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RESEARCH OF THE ULTRASOUND IRONING PROCESS WITH AN INITIAL GAP BETWEEN THE TOOL AND THE PRODUCT

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The article presents a comprehensive theoretical and experimental study of the contact area between the tool and the part in the process of ultrasonic smoothing with an initial gap. It is established that the contact area is a determining parameter that affects the distribution of contact pressures, the nature of the deformation of the surface layer, tool wear, and the quality of the machined surface.

At the first stage of implementation, contact pressures reach a maximum with a minimum contact area. There are first and second loading: the first is characterized by the predominance of plastic deformation of micro -unevennesses, the second is characterized by elastic deformation, which leads to the formation of two contact zones - elastic and elastic-plastic.

It has been experimentally proven that the deformation of micro-roughness occurs by pressing the protrusions into the depressions, and not by shear. This was confirmed by the processing of steel samples 45 (hardness 200 HB, initial Ra = 4 μm) using a solid lubricant (cadmium iodide), which eliminates the shear component. After smoothing (gap δ = 4 μm, amplitude ξ = 12 μm, feed S = 0.01 mm/rev, speed V = 90 m/ min, tool VK15, R = 2 mm) the roughness decreased to Ra = 0.25 – 0.32 μm, the tops of micro-roughness became flat, and there were no textures on the micro-sections, which allows us to ignore the non-contact deformation wave.

Experimental determination of the contact shape (deposition of a copper layer on the tool) showed proximity to an ellipse with a difference of semiaxes of no more than 9%. Mathematical models were developed: penetration depth, semiaxes of the ellipse, tool paths in the directions of rotation and feed, areas of elastic-plastic F_{pp} and full F of the contact zones. The analysis revealed a weak dependence of the area on the processing speed (≤6% in the range of 0 – 2.2 m/s) and independence of F_{pp} from the feed within certain limits.

The improved model, taking into account the elastic recovery of the impression (radius r_3), determined the optimal feed $S = r_1 – r_3$ (0.037–0.16 mm depending on h and R), which ensures the stability of contact pressures, the invariance of roughness and maximum productivity. Experimental verification confirmed the consistency of the calculated and empirical data.

The results allow predicting process parameters, optimizing ultrasonic smoothing modes to obtain submicron roughness, strengthening the surface without texture, and improving the performance properties of parts. The developed dependencies are suitable for integration into adaptive processing control systems in digital manufacturing.

Key words: *ultrasonic smoothing, contact area, initial gap, elastic-plastic deformation, penetration depth, contact pressures, micro-roughness, elastic recovery, surface roughness.*

Eq. 23. Fig. 4. Table. 2. Ref. 9.

1. Problem formulation

In modern mechanical engineering and materials science, considerable attention is paid to methods of surface treatment of parts, which ensure the improvement of the quality of the surface layer, wear resistance and operational characteristics of products. One of the promising areas is ultrasonic processing, in particular ultrasonic smoothing, which combines mechanical action with high-frequency acoustic vibrations. This process allows to achieve high surface smoothness, reduce roughness and improve the microstructure of the material without significant heating or deformation of the part. However, in the case of ultrasonic smoothing with a preliminary gap (initial gap), specific features of the dynamics of the interaction of the tool and the part arise, which require detailed analysis to optimize technological parameters.

In ultrasonic smoothing with a preliminary gap, the contact area of the tool with the part changes during the oscillation period from zero to the maximum value when the tool penetration depth changes from 0 to h. It is obvious that the contact area is a function that depends on the tool radius, penetration depth, part

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diameter, feed and machining speed [1, 2]. This dynamic change in the contact area affects the distribution of force loads, thermal effects and the final surface quality. In the absence of contact (at zero penetration depth), the process does not occur, while at maximum penetration, intensive deformation of the surface layer is achieved. Such cyclicity of oscillations leads to uneven wear of the tool, possible vibration resonances and variations in roughness parameters, such as Ra or Rz.

