UDC 620.178.3

https://doi.org/10.33271/nvngu/2020-2/053

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DEVELOPMENT AND RESEARCH OF THERMOPLASTIC METHODS FOR HARDENING DETAILS

Purpose. Clarification of the influence of the temperature factor on the quality of the machined surface and the calculation of the contact area of the “workpiece-indenter” depending on the design features of the tool and the machined surface, in order to use the results obtained when assigning processing modes.

Methodology. Experimental studies on the influence of the temperature factor on the hardening process were carried out at a specialized facility developed at the Department of Engineering and Woodworking Technology of CNUT (Chernihiv National University of Technology). The three-roller pneumatic device was mounted on a support of the lathe-screw machine model 1K62. Workpieces were mounted on a special mandrel in a three-jaw chuck. The spindle speed was set using an electronic tachometer; the pressure on the rollers was recorded by a pressure gauge. Before the rolling, the workpiece was kept in a laboratory electric furnace, the preheat temperature was recorded by a logometer. Since the surface quality of surface plastic deformation (SPD) treatment with heating depends on a large number of factors, a central second-order rotatable composite layout was used to obtain the multifactor model. On the basis of a priori information and the results of the previous experiments, the feed (S, mm/rev), pressure (P, H) and preheat temperature (T, °C) were taken as factors determining the process. The surface layer hardness was taken as the initial parameter.

Findings. In the study of preheating SPD, the influence of the temperature factor on the hardness of the surfaces of the workpieces was confirmed. Moreover, under different processing modes, this effect occurs in different ways. Probably, this is due to the addition of thermal energy, which is due to the deformation of the surface layer and the heat supplied from the outside. For the investigated steels it is determined that within the limits of 300– 450 °C under the modes used during rolling-in $V = 30–70$ m/min; $S = 0.2–0.4$ mm/rev; $P = 300–2000$ N the temperature has a positive effect on the hardness of the rolled-in surface.

Originality. The obtained dependence of the contact area of the indenter-workpiece, depending on the geometrical parameters of the running surface and the tool can be used in selecting the shape and size of the tool, depending on the specific conditions of contact, in the design of new and improvement of existing methods and means of SPD.

Practical value. Using modern software and calculations according to the formulas above, we can predict the quality when machining curvilinear surfaces with variable radius of curvature. And since the specific pressure required for the plastic deformation process to be known depends on the contact area and the force applied to the indenter, it is possible to adjust the reinforcement process by varying the force applied to the indenter depending on the changing contact area.

Keywords: *hardening, surface layer, temperature, pressure, hardness, contact area, indenter*

Introduction. Surface plastic deformation (SPD) treatment methods have been sufficiently studied to date. Plastic deformation is the displacement of groups of atoms relative to each other. This moves parts of the crystal along one or more crystallographic planes at a distance greater than the distance between atoms 1000 times.

The plasticity of metals and alloys depends on the nature of the stress state. The closer it is to the state of volumetric (hydrostatic) compression, the more plastic under the same conditions it features. This is explained by the fact that volumetric compression complicates inter-crystalline deformation, which contributes to fracture.

The choice of treatment modes is based on the requirements made to the detail taking into account such factors as the physical and mechanical properties of the material being processed, the nature of the pre-treatment and others.

It is known that the treatment modes affect the quality of the treated surface (depth and degree of slander, macro- and micro-irregularities, the nature of the distribution of internal stresses), while due to deformation, heat energy is released [1].

The development of modern mechanical engineering requires the use of materials with high specific strength, including high-strength steels with a martensitic structure. However, under cyclic and dynamic loads, these materials are characterized by reduced operational stability. It is not possible to provide a combination of high rates of static, dynamic and fatigue strength by conventional methods due to low resistance to brittle fracture and high sensitivity to stress concentration. In this case, the use of combined methods for strengthening is promising.

As a result of strengthening SPD, it is possible to use high-strength steels with a martensitic structure for parts with a high concentration of stresses subjected to considerable cyclic loading. In the efficiency of increasing the fatigue strength in the presence of sources of stress concentration, the SPD in most cases exceeds other types of deformation and chemical-thermal strengthening [2]. With optimal SPD modes, the durability of parts at overloads is increased by tens of times, and the endurance limit is 1.5–3 times [3]. In this case, the SPD is more stable and less dependent on the type (form) of structural stress concentrators compared to other types of strengthening [4].

Literature review. Existing studies have shown that the strengthening of rolling in the heated state compared with rolling at room temperature leads to an additional increase in fatigue strength by 7–22 % [5]. The optimum temperature is in the region of pre-crystallization temperatures. In the study on the effect of preheating temperature on the hardness of the surface layer of the workpiece after rolling, there was found an increase in surface hardness by 10–12 % compared with cold rolling.

