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INVESTIGATION OF THE PROCESS OF SMOOTHING WITH ULTRASOUND

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Досліджено та змодельовано процес поверхневого пластичного деформування з ультразвуком. Проведено аналіз контактної взаємодії інструмента з деталлю в процесі ультразвукового вигладування з попереднім зазорм. Аналіз дає можливість розраховувати зміну розмірів деталі в процесі обробки в залежності від режимів. Розроблені залежності площі контакту при ультразвуковому вигладжуванні з попереднім зазором від параметрів обробки. Проведено експериментальне дослідження впливу параметрів процесу ультразвукового вигладжування на параметри якості поверхневого шару деталі. Встановлено, що для забезпечення необхідної шорсткості і точності глибина впровадження не повинна перевищувати 7 мкм, особливо при обробці деталей які виготовлені із матеріалів з низьким модулем пружності.

Для проведення досліджень розроблено стенд на базі токарно-гвинторізного верстата особливо високої точності 16Б05АФ10. Всі додаткові пристрої та інструмент кріпляться в різцетримачі верстата.

Розроблено методику вимірювання часу контакту інструмента з виробом при ультразвуковому вигладжуванні з попереднім зазором.

Встановлено, що деформація мікронерівностей проходить за рахунок вдавлювання виступів мікронерівностей у западини, так як зсувну деформацію виключили за рахунок застосування твердого мастила. Про те, що зсувна деформація відсутня, говорить і той факт, що на мікрошліфах обробленої поверхні не вдалося виявити текстури, хоча зміцнення поверхні спостерігалось. Базуючись на цьому висновку, можливо не враховувати позаконтактну хвилю деформації.

Отримані аналітичні залежності площі контакту при ультразвуковому вигладжуванні з попереднім зазором від параметрів обробки, а саме:швидкості обробки, подачі, радіуса робочої поверхні інструменту. Результати математичного моделювання і експериментальні дані достатньо близькі. Визначена область оптимальних подач, що дає можливість отримувати поверхні з мінімальною шорсткістю або з мікрорельєфом

Ключові слова: поверхневе пластичне деформування, ультразвукове вигладжування, деталь, глибина, подача, швидкість обробки

1. Introduction

Production efficiency improvement and creation of competitive products under conditions of market economy are inseparably linked to the development of fundamentally new technologies based on non-traditional approaches to organization of work processes of formation and strengthening.

Durability of a large number of parts directly relates to the wear of working surfaces. An increase in microhardness and a smooth, rounded shape of micro-irregularities affect an increase in wear resistance. Surface plastic deformation contributes to creation of favorable conditions for an increase in the wear resistance of a surface. Surface plastic deformation provides an increase in wear resistance, fatigue resistance, contact resistance and other operational properties of parts, being machined, by 20–50 % [1].

At the same time, significant deforming efforts, which limit application of hard and thin-sided parts for a treatment due to emerging of geometric errors, are characteristic for traditional methods of strengthening technology, such as rolling, flaring and even smoothing. Introduction of ultrasonic oscillation into a zone of treatment reduces resistance of plastic deformation and frictional forces on contact surfaces, which leads to a significant reduction in static deforming efforts ultimately.

The above features of the process led to the emergence of a new direction of surface plastic deformation – hardening treatment with a tool that fluctuates with ultrasonic frequency (ultrasonic machining) [2–4]. Ultrasonic machining provides obtaining of specified properties of a surface layer – partially or completely regular microrelief, creation of residual compression stresses in a surface layer of treated surfaces [2, 5, 6]. The technological method of treatment and modes determine effectiveness of ultrasonic machining mainly [5]. Thus, the subject is interesting and relevant. Conduction of a study in such direction has a great application value in connection with possibility of saving of energy and improvement of operational and technical properties.

2. Literature review and problem statement

The problem of increasing of operational reliability of machines is becoming more important in connection with an increase in mechanical, thermal and other types of influence on parts [6].

A surface layer of a part undergoes a significant physical and mechanical impact: mechanical, thermal, magnetic, chemical, and others under conditions of operation.

In most cases, operational properties of a surface of parts deteriorate, for example, wear, corrosion, fatigue cracks and other elements of surface destruction. Therefore, the requirements, which relate to a surface layer of a part, are stricter [1].

There is a large number of methods of surface hardening developed based on either application of coatings or a change of a state (modification) of a surface for parts, destruction of which begins with a surface.

At application of a coating, we achieve strengthening of a part by precipitation of materials that differ in their properties from a base metal but meet the conditions of operation on a surface most fully.

At modification of a surface layer, physical and chemical changes in metal undergo a change in its resistance to destruction. We can realize modification by deformation strengthening (surface plastic deformation), surface heat treatment, diffusion metallization. There is no universal method for strengthening of parts since the same method in some cases of operation can give a positive effect as well as a negative one.

Surface plastic deformation (SPD) is a treatment of parts by pressure (without removal of chips), where only a surface layer deforms plastically. A tool carries out SPD. Deforming elements (DE) of a tool: balls, rollers, or bodies of another configuration) interact with a treated surface. As a result, there is a significant reduction in roughness and strengthening of a surface layer [2–4].

Studies from the sources given above consider mainly identification of general and partial patterns of SPD with a large variety of means for implementation of such type of treatment.

There are two conventional groups among different ways of SPD implementation: static and dynamic or shock. In static methods, a tool acts on a surface to be treated with a certain constant effort. They include various ways of smoothing and rolling, as well as burnishing.

In dynamic ways, a deformation effort varies from zero or some other definite value to the maximum. In this case, a contact between a part and a deforming element can be constant or periodic.

Dynamic ways include various methods of chasing treatment by fraction, oscillation treatment, etc. [7].

Each of SPD methods finds its application under production conditions, but they all have both advantages and a number of shortcomings.

Static SPD methods became most widespread due to relative simplicity of implementation and stability of a treatment process [6].

Strengthening rolling with a roll is for a treatment of external cylindrical surfaces, ends and edges of holes, flat and shaped surfaces.

The method of rolling with a roll increases fatigue strength and durability. Ability to get a surface with a low roughness. The residual stresses extend to a great depth. A limit of endurance rises by more than 4 times in corrosive environment.

When a ball rolling method is applied, there is a self-placing of a ball during a treatment, which ensures a less rough surface at low pressure of a ball. We can also note the following advantages: simplicity of construction and versatility of a roller, a fatigue strength can be increased by 30–60 %, and a peening depth does not exceed 5 mm for soft materials. The disadvantages of the method are:

– the absolute value of residual stresses is small;

– treatment proceeds at small feed (0.06–0.47 mm/rev), which increases a treatment time;

– quality of the treatment depends on the properties of a material being treated, a state of an original surface, and rolling modes.

Smoothing is one of the simplest ways of surface plastic deformation. Its characteristics are high performance and tool stability [7]. Smoothing makes it possible to achieve roughness R_a=0.32–0.10 µm, the microhardness increases during the treatment, and compressive residual stresses emerge in a surface layer.

