The choice of treatment modes is based on the requirement of 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 slandar, 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.

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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 on the homogeneity 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 initial moment. 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: 
\[
HRC = 20.1922 + 0.009176T + 1.81709P + 10.8559S - 0.0444TP - 472 - 0.2036TS - 0.0148P^2 + 0.55549P^2 - 6.71053S^2;
\]

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

| Factors | Name of the level of variation | intervals of factors variation |
|---------|-------------------------------|-------------------------------|
| X1 (T, °C) | X2 (P, H) | X3 (S, mm/rev) | X4 |
| Sidereal shoulder (−α) | 47.7 | 318 | 0.266 |
| Lower | 150 | 1000 | 0.30 | ΔX4 = 150 °C |
| Zero | 300 | 2000 | 0.35 | ΔX4 = 500 H |
| Upper | 450 | 3000 | 0.40 | ΔX4 = 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 |
|------------|-------|---------|---------------------|
|            |       | $X_1$ | $X_2$ | $X_3$ | $Y_1'$ | $Y_{1''}$ | $Y_{1'''}$ | $Y_2'$ | $Y_{2''}$ | $Y_{2'''}$ | $Y_3'$ |
| 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    | 27     | 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     | 24.4   | 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     | 34   |
| 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     | 34      | 35     | 33.5 |
| 14         | +1    | 0     | 0     | +1.682| 23.5   | 25      | 24       | 24.4   | 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     | 32.5     | 32      | 31     | 32.2 |
| 20         | +1    | 0     | 0     | 0     | 24.5   | 25.5    | 23       | 24     | 34       | 34      | 30.5   | 32.8 |

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 $S = 0.2; 0.4; 0.6; 0.8; \text{mm/rev}$ respectively; 5, 6, 7, 8 is the same for C55 steel

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 steel 34Cr4 when temperatures $T = 50; 200; 350; 500\, ^\circ C$, respectively; 5, 6, 7, 8 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, \( R_i = R_p = 3\text{–}25 \text{ mm} \) are most often used; by a roller – \( R_i \neq R_p; R_i = 10\text{–}100 \text{ mm}; \) by a plate – \( R_i = \infty; R_p = 3\text{–}25 \text{ mm}; \) when rigging a ring, depending on the diameter of the part, there can be used \( R_i < 0; R_p = 40\text{–}200 \text{ mm}. \) 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

\[
(x - a)^2 + y^2 = R_w^2, \quad (1)
\]

\[
a = OX = R_i + R_w - z_1, \quad (2)
\]

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 \( z = R_i \) respectively. Then, owing to the fact that \( ED' = OD = OX + XD = R_i - R_p + OX, \) we find \( OX \)

\[
OX = \sqrt{OY^2 - DD^2} = \sqrt{R_p^2 - z_1^2},
\]

and

\[
ED' = R_i - R_p + \sqrt{R_p^2 - z_1^2}. \quad (3)
\]

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

\[
x^2 + y^2 = \left( R_i - R_p + \sqrt{R_p^2 - z_1^2} \right)^2, \quad (4)
\]

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

\[
AC = \sqrt{OC^2 - OA^2} = \sqrt{R_i^2 - (R_p - z_1)^2}. \quad (5)
\]

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)

\[
\begin{align*}
\left( x - a \right)^2 + y^2 &= \left( R_i - R_p + \sqrt{R_p^2 - z_1^2} \right)^2, \\
\left( x - a \right)^2 &= R_i^2 - x^2.
\end{align*}
\]

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

\[
y^2 \left( x - a \right)^2 = R_i^2 - x^2. \quad (6)
\]

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

- \( a \) – when \( S = 0.2 \text{ mm/rev}; \)
- \( b \) – when \( S = 0.6 \text{ mm/rev}; \)
- \( 1, 2, 3 \) – for \( 34 \text{Cr}4 \) steel at temperatures \( T = 50; 250; 500 \text{ °C}, \) respectively;
- \( 4, 5, 6 \) are the same for \( \text{C}55 \) steel

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 \( x \)

\[
\frac{a^3}{2a} + \left( R_z - R_y + \sqrt{R_y^2 - z^2} \right) - R_y = x.
\] (7)

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

\[
x = R_z - R_y + \sqrt{R_y^2 - z^2}.
\] (8)

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

\[
S = 4 \int_0^R R_y \left( R_z - R_y + \sqrt{R_y^2 - z^2} \right) dz.
\] (12)

To simplify the presentation we will designate

\[
c(z) = R_z - R_y + \sqrt{R_y^2 - z^2},
\] (11)

and after having integrated on \( x \), we obtain

\[
S = 4R_y \int_{R_y-z}^R \frac{t}{\sqrt{R_y^2 - (t + R_y - R_z)^2}} \times
\]

\[
\times \arcsin \left\{ \frac{t^2 - (a - R_y)^2 \cdot \left( a + R_y \right)^2 - t^2}{2at} \right\} dt.
\] (13)