This phenomenon is at the heart of the method for reinforcing heated parts [6]. The normal (room) temperature at which the workpiece surfaces are carried out in production conditions is not optimal in terms of the reinforcing effect. Therefore, the current limit for improving the qualitative characteristics of the surfaces of parts can be significantly increased by applying optimal temperature regimes.

Thus, according to scientific research, we see that surface plastic deformation in combination with other methods for strengthening provides a variety of characteristics of the strength of the workpiece [7]. Thus, the SPD with chemical-thermal treatment increases both fatigue and contact strength [8]; electroplated SPD provides increased corrosion resistance and wear resistance without reducing cyclic strength; SPD with isothermal hardening creates a favorable combination of properties, viscosity, plasticity and fatigue strength [9]; high-temperature thermomechanical machining (HTM) SPD increases cyclic load resistance and fracture toughness [10].

Unsolved aspects of the problem. To apply the SPD with heating in production, it is necessary to conduct the whole range of studies on thermal and force effects on the performance of machine parts, to identify optimal processing modes at different ways of processing and types of instrument, to define dependence of contact patch on the shape of the indenter, thermal management in the area of treatment.

Purpose. Clarification of the influence of the temperature factor on the quality of the machined surface and the calculation of the contact area of the "workpiece-indenter" depending on the design features of the tool and the machined surface, in order to use the results obtained while assigning processing modes.

Results. As workpieces, cylindrical samples were used with a diameter of 30 mm and a length of 60 mm, made of widespread in the engineering of steel 34Cr4 and C55 (DIN).

Experimental studies of the influence of the temperature factor on the hardening process were carried out at a specialized facility developed at the Department of Engineering and Woodworking Technology of Chernihiv National University of Technology. The three-roller pneumatic device was mounted on a support of the lathe-screw machine model 1K62. Workpieces were mounted on a special mandrel in a three-jaw chuck. The spindle speed was set using an electronic tachometer; the pressure on the rollers was recorded by a pressure gauge. Before the rolling-in, the workpiece was kept in a laboratory electric furnace, the preheat temperature was recorded by a logometer.

Since the surface quality when processed with the SPD heated depends on many factors, central planning rotatable composite of the second order was used for the multifactor model. On the basis of a priori information and the results of the previous experiments, the feed (S, mm/rev), pressure (P, H) and preheat temperature (T, °C) were taken as determining the process. The levels and intervals of variation of the factors are presented in Table 1. The hardness of the surface layer was taken as the initial parameter.

Before processing the SPD, the samples were heated in a laboratory electric furnace and maintained at a predetermined temperature for 10–30 min in order to stabilize the temperature at the intersection of the sample. At each point in the factor space, three experiments were randomized over time. After the SPD was processed and the samples were cooled to room temperature, a hardness measurement of at least five points on the surface was carried out. The average result of these measurements was taken as the output of this experience. The matrix and the results of the experiment are presented in Table 2.

As a result of the experiment plan, the mathematical dependence of the surface hardness on the feed, pressure, and preheat temperature was obtained. Statistical verification of the adequacy of the model was carried out by the known method. The calculations were performed on a PC.

To study the response surface, a graphical interpretation of the obtained dependencies was performed by the method of sections. The results are presented in Figs. 1–3.

Determining the contact area of the workpiece-indenter. The processing of workpieces by surface plastic deformation with preheating at different processing modes leads to a change in surface hardness. The obtained mathematical dependence of the surface hardness on the basic parameters of the process (P, T, S), allows establishing the degree of influence of each of the factors on the initial parameter of the process. It is established that the effect of the parameters is different depending on the material being processed.

Consider the example of the response surface equation obtained for steel 34Cr4: $HRC = 20.1922 + 0.009176T + 1.81709P + 10.8559S - 0.0444TP - 4T2 - 0.20368\mathrm{TS} - 0.0148P2 + 0.55549PS - 6.71105S2$; it is seen that the most significant factor influencing the increase in the hardness of the treated surface is the feed S, this is because the studied interval of variation of the factors of increase in the feed leads to a violation of the nature of the contact of the indenter with the workpiece: increased slippage of the indenter replaces the process of rolling in the process of close-up. This fact testifies to the imperfection of the running device used. It was found that with increasing pressure, the hardness increases at the feed rate $S = 0.2$ mm/rev for 34Cr4 steel. The intensity of hardening is higher than at $S > 0.2$ mm/rev, which is explained by more frequent influence of the deforming element on the surface, with the increase in preheating, the surface hardness increases (Fig. 3).

At a temperature of $T = 20–250$ °C with increasing pressure for C55 steel, an increase in hardness is also observed, except for a temperature of $T = 500$ °C. The latter can be explained by the decrease in strength due to the total effect of heat supplied from the outside and heat released by force.