The advantage of diamond smoothing prior to other treatment methods, such as turning operation or fine grinding, is that the process is more productive and simple enough. A surface layer is free of abrasive inclusions at smoothing of parts, which improves the performance of parts. A change in physical and mechanical properties of a treated surface influences operational characteristics especially – an increase in hardness and wear resistance. The most effective is to use smoothing of not less than grade 10 to achieve surface roughness.

But the process of diamond smoothing has its disadvantages. Because the improvement of the surface quality (roughness) does not increase accuracy of parts to the same extent, but only within a material deformed [8]. The presence of edge effects also reduces the accuracy of a treatment significantly. And this is due to the presence of the force of tool pressing. The phenomenon is especially noticeable at a treatment of soft materials: aluminum alloys, brass, and others. Therefore, the diamond smoothing method is not recommended for a treatment of aluminum alloys.

In addition, the presence of the pressing force is a cause of a tool wear, which results in loss of accuracy, as well as distortion of a geometric form of non-rigid parts, which makes the method unacceptable for a treatment of such class of parts.

The most effective method of surface plastic deformation is the process of the strengthening finishing treatment with ultrasound [2, 9, 10]. The principle of the treatment is that ultrasonic oscillations affect a deforming element (indenter). The tool performs oscillations with a certain amplitude in the direction of introduction into a treated surface. The tool is a ball (usually made of steel 2S 135) or a spherical indenter.

Paper [5] proposes to apply SPD with the application of a regular microrelief. The experimental industrial inspection investigated effects of parameters and processing modes on tightness of coupling, workability and durability of contacting surfaces. This made possible to improve operational properties of «plunger-body» friction pairs.

Work [9] presents studies aimed at elaboration of samples of technical titanium and wear after a treatment by different methods of SPD. As a result of the studies, authors found that the wear of operation is 2 times less on surfaces treated with SPD. Thus, we can assume that an increase in wear resistance of titanium alloys increases as a result of optimization of geometric and physical parameters of treated surfaces.

It is possible to increase durability and endurance of products by creation of optimum fields of residual stresses in bodies of parts [10]. One of such methods is a thermoplastic strengthening method. There are two stages for the solution of the task of creation of fields of final stresses: first, we should determine a temperature field, and then we should calculate residual stresses and plastic deformations.

The use of combined treatment with different methods of SPD, as well as a treatment by SPD methods in combination with other methods of strengthening increase operation efficiency of parts [11].

For example, a surface treatment by means of SPD methods for a chromium coating provides the highest quality and durability of a chromium coating. We can strengthen cylindrical surfaces of friction of parts of titanium by a combined method. Initially, electro spark microalloying, saturation and coating of a surface with super-hard materials, and then rigid rolling. Rolling provides the required precision and roughness of a surface, it also reduces a harmful effect of microalloying on fatigue resistance.

Works [1, 3, 6] describe the interaction of a tool with a surface treated with a smoothing and oscillation smoothing sufficiently. Papers [7, 12] present the interaction of a tool with a part in the process of ultrasonic diamond smoothening. They show that a use of ultrasonic oscillations during diamond smoothing reduces the static strength of smoothing and improves the surface quality.

Work [13] proposes the smoothing process carried out with the continuous interaction of a tool with a treated surface. At the same time, authors of a work [7] established that the impulse mode of deformation is most effective for processes of plastic deformation with superposition of ultrasonic oscillations. At this mode, an operation surface of a tool is separated from a surface of a part periodically. In this case, it is possible to reduce the static force of deformation to 90 % [14]. In addition, paper [15] shows that this mode contributes to increase in in «fictitious» hardness of a part. However, in most cases, this mode is not implemented in practice, because elastic deformations of a surface to be treated exceed an amplitude of tool's oscillations.

3. The aim and objectives of the study

The objective of the study is to substantiate technological parameters of smoothing, which provide the optimum quality of a surface of parts to be treated. This will make possible to make recommendations on the main parameters of the technological process based on the study of process mechanics.

To accomplish the aim, the following tasks have been set:

– to investigate the essence of contact phenomena of ultrasonic smoothing with a preceding gap by analytical research;

– to establish relationship between individual factors, which act in the process of ultrasonic smoothing, in the form of formulas that make possible to carry out analytical calculations of treatment modes.

4. Materials and methods of the study

A base of the description of surface plastic deformation with ultrasound is a use of rheological models of materials that reflect their real elastic plastic properties. Such approach can reveal a mechanism of ultrasonic influence on the process of plastic deformation.

We used the following materials in the study of the process of surface plastic deformation with ultrasound: steel 10 (100 HB), 45 (150 HB, 50 HRC), 2S 135 (210 HB, 55 HRC), aluminum alloys D16T (120 HB), B95 (190 HB). We performed the smoothing with a tool with a tip of a hard alloy VK15 with a radius of a sphere of 1, 2, 4 and 6 mm.

5. Contact interaction between a tool and a part in the process of ultrasonic smoothing with a preceding gap

We propose the method of ultrasonic smoothing for realization of the mode of impulse deformation, and consequently, for obtaining benefits of such a mode [10, 11, 16, 17]. Its essence is the fact that there is a preceding gap δ established between part 2 and tool 1 (Fig. 1). Tool 1 in the form of a spherical tip attached to the magnetostrictive converter concentrator provides motion of feed and oscillatory motion with f frequency and ξ amplitude along a normal to the surface to be treated.

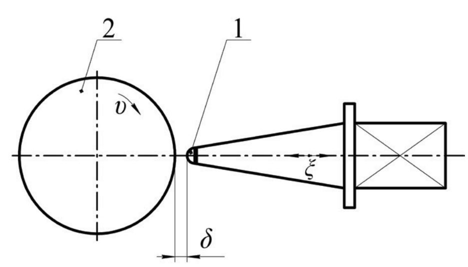

Fig. 1. Scheme of ultrasonic smoothing with a preceding gap: 1 – a tool; 2 – a part

The gap δ must be less than the amplitude of oscillations ξ. In the process of treatment, the tool periodically penetrates the surface of the part to depth:

$$h = \xi - \delta - h_{el}, \quad (1)$$

where h_{el} is the elastic imprint of parts.

After introduction, a tool separates from a treated surface. A dynamic load applies to a part only. This method gives possibility to treat non-rigid and intermittent surfaces of parts, it does not give blockages and influxes on ends. In literary sources, there are no similar schemes of surface plastic deformation. Therefore, to determine conditions under which superficial plastic deformation takes place, it is necessary to conduct theoretical and experimental studies of the contact interaction of a tool with a part in the process of ultrasonic smoothing with a preceding gap. We developed an installation for the study (Fig. 2) based on the automatic screw machine with a particularly high accuracy 16V05AF10. All additional devices and tools were attached to the tool holder.