Consider an indefinite integral

\[
I = \int \frac{\arcsin \frac{a^2 + R_z^2 - z^2 - R_y^2}{2a \sqrt{R_y^2 - z^2}}}{2a} dz.
\] (14)

Integrating in parts, we find

\[
I = z \arcsin \frac{a^2 + R_z^2 - z^2 - R_y^2}{2a \sqrt{R_y^2 - z^2}} + I_1,
\] (15)

where

\[
I_1 = \int \frac{z^2 \left( a^2 - R_y^2 - R_z^2 + z^2 \right)}{\sqrt{(a - R_y)^2 - R_y^2 + z^2} \cdot \sqrt{R_z - (a - R_y)^2 - z^2}} dz.
\] (16)

As \( R_y^2 - (a - R_y)^2 = R_z - (a - R_y)^2 > 0 \), we will make a replacement

\[
\frac{z}{\sqrt{R_y^2 - (a - R_y)^2}} = \sqrt{1 - t^2}.
\] (17)

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

\[
S = 4R_y \int_0^1 \frac{c(z)}{\sqrt{1 - t^2} \cdot \sqrt{1 - k^2}} \times
\]

\[
\times \arcsin \left\{ \frac{c \left( a^2 - R_y^2 - R_z^2 + z^2 \right)}{2a c(z)} \right\} dz,
\] (21)

where \( I \) is a polynomial from \( t \), 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 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 \( R_z = R_y \). Then formula (12) can be represented as follows

\[
S = 4R_z \int_0^R \frac{t}{\sqrt{R_y^2 - (t + R_y - R_z)^2}} \times
\]

\[
\times \arcsin \left\{ \frac{t^2 - (a - R_y)^2 \cdot \left( a + R_y \right)^2 - t^2}{2at} \right\} dt.
\] (18)

If we accept now \( k = \frac{z_1 (2R_z - z_0)}{4aR_y} \), then we will get

\[
I_1 = \int \frac{z_1 (2R_z - z_0)}{4aR_y} \times
\]

\[
\times \frac{f(t^2)}{2aR_y} \frac{1}{\sqrt{1 - t^2} \cdot \sqrt{1 - k^2} t^2} dt.
\] (19)

As \( f(t^2) \) is a polynomial from \( t \), then the integral of expression (19) is not taken in the final form. It can be represented 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 \( C \) relative to the surface of the part (Fig. 4).

As the surface of the part is limited by the radius \( R_y \), 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 \( R_y \).

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

\[
S = \int_0^1 \frac{\arcsin \left\{ \frac{c \left( a - R_y^2 - R_z^2 + z^2 \right)}{2a c(z)} \right\}}{\sqrt{1 - t^2} \cdot \sqrt{1 - k^2} t^2} dz.
\] (20)

where \( a \) is determined by the formula (2); \( c(z) \) — by the formula (11).
where $H_w$ is the width of the part; $H_t$ 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

$$S = 4 \lim_{R_p \to \infty} \int_{0}^{\min \left( \frac{H_w}{2}, \frac{H_t}{2}, \sqrt{z(2R_z - z)} \right)} \frac{c(z)}{\sqrt{R_p^2 - z^2}} \times \arcsin \left( \frac{\sqrt{c^2(z) - (a - R_p)^2} \cdot \sqrt{a + R_p} \cdot \sqrt{a + R_p} - c^2(z)}{2aR_p} \right) \, dz. \quad (23)$$

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

$$\varphi(z) = \lim_{R_p \to \infty} f(z, R_p) = R_p \arcsin \left( \frac{R_p^2 - (a - R_p)^2 \cdot \sqrt{a + R_p} - z^2}{\sqrt{1 - \frac{z^2}{R_p^2}} - R_p^2} \right). \quad (24)$$

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

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

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

$$\frac{c(z)}{\sqrt{R_p^2 - z^2}} \leq \frac{R_p - R_z + \sqrt{R_p^2 - z^2}}{1 - \frac{z^2}{R_p^2}} \leq \frac{R_p - b}{R_p} \leq 2(R_p + b).$$

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

$$S = 4bR_p \arcsin \left( \frac{\sqrt{c^2(z) - (a - R_p)^2} \cdot \sqrt{a + R_p} \cdot \sqrt{a + R_p} - c^2(z)}{2aR_p} \right), \quad (25)$$

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

$$S = 4bR_p \arcsin \left( \frac{\sqrt{c^2(z) - (a - R_p)^2} \cdot \sqrt{a + R_p} \cdot \sqrt{a + R_p} - c^2(z)}{2aR_p} \right), \quad (26)$$

where $b = \min \left( \frac{H_w}{2}, \frac{H_t}{2}, \sqrt{z(2R_z - z)} \right)$. 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 workpiece 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 $F = 30–70$ 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-tool, 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 contacting 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.

