Power parameters of the process of hardening of cylindrical parts by a toroidal roller by the method of surface plastic deformation

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Abstract. A theoretical study of the influence of various technological factors on the force parameters of the hardening process of a cylindrical blank by a method of surface plastic deformation was performed. Based on the approximate model of plastic deformation propagation, an engineering technique has been developed that allows one to specify the force regimes of the surface hardening process with a toroidal roller, taking into account the required degree of deformation of the hardened layer, taking into account the mutual influence of the geometric parameters of the workpiece, the deforming roller and the required depth of cold work. The results of the theoretical study are in good agreement with the known experimental data and can be used in the development of technological operations for hardening machine parts by rolling in rollers or balls.

1. Introduction

Strengthening of parts made of metals and their alloys by the method of surface plastic deformation (SPD) is an effective means of increasing the working life of technological and transport machines [1-11]. Particularly widely used is a surface hardening of shafts and axes by rollers or balls (figure 1). The main technological parameters of the process are the force of plastic deformation, the axial feed of the roller, the depth and degree of deformation of the hardened layer, which is in a rigid relationship with the geometric parameters of the deforming elements and billet [12-15]. Technological processing modes are assigned in accordance with the operating conditions of the part, which ensures the highest hardening efficiency [1–5, 16, 17].

In this case, the degree of deformation of the hardened layer is determined through the geometrical parameters of the residual print or by the relative change in hardness of the workpiece material. In the real conditions of the hardening process, under the contact surface of the roller, a local deformation center is formed in which the material, testing the action of the surrounding volumes, is under conditions of comprehensive uneven compression. Therefore, the force parameters of the hardening process must be determined first of all, depending on the size and shape of the center of plastic deformation.

The aim of the article is to develop an engineering technique that allows one to specify the force regimes of the process of surface hardening of a cylindrical billet by a toroidal roller, taking into account the required degree of deformation of the material, determined taking into account the mutual...
influence of the geometric parameters of the workpiece, the deforming roller and the required depth of cold work.

2. Main provisions and analytical dependencies
Let us consider the process of hardening the outer surface of a cylindrical part with a torus roller (figure 1).

Under conditions of processing with the creation of a local center of deformation, the volume of material experiencing a comprehensive uneven compression is limited by the cone of sliding of the deforming element formed under the contact surface [18, 19].

Construction of slip cones is performed using an approximate model of propagation of plastic deformation [18], in accordance with which lines of the main shear stresses are drawn from the points of the perimeter of the contacting surface, at an angle $\beta = 45^\circ$ to the direction of the external compressive force. In the process of hardening, the external compressive forces are directed along the normals to the contact surface of the deforming roller and the workpiece.

In the general case, the cone of sliding can be a rather complex figure, because its outlines are completely determined by the shape of the perimeter of the contact surface. The features of the shape of the local focus of deformation arising in the process of hardening in accordance with the proposed procedure are taken into account by considering two sections of the cone of slip located in mutually perpendicular planes $yz$ and $xy$ (figure 2, a, b).

The section of the slip cone in the plane $yz$ (figure 2, a) is obtained by drawing the lines of the main shear stresses through points A and B at an angle $\beta$ to the direction of the normal $n_1 - n_1$ and $n_2 - n_2$. The figure ABC thus obtained is the cross-section of the slip cone in the plane $yz$. In this case, the smallest distance from the initial surface of the workpiece to the vertex C of the slip cone $h_R$ will be equal to the depth of propagation of plastic deformation in the plane $yz$, i.e. depth of work hardening in a given plane.

In the same way, the section of the cone of sliding AEF (figure 2, b) in the plane $xy$ is constructed. In this case, the distance $h_y$ will be equal to the depth of propagation of plastic deformation (depth of cold work) in a given plane.