Table 1

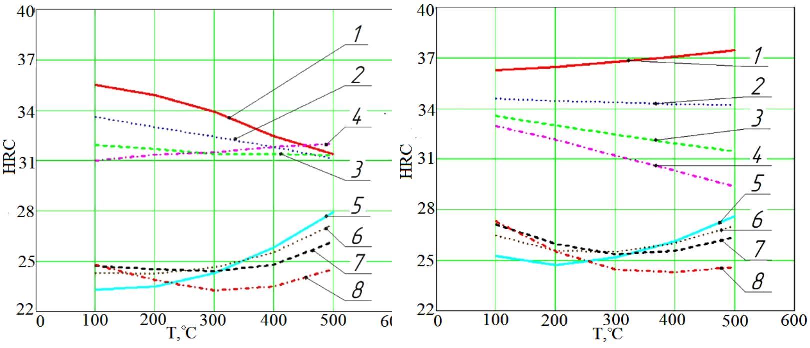
Levels and intervals of factors variation

Name the level of variation	Factors			intervals of factors variation
	X_1 (T, °C)	X_2 (P, H)	X_3 (S, mm/rev)	
Sidereal shoulder (−α)	47.7	318	0.266	
Lower	150	1000	0.30	$\Delta X_1 = 150$ °C
Zero	300	2000	0.35	$\Delta X_2 = 500$ H
Upper	450	3000	0.40	$\Delta X_3 = 0.05$ mm/rev
Sidereal shoulder (+α)	552.5	3682	0.434	

Table 2

Planning matrix and experiment results

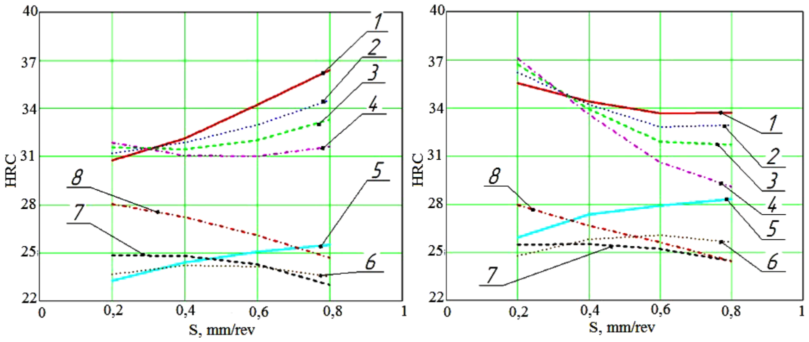
Experiment	X_0	Factors			Initial parameters							
		X_1	X_2	X_3	Y_1'	Y_1''	Y_1'''	$\bar{Y}_1^*$	Y_2'	Y_2''	Y_2'''	$\bar{Y}_2^*$
1	+1	–1	–1	+1	25	26	24	25	28	30.5	30	29.5
2	+1	–1	+1	+1	27	26	26	26.3	34.5	34	33.5	34
3	+1	+1	–1	+1	25.5	25	24.5	25	32	32	32.5	32.2
4	+1	+1	+1	+1	25.5	24.5	24	24.7	33.5	32	32	32.5
5	+1	–1	–1	–1	28.5	25.5	24.5	26.2	36.5	35.5	36	36
6	+1	–1	+1	–1	24.5	26	24.5	24.7	33.5	34	35	34.2
7	+1	+1	– 1	–1	27.5	24	25.5	26.3	34.5	25	31.5	30.3
8	+1	+1	+1	–1	23	25	23.5	23.8	34.5	34	31.5	33.3
9	+1	–1. 682	0	0	29	28	30	29	33.5	36	31.5	33.7
10	+1	+1.682	0	0	24.5	25.5	23.5	24.5	32	33.5	34	33.2
11	+1	0	–1.682	0	25.5	24.5	25.5	25.2	36.5	34.5	34	35
12	+1	0	+1.682	0	23	25	25.5	24.5	29	29	31	29.7
13	+1	0	0	–1.682	24	24.5	23.5	24	34.5	31	35	33.5
14	+1	0	0	+1.682	23.5	25	24	24.2	33.5	34	35	34.2
15	+1	0	0	0	24	26.5	26.5	25.7	34	38.5	35	35.8
16	+1	0	0	0	21.5	22	21.5	21.2	33	32.5	30	31.8
17	+1	0	0	0	21.5	21.5	22	21.2	34	33	32.5	33.2
18	+1	0	0	0	26.5	24	25.5	25	33.5	33	33.5	32.2
19	+1	0	0	0	25	26	25.5	25.5	33	32.5	31	32.2
20	+1	0	0	0	24.5	25.5	23	24.3	34	34	30.5	32.8



a *b*

Fig. 1. Effect of additional heating before rolling on the hardness of the running surface:

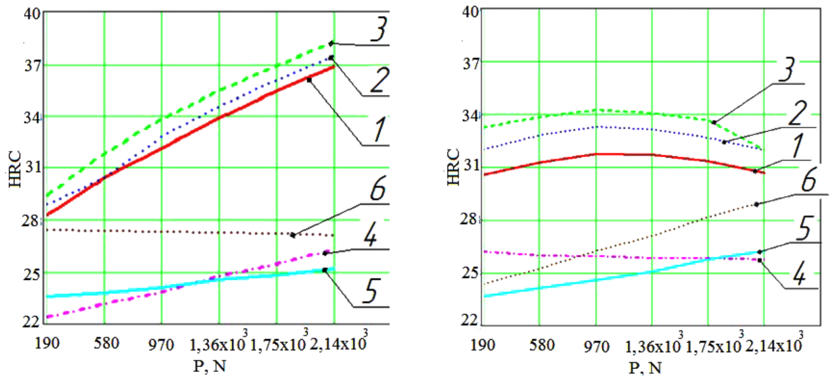
a – at P = 580 N; b – at P = 1730 N; 1, 2, 3, 4 – for steel 34Cr4 when feeding S = 0.2; 0.4; 0.6; 0.8; mm/rev respectively; 5, 6, 7, 8 is the same for C55 steel



a *b*

Fig. 2. Effect of feed on the hardness of the running surface:

a – at P = 580 N; b – at P = 1730 N; 1, 2, 3, 4 – for 34Cr4 steel at temperatures T = 50; 200; 350; 500 °C, respectively; 5, 6, 7, 8 are the same for C55 steel



a *b*

Fig. 3. Effect of pressure on the hardness of the running surface:

a – when S = 0.2 mm/rev; b – when S = 0.6 mm/rev; 1, 2, 3 – for 34Cr4 steel at temperatures T = 50; 250; 500 °C, respectively; 4, 5, 6 are the same for C55 steel

Output of the formula for calculating the contact area of a tool part.

The existing types of indenters are characterized by the following basic geometric parameters (Fig. 4): R_i – indenter radius, mm; R_p – profile radius, mm.

When realizing the methods of rolling by a sphere, $R_i = R_p = 3–25$ mm are most often used; by a roller – $R_i \neq R_p$; $R_i = 10–100$ mm; $R_p = 3–25$ mm; by a plate – $R_i = \infty$; $R_p = 3–25$ mm; when rigging a ring, depending on the diameter of the part, there can be used $R_i < 0$; $R_p = 40–200$ mm. These types of tools are given to one type – torus. Then the general scheme of the process can be represented by rolling out the external cylindrical surfaces with the radius of the part $R_w > 0$, the plane surfaces $R_w = \infty$, the inner cylindrical surfaces $R_w < 0$.

Consequently, the sum is reduced to determining the contact area of two figures (Fig. 4).

The equation of the part's surface is the following

$$(x-a)^2 + y^2 = R_w^2; \tag{1}$$

$$a = OO_2 = R_i + R_w - z_1, \tag{2}$$

where z_1 is the depth of penetration of the indenter into the surface of the part, mm.

To compile the equation of the indenter surface, which is the body of rotation, it is necessary to know the radius of rotation at an arbitrary point of the surface. But as there is a profile radius R_p, the radius of the rotation of the generator will depend on the coordinate (Fig. 5). Choose an arbitrary point F on the axis OZ, which lies between points O and F, which have Z coordinates $z = 0$ and $z = R_p$ respectively. Then, owing to the fact that $ED' = OD = OO_1 + O_1D = R_i - R_p + O_1D$ from the rectangular triangle O_1DD_1, we find O_1D

$$O_1D = \sqrt{O_1D'^2 - DD'^2} = \sqrt{R_p^2 - z^2},$$

and

$$ED' = R_з - R_p + \sqrt{R_p^2 - z^2}. \tag{3}$$

Knowing the radius of rotation of the points of the generating indenter, depending on the coordinate Z, we can write the equation of the indenter surface

$$x^2 + y^2 = \left(R_з - R_p + \sqrt{R_p^2 - z^2}\right)^2. \tag{4}$$

To determine the boundaries of the change, we find the coordinates of point C (Figs. 4, 5) from the rectangular triangle

$$AC = \sqrt{O_1C^2 - O_1A^2} = \sqrt{R_p^2 - \left(R_p - z_1\right)^2}. \tag{5}$$

We find the limits of the change in x as a function of z. x varies within the limits of the curve of the intersection of the indenter surfaces at $y = 0$. It is necessary to solve the system for determining the intersection curve of two surfaces, which consists of the indenter surface equation (4) and the surface equation of the part (1), that is, the system of equations (6)

$$\begin{cases} x^2 + y^2 = \left(R_з - R_p + \sqrt{R_p^2 - z^2}\right)^2 \\ (x-a)^2 = R_w^2 - y^2 \end{cases}. \tag{6}$$