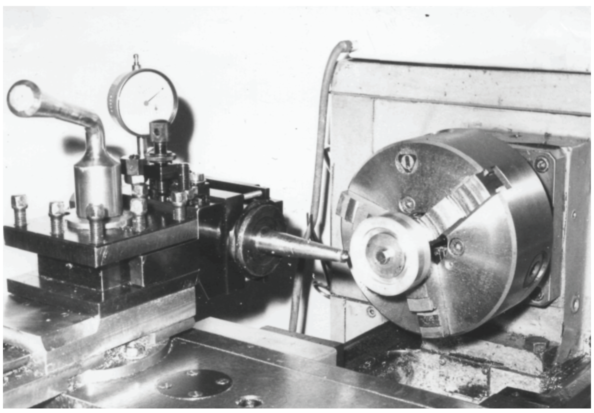

Fig. 2. General view of the installation for smoothing

One of the most important elements of the technological process is the appointment of distortion allowances for a treatment. This is especially important for a treatment of exact parts. According to paper [18], a size of parts after diamond smoothing can vary by 3–5 μm. Authors of work [19] noted that a size of a part almost does not change after ultrasonic smoothing. We can determine a size of a distortion allowance for such operation by formula:

$$\Delta D = b \cdot R_{adev}, \quad (2)$$

where ΔD is the distortion allowance per diameter, μm; b is a coefficient, which depends on a material of a part (for steel 45 $b=4.6$); R_{adev} is the average arithmetic deviation of an initial surface profile, μm.

Paper [15] shows that the following dependence determines plastic deformation at the smoothing:

$$U = 0.05 \cdot P - 0.5, \quad (3)$$

where P is the smoothing force.

As we can see from the above dependences (2), (3), they do not take directly into account mechanical characteristics of a material of a part, a radius of a tool, a depth of a tool's introduction into a part. Therefore, we carried out a series of experiments to study an influence of treatment modes on a change in a size of parts. We carried out experiments using the following samples of steels 10 (100 HB), 45 (150 HB, 50 HRC), 2S 135 (210 HB, 55 HRC), aluminum alloys D16T (120 HB), B95 (190 HB). We carried out the smoothing with a tool with a tip of the hard alloy VK15 with a radius of sphere of 1, 2, 4 and 6 mm. We measured sizes of parts before and after the treatment at the measuring machine made by «Olivetti» company, as well as with a lever brace with a division value of 1 μm. Fig. 3 shows the experimental dependences of change in the diameter of a part on the depth of the introduction of a tool tip during the treatment of aluminum alloys.

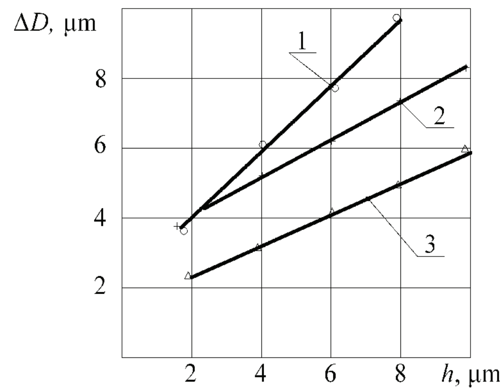

Fig. 3. Dependence of the diameter change of a part on the depth of the introduction: 1 — D16T; 2 — B95; 3 — PV90

As we can see from the above dependences, the change in the diameter depends on hardness of a material of a part. The higher the hardness, the less the change. The initial roughness of the treated surface also significantly influences the change in the diameter after the treatment (Fig. 4).

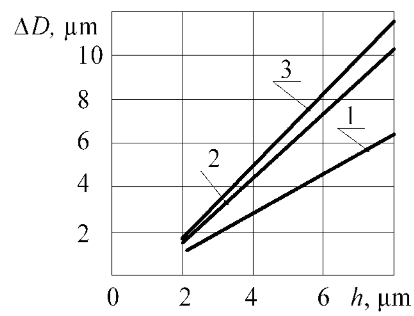

Fig. 4. Dependence of change in the diameter of a part on the depth of the introduction of an indenter at different output roughness of the treated material — D16; ξ — 12 μm; S — 0.01 mm/rev; R — 2 mm; 1 — R_a 0.01; 2 — R_a 0.07; 3 — R_a 1.5

The effect decreases at low depths of introduction because only peaks of micro roughnesses are rumpled. As the depth of introduction increases, higher peaks are rumpled more intensively, as there are significant contact pressures in the contact area due to the small actual contact area. The dependences are of the same nature for all investigated materials. Fig. 5 shows a change in the diameter of a part after the treatment with tips at different radii of a sphere.

At the treatment with a tool with a smaller radius of a sphere of a tip, the diameter of a part decreases more than at the treatment with a tool with a larger radius with the same depth of introduction. This is due to the fact that contact hinges relate to the contact area of a tool with a part. Obviously, for a tool with a smaller radius of a sphere of a tip, the contact area is smaller, and, accordingly, the contact pressure is greater than for a tool with a larger radius of an operation sphere.

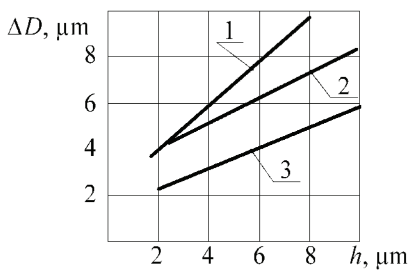

Fig. 5. Dependence of change in the diameter of a part on the radius of a sphere of a tip of the treated material – D16; ξ – 12 μm; *S* – 0.01 mm/rev; *V* – 1.33 m/s; 1 – *R*=2 mm; 2 – *R*=4 mm; 3 – *R*=6 mm

We conducted a complete factor experiment to find dependences for determination of a change in the diameter of a part after the treatment [8]. We took the following as variable factors:

– hardness of material of a part *HB* 100–200;
– depth of introduction $h=2–8$ μm;
– a radius of an operation sphere of a tool $R=2–6$ mm;
– initial roughness of a surface $R_a=0.4–4$ μm.

The objective function takes the form:

$$h_{pl}=C_0\cdot HB^m\cdot h^n\cdot R^p\cdot R_a^t, \tag{4}$$

where C_0 is a constant coefficient; *m, n, p, t* are the unknown power indices.

After the transformation we obtain:

$$h_{pl}=29.89\cdot 10^6\cdot HB^{-3.512}\cdot R^{-0.504}\cdot R_a^{0.189}\cdot h^{1.305\ln HB-5.43}. \tag{5}$$

Equation (5) makes it possible to calculate a value of plastic deformation at the ultrasonic smoothing with a preceding gap, and hence the change in a size of parts after the treatment.

Similarly, we obtain an equation for calculation of change in the size of parts after the ultrasonic smoothing of hardened steels with HRC 50...55 hardness. It takes the following form:

$$h_{pl}=0.0165\cdot R^{-0.55}\cdot R_a^{0.15}\cdot h^{2.198}. \tag{6}$$

Boundaries of the variables in dependence (6) are the same as in (5). We performed calculations of regression coefficients on a PC using the software EXCEL 2016.

