Gulmira BULEKBAYEVA, Amina BUKAYEVA[*],
Abzal TABYLOV, Nabat SUYEUOVA,
Almira MADIYAROVA, Kamar RZAYEVA,
Marzhan CHAZHABAYEVA

ANALYSIS OF THE INFLUENCE OF ROLLING MODES ON THE GEOMETRIC PARAMETERS OF THE ZONE OF SURFACE PLASTIC DEFORMATION OF A PART

Structural strengthening of the surface layer material by surface plastic deformation ensures the formation of low roughness, a given depth and degree of hardening, and reduces residual compressive stresses in the surface layers. In the processes of surface plastic deformation by rolling with rollers, the microgeometric and physical-mechanical characteristics of surfaces are formed as a result of deformation of the surface layer of the part under the force of the roller on the surface being processed. In this case, the processes of plastic deformation of the surfaces of parts do not occur throughout the entire volume, but are localized in the zone immediately adjacent to the working profile of the roller in contact with the surface. This requires determining the geometric characteristics of the contact zone and establishing their dependence on the rolling modes. The purpose of this study is to study the influence of rolling modes on the geometric parameters of the surface plastic deformation zone, to determine their optimal ratios for stabilizing the contact zone of the roller and the surface of the part, obtaining a new microrelief of the surface layer of the part, ensuring high quality indicators.

1. INTRODUCTION

The main direction of increasing the performance and durability of parts is the structural strengthening of the surface layer material using the method of surface plastic deformation. These methods are productive, easy to implement, economical, provide the formation of low roughness, a given depth and degree of hardening, residual compressive stresses in surface layers, fine-grained structure and other quality indicators of the surface layer of processed parts [1–4]. Static surface plastic deformation methods have recently become quite widely

used to restore the dimensions of worn parts. For example, by rolling a roller on the worn surface of a part, a relief consisting of ridges and depressions of a certain configuration is extruded, and then the surface is smoothed by a roller with a cylindrical working surface [5].

Rolling creates a surface microrelief that has a number of specific features. However, until now only the height parameters of the surface roughness processed by rolling have been studied, but height parameters alone cannot assess such an important surface characteristic as wear resistance. Treated surfaces can have the same height parameters and very different wear resistance. Therefore, it is advisable to normalize not only the height, but also the shape of irregularities, using horizontal parameters [6].

Research in [7, 8] has shown that, to a greater extent than physical and mechanical properties, the operational properties of machine parts and devices are influenced by the microgeometry of surfaces, including pressure-treated surfaces. When regular microreliefs are formed on rubbing surfaces that are optimal for various operating conditions, the contribution to a significant increase in their wear resistance of hardening is about 25–30%, and geometry optimization is 70–75%. With the advent of a new direction – regularization of surface microgeometry – it is necessary to consider two aspects of the problem of surface quality: in relation to rough surfaces and surfaces with a regular microrelief.

2. METHODOLOGY

Let us analyse the mechanism of formation of rough surfaces during surface plastic deformation. Finishing by pressure is based on the property of metals and other materials to plastically deform when cold. Its essence lies in the fact that under the pressure of a hard metal, carbide and diamond tool (roller, ball, spherical tip, smoothing piercing or broach), the protrusions of the original microrelief of the processed surface are plastically deformed, i.e. compressed, forming a new microrelief with more uniform shape, height and relative position of reinforced irregularities of significantly lower height than the original ones. Figure 1 shows a diagram of the deformation of surface irregularities during rolling with a roller with the formation of a new surface microrelief.
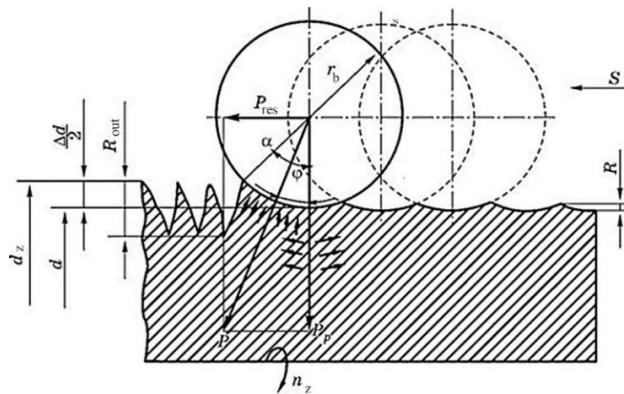