The relevance of the problem of determining the contact area between the tool and the product is due to the need to increase the efficiency of ultrasonic technologies in industry. Modern requirements for parts, especially in the aviation, automotive and medical industries, involve achieving submicron surface roughness with minimal resource consumption. Traditional machining methods, such as grinding or polishing, often do not provide sufficient quality due to thermal deformations or low productivity. Ultrasonic smoothing with an initial gap offers advantages: it allows you to control the depth of penetration due to the amplitude of oscillations, which contributes to the formation of a hardened surface layer with increased hardness and corrosion resistance. However, the lack of accurate mathematical models for calculating the contact area makes it difficult to predict the results of machining and optimize the modes.

Existing studies in this area, for example, works [1, 3], focus on empirical dependences of the contact area on the geometric parameters of the tool and the part. The authors of [2] propose analytical expressions for static contact, but do not take into account the dynamic aspects of ultrasonic vibrations, such as frequency and amplitude. The models [4] consider the influence of feed and processing speed on the heat balance, but ignore the role of the initial gap, which determines the initial phase of interaction. This leads to inaccuracies in prediction, especially for parts of complex shape, where the diameter of the part varies along the length. In addition, experimental data are often limited to laboratory conditions, without taking into account real industrial factors, such as machine tool vibrations or material heterogeneity of the part.

Therefore, the development of new methods for processing parts surfaces, which allow obtaining high quality parameters of the surface layer of the part, is an urgent task today. In particular, it is necessary to create a theoretical basis for determining the contact area in dynamic conditions of ultrasonic smoothing with an initial gap. This includes the formulation of a mathematical model that integrates geometric parameters (tool radius R, part diameter D, insertion depth h), kinematic factors (feed S, processing speed V) and acoustic characteristics (frequency f, amplitude A). Such a model should take into account the cyclicity of the process: from zero contact (gap > A) to full insertion (gap < h).

In the context of global trends towards digitalization of production (Industry 4.0), accurate determination of the contact area will become the basis for integration with AI-monitoring systems, which will allow to automate the settings of processing parameters. This is especially relevant for Ukraine, where the machine-building industry strives for innovations to increase competitiveness in the global market. Thus, the research problem statement focuses on filling the gaps in the theory of ultrasonic smoothing, ensuring the transition from empirical methods to scientifically based models.

2. Analysis of recent research and publications

Contact pressures at the first stage of implementation, when the contact area of the tool is close to zero, reach maximum values. When considering the contact area, it is necessary to distinguish between the first and repeated application of the load. If during the first application of the load the plastic deformation of the protrusions of micro-irregularities prevails, then during repeated loading, without displacement of the contacting surfaces, the deformation will be elastic [3]. As a result, the contact area of the tool with the part during repeated loading should consist of two zones, namely - elastic and plastic or elastic-plastic. In the future, when considering the contact area, we will have in mind its maximum value.

In works [4-6] it is shown that during dynamic interaction of a tool with a part, deformation of the part surface is carried out by introducing the tool into the part surface. To find out how the deformation of micro-roughnesses occurs - by pressing or shearing, the following experiment was conducted. It is known [6] that when using solid lubricants such as molybdenum disulfide or cadmium iodide in the processes of surface plastic deformation, shear deformation is localized in the lubricant layer. At the same time, if the deformation is carried out by shearing, then the surface roughness after processing does not change. Therefore, samples made of steel 45, with a hardness of 200 HB and an initial surface roughness *of* $R_a = 4\ \mu m$ were smoothed. Smoothing was carried out under the following conditions: gap $\delta = 4\ \mu m$, oscillation amplitude $\xi = 12\ \mu m$, feed $S = 0.01$ *mm/rev*, machining speed $V = 90$ *m/ min* with a tool made of hard alloy VK15 with a radius of the working sphere $R = 2$ *мм*. Cadmium iodide was used as a lubricant. Before and after processing, the surface roughness was measured by *Ra* and took a surface profile. The roughness of the treated surface decreased to $R_a = 0.25\text{-}0.32\ \mu m$. On the profile, the vertices of the microirregularities of the untreated surface are pointed. At the same time, the tops of the micro-irregularities of the treated surface are flat.