Equations (5), (6) make it possible to calculate a distortion allowance for a treatment of cylindrical parts, in this case:

$$\Delta D=2h_{pl}. \tag{7}$$

However, uneven hardness of metal workpiece, surface roughness, as well as a depth of tool's introduction into a part due to, for example, tapering of a workpiece is possible in the process of a treatment. This will change the diameter of a part along the generatrix. The change may exceed the acceptable limit at a treatment of exact parts. Therefore, we must control sizes of such parts during a treatment. Let us consider how it is possible to perform such control.

Let us record a tool motion in the form:

$$u(t)=\zeta\cdot\sin\omega\cdot t, \tag{8}$$

where $\omega=2\pi\cdot f$ is a circular frequency of oscillations, f is the frequency of oscillations.

According to Fig. 1, a tool will pass δ path for t_1 time before a contact with a surface of a part. We record the equation of motion of a tool for this period:

$$\zeta\cdot\sin\omega\cdot t_1=\delta. \tag{9}$$

After a tool reaches the surface of a part, according to (1) it is introduced into a part at a depth $h=\zeta-h_{pl}$, and in general, since the beginning of the oscillation period, the motion is equal to the amplitude of oscillations ζ. The motion occurs over time t_2. The equation of motion in this interval takes the form:

$$\zeta\cdot\sin\omega\cdot t_2=\zeta. \tag{10}$$

Elastic and plastic deformation of the surface of a part occurs over this period. At the next stage, the direction of a speed vector changes to the opposite and a tool moves from the surface of a part. During this time, it is in contact with a part along the path, which is equal to elastic restoration of a part itself h_{pl} and the deformed surface h_{els} over time t_3. If we ignore a value of elastic restoration of a part h_{pl}, then the equation of motion for this period is as follows:

$$\zeta\cdot\sin\omega\cdot t_3=h_{els}. \tag{11}$$

It is obvious that a contact time of a tool with a part is equal to:

$$t_k=t_2-t_1+t_3. \tag{12}$$

We determine according to (9)–(11):

$$t_1=\frac{1}{\omega}\arcsin\frac{\delta}{\zeta}; \tag{13}$$

$$t_2=\frac{\pi}{2\omega}; \tag{14}$$

$$t_3=\frac{1}{\omega}\arcsin\frac{h_{els}}{\zeta}. \tag{15}$$

We substitute (13) to (15) into (12), make simple transformations and obtain:

$$t_k=\frac{1}{\omega}\left(\arccos\frac{\delta}{\zeta}+\arcsin\frac{h_{els}}{\zeta}\right). \tag{16}$$

Plastic deformation of protrusions dominates, of course, at the smoothing of parts with a preceding surface roughness $R_a\geq 1.25...0.63$ μm for the first load [7, 15, 18]. In this case, a material behaves as rigid-plastic, and expression (16) for the case takes the form:

$$t_k=\frac{1}{\omega}\arccos\frac{\delta}{\zeta}. \tag{17}$$

We can determine a value of elastic deformation of the surface of a part h_{els}:

$$h_{els}=\xi\cdot\sin\left(\omega\cdot t_k-\arccos\frac{\delta}{\xi}\right). \tag{18}$$

If we ignore an elastic imprint of a part during the treatment, a value of plastic deformation of a surface of a part is:

$$h_{pl} = \xi - \delta - h_{els}. \quad (19)$$

We substitute (18) into (19), make simple transformations and obtain:

$$h_{pl} = \xi\left[1 - \sin\left(\omega \cdot t_k - \arccos\frac{\delta}{\xi}\right)\right] - \delta. \quad (20)$$

For rigid-plastic materials:

$$h_{pl} = \zeta\left(1 - \cos\omega \cdot t_k\right). \quad (21)$$

Considering (20), (21), a change in the diameter of a cylindrical surface:

$$\Delta D = 2\left[\zeta\left(1 - \sin\left(\omega \cdot t_k - \arccos\delta/\zeta\right)\right) - \delta\right]; \quad (22)$$

$$\Delta D = 2\zeta\left(1 - \cos\omega \cdot t_k\right). \quad (23)$$

Thus, using the above, it is possible to control a size of a part during the treatment if to control a contact time of a tool and a part. This makes possible to automate the process of smoothing with a preceding gap.

When calculating a contact time of a tool and a part, we assumed that a tool penetrated a surface of a part at a depth h, which is equal to the difference between the amplitude of oscillations ζ and the gap δ. We used the results of experiments on the smoothing of parts of aluminum alloys D16T (HB 120), B95 (HB 180) and tempered steel 45 (HRC 50) to test the assumption. We smoothed the parts of aluminum alloys with a carbide tip with a radius of sphere of tip of 2 mm at a depth of introduction of 2, 4 and 6 μm. We used a tool with a radius of an operation part of 1 mm with depths of introduction of 4, 6 and 8 μm for the smoothing of steel 45. We determined a value of plastic deformation h_{pl} in experiments. According to the value of plastic deformation by the dependence (24) [7], we calculate a normal strength of the smoothing N:

$$h_{pl} = \frac{N}{2\pi R C \sigma_s} - \frac{3}{8} I \left(N \pi C \sigma_s\right)^{1/2}, \quad (24)$$

where C became the value ($C \approx 3$); σ_S is the boundary of fluidity of a material of the part;

$$I = \frac{1 - \mu_1^2}{E_1} + \frac{1 - \mu_2^2}{E_2},$$

where μ_1, μ_2 are the Poisson ratios of a material of the tool and a part, respectively; E_1, E_2 are the moduli of elasticity of a material of the tool and a part, respectively.

Based on N obtained from (24), we calculate a value of elastic deformation according to dependence (25) [7]:

$$h_{els} = 0.75 I \sqrt{N \cdot \pi \cdot C \cdot \sigma_S}. \quad (25)$$

Table 1 gives results of experiments and calculations.

Table 1

Experimental and calculational deformation values

Material of a part	Experimental and calculational parameters	Depth of introduction, μm		
		2	4	6
D16T, HB 120	h_{el} experimental, μm	2	3	5
	h_{els}, calculated according to (25), μm	4	5	6
	$\Sigma(h_{pl}+h_{els})$, μm	6	8	11
B95, HB 180	h_{pl} experimental, μm	0.5	2	4
	h_{els}, calculated according to (25), μm	5.3	7	9
	$\Sigma(h_{pl}+h_{els})$, μm	5.8	9	13
Steel 45, HRC 50	h_{pl} experimental, μm	0.5	1	2
	h_{els}, calculated according to (25), μm	4.3	5	6
	$\Sigma(h_{pl}+h_{els})$, μm	4.8	6	8

As we can see from calculations and experimental data, the sum of elastic and plastic deformations in all cases exceeds the depth of introduction of a tool to a surface of a part. Consequently, the assumption that a tool is introduced into a part at a depth equal to the difference between the amplitude of oscillations and the previous gap is correct.