From the second equation of system (6), we find

$$y^2 (x-a)^2 = R_w^2 - (x-a)^2.$$

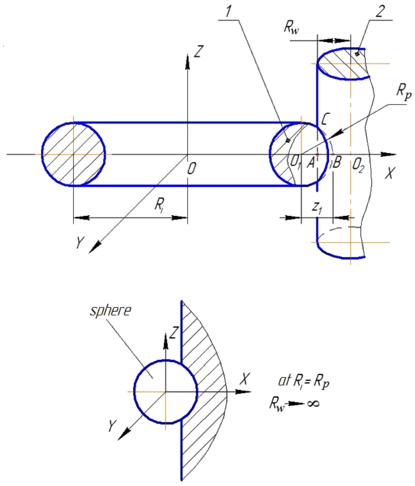


Fig. 4. General calculation scheme:

1 – indenter; 2 – processing part

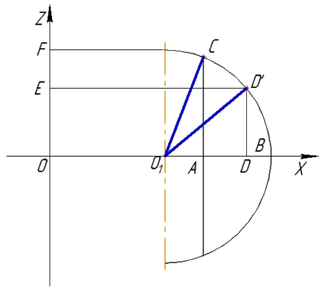


Fig. 5. Graphical interpretation of the indenter working surface

Substituting the obtained expression in the first equation of the system (6) and having solved it relatively to x, we obtain the lower bound of the change x

$$x = \frac{a^2 + \left(R_з - R_p + \sqrt{R_p^2 - z^2}\right)^2 - R_w}{2a}. \tag{7}$$

From equation (4) for $y = 0$, we find the upper limit of the change

$$x = R_з - R_p + \sqrt{R_p^2 - z^2}. \tag{8}$$

If a smooth unequivocal surface is given by the equation $y = f(x)$, then the surface area is expressed by the formula

$$S = \iint_D \sqrt{1 + \left(\frac{\partial y}{\partial x}\right)^2 + \left(\frac{\partial y}{\partial z}\right)^2}\, dxdz, \tag{9}$$

where D is projection of this surface onto the XOZ area.

As this surface is symmetric respectively to the coordinate areas XOZ and XOY, it is sufficient to find the area of the surface located in a certain octant, limited on z by area XOY and by point C, and on x – by curves, given by the equations (7) and (8). Because the wanted surface belongs to the surface of the instrument, the solution of the equation of the tool surface (4) is relative to y, and substituting the expression in (9) we found

$$S = 4 \int_0^{\sqrt{z_1(2R_p - z_1)}} dz \int_{\frac{a^2 + \left(R_i - R_p + \sqrt{R_p^2 - z^2}\right)^2 - R_w}{2a}}^{R_з - R_p + \sqrt{R_p^2 - z^2}} \frac{R_p\left(R_i - R_p + \sqrt{R_p^2 - z^2}\right)}{R_p\left(R_i - R_p + \sqrt{R_p^2 - z^2}\right)} dx. \tag{10}$$

To simplify the presentation we will designate

$$c(z) = R_з - R_p + \sqrt{R_p^2 - z^2}\ , \tag{11}$$

and after having integrated on x, then replacing $t = c(z)$, we will obtain

$$S = 4R_p \int_{R_i - Z_1}^{R_i} \frac{t}{\sqrt{R_p^2 - \left(t + R_p - R_i\right)^2}} \times$$
$$\times \arcsin\left(\frac{\sqrt{t^2 - \left(a - R_w\right)^2} \cdot \sqrt{\left(a + R_w\right)^2 - t^2}}{2at}\right) dt. \tag{12}$$

In order to show that it is not possible to obtain an analytic expression for the exact calculation of the contact area, we will show that the integral in formula (12) is not taken in elementary functions. For this, we introduce a simplification in the expression (12), that is, we suppose that the processing is carried out by a sphere $R_i = R_p$. Then formula (12) can be represented as follows

$$S = 4R_i \int_0^{\sqrt{Z_1(2R_i - Z_1)}} \left(\frac{\pi}{2} + \arcsin\frac{a^2 + R_i^2 - z^2 - R_w^2}{2a\sqrt{R_i^2 - z^2}}\right) dz. \tag{13}$$

Consider an indefinite integral

$$I = \int \arcsin\frac{a^2 + R_i^2 - z^2 - R_w^2}{2a\sqrt{R_i^2 - z^2}} dz\ . \tag{14}$$

Integrating in parts, we find

$$I = z\arcsin\frac{a^2 + R_i^2 - z^2 - R_w^2}{2a\sqrt{R_i^2 - z^2}} + I_1\ , \tag{15}$$

where

$$I_1 = \int \frac{z^2\left(a^2 - R_w^2 - R_i^2 + z^2\right)}{\sqrt{\left(a - R_w\right)^2 - R_i^2 + z^2} \cdot \sqrt{(R_i - (a - R_w)^2) - z^2}} dz. \tag{16}$$