Thus, it can be concluded that the deformation of micro-roughnesses occurs due to the pressing of the protrusions of micro-roughnesses into the depressions, since shear deformation was excluded due to the use of solid lubricant. The fact that shear deformation is absent is also indicated by the fact that it was not possible to detect textures on the micro-sections of the treated surface, although surface hardening is observed. Based on this conclusion, it is possible to disregard the non- contact deformation wave that occurs in front of the tool in the processes of smoothing with continuous contact and affects the contact area [7-9].

3. The purpose of the article

The aim of the scientific work is to develop theoretical foundations and mathematical models for the accurate determination of the contact area between the tool and the part in the process of ultrasonic smoothing with an initial gap. In particular, it is planned to establish the dependence of the contact area on the main technological parameters (depth of penetration, radius of the tool, diameter of the part, amplitude and frequency of ultrasonic vibrations, feed, processing speed) and take into account the dynamic nature of the interaction during the period of oscillations. This will allow explaining the mechanisms of contact pressure formation, the nature of the deformation of the surface layer (elastic-plastic and plastic) and predicting the final parameters of the quality of the processed surface, in particular roughness and degree of hardening.

4. Results and discussion

The contact surface was made by applying a thin layer of copper to a hard alloy indenter by galvanic method, or by wiping the tip with a cloth soaked in a solution of copper sulfate. After processing with such a tip, the copper layer in the contact zone was wiped off, which made it possible to measure the contact area. Studies have shown that the contact surface of the tool with the part is a figure close to an ellipse, although the semi-axes of the ellipse differ slightly in length.

During the contact time, during the oscillation period, the working sphere of the tool with radius R will penetrate into the surface of the cylindrical part with radius R_1 to a depth h (Figure 1), which, if we neglect the elastic displacement of the part h_{pr}, is:

$$h = \xi - \delta \tag{1}$$

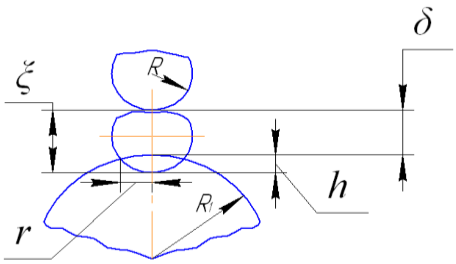

Fig. 1. Scheme of tool insertion into the part during the period of oscillations in the direction of part rotation

WITH geometric considerations semi-axis of the ellipse in the direction of rotation of the part:

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

Expression (2) can be simplified by ignoring small higher-order quantities,

$$r = \sqrt{\frac{2hRR_1}{R + R_1}}. \tag{3}$$

Half the contact length in the feed direction:

$$r_1 = \sqrt{h(2R - h)}. \tag{4}$$

Using (3), (4) we calculated contact lengths in the direction of rotation and feed, they differ by no more than 9 %, which coincides with experimental data.

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

$$L = \int_{t_1}^{t_2+t_3} V dt. \tag{5}$$

Substituting the values t_1, t_2, t_3, we obtain:

$$L = \int_{\frac{1}{\omega}\arcsin\frac{\delta}{\zeta}}^{\frac{1}{\omega}\left(\frac{\pi}{2}+\arcsin\frac{h_{ïðï}}{\zeta}\right)} V dt = \frac{V}{\omega}\left(\arccos\frac{\delta}{\zeta}+\arcsin\frac{h_{ïðï}}{\zeta}\right). \qquad (6)$$