In general, the degree of deformation is defined as the ratio of absolute strain to the initial size of the deformable element, within which plastic deformation extends.
Figure 2. Construction of sections of a cone of sliding: a) section of the slip cone $ABC$ in the plane $yz$; b) section of the slip cone $AEF$ in the plane $xy$; $\Delta h_R$ and $\Delta h_D$ - the depth of introduction of the roller into the metal of the workpiece in the planes $yz$ and $xy$; $h_R$ and $h_D$ is the distance from the surface of the workpiece to the vertex of the slip cone in the planes $yz$ and $xy$; $\theta_R$ and $\theta_D$ - the angle of contact of the roller with the workpiece in the planes $yz$ and $xy$; $\beta$ – the angle of inclination of the lines of the main shearing stresses to the normals of the contact surface (it is assumed in the calculations $\beta = 45^\circ$).

Consequently, the degree of deformation of the hardened workpiece layer is determined as the average value within the deformation center by the formula

$$\varepsilon = \frac{\sum_{i=1}^{n} \frac{\Delta h_i}{h_i}}{n},$$

where $\Delta h_i$ is the depth of the roller insertion into the workpiece material in the $i$ section, directed along the normal to the contact surface;

$h_i$ – the depth of propagation of plastic deformation (depth of cold work) in the material of the workpiece in the $i$-th section (equal to the distance from the surface of the workpiece to the vertex of the section of the cone of sliding);

$n$ – the total number of sections in which determined $\Delta h_i$ and $h_i$.

Parameters $\Delta h_i$ and $h_i$ in the equation (1) should be determined to take into account the mutual influence of the geometric parameters of the workpiece, the deforming roller, and the hardening depth.

3. Determination of the degree of deformation of the strengthened metal in the plane $yz$ (figure 2, a)

The depth of embedding the roller in the workpiece in the plane $yz$

$$\Delta h_R = AB \cdot \sin \frac{\theta_R}{2} = 2R \cdot \sin^2 \frac{\theta_R}{2}.$$  

The depth of propagation of plastic deformation in the plane $yz$

$$h_R = BC \cdot \cos(\beta - \theta_R) = R \cdot \frac{\sin \theta_R \cdot \sin(\beta + \theta_R)}{\sin(\beta - \frac{\theta_R}{2})}.$$
Equation 3 establishes the relationship between the ratio \( \frac{R}{h_R} \) and the angle of contact between the roller and the workpiece \( \theta_R \) in the form (on condition \( \beta = 45^\circ \))

\[
\frac{R}{h_R} = \frac{\sin \left( 45^\circ - \frac{\theta_R}{2} \right)}{\sin \left( \frac{\theta_R}{2} \cdot \sin \left( 45^\circ + \theta_R \right) \right)}.
\tag{4}
\]

After substituting (2) and (3) in (1), we obtain equation for determining the degree of deformation of a strengthened layer in the \( yz \) (for \( n = 1 \) and \( \beta = 45^\circ \))

\[
\varepsilon_{yz} = \frac{\Delta h_R}{h_R} = \frac{2 \cdot \sin \left( \frac{\theta_R}{2} \right) \cdot \sin \left( 45^\circ - \frac{\theta_R}{2} \right)}{\sin \left( 45^\circ + \theta_R \right)}.
\tag{5}
\]

4. Determination of the degree of deformation of the reinforced metal in the plane \( xy \) (figure 2, b)
The angle of contact between the roller and the workpiece in the plane \( xy \)

\[
\theta_d = \arccos \left( \frac{|O_1O_2| + \left( \frac{d}{2} \right)}{2 \cdot |O_1O_2| \cdot \left( \frac{D}{2} \right)} \right),
\tag{6}
\]

where \( |O_1O_2| = \frac{D}{2} + \frac{d}{2} - \Delta h_R \) is the distance between the axes of rotation of the roller and the workpiece.