As $R_i^2 - \left(a - R_w\right)^2 = R_i^2 - \left(R_i - z_1\right)^2 > 0$ we will make a replacement

$$\frac{z}{\sqrt{R_i^2 - \left(a - R_w\right)^2}} = \sqrt{1 - t^2}. \tag{17}$$

Then after the corresponding simplifications, formula (16) will be the following

$$I_1 = \int \frac{z_1\left(2R_p - z_1\right)\left(1 - t^2\right)\left(2R_w\left(R_i - z_1\right) + z_1\left(2R_i - z_1\right)t^2\right)}{2\sqrt{aR_w} \cdot \sqrt{1 - t} \cdot \sqrt{1 - \frac{z_1\left(2R_i - z_1\right)}{4aR_w}t^2}} dt. \tag{18}$$

If we accept now $k = \sqrt{\frac{z_1\left(2R_i - z_1\right)}{4aR_w}}$, then we will get

$$I_1 = -\frac{z_1\left(2R_i - z_1\right)}{2\sqrt{aR_w}} \int \frac{f\left(t^2\right)}{\sqrt{1 - t^2} \cdot \sqrt{1 - k^2t^2}} dt, \tag{19}$$

where

$$(t^2) = (1 - t^2)(2R_w(R_i - z_1) + z_1(2R_i - z_1)t^2). \tag{20}$$

As $f(t^2)$ is a polynomial from t^2, then the integral of expression (19) is not taken in the final form. It can be represented as the sum of elliptic integrals.

Substituting I_1 into formula (15), we see that integral I is not taken in the final form. Consequently, the integral in formula (13) is also not taken in the final form.

So, it has been proved that it is impossible to obtain an analytical equation for accurate calculation of the contact area. Therefore, it is expedient to calculate the contact area in the formula (12) by approximate methods, without representing the contact area as the sum of elliptic integrals.

To determine the use limits of formula (12) for calculating the contact area of the part with the indenter, we consider the position of point C relatively to the surface of the part (Fig. 4). As the surface of the part is limited by the radius R_w, the point C may be outside of it, because the coordinate of the point C on Z depends on the radius of the profile of the indenter R_p.

In this case, it is necessary to integrate on Z, taking into account the actual dimensions of the part, that is, formula (12) is not suitable to calculate the contact area. The second case is not suitable for formula (12), when the width of the indenter is such that the point C lies outside the indenter surface. In this case, it is necessary to integrate with the actual sizes of the indenter. Consequently, taking into account the above cases, formula (12) should be corrected

$$S = 4R_p \int_0^b \frac{c(z)}{\sqrt{R_p^2 - z^2}} \times$$
$$\times \arcsin\left(\frac{\sqrt{c^2(z) - \left(a - R_w\right)^2} \cdot \sqrt{\left(a + R_w\right)^2 - c^2(z)}}{2ac(z)}\right) dz, \tag{21}$$

where a is determined by the formula (2); $c(z)$ – by the formula (11)

$$b = \min\left(\frac{H_w}{2}, \frac{H_i}{2}, \sqrt{z_1\left(2R_i - z_1\right)}\right), \qquad (22)$$

where H_w is the width of the part; H_i is the width of indenter.

If the indenter has a rectangular profile, that is $R_p = \infty$, then in this case, the boundary transition can be obtained from the formula for calculating the contact area. To do this, you have to find the boundary of expression (21) with $R_p \to \infty$, that is, in this case

$$S = 4\lim_{R_p \to \infty} \int_0^b \frac{c(z)}{\sqrt{R_p^2 - z^2}} \times$$
$$\times \arcsin\left(\frac{\sqrt{c^2(z) - \left(a - R_w\right)^2} * \sqrt{\left(a + R_w\right)^2 - c^2(z)}}{2ac(z)}\right) dz. \qquad (23)$$

Consider the subintegral expression as a function of two variables $f(z, R_p)$, it is easy to be sure that this function is continuous for arbitrary R_p (due to the fact that $R_p > z$) and there is a continuous boundary function for it

$$\varphi(z) = \lim_{R_{np} \to \infty} f\left(z, R_p\right) =$$
$$= R_i \arcsin\sqrt{R_i^2 - \left(a - R_w\right)^2} \cdot \sqrt{\left(a + R_w\right)^2 - R_i^2}. \qquad (24)$$

In addition, the function $f(z, R_p)$ will be evenly bounded in the integral $0 \le z \le b$ with $R_p \ge 2b$. Indeed, because the function of arcsine is always limited, it remains to show the limitation of the function

$$\frac{c(z)}{\sqrt{R_p^2 - z^2}} = \frac{R_i - R_p + \sqrt{R_p^2 - z^2}}{\sqrt{1 - \frac{z^2}{R_p^2}}}.$$

By virtue of obvious inequalities $(A - B)^2 \le A^2 - B^2 \le (A + B)^2$ we can write

$$\frac{c(z)}{\sqrt{R_p^2 - z^2}} \le \frac{R_i - R_p + R_p + z}{1 - \frac{z}{R_p}} \le \frac{R_i - b}{1 - \frac{b}{R_p}} \le 2\left(R_i + b\right).$$