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

$$2a = L + 2r = \frac{V}{\omega}\left(\arccos\frac{\delta}{\xi}+\arcsin\frac{h_{ïðï}}{\xi}\right)+2\sqrt{\frac{2hRR_1}{R+R_1}}. \qquad (7)$$

At the same time, the path in the feed direction:

$$L_1 = \int_{\frac{1}{\omega}\arcsin\frac{\delta}{\zeta}}^{\frac{1}{\omega}\left(\frac{\pi}{2}+\arcsin\frac{h_{ïðï}}{\zeta}\right)} \frac{VS}{\pi D_1} dt = \frac{VS}{\pi D_1 \omega}\left(\arccos\frac{\delta}{\zeta}+\arcsin\frac{h_{ïðï}}{\zeta}\right) \qquad (8)$$

where S is the longitudinal feed, D_1 – diameter of the part.

Taking into account (8), the contact length in the feed direction is:

$$2a_1 = L_1 + 2r_1 = \frac{VS}{\pi D_1 \omega}\left(\arccos\frac{\delta}{\zeta}+\arcsin\frac{h_{ïðï}}{\zeta}\right)+2\sqrt{h(2R-h)}. \qquad (9)$$

As calculations show, the contact length in the feed direction a_1 does not depend on the rotation speed and the feed rate. At the same time, the contact length in the rotation direction changes with the speed, but this change in the speed range from 0 to 2.2 *m/s* is no more than 6 %.

For one complete revolution of the part, the tool moves relative to the part axis by the feed rate *S*. Part of the spherical working surface of the tool contacts elastically with the surface of the part processed at the previous stage (the surface is bounded by the curve AESD, Figure 2), the other part of the tool contacts elastically - plastically or plastically on the surface bounded by the curve ABCE. The areas of these surfaces are determined by writing the equations of the ellipses shown in Figure 2.

$$y = \frac{a}{a_1}\sqrt{a_1^2 - x^2} \qquad (10)$$

$$y = \frac{a}{a_1}\sqrt{a_1 - x^2} \qquad (11)$$

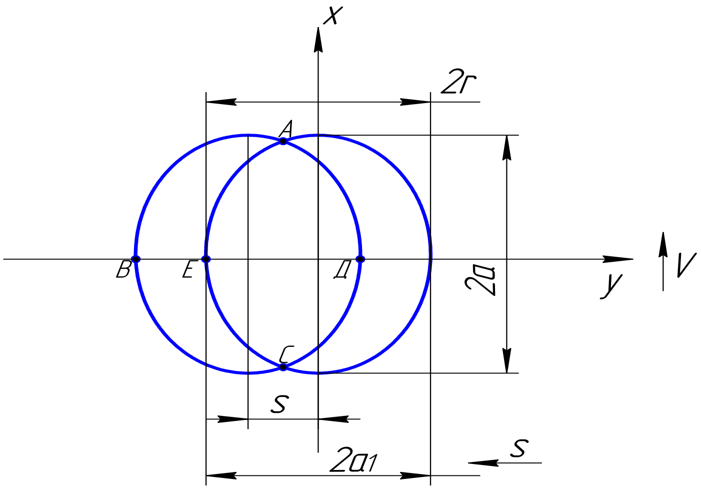

Fig. 2. Diagram of the interaction of the tool with the part

The coordinate *x of* the points A and C of the intersection of the ellipses by solving (10) and (11) together.

$$x = S/2.$$

It is obvious that the area of the elastic-plastic part of the contact zone is determined by the following dependence:

$$F = 2\int_{S/2}^{S+a_1}\frac{a}{a_1}\sqrt{a_1^2-(x-S)^2}\,dx - 2\int_{S/2}^{a_1}\frac{a}{a_1}\sqrt{a_1^2-x^2}\,dx = \frac{aS}{2a_1}\sqrt{4a_1^2-S^2}+2aa_1\cdot\arcsin\frac{S}{2a_1} \qquad (12)$$

Complete the contact area is equal to:

$$F_{\ddot{i}} = \pi \cdot a \cdot a_1. \qquad (13)$$

Analysis of dependencies (12), (13) (Table 1) shows that the area of the elastic-plastic contact zone and the total contact area depend little on the processing speed.