Fig. 1. Scheme of deformation of surface irregularities during rolling with a roller dz – workpiece diameter; d – part diameter; $\Delta d/2$ – is the magnitude of residual deformation; R_{out} – height of unevenness of the original surface of the workpiece; R – height of irregularities surface of the part after rolling

All main quality indicators and, first of all, the values of parameters and characteristics of microgeometry are most influenced by the maximum values of normal and tangential stresses arising in the deformation zone, as well as the ratio of their values, which determines the direction of deformation and movement of the metal in the contact zone of the deforming element with the treated surface. Thus, the problem comes down to determining the magnitudes and directions of the principal stresses considered in the theory of elasticity and plasticity. This problem, as applied to the elastoplastic deformation of uneven microreliefs of technical surfaces processed by various methods of finishing by pressure, has not yet been solved with sufficient accuracy for practice. [9, 10].

2. RESULTS AND DISCUSSION

In the processes of surface plastic deformation by the rolling method, the force action of the roller on the surface being processed causes the emergence of microgeometical and physical-mechanical characteristics of the surface layer of the parts [11, 12]. It should be noted that these processes will not occur throughout the entire volume, but will be localized in the zone of contact (deformation) of the working profile of the roller with the surface of the part. This is accompanied by the formation of certain geometric characteristics of the deformation zone, depending on the processing modes by rolling with a roller. To study and analyse the patterns of changes in the plastic deformation zone, photographic methods were used that recorded the contact zones of the working profile of the roller with the surface of the part and determined its geometric parameters with high accuracy [13, 14].

In the axial section of the part processed by rolling, the size and shape of surface irregularities formed in the contact zone were considered. The geometric characteristics of the deformation zone were determined by the angles of coverage of the roller with the metal of the part (Fig. 2). Deformation of the surface layer of the part during rolling occurred both in front of the roller and behind it with the formation of a wave of metal in the direction of feed and in the opposite direction. In this case, two different angles of coverage of the roller by the metal wave were identified. The first angle φ_1 is measured from the radius of the roller profile drawn through the top point of the metal wave arising in front of the roller in the feed direction to the axis of symmetry of the roller profile. The second angle φ_2 is measured from the radius of the roller profile drawn through the top point of the metal wave arising behind the roller in the direction opposite to the feed, also to the axis of symmetry of the roller profile.

It follows from this that when considering the longitudinal section of the contact zone of the roller and the part, the amount of plastic deformation of the surface layer of the part during the rolling process is characterized by the value of the total angle of coverage of the roller by the surface layer of the metal of the part:

$$\varphi_c = \varphi_1 + \varphi_2 \tag{1}$$

Wave height metal, emerging before the roller in the direction submissions, determined by the angle φ_1 and the wave height metal, arising behind the roller in the opposite direction submission angle φ_2 (Fig. 2).

The values of these angles in the process of rolling were determined by experimental method with the use of photography of the plastic deformation zone, which revealed the zone of plastic flow of the metal.
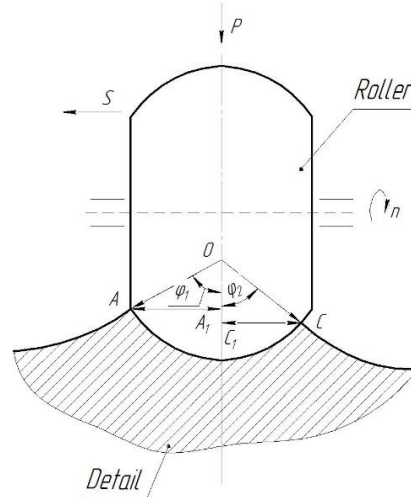

Fig. 2. Diagram of the contact zone of the roller with the part: rolling with longitudinal feed S and rolling force P

Based on the results of the experiment, the geometric parameters of the zone were determined - measurements were taken chords AA_1 and CC_1.