6. Investigation of the time of contact between a tool and a part

We carried out an experimental study of a time of a contact of a tool and a part to verify the dependence (16) according to the following procedure. To measure a time of a contact of a tool with a product, we placed part 1 (Fig. 6) on mandrel 2, which is isolated from a machine tool. We switched the machine tool and the mandrel on to the electrical circuit with a help of current collector 3. It consists of a galvanic element or a source of direct current 4 and condenser 5, as well as an electronic oscilloscope 6 of C1-57 type and a frequency meter of F5041 type. During the treatment of part 1 by tool 8, the electrical circuit periodically closed and opened. We recorded this at the oscilloscope's screen in the form of rectangular pulses.

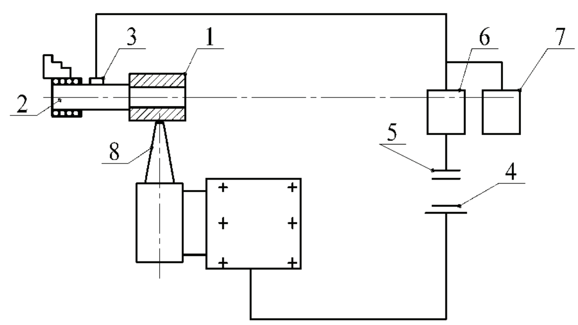

Fig. 6. Schematic of measuring the time of a contact between a tool and a part: 1 — part; 2 — mandrel; 3 — current collector; 4 — DC source; 5 — condenser; 6 — oscilloscope; 7 — frequency meter; 8 — magnetostrictive converter with a tool

We determined the time of contact knowing duration of the oscilloscope extend along the width of a pulse. We also recorded this time by the frequency meter, which was switched on to the time measurement mode. We switched capacitor 5 on to a circuit to exclude an action of a constant component.

Fig. 7 shows experimental and calculational dependences of contact time on the preceding gap at the treatment of steels of different hardness according to (16). The solid lines show the calculational values, the points are experimental ones.

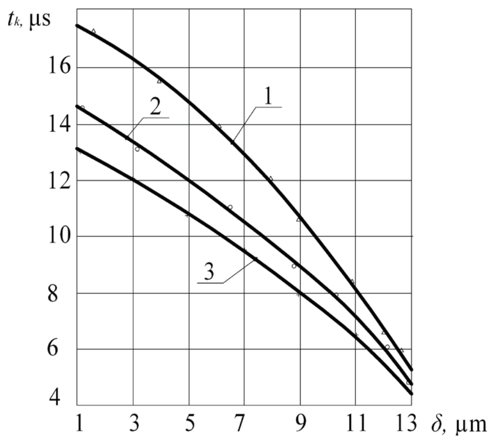

Fig. 7. Dependence of the time of contact on a gap; ξ = 15 µm; R = 2 mm; R_a = 1.4 µm: 1 – steel 45, 50 HRC; 2 – steel 45, 200 HB; 3 – steel 10, 100 HB

As we can see in Fig. 7, the time of a contact increases with an increase in the hardness of a material. Because with the increase in hardness of a material, elastic deformation increases and, as follows from (16), a time of a contact increases.

A time of a contact increases also for all investigated materials with an increase in the radius of an operation sphere of a tool (Fig. 8, 9). With an increase of the radius of an operation sphere of a tool, a contact area of a tool with a part increases, and, consequently, contact presses in the deformation zone reduce. This leads to the predominance of elastic deformations over plastic ones and, consequently, to an increase of a time of a contact.

As we can see in Fig. 7–9, the hardness of a material of a part and a radius of a tool have little effect on a time of a contact at depths of introduction of a tool, which is approximately equal to the height of micro roughnesses.

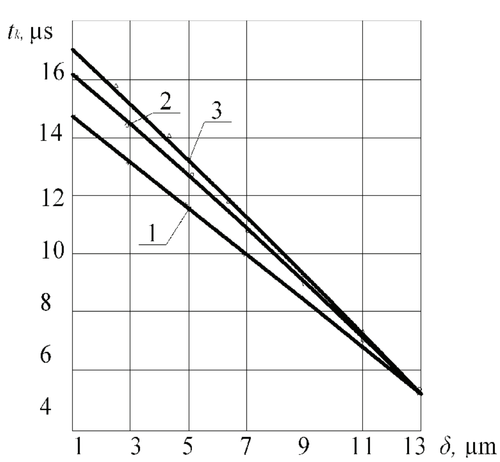

Fig. 8. Dependence of the time of contact on a gap; ξ = 15 µm; steel 45; R_a = 1.4 µm: 1 – R = 2 mm; 2 – R = 4 mm; 3 – R = 6 mm

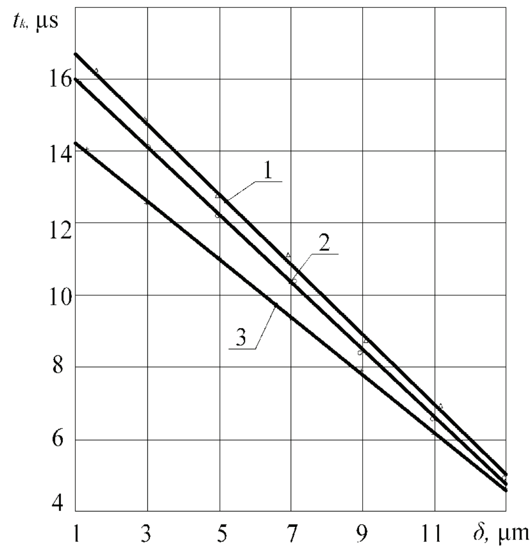

Fig. 9. Dependence of the time of contact on a gap; ξ = 15 µm; D16T; R_a = 1.4 µm: 1 – R = 2 mm; 2 – R = 4 mm; 3 – R = 6 mm

This is due to the fact that, according to [7, 20], for such deformation conditions, plastic deformation dominates and material of a part behaves as rigid-plastic, and a time of a contact corresponds to the dependence (17).

7. The area of contact between a tool and a part

At ultrasonic smoothing with a preceding gap, a contact area of a tool and a part varies during the period of oscillation from zero to the maximum value when the depth of tool's implementation changes from 0 to h. Obviously, a contact area is a function that depends on a tool radius, depth of introduction, part diameter, feed rate and treatment speed.

Contact presses in the first stage of introduction, when the tool contact area is close to zero, reaches the maximum values. It is necessary to distinguish between the first and repeated application of a load when we consider a contact area. If plastic deformation of micro roughnesses dominates during the first application of a load, then during re-loading, without displacement of contacting surfaces, deformation will be elastic [7]. As a result, a contact area of a tool with a part during repeated loading should consist of two zones, namely elastic and plastic, or elastic-plastic. In the future, when considering an area of contact, we will keep in mind its maximum value.