Therefore, the subintegral function $f(z, R_p)$ is limited for all $0 \le z \le b$ and $R_p \ge 2b\,|f(z, R_p)| \le \pi(R_i + b) = \text{const}$ and that is why in the expression (23) we can perform a boundary transition under the integral sign, then

$$S = 4\int_0^b R_i \arcsin\left(\frac{\sqrt{z_1\left(2R_i - z_1\right)}\sqrt{\left(a + R_w\right)^2 - R_i}}{2aR_i}\right) dz. \qquad (25)$$

And since the subintegral function in this case does not depend on z, then for the tool of the rectangular profile, the contact area is equal to

$$S = 4bR_i \arcsin\left(\frac{\sqrt{z_1\left(2R_i - z_1\right)}\sqrt{\left(a + R_w\right)^2 - R_i}}{2aR_i}\right), \qquad (26)$$

where $b = \min\left(\frac{H_w}{2}, \frac{H_i}{2}\right)$.

The obtained dependences (21, 22, 26) can be used to specify processing modes, to choose the shape and size of the tool, depending on the specific contact conditions, when designing new ones and improving existing methods and means of the SPD (surface plastic deformation).

Conclusions. The influence of the temperature factor on the hardness of the processed workpieces surfaces was confirmed during the study of the SPD (surface plastic deformation) with preheating. Moreover, this effect occurs in different ways under different modes of processing. This is probably due to the addition of thermal energy, which arises from the deformation of the surface layer and the heat, supplied from the outside. It is known that during the deformation at different speeds, there is different heat dissipation. It means that the very mode of rotation (speed, supply, and others) causes the different heat dissipation in the surface layer. Thus, the metal strength decreases when the total effect of temperature factors exceeds the recrystallization threshold. It was not possible to precisely determine the value of the temperature of the preheating for the investigated steels, but it was noted, that within the limits of 300–450 °C in the modes, used for rolling $V = 30–70$ m/min; $S = 0.2–0.4$ mm/rev; $P = 300–2000$ H, the influence of temperature positively affects the hardness of the rolled surface.

The most significant factor influencing the increase in the hardness of the treated surface is the feed S, this is because in the studied interval of variation of the factors of increase in the feed leads to a violation of the nature of the contact of the indenter with the workpiece: increased slippage of the indenter replaces the process of rolling in the process close to smoothing.

It is established that with increasing pressure, the hardness increases at the feed rate $S = 0.2$ mm/rev for 34Cr4 steel. The intensity of strengthening is higher than $S > 0.2$ mm/rev, due to more frequent impact deforming element to the surface.

Depending on the hardness of the material being treated, the radius of the indenter is projected. The harder the material is, the smaller the radius of the indenter is. Thus, the contact area of the indenter with the workpiece under certain processing modes increases the condition of the surface layer of the workpiece material.

The obtained dependence of the contact area the indenter-workpiece, depending on the geometric parameters of the surface, which is rolling up, and on the instrument, can be used when choosing the shape and size of the tool, depending on the specific contact conditions, when constructing new and improving existing methods and means of SPD.

Using modern software, calculations, by the given formulas, will allow us to predict the quality of the processing of curvilinear surfaces with a variable radius of curvature. And as the specific pressure, which is necessary for the process of plastic deformation, follows the known relationship to the area of contact and the force applied to the indenter, it is possible to adjust the strengthening process by changing the force, applied to the indenter, depending on the area of the contact, which is changing.

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Розробка й дослідження термопластичних методів зміцнення деталей

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Мета. Уточнення впливу температурного фактору на якість обробленої поверхні й розрахунок площі контакту «заготовка – індентор» у залежності від конструктивних особливостей інструменту та оброблюваної поверхні з метою використання отриманих результатів при призначенні режимів обробки.

Методика. Експериментальні дослідження впливу температурного фактору на процес зміцнення проводилися на спеціалізованій установці, розробленій на кафедрі технологій машинобудування та деревообробки НУ «ЧП» (Національний університет «Чернігівська політехніка»). Трироликовий пневматичний пристрій встановлювався на супорті токарно-гвинторізного верстата моделі 1К62. Оброблювані заготовки встановлювалися на спеціальній оправці у трикулачковому патроні. Частота обертання шпинделя встановлювалася за допомогою електронного тахометра, тиск на ролики реєструвався за манометром. Перед обкатуванням заготовки витримувалися в лабораторній електропечі, температура попереднього підігріву реєструвалася логометром. Так як якість поверхні при обробці поверхневим пластичним деформуванням (ППД) з підігрівом залежить від великої кількості факторів, то для отримання багатофакторної моделі застосовувалося центральне рототабельне композиційне планування другого порядку. На підставі апріорної інформації й результатів попередніх експериментів в якості чинників, що визначають процес, були прийняті подача (S, мм/об), тиск (P, Н) і температура попереднього підігріву (T, °С). В якості вихідного параметра була прийнята твердість поверхневого шару.