Taking into account the increase m and the radius of the roller profile R_{rp}, the angles of coverage of the roller with the surface layer of metal details were determined from the following ratios:

$$sin\varphi_1 = \frac{AA_1}{R_{rp}m} \tag{2}$$

$$sin\varphi_2 = \frac{CC_1}{R_{rp}m} \tag{3}$$

Using the found angle values in radians, graphs of their dependences on the main rolling modes were constructed.

Let us determine the influence of roller rolling modes on the geometric parameters of the plastic deformation zone. To this end, let us analyse work [15], where, using the method of experimental planning, changes in the angles of coverage of the roller with the metal of the part were studied depending on the main rolling modes: longitudinal feed and transverse rolling force.

Taking into account the fact that all the dependencies characterizing the processes during plastic deformation had a nonlinear form, a symmetrical second-order orthogonal design for two factors with one experiment in the center was used to conduct the experiment. A second-order polynomial of the form was adopted as a mathematical model.

$$Y_1 = B_0 + B_1X_1 + B_2X_2 + B_{12}X_1X_2 + B_{11}X_{12} + B_{22}X_{22} \tag{4}$$

The values in equation 4 in relation to the question of surface roughness and rolling are denoted by: B_0, B_1, B_2, B_{11}, B_{12} - coefficients taking into account linear, main effects of the

factor, for example, B_{22} - quadratic effect of interaction of two factors (effect of pair interaction, showing the strength of the influence of one of the factors depending on the level at which the other is located); X_1, X_2, X_{12}, X_{22} - linear effects of factors (code values of variable parameters of rolling modes: longitudinal feed and transverse rolling force) affecting the geometric parameters of the plastic deformation zone - this explanation is included in the text. The values of the varied parameters are given in Table 1.

The values of the metal wave angle in front of the roller φ_1 – the metal wave angle behind the roller φ_2 and the total angle of coverage of the roller by the material of the part φ_c were determined. Angle measurements were made from photographs and the experiments were repeated three times. Cylindrical workpieces made of steel 45 in the delivered condition (HV 187) were rolled with a roller with a working profile radius $R_{rp} = 2$ mm, the range of modes used is given in Table 1.

Table 1. Factor levels and intervals of variation modes used

Factor levels and variation intervals	Natural values		Code values	
	Force P, N	Feed S, mm/rev	X_1	X_2
Main level	2520	0.175	0	0
Variation interval	730	0.35	1	1
Top level	3540	0.05	+1	+1
Lower level	1340	0.7	−1	−1

Table 2 shows the results of the homogeneity of the obtained variances of parallel experiments conducted according to the Cochran criterion.

Table 2. Response table

S.No	Factor X_1	Factor X_2	Y_1	Y_2
1	0	0	0.1884	−0.1531
2	1	1	0.18475	−0.0984
3	+1	+1	0.18475	−0.0984
4	-1	-1	0.21995	−0.2078

According to the experiment data, the variances of parallel experiments were:

For $Y_1 = S_{u1}^2 = 4.427 * 10^{-4}$,

For $Y_2 = S_{u2}^2 = 0.904 * 10^{-4}$,

where: Y_1, Y_2 are the average values of the angle of coverage of the roller with the workpiece material in the direction of feed φ_1 and the average values of the angle of coverage of the roller with the workpiece material in the direction opposite to the feed φ_2, respectively [16].