Taking into account this fact, as well as the fact that the axes of the imprint differ by no more than 8%, the elliptical shape of the imprint can be replaced by a circular one with radius $r_{1,}$ which is calculated by formula (4). In this case, equation (12) for the elastic-plastic contact zone takes the form

$$F = \frac{S}{2}\sqrt{4r_1^2 - S^2} + 2r_1^2 \arcsin\frac{S}{2r_1}. \qquad (14)$$

Full print area

$$F_{\ddot{i}} = \pi \cdot r_1^2. \qquad (15)$$

Table. 1

Values of elastic-plastic and total contact area

h, m km	V, m/s	R =2 mm		R =4 mm		R =6 mm	
		F, mm ^{2}	F_{n}, mm ^{2}	F, mm ^{2}	F_{n}, mm ^{2}	F, mm ^{2}	F_{n}, 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

When deriving dependencies (12), (13), elastic recovery was not taken into account. imprint made at the previous stage of deformation, therefore, below we will consider a model that more closely corresponds to the real conditions of contact between the tool and the part. During a full rotation of the part, the tool will move relative to the part axis by the feed amount S, while the spherical working surface of the tool at the final stage of deformation will make a hole with a radius r_1 (Figure 3).

Part of the working surface of the tool performs elastic-plastic deformation in the shaded area, the other part of the working surface performs elastic deformation when interacting with a spherical imprint with radius $r_{3,}$ performed at the previous stage of deformation. The coordinate x *We determine the points* A and B of intersection of the circles bounding the traces by solving the equations of the circles (16), (17) together.

$$x^2 + y^2 = r_3^2 \qquad (16)$$

$$(x - S)^2 + y^2 = r_1^2 \qquad (17)$$

$$x = \frac{r_3^2 - r_1^2 + S^2}{2S} \qquad (18)$$

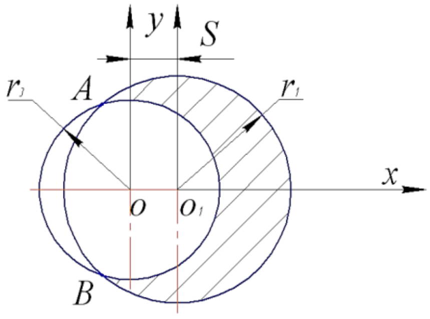

Fig. 3. Tool interaction diagram with the part at elastic restoring the print

It is obvious that the area of the elastic-plastic contact zone is determined as follows:

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

$$= \frac{\pi}{2}\left(r_1^2 - r_3^2\right) - \frac{r_3^2 - r_1^2 - S^2}{2S}\sqrt{r_1^2 - \left(\frac{r_3^2 - r_1^2 - S^2}{2S}\right)^2} - r_1^2 \arcsin\frac{r_3^2 - r_1^2 - S^2}{2S \cdot r_1} + \tag{19}$$

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

Equation (19) is valid under the condition:

$$r_1 + r_3 \geq S \geq r_1 - r_3 \tag{20}$$

If $S \leq r_1 - r_3$ the area of the elastic-plastic contact zone does not depend on the feed and is calculated as follows:

$$F = \pi\left(r_1^2 - r_3^2\right) \tag{21}$$

In this case, the contact area of the tool with the part completely overlaps the plastic imprint made in the previous deformation cycle and the total contact area is calculated by the formula:

$$F_{ï} = \pi \cdot r_1^2. \tag{22}$$

If $S \geq r_1 + r_3$ the spherical working surface of the tool does not overlap the imprint made on the previous deformation cycle. In this case, the elastic-plastic and total contact areas coincide and are calculated by the formula (2 2). Calculate r_3 according to the dependence [3]