Paper [18] shows that when a tool is dynamically interacting with a part, deformation of a surface of a part goes due to introduction of a tool into a surface of a part. We conducted the following experiment to find out how deformation of micro roughnesses occurs – by pressing or displacement. We know [6] that when applying solid lubricants such as molybdenum disulfide or cadmium iodide in the processes of surface plastic deformation, shift deformation localizes in a lubricant layer. In this case, if deformation is carried out by a displacement, then surface roughness does not change after the treatment. Therefore, there was a smoothing of samples of steel 45, hardness 200 HB and the initial roughness of surface R_a = 4 µm. We carried out the smoothing under the following modes: δ = 4 µm, ξ = 12 µm, S = 0.01 mm/rev, V = 90 m/min by a tool made of hard alloy VK 15 with a radius of an operation sphere $R=2$ mm. We used iodine cadmium as a lubricant. We measured the roughness of a surface along R_a and made a surface profilogram before and after the treatment. The roughness of the treated surface decreased to $R_a=0.25...0.32$ μm. Peaks of micro roughnesses of a raw surface were sharp on the profilogram. At the same time, peaks of micro roughnesses of the treated surface were flat.

Thus, we can conclude that deformation of micro roughnesses proceeds due to the pressing of micro roughnesses to hollow spots, since we can exclude shift deformation due to a use of solid lubricant. The fact that shift deformation is absent is also stated by the fact that we cannot detect a texture on the surface of machined surfaces, although we can observe surface hardening. Based on this conclusion, we can ignore a non-contact wave of deformation that arises before a tool in processes of smoothing with continuous contact [6, 7, 20].

We carried out experimental investigation of the contact surface by placing a thin layer of copper on a carbide indenter by a galvanic method, or by rubbing a tip with a cloth soaked in a solution of sulfuric acid copper. After the treatment with such a tip in a contact area, a layer of copper was erased, which made possible to measure a contact area. Studies showed that a contact surface of a tool and a part is a figure close to an ellipse, although a half-width of an ellipse are slightly different in length.

According to (1), during a contact, during the period of oscillation, an operation sphere of a tool of radius R is introduced into a surface of a cylindrical part with a radius R_1 at a depth h (Fig. 10), which, if we neglect the elastic imprint of part h_{el}, is:

$$h=\xi-\delta. \qquad (26)$$

For geometric reasons, half of the axis of an ellipse in the direction of rotation of a part:

$$r=\sqrt{R^2-\left(R-\frac{2hR_1+h^2}{2\left(R+R_1+h\right)}\right)^2}. \qquad (27)$$

We can simplify an equation (27) disregarding small values of higher order:

$$r=\sqrt{\frac{2hRR_1}{R+R_1}}. \qquad (28)$$

Table 2 gives values r calculated by equation (28) for different depths of introduction at $R_1=30$ mm.

Half the length of a contact in the direction of feed:

$$r_1=\sqrt{h\left(2R-h\right)}. \qquad (29)$$

We calculated values r_1 from equation (29), Table 3.

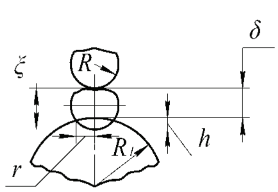

Fig. 10. Schematic of introducing a tool to the part during the period of oscillation in the direction of rotation of the part

Table 2

Value of length (μm) of a contact in the direction of rotation of a part

h, μm	R, mm		
	2	4	6
1	61	84	100
2	87	119	141
3	106	146	173
4	122	168	200
5	137	188	224
6	150	206	245
7	162	222	265
8	173	238	283
9	184	252	300
10	194	260	316

Table 3

Value of contact length (μm) in the direction of feed

h, μm	R, mm		
	2	4	6
1	63	89	109
2	89	126	155
3	109	155	189
4	126	179	219
5	141	200	245
6	155	219	268
7	167	237	289
8	179	253	309
9	189	268	328
10	200	283	346

As we can see from Tables 2, 3, the calculated values of a contact length in the direction of rotation and feed differ by not more than 9 %, which coincides with the experimental data.

During the interaction of a tool with a part it will pass path L in the direction of rotation, which is equal to:

$$L=\int_{t_1}^{t_2+t_3} V\mathrm{d}t. \qquad (30)$$

We substitute values t_1, t_2, t_3 in (13)–(15) and obtain:

$$L=\int_{\frac{1}{\omega}\arcsin\frac{\delta}{\zeta}}^{\frac{1}{\omega}\left(\frac{\pi}{2}+\arcsin\frac{h_{els}}{\zeta}\right)} V\mathrm{d}t=\frac{V}{\omega}\left(\arccos\frac{\delta}{\zeta}+\arcsin\frac{h_{els}}{\zeta}\right). \qquad (31)$$

It is obvious that a contact length in the direction of rotation taking into account the treatment speed is:

$$2a=L+2r=\frac{V}{\omega}\left(\arccos\frac{\delta}{\xi}+\arcsin\frac{h_{els}}{\xi}\right)+2\sqrt{\frac{2hRR_1}{R+R_1}}. \qquad (32)$$

At the same time, a path is in the direction of feed:

$$L_1=\int_{\frac{1}{\omega}\arcsin\frac{\delta}{\zeta}}^{\frac{1}{\omega}\left(\frac{\pi}{2}+\arcsin\frac{h_{els}}{\zeta}\right)}\frac{VS}{\pi D_1}\mathrm{d}t=\frac{VS}{\pi D_1\omega}\left(\arccos\frac{\delta}{\zeta}+\arcsin\frac{h_{els}}{\zeta}\right), \quad (33)$$

where S is the longitudinal feed; D_1 is the diameter of a part.

Considering (33), the length of contact in the direction of feed:

$$2a_1=L_1+2r_1=$$
$$=\frac{VS}{\pi D_1\omega}\left(\arccos\frac{\delta}{\zeta}+\arcsin\frac{h_{els}}{\zeta}\right)+2\sqrt{h(2R-h)}. \quad (34)$$

Table 4 gives values of a and a_1 calculated according to (33), (34).

Table 4

Value of contact length in the direction of rotation a and a_1 (μm)

h, μm	V, m/s	R=2 mm		R=4 mm		R=6 mm	
		a	a_1	a	a_1	a	a_1
1	0	61	63	84	89	100	109
	0.1	61	63	84	89	100	109
	0.8	63	63	85	89	101	109
	1.5	64	63	87	89	102	109
	2.2	65	63	88	89	104	109
5	0	137	141	188	200	224	245
	0.1	137	141	188	200	224	245
	0.8	141	141	192	200	228	245
	1.5	144	141	195	200	232	245
	2.2	147	141	199	200	232	245
10	0	194	200	266	283	316	346
	0.1	195	200	267	283	317	346
	0.8	200	200	272	283	323	346
	1.5	205	200	278	283	328	346
	2.2	210	200	283	283	334	346

As calculations show, a length of a contact in the direction of feed a_1 does not depend on rotation speed and a value of feed. At the same time, a contact length in the direction of rotation varies with a change in speed, but the change in the range of speeds from 0 to 2.2 m/s is not more than 6 %.