The Cochren test is a nonparametric statistical test used to test whether two or more exposures have the same effect on groups. The Kochren test is calculated by the formula $G_p = \frac{s_{max}^2}{\sum m s_m^2}$, is the ratio of the maximum variance to the sum of all variances, where m – the number of sampled variances.

The homogeneity of the obtained variances of parallel experiments was checked using the Cochran criterion, which has the following values: for Y_1: $Gp = 0.383$, for Y_2: $Gp = 0.201$.

The obtained values of the Cochran criterion were compared with the tabulated ones with a number of degrees of freedom of 2 and a number of experiments of 9 at the selected significance level $\alpha = 0.05$ equal to $G_{table.} = 0.478$, and since they are smaller, we accept the hypothesis about the homogeneity of the resulting variances.

Table 3. Variance analysis (ANOVA) for the maximum thinning rate of the stamping sheet

Source	Statistical analysis					
	Sum of Squares	*df*	Mean Square	*F*-Value	*P*-Value	Significant
Model	463.39	9	51.49	87.87	<0.0001	*
X_1	2.99	1	2.99	5.1	0.0585	
X_2	97.23	1	97.23	165.94	<0.0001	*
X_3	55.34	1	55.34	94.44	<0.0001	*
$X_1 X_2$	0.198	1	0,198	0.338	0.5792	
$X_1 X_3$	0.4489	1	0.4489	0.7661	0.4104	
$X_2 X_3$	1.12	1	1.12	1.92	0.2087	
X_1^2	4.54	1	4.54	7.75	0.0271	
X_2^2	191.2	1	191.2	362.32	<0.0001	*
X_3^2	88.56	1	88.56	151.15	<0.0001	*
Residual	4.1	7	0.5859			
Lack of Fit	1.59	3	0.5288	0.841	0.5382	not sig.
Pure Error	2.52	4	0.6288			
Cor Total	467.49	16				

Note: $R^2 = 0.9912$, $R^2(A_{dj}) = 0.9799$, $R^2(Pre) = 0.9373$, A_{deq} precision (S/N) = 30.6107
"*" indicates model term is highly significant ($P<0.01$)

The required regression equations, taking into account the obtained variances and the significance of the coefficients, have the form:

$$Y_1 = 0.1884 + 0.0947X_1 - 0.1123X_2 + 0.08425X_2^2 - 0.0703X_1X_2$$

$$Y_2 = -0.1531 + 0.0295X_1 + 0.0252X_2 \tag{5}$$

The assumption about the adequacy of the obtained equations was checked using the Fisher criterion. From the obtained equations it is clear that the feed has a significant effect on the magnitude of the metal waves, and the metal wave in front of the roller is even greater than the rolling force when changing modes in the studied range. With increasing feed, the height of the metal wave in front of the roller decreases, and behind the roller it increases. The obtained conclusions are confirmed by the studies presented in [17].

The regression equation for the total angle of coverage of the roller with the metal of the part will have the form:

$$Y = Y_1 + Y_2$$

$$Y = 0.3415 + 0.1242X_1 - 0.0071X_2 + 0.0043X_2^2 - 0.0703X_1X_2 \tag{6}$$

To verify the results obtained when planning the experiment and to study the magnitude of metal waves in regimes outside the considered range of their change, additional studies were carried out.