### References

1. Kalchenko, V., Yeroshenko, A., & Boyko, S. (2018). Crossing axes of workpiece and tool at grinding of the circular trough with variable profile. Acta Mechanica et Automatica, 12(4), 281-285. https://doi.org/10.2478/ama-2018-0043.
2. Zhaoyang, Jin, Keyan, Li, Xintong, Wu, & Hongbiao, Dong (2015). Modelling of microstructure evolution during thermoplastic deformation of Steel by a finite element method. Materials Today: Proceedings, 2S, 460-465. https://doi.org/10.1016/j.matpr.2015.05.062.
3. Grajcar, A., Kozlowska, A., & Grzegorczyk, B. (2018). Strain hardening behavior and microstructure evolution of high-manganese steel subjected to interrupted tensile tests. Metals, 8(2), 122. https://doi.org/10.3390/met8020122.
4. Ehsan Ban, J., Matthew Franklin, Sungmin Nam, Lucas R. Smith, Hailong Wang, Rebecca G. Wells, Ovijit Chaudhuri, & Vivek B. Shenoy (2018). Mechanisms of Plastic Deformation in Collagen Networks Induced by Cellular Forces. Bio-physical journal, 114(2), 450-461. https://doi.org/10.1016/j.bpj.2017.11.3739.
Розробка й дослідження термопластичних методів зміцнення деталей

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Мета. Уточнення впливу температурного фактора на якість обробленої поверхні й розрахунок площі контакту «заготовка ‒ індетор» у залежності від конструктивних особливостей інструменту та оброблюваної поверхні з метою використання отриманих результатів при призначеній режимі обробки. Методика. Експериментальні дослідження впливу температурного фактора 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 верстації 1К62. Обрабатувані заготовки уставлялись на спеціалізованій оправці в трикулачковому патроні. Частота обертання шпинделя встановлювалася за допомогою електронного тахометра, тиск на ролики реєструвався за манометром. Перед обкатуванням заготовки вимірювалися в лабораторній електропечі, температура подійного підігріву реєструвалась логометром. Так як якість поверхні при обробці поверхні пластичним деформуванням (ППД) з підігрівом залежить від великих кількості факторів, то для отримання багатофакторної моделі застосовувалось центральне ротатабельне композиційне планування другого порядку. На підставі априорної інформації й результатів попередніх експериментів в якості чинників, що визначають процес, були прийняти: початок (3, мм/об), тиск (P, H) і температура попереднього підігріву (T, °C). Як виходні параметри була прийнята твердість поверхневого шару. Результати. При дослідженні ППД з попереднім підігрівом підтримувалося баланс температурного фактора на твердість поверхні обробленої заготовки. Причому, за різних режимів обробки цей вплив відбувається по-різному. 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 °C при режимах, які зазначаються при обкатуванні V = 30‒70 м/хв; S = 0,2‒0,4 мм/об; P = 300‒2000 H температура підігріву впливає на твердість обробленої поверхні.

Наукова новизна. Отримана залежність площі контакту «індетор ‒ заготовка», у залежності від 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 і розрахунки за приведеними формулами, можливо прогнозувати якість при обробці критоволінійних поверхонь зі змінним радіусом кривини. Так як питомий тиск, необхідний для протікання процесу пластичного деформування, знаходиться у відносій за- висимості від площа контакту й сили, що прикладається до індетора, то можна регулювати процес зміцнення змінюючи силу, яку прикладають до індетора, у залежності від площ контактів, що змінюється.

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

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 ‒ индетор» 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 Черновская политехника). Трехроликовое пневматическое устройство устанавливалось на суппорте токарно-винторезного станка модели 1К62. Обрабатываемые заготовки устанавливались на специальной оправке в трехкулачковом патrone. Частота вращения шпинделя устанавливалась за допомогою электронного тахометра, тиск на ролики реєструвався за манометром. Перед обкатуванням заготовки вимірювалися в лабораторній електропечі, температура попереднього підігріву реєструвалась логометром. Так як якість поверхні при обробці поверхні пластичним деформуванням (ППД) з підігрівом залежить від великої кількості факторів, то для отримання багатофакторної моделі застосовувалось центральне ротатабельное композиционное планирование другого порядка. На підставі априорної інформації й результатів попередніх експериментів в якості чинників, що визначають процес, були прийняті: початок (3, мм/об), тиск (P, H) і температура попереднього підігріву (T, °C). Як виходні параметри була прийнята твердість поверхневого шару. Результаты. При исследовании ППД с предварительным подогревом отмечено 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 °С 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 изменения силу, которую прикладывают к индентору, в зависимости от меняющейся площади контакта.

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

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