The depth of propagation of plastic deformation in the workpiece material in the plane \( xy \) (figure 2, b) is determined by the equation

\[
h_d = \frac{D}{2} \cdot \frac{\sin \left( \frac{\theta_d}{2} \right) \cdot \sin \left( \beta + \theta_d \right)}{\sin \left( \beta - \frac{\theta_d}{2} \right)}.
\tag{7}
\]

The depth of introduction of the deforming roller into the workpiece material in the plane \( xy \)

\[
\Delta h_d = AE \cdot \sin \left( \frac{\theta_d}{2} \right) = D \cdot \sin^2 \left( \frac{\theta_d}{2} \right).
\tag{8}
\]

After substituting (7) and (8) in (1), we obtain equation for determining the degree of deformation of a hardened layer in the (for \( n = 1 \) and \( \beta = 45^\circ \))

\[
\varepsilon_{xy} = \frac{\Delta h_d}{h_d} = \frac{2 \cdot \sin \left( \frac{\theta_d}{2} \right) \cdot \sin \left( 45^\circ - \frac{\theta_d}{2} \right)}{\sin \left( 45^\circ + \theta_d \right)}.
\tag{9}
\]
Finally, the degree of deformation of the strengthened material in the slip cone (deformation center) is determined in accordance with equation (1) as the arithmetic mean over the two planes \(yz\) and \(xy\)

\[
\varepsilon = \frac{\varepsilon_{yz} + \varepsilon_{xy}}{2} \cdot 100\%.
\] (10)

The accuracy of determining the degree of deformation of the strengthened layer by equation (10) will increase if the total number of cross sections in which \(\Delta h\) and \(h\) are determined is increased.

5. Determination of the deformation force
In this article, the deformation force \(F\) necessary for surface hardening is determined by a simplified procedure, in accordance with which the working toroidal surface of the roller is replaced by the equivalent surface of the ball (figure 3).

With an accuracy sufficient for engineering calculations, it is assumed that the contact pressures on the working surface of the ball are equal to the resistance of deformation of the workpiece material, taking into account hardening. Taking into account this assumption, the plastic deformation force is determined by the equation

\[
F = \sigma_s \cdot A_b,
\] (11)

where \(A_b = \frac{\pi \cdot D_b \cdot \Delta h_b}{4}\) is the area of the contact surface of the ball and workpiece, \(mm^2\); \(D_b = \sqrt{D \cdot 2R}\) is the diameter of the ball; \(\Delta h_b = D_b \cdot \sin^2 \frac{\theta}{2}\) is the depth of ball penetration into the workpiece material, \(\theta = \sqrt{\theta_b \cdot \theta_d}\) is the contact angle of the ball with the surface of the workpiece; \(\sigma_s = \sigma_{0.2} + g \cdot \varepsilon_b\) is the resistance of deformation of the material of the workpiece taking into account hardening, MPa, \(\sigma_{0.2}\) is the conditional yield point of the material of the initial workpiece; \(g\) and \(b\) – the empirical coefficients of hardening of the workpiece material; \(\varepsilon\) – the degree of deformation of the material when hardened by a ball, determined in accordance with equation 10.

Figure 3. Schematic diagram of the process of hardening the cylindrical blank with a ball: a) in the plane \(yz\); b) in the plane \(xz\)
6. Construction of graphical dependencies and practical application of the developed methodology

Initial data for calculating the strength parameters of the hardening process:

- workpiece material;
- $d$ – the outer diameter of the initial workpiece;
- $h$ – the required depth of the hardened workpiece layer (depth of work hardening).

In the presented article, calculations are performed for steel 45 in a normalized state having the following mechanical characteristics [20]:

$$\sigma_{0.2} = 35 \frac{kgf}{mm^2}, \quad \delta = 8.66 \frac{kgf}{mm^2}, \quad b = 0.48.$$

The diameter of the initial workpiece $d = 70$ mm.

In engineering calculations, the depth of cold work is usually determined by empirical dependence

$$h = K_d \cdot d \quad (12)$$

where $K_d$ is the coefficient of relative depth of the hardened layer.