$$\rho^2 = \frac{N}{\pi \cdot C \cdot \sigma_S}, \tag{23}$$

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

The application of feeds $S \leq r_1 - r_3$ does not change the area of the elastic-plastic contact zone and, as a result, does not cause changes in the contact pressures in the deformation zone. This allows us to assume that the application of feeds within the specified limits will not cause changes in the roughness of the treated surface, and the feed $S = r_1 - r_2$ is optimal from the point of view of productivity. It is interesting to note that the values of the optimal feeds given in [7] for smoothing chrome coatings S = 0.02 – 0.15 *mm/rev* coincide with the values of feeds $S = r_1 - r_3$, obtained by our calculation (Table 2).

Table. 2

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

h, microns	*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

Calculations were performed for the processing conditions of steel 45, 200 HB with the initial surface roughness of the part R_a = 1.2 *μm.*

The results of experimental verification of the dependences (19) are shown in Figure 4. Solid lines show the calculated dependence of the contact area on the feed, dots - experimental data. As can be seen from Figure 4, the experimental and calculated data match well. The use of feeds $S \geq r_1 + r_3$, at which the impressions made at the previous and current stages of deformation do not overlap, make it possible to obtain surfaces with microrelief.

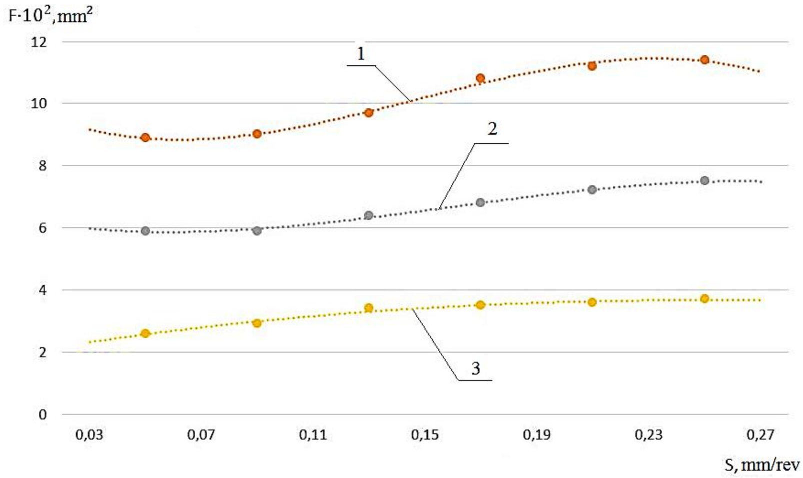

Fig. 4. Dependence of contact area on feed when machining steel 45: 1 – R = 6 mm; 2 – R = 4 mm; 3 – R =2 mm.

5. Conclusion

The conducted study of the dynamics of the contact of the tool with the part during ultrasonic smoothing with an initial gap allowed us to establish the key patterns of the formation of the interaction area. It was found that the contact pressures reach a maximum at the initial stage of implementation, when the contact area is close to zero. It is important to distinguish between the first and repeated loading: during the first, plastic deformation of micro-unevenness prevails, while during the second, elastic, which leads to the formation of two contact zones - elastic and elastic-plastic. Experiments using solid lubricant (cadmium iodide) on samples of steel 45 (hardness 200 NV, initial roughness Ra = 4 μm) confirmed that the deformation of micro-unevenness occurs mainly due to the pressing of protrusions into depressions, and not shear, since the roughness decreased to R_a = 0.25-0.32 μm, the peaks became flat, and the textures on the micro-cuts were absent. This allows us to ignore the non-contact deformation wave characteristic of continuous contact.