A tool moves relative to the axis of a part by a value of feed S for one complete turning of a part. The part of a spherical operation surface of a tool contacts elastically with a surface of a workpiece machined in the previous treatment step (a surface is limited by the curve of *AESD*, Fig. 11), the other part of a tool contacts elastic-plastically or plastically on a surface limited by *ABCE* curve. We determine areas of these surfaces by equations of ellipses shown in Fig. 11.

$$y=\frac{a}{a_1}\sqrt{a_1^2-x^2}; \quad (35)$$

$$y=\frac{a}{a_1}\sqrt{a_1-x^2}. \quad (36)$$

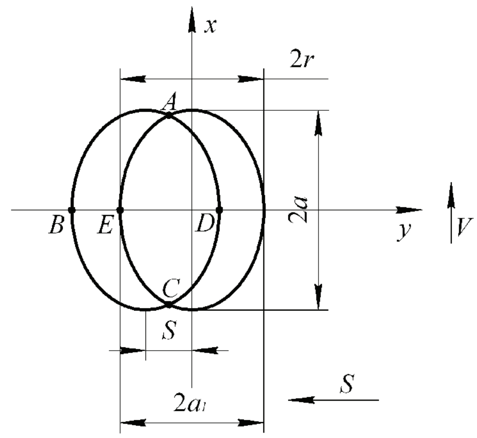

Fig. 11. Schematic of interaction between a tool and a part

We determine x coordinate of A and C points of the intersection of ellipses by solving jointly (35) and (36).

$$x=S/2.$$

It is obvious that the following dependence determines the area of an elastic-plastic part of a contact zone:

$$F=2\int_{S/2}^{S+a_1}\frac{a}{a_1}\sqrt{a_1^2-(x-S)^2}\mathrm{d}x-2\int_{S/2}^{a_1}\frac{a}{a_1}\sqrt{a_1^2-x^2}\mathrm{d}x=$$
$$=\frac{aS}{2a_1}\sqrt{4a_1^2-S^2}+2aa_1\cdot\arcsin\frac{S}{2a_1}. \quad (37)$$

Full contact area is equal to:

$$F_p=\pi\cdot a\cdot a_1. \quad (38)$$

Analysis of dependences (37), (38) (Table 5) shows that the area of the elastic-plastic contact zone and the total contact area does not depend on a treatment speed.

Table 5

Value of the elastic-plastic area and the full contact area

h, μm	V, m/s	R=2 mm		R=4 mm		R=6 mm	
		F, mm^2	F_p, mm^2	F, mm^2	F_p, mm^2	F, mm^2	F_p, mm^2
1	0	0.011	0.012	0.016	0.0235	0.0193	0.0342
	0.1	0.011	0.012	0.016	0.0235	0.0193	0.0343
	0.8	0.011	0.012	0.016	0.0239	0.0196	0.0347
	1.5	0.011	0.013	0.016	0.0243	0.0198	0.0352
	2.2	0.011	0.013	0.016	0.0247	0.02	0.0356
5	0	0.0268	0.0607	0.0372	0.118	0.0445	0.172
	0.1	0.0269	0.0609	0.0373	0.118	0.0446	0.173
	0.8	0.0276	0.0624	0.0380	0.121	0.0453	0.175
	1.5	0.0282	0.0638	0.0386	0.123	0.0460	0.178
	2.2	0.0289	0.0653	0.0394	0.125	0.0467	0.181
10	0	0.0384	0.122	0.0529	0.236	0.0630	0.343
	0.1	0.0385	0.122	0.0531	0.237	0.0639	0.347
	0.8	0.0395	0.125	0.0541	0.242	0.0643	0.354
	1.5	0.0405	0.128	0.0552	0.247	0.0654	0.360
	2.2	0.0415	0.132	0.0563	0.251	0.0666	0.366

Given this fact, as well as the fact that axes of an imprint differ from each other by no more than 8 %, the ellipsoid form of an imprint can be replaced by a circle radius r_1, which we calculate from formula (29). In this case, equation (37) for the elastic-plastic contact zone takes the form:

$$F = \frac{S}{2}\sqrt{4r_1^2 - S^2} + 2r_1^2 \arcsin\frac{S}{2r_1}. \quad (39)$$

The total area of an imprint is:

$$F_p = \pi \cdot r_1^2. \quad (40)$$

We did not did not take into account elastic restoration of an imprint performed at the previous stage of deformation when we constructed dependences (37), (38), therefore, let us consider below a model that corresponds to the real conditions of contact of a tool and a part more closely. With full a turn of parts, a tool moves relative to the axis of a part by the value of feed S, and a spherical operation surface of a tool executes a hole of r_1 radius (Fig. 12).

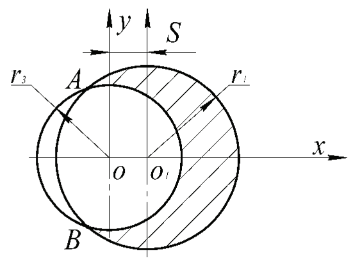

Fig. 12. Schematic of interaction between a tool and a part with elastic restoration of an imprint

The part of the operation surface of a tool performs elastic-plastic deformation in the shaded area, the other part of the operation surface performs elastic deformation at interaction with a spherical reflection of r_3 radius executed at the previous stage of deformation. We determine the x coordinate of A and B points of the intersection of the circles, which bound imprints, by solving equations of the circles (41), (42) jointly.

$$x^2 + y^2 = r_3^2; \quad (41)$$

$$(x - S)^2 + y^2 = r_1^2; \quad (42)$$

$$x = \frac{r_3^2 - r_1^2 + S^2}{2S}. \quad (43)$$

It is obvious that we can determine the area of the elastic-plastic zone of contact as follows:

$$F = 2\int_{\frac{r_3^2 - r_1^2 + S^2}{2S}}^{S + r_1} \sqrt{r_1^2 - (x - S)^2}\,dx - 2\int_{\frac{r_3^2 - r_1^2 + S^2}{2S}}^{r_3} \sqrt{r_3^2 - x^2}\,dx =$$

$$= \frac{\pi}{2}\left(r_1^2 - r_3^2\right) - \frac{r_3^2 - r_1^2 - S^2}{2S}\sqrt{r_1^2 - \left(\frac{r_3^2 - r_1^2 - S^2}{2S}\right)^2} - r_1^2 \arcsin\frac{r_3^2 - r_1^2 - S^2}{2S \cdot r_1} +$$

$$+ \frac{r_3^2 - r_1^2 + S^2}{2S}\sqrt{r_3^2 - \left(\frac{r_3^2 - r_1^2 + S^2}{2S}\right)^2} + r_3^2 \arcsin\frac{r_3^2 - r_1^2 + S^2}{2S \cdot r_3}. \quad (44)$$

Equation (44) is valid for condition:

$$r_1 + r_3 \geq S \geq r_1 - r_3. \quad (45)$$

If $S \leq r_1 - r_3$, the area of the elastic–plastic zone of contact does not depend on feed and we calculate it as follows:

$$F = \pi\left(r_1^2 - r_3^2\right). \quad (46)$$

In this case, the contact area of a tool and a part completely overlaps the plastic imprint made on the previous cycle of deformation and we calculate the full contact area by the formula:

$$F_p = \pi \cdot r_1^2. \quad (47)$$

If $S \geq r_1 + r_3$, the spherical operation surface of a tool does not overlap the imprint executed in the previous deformation cycle. In this case, the elastic-plastic and the full contact area coincide and we calculate them using formula (47). To determine r_3, it is necessary to substitute the value of h_{pl} from (5) instead of h or to calculate using dependence [7]:

$$\rho^2 = \frac{N}{\pi \cdot C \cdot \sigma_S}, \quad (48)$$

where ρ is the radius of the contact area of the restored imprint.