Результати. При дослідженні ППД із попереднім підігрівом підтверджено вплив температурного фактора на твердість поверхонь оброблених заготовок. Причому, за різних режимів обробки цей вплив відбувається порізному. Вірогідно, це відбувається по причині додавання теплової енергії, що виникає за рахунок роботи деформування поверхневого шару й тепла, яке підводиться ззовні. Для досліджуваних сталей визначено, що в межах 300–450 °С при режимах, які застосовуються при обкатуванні $V = 30–70$ м/хв; $S = 0{,}2–0{,}4$ мм/об; $P = 300–2000$ Н температура позитивно впливає на твердість обкатаної поверхні.

Наукова новизна. Отримана залежність площі контакту «індентор – заготовка», у залежності від геометричних параметрів поверхні, що обкатується, та інструменту може бути використана при виборі форми й розмірів інструменту в залежності від конкретних умов контактування, при конструюванні нових і вдосконаленні наявних методів і засобів ППД.

Практична значимість. Використовуючи сучасне програмне забезпечення й розрахунки за приведеними формулами, можливо прогнозувати якість при обробці криволінійних поверхонь зі змінним радіусом кривизни. Так як питомий тиск, необхідний для протікання процесу пластичного деформування, знаходиться у відомій залежності від площі контакту й сили, що прикладається до індентора, то можна регулювати процес зміцнення змінюючи силу, яку прикладають до індентора, у залежності від площі контакту, що змінюється.

Ключові слова: *зміцнення, поверхневий шар, температура, тиск, твердість, площа контакту, індентор*

Разработка и исследование термопластических методов упрочнения деталей

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Цель. Уточнение влияния температурного фактора на качество обработанной поверхности и расчет площади контакта «заготовка – индентор» в зависимости от конструктивных особенностей инструмента и обрабатываемой поверхности с целью использования полученных результатов при назначении режимов обработки.

Методика. Экспериментальные исследования влияния температурного фактора на процесс упрочнения проводились на специализированной установке, разработанной на кафедре технологий машиностроения и деревообработки НУ «ЧП» (Национальный университет «Черниговская политехника»). Трехроликовое пневматическое устройство устанавливалось на суппорте токарно-винторезного станка модели 1К62. Обрабатываемые заготовки устанавливались на специальной оправке в трехкулачковом патроне. Частота вращения шпинделя устанавливалась с помощью электронного тахометра, давление на ролики регистрировалось по манометру. Перед обкаткой заготовки выдерживались в лабораторной электропечи, температура предварительного подогрева регистрировалась логометром. Так как качество поверхности при обработке поверхностным пластическим деформированием (ППД) с подогревом зависит от большого количества факторов, то для получения многофакторной модели применялось центральное рототабельное композиционное планирование второго порядка. На основании априорной информации и результатов предыдущих экспериментов в качестве факторов, определяющих процесс, были приняты подача (S, мм /об), давление (P, Н) и температура предварительного подогрева (T, °С). В качестве исходного параметра была принята твердость поверхностного слоя.

Результаты. При исследовании ППД с предварительным подогревом подтверждено влияние температурного фактора на твердость поверхностей обработанных заготовок. Причем, при различных режимах обработки это влияние происходит по-разному. Вероятно, это происходит из-за добавления тепловой энергии, возникающей за счет работы деформирования поверхностного слоя и тепла, которое подводится извне. Для исследуемых сталей определено, что в пределах 300–450 °C при режимах, применяемых при обкатке $V = 30–70$ м/мин; $S = 0,2–0,4$ мм/об; $P = 300–2000$ Н температура положительно влияет на твердость обкатанной поверхности.

Научная новизна. Полученная зависимость площади контакта «индентор – заготовка», в зависимости от геометрических параметров поверхности обкатки и инструмента, может быть использована при выборе формы и размеров инструмента в зависимости от конкретных условий контакта, при конструировании новых и совершенствовании имеющихся методов и средств ППД.

Практическая значимость. Используя современное программное обеспечение и расчеты по приведенным формулам, возможно прогнозировать качество при обработке криволинейных поверхностей с переменным радиусом кривизны. И так как удельное давление, необходимое для протекания процесса пластического деформирования, находится в известной зависимости от площади контакта и силы, что прикладывается к индентору, то можно регулировать процесс упрочнения изменяя силу, которую прикладывают к индентору, в зависимости от меняющейся площади контакта.

Ключевые слова: *упрочнение, поверхностный слой, температура, давление, твердость, площадь контакта, индентор*

Recommended for publication by S. D. Tsybulia, Doctor of Technical Sciences. The manuscript was submitted 29.05.19.