According to the results of fatigue tests [16], it is recommended to take $0.01 \leq K_d \leq 0.05$, in [12] the best results were obtained when $K_d = 0.5...0.7$ a range was established in $0.02 \leq K_d \leq 0.1$ [1].

Based on the recommendations given for the given workpiece diameter $d = 70$ mm, the required hardening depth is adopted $h = h_g = 5$ mm.

The depth of propagation of plastic deformation is determined by the greatest distance from the surface of the workpiece to the vertex of the slip cone in the sections considered. Therefore, it is of interest to establish a relationship between dimensions $h$ and $D$ in the entire range of the parameters considered. To this end, the coefficient of change in the height of the slip cone $K_h$ is determined in the form

$$K_h = \frac{h}{D} \quad (13)$$

Analysis of the graphical dependences of the coefficient $K_h$ change on the parameters $\frac{R}{h}$ and $D$ (figure 4) shows that the depth of propagation of plastic deformation in the plane $yz$ is always greater than in the plane $xy$. Therefore, in this case, the parameter $h$ must be assigned, guided by the depth of propagation of plastic deformation in the plane $yz$ (i.e., adopted $h = h_g$), which was done in the presented study.

From the analysis of graphical dependencies (figure 5) it is seen that the degree of deformation of the hardened layer rises to the maximum value at an angle $\theta_h = 45^\circ$. At the same time, the greatest degree of deformation in the hardening process is achieved when the roller is treated with a smaller ratio value $\frac{D}{d}$.

In accordance with the graph in figure 6, for any value of the contact angle parameter $\frac{D}{d}$, a ratio $\frac{R}{h} \approx 1$ corresponds to $\theta_h = 45^\circ$. Thus, from the analysis of the graphical dependencies shown in figure 5 and figure 6, it follows that the greatest degree of deformation of the reinforced layer can be ensured during the roller treatment with the ratio $\frac{R}{h} \approx 1$. 
Using the developed technique presented by equations (1) - (15), the effect of the parameters $\frac{R}{h}$ and $\frac{D}{d}$ on the degree of deformation $\varepsilon$ that can be provided in the hardened layer during roller treatment is analyzed. Analysis of the graphical dependencies (figure 7, a) shows that with decreasing parameters $\frac{R}{h}$ and $\frac{D}{d}$, the degree of deformation of the strengthened layer is increased.

Within the range of the parameter $\frac{D}{d}$ variation, the greatest degree of deformation is achieved by a roller having a profile radius $r$ value of approximately $h$ (i.e. $\frac{R}{h} \approx 1$). To each value of the parameter $\frac{D}{d}$, there corresponds its own value of the greatest degree of deformation, which we call the limit and denote it $\varepsilon_{\text{max}}$. For example, when processing a roller having parameters $\frac{D}{d} = \frac{5}{7}$ and $\frac{R}{h} \approx 1$ the limiting degree of deformation $\varepsilon_{\text{max}} \approx 0.24$. This degree of deformation can be ensured in one pass of the roller.
Figure 6. Dependence of the ratio $\frac{R}{h}$ on the contact angle of the roller with the workpiece $\theta_k$ for any values of the parameter $\frac{D}{d}$; $h = 5$ mm; $d = 70$ mm

Provide the required value of the degree of deformation can be due to the application of an appropriate deformation force $F$. The figure 7, b shows graphical dependencies, which allow assigning the deformation force depending on the parameters $\frac{R}{h}$ and $\frac{D}{d}$. The required deformation force has a maximum at the parameter values $\frac{R}{h} \approx 3.5$.

Figure 7. Dependence of the degree of deformation of the hardened layer and the deformation force $F$ on the ratio $\frac{R}{h}$: a) dependence $\varepsilon = \frac{R}{h}$; (b) dependence $F = \frac{R}{h}$; 1 - $\frac{D}{d} = \frac{5}{7}$; 2 - $\frac{D}{d} = \frac{10}{7}$; 3 - $\frac{D}{d} = \frac{15}{7}$; $h = 5$ mm; $d = 70$ mm

Exceeding the actual deformation force above the theoretical value (figure 7) will cause excessive deformation and, consequently, a decrease in the quality of the finished product.