Experimental determination of the contact shape by applying a copper layer to the tool showed that the interaction surface is close to an ellipse with a slight difference in semiaxes (up to 9%). The developed mathematical models, including formulas for the penetration depth, semiaxes of the ellipse, paths L in the directions of rotation and feed, and the areas of the zones, take into account the geometry (radii R, R1), kinematics (speed V, feed S) and dynamics of oscillations. The analysis showed a minimal dependence of the areas on V (change up to 6% in the range 0-2.2 m/s).

Experimental verification confirmed the adequacy of the models: the calculated and empirical data coincide, and at $S > r_1 + r_3$ a surface microrelief is formed. The results obtained allow predicting process parameters, optimizing modes for improving the quality of the surface layer (roughness reduction, texture-free hardening) in mechanical engineering. Prospects include the integration of models into CAD systems for adaptive control of ultrasonic smoothing, which will contribute to increasing the efficiency of industrial technologies.

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ДОСЛІДЖЕННЯ ПРОЦЕСУ УЛЬТРАЗВУКОВОГО ВИГЛАДЖУВАННЯ З ІНІЦІАЛЬНИМ ПРОМІЖКОМ МІЖ ІНСТРУМЕНТОМ ТА ВИРОБОМ

У статті представлено комплексне теоретичне та експериментальне дослідження площі контакту між інструментом і деталлю в процесі ультразвукового вигладжування з ініціальним зазором. Встановлено, що площа контакту є визначальним параметром, який впливає на розподіл контактних тисків, характер деформації поверхневого шару, знос інструмента та якість обробленої поверхні.

На першій стадії впровадження контактні тиски досягають максимуму при мінімальній площі контакту. Розрізняють перше та повторне навантаження: перше характеризується переважанням пластичної деформації мікронерівностей, повторне – пружною деформацією, що призводить до утворення двох зон контакту – пружної та пружно-пластичної.

Експериментально доведено, що деформація мікронерівностей відбувається шляхом вдавлювання виступів у западини, а не зсуву. Це підтверджено обробкою зразків сталі 45 (твердість 200 HB, вихідна Ra = 4 мкм) з використанням твердого мастила (йодистого кадмію), що виключає зсувну складову. Після вигладжування (зазор δ = 4 мкм, амплітуда ξ = 12 мкм, подача S = 0,01 мм/об, швидкість V = 90 м/хв, інструмент ВК15, R = 2 мм) шорсткість зменшилася до Ra = 0,25–0,32 мкм, вершини мікронерівностей стали плоскими, текстури на мікрошліфах відсутні, що дозволяє ігнорувати поза-контактну хвилю деформації.

Експериментальне визначення форми контакту (нанесення шару міді на інструмент) показало близькість до еліпса з різницею напівосей не більше 9 %. Розроблено математичні моделі: глибина впровадження, напівосі еліпса, шляхи інструмента в напрямках обертання та подачі, площі пружно-пластичної F_{nn} та повної F зон контакту. Аналіз виявив слабку залежність площі від швидкості обробки (≤6 % у діапазоні 0–2,2 м/с) та незалежність F_{nn} від подачі в певних межах.

Удосконалена модель з урахуванням пружного відновлення відбитка (радіус r_3) визначила оптимальну подачу $S = r_1 - r_3$ (0,037–0,16 мм залежно від h та R), при якій забезпечується стабільність контактних тисків, незмінність шорсткості та максимальна продуктивність. Експериментальна перевірка підтвердила узгодженість розрахункових і емпіричних даних.

Результати дозволяють прогнозувати параметри процесу, оптимізувати режими ультразвукового вигладжування для отримання субмікронної шорсткості, зміцнення поверхні без текстури та підвищення експлуатаційних властивостей деталей. Розроблені залежності придатні для інтеграції в адаптивні системи керування обробкою в умовах цифрового виробництва.

Ключові слова: *ультразвукове вигладжування, площа контакту, ініціальний зазор, пружно-пластична деформація, глибина впровадження, контактні тиски, мікронерівності, пружне відновлення, шорсткість поверхні.*

Ф. 23. Рис. 4. Табл. 2. Літ. 9.

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