The use of feed $S \leq r_1 - r_3$ does not change the area of the elastic-plastic contact zone and, as a result, does not cause changes in contact pressures in the deformation zone. This gives possibility to assume that application of supplies within the specified limits will not cause a change in roughness of the treated surface, and feed $S = r_1 - r_2$ is optimal in terms of performance. It is interesting to note that values of optimal feedings given in paper [7] coincide with feed values $S = r_1 - r_3$ obtained by calculation (Table 6) at smoothing of chrome coatings $S = 0.02–0.15$ mm/rev.

Table 6

Values $r_1 - r_3$, mm at different depths of introduction

h, μm	R, mm								
	2			4			6		
	r_1	r_3	$r_1 - r_3$	r_1	r_3	$r_1 - r_3$	r_1	r_3	$r_1 - r_3$
1	0.063	0.026	0.037	0.089	0.030	0.059	0.110	0.035	0.075
2	0.089	0.044	0.045	0.126	0.052	0.074	0.150	0.058	0.092
3	0.109	0.059	0.05	0.155	0.071	0.084	0.190	0.078	0.112
4	0.126	0.074	0.052	0.179	0.087	0.092	0.220	0.097	0.123
5	0.141	0.087	0.053	0.199	0.103	0.096	0.240	0.115	0.125
6	0.155	0.099	0.051	0.219	0.119	0.100	0.270	0.130	0.140
7	0.167	0.111	0.056	0.236	0.133	0.106	0.290	0.150	0.140
8	0.178	0.123	0.055	0.253	0.147	0.109	0.310	0.160	0.150
9	0.189	0.135	0.054	0.268	0.159	0.109	0.330	0.180	0.150
10	0.199	0.146	0.053	0.282	0.174	0.108	0.350	0.190	0.160

We performed calculations for conditions of steel 45, 200 HB treatment with initial roughness of a part surface of $R_a = 1.2$ μm.

Fig. 13 shows results of the experimental verification of dependences (43).

The solid lines show the calculated dependence of the contact area on feed, and the points show the experimental data. As we can see in Fig. 13, experimental and calculational data coincide well. The use of feeds $S \geq r_1 + r_3$, imprints of which are made at the previous and the current stages of deformation and are not overlapped, gives opportunity to get surfaces with a microrelief.

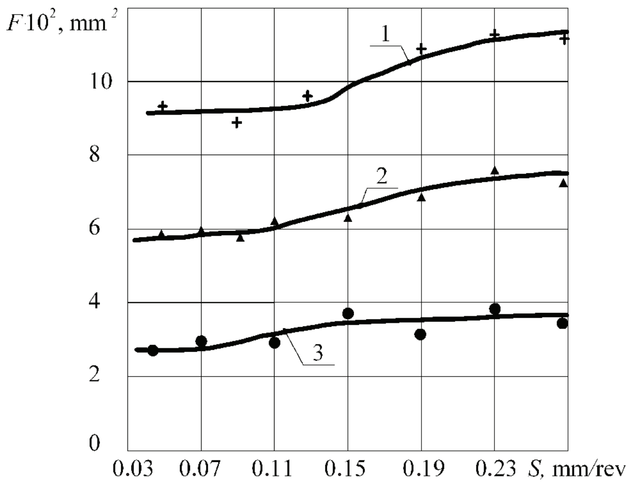

Fig. 13. Dependence of contact area on feed during treatment of steel 45: 1 – R=6 mm; 2 – R=4 mm; 3 – R=2 mm

8. Discussion of results of studying the ultrasonic smoothing

The study investigated and simulated the process of surface plastic deformation with ultrasound. A developed experimental test installation made possible to investigate technological parameters of the smoothing process with a preceding gap. As a result of experimental studies, we found possible to obtain a surface with a low roughness of a surface. The smoothing scheme with a preceding gap makes possible to realize a mode of impulse deformation, which provides a break of a contact of a tool and a workpiece during the treatment, which eliminates stiffening of a surface of a tool and a workpiece. We derived dependence (5) to determine plastic deformation with ultrasonic smoothing with a preceding gap, which makes it possible to determine sizes of a part after the treatment, as well as the plastic deformation value of the material HB 100–200. We also derived dependence (6) for calculation of a size of a part after the smoothing of hardened steels HRC 50–55. We developed dependences (16), (17) to determine the time of contact between a tool and a part. This made it possible to control a size of a part during the treatment and to fix a time of a contact of a tool and a part.

We developed a scheme of measurement of the time of contact between a tool and a part. Investigation of this parameter showed that contact time increases with an increase in the hardness of a material (Fig. 7). As the radius of an operation sphere of a tool increases, contact time increases a well (Fig. 8, 9). Material hardness of a part and a tool radius have little effect on the time of contact if the depth of the tool's introduction is approximately equal to the height of micro roughnesses. This is due to the fact that for such deformation conditions, plastic deformation prevails, and the material of a part behaves rigidly-plastically, and the contact time corresponds to dependence (17). We derived dependence (44) to determine the area of the elastic-plastic zone of a contact. The dependence makes it possible to determine values of feed, with a help of which we can obtain surfaces with a low roughness or a surface with a microrelief. The development of the study is to study the interaction between a tool and a different profile of an operation part as we used a tool with a spherical shape of a surface with a radius of 6, 4 and 2 mm in this study.

9. Conclusions

1. The derived dependences (5) and (6) to determine plastic deformation after smoothing show that a value of plastic deformation depends on the hardness of a workpiece and a radius of an operation area of a tool and initial roughness of the part. The greater hardness and a radius of a tool are, the smaller is the value of plastic deformation.

2. We established that plastic deformation decreases with an increase in a time of a contact from 6 to 17 μs as a result of prevalence of elastic deformations over the plastic ones.

3. We defined a contact area, the optimum value of feed and an influence of a smoothing parameter on them, which makes it possible to obtain a microrelief on the part surfaces or a surface with low roughness. The optimal feed rate, in terms of efficiency, is 0.02–0.15 mm/rev.

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