7. Conclusions
The presented engineering technique allows to assign force regimes of surface hardening of a cylindrical part by a roller taking into account the required degree of deformation of the hardened layer, determined taking into account the mutual influence of geometrical parameters of the workpiece, the deforming roller and the necessary depth of cold work. The obtained analytical and graphical dependences are in good agreement with the known experimental data [1, 3, 4, 11] and can be used in designing the processes of hardening of shafts and axes by a roller or a ball.
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References
[1] Shkolnik L M and Shakhov V I 1964 Technology and adaptations for hardening and finishing of parts by rolling (Moscow: Mashinostroenie Publishing)
[2] Kudryavtsev I V 1965 Increasing the durability of machine parts by the method of surface hardening (Moscow: Mashinostroenie Publishing)
[3] Braslavskiy V M 1975 Technology for running large parts with rollers (Moscow: Mashinostroenie Publishing)
[4] Odintsov L G 1987 Hardening and finishing of parts by surface plastic deformation (Moscow: Mashinostroenie Publishing)
[5] Meyer D 2012 Heat treatment-free production of surface hardened components by mechanically induced hardening Dissertation, University of Bremen
[6] Brinksmeier E, Garbrecht M, Meyer D, Dong J 2008 Surface hardening by strain induced martensitic transformation Production Engineering – Research and Development 2 pp 109–116
[7] El - Tayeb N S M, Low K O, Brevern P V 2006 Influence of roller burnishing contact width and burnishing orientation on surface quality and tribological behaviour of Aluminium 6061 Journal of Materials Processing Technology 186(1-3) pp 272–278
[8] Brinksmeier E, Garbrecht M, Meyer D 2008 Cold Surface Hardening CIRP Annals 57(1) pp 541–544
[9] Meyer D, Brinksmeier E, Hoffmann F 2011 Surface hardening by cryogenic deep rolling Procedia Engineering 19 pp 258–263
[10] Zaydes S A 2014 Surface plastic deformation processing (Irkutsk: Irkutsk State Technical University Publishing)
[11] Smelyanskiy V M 2002 Mechanics of hardening of parts by surface plastic deformation (Moscow: Mashinostroenie Publishing)
[12] Kheyfets S G 1952 Analytic determination of the depth of the riveted layer during rolling by rollers of steel parts New research in the field of strength of engineering materials, Proceedings of CNIITMASH 49 pp 7–17
[13] Kudryavtsev I V, Petushkov G E 1966 The influence of the curvature of surfaces on the depth of plastic deformation in the case of hardening of parts by surface hardening Vestnik mashinostroeniya pp 41–43
[14] Drozd M S, Fedorov A V, Sidyakin Y I 1972 Calculation of the depth of propagation of plastic deformation in the contact zone of bodies of arbitrary curvature Vestnik mashinostroeniya pp 54–57
[15] Drozd M S, Matlin M M, Sidyakin Y I 1986 Engineering calculations of elastoplastic contact deformation (Moscow: Mashinostroenie Publishing)
[16] Kudryavtsev I V 1976 Fundamentals of rational choice of regimes for hardening of small fillets of the shafts by surface plastic deformation Questions of strength of large machine parts, Proceedings of CNIITMASH 112 pp 190–200
[17] Kudryavtsev I V 1983 Selection of the basic parameters of hardening of rollers by roller rolling Vestnik mashinostroeniya pp 1–8
[18] Gubkin S I 1947 Theory of metal forming (Moscow: Metallurgizdat Publishing)
[19] Presnyakov A A 1988 The center of deformation in the processing of metals by pressure (Alma - Ata: Nauka Publishing)
[20] Tretyakov A V, Zuyuzin V I 1973 Mechanical properties of metals and alloys in pressure treatment (Moscow: Metallurgiya Publishing)