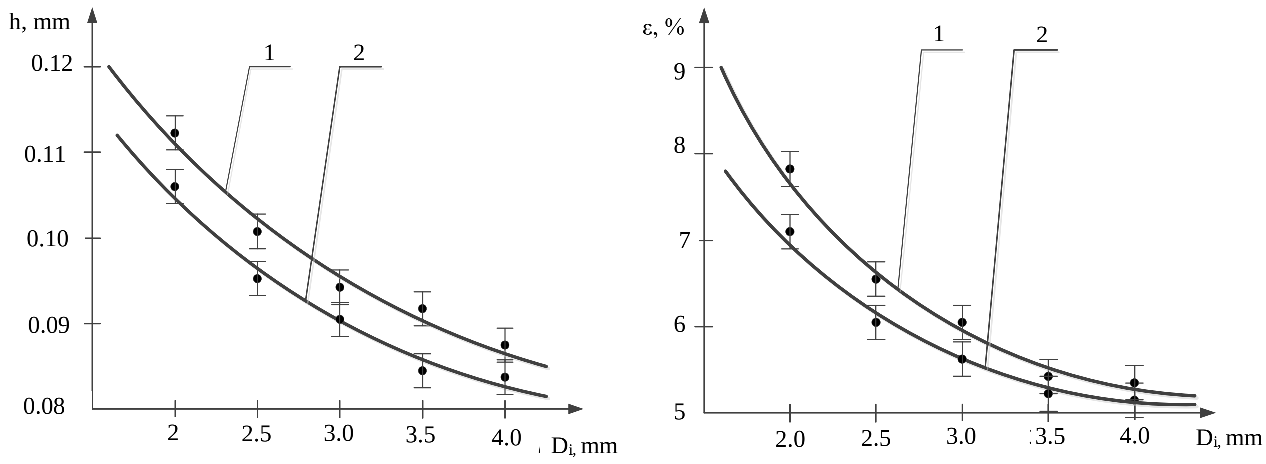


Fig. 4. Dependence of the surface roughness on the Brinell hardness of the part



a) *b)*

Fig. 5. Dependence of hardening parameters on Brinell hardness for various materials: *a* — on the depth of the hardened layer; *b* — on the degree of deformation



a) *b)*

Fig. 6. Dependence of hardening parameters on diameter of the indenter: *a* — depth of the hardened layer; *b* — degree of deformation. 1 — steel 45 sample material; 2 — HVG steel sample material

Discussion and Conclusion. Based on the results of the conducted research, the following conclusions can be drawn:

1. A theoretical dependence has been obtained that provides determining the kinetic energy of the indenter under processing with an oscillating tool — an eccentric hardener.

2. Dependences have been obtained for determining the diameter and depth of the plastic print, as well as the surface roughness according to parameter Ra, the depth of the hardened layer and the degree of deformation that provide predicting the quality of the treated surface.

3. The results of theoretical and experimental studies of the treatment process with an eccentric hardener were compared. The discrepancy in the results did not exceed 15%.

4. The process under study is subject to further investigation in order to determine other parameters of the quality of the treated surface, e.g., the magnitude of residual stresses in the surface layer, and [5, 6, 20] also to expand the range of treatment modes and design parameters in order to determine their optimal range.

5. The dependences obtained for determining the key parameters of the surface layer quality make it possible to predict the results of processing and can be used to design processes with an eccentric hardener.

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