The results of the study of changes in angle φ_1 from feed and rolling force are shown in Fig. 3 and 4, respectively, from which it can be seen that with increasing feed, the wave of metal in front of the roller stabilizes. When rolling with a force of 730 ... 1340 N, such stabilization occurs at feeds of about 0.5 ... 0.27 mm/rev. A wave of plastic deformation of significant height is formed in front of the roller during rolling with forces of 500... 4,000 N and above.
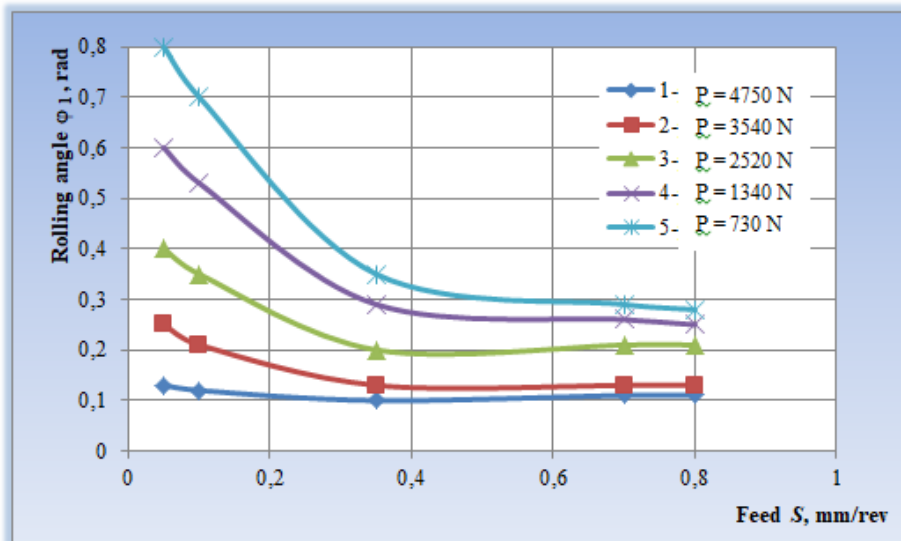

Fig. 3. Effect of the angle of coverage of the roller by the material of the part in the direction submissions φ_1 from feed *S* mm/rev
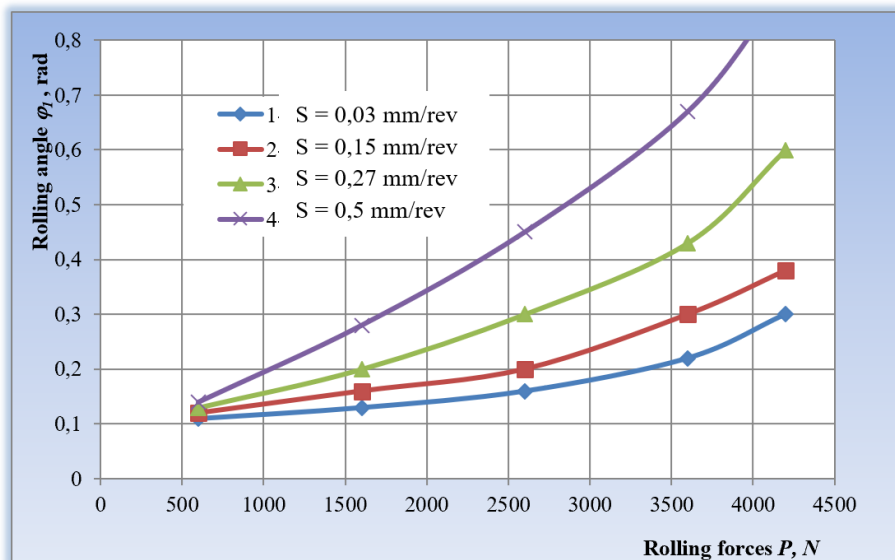

Fig. 4 Effect of the angle of coverage of the roller by the material of the part in the direction submission φ_1 from rolling force *P, N*

With the rolling force increases, the wave of metal in front of the roller increases, and at low feeds of about 0.05 mm/rev and rolling forces of more than 4,000 N reaches very significant sizes, which can lead to complete destruction of the machined surface. The

regression equation obtained when processing experimental data as a result of planning experiments is linear due to the statistical insignificance of the coefficients for the quadratic terms of the mathematical model used. But from the graph of the dependence of the angle φ_2 on the feed S (Fig. 5) and the rolling force (Fig. 6) it is clear that such an approximation will approximately correspond to the actual picture of the change in the metal wave angle behind the roller φ_2 at low rolling forces 730 ... 1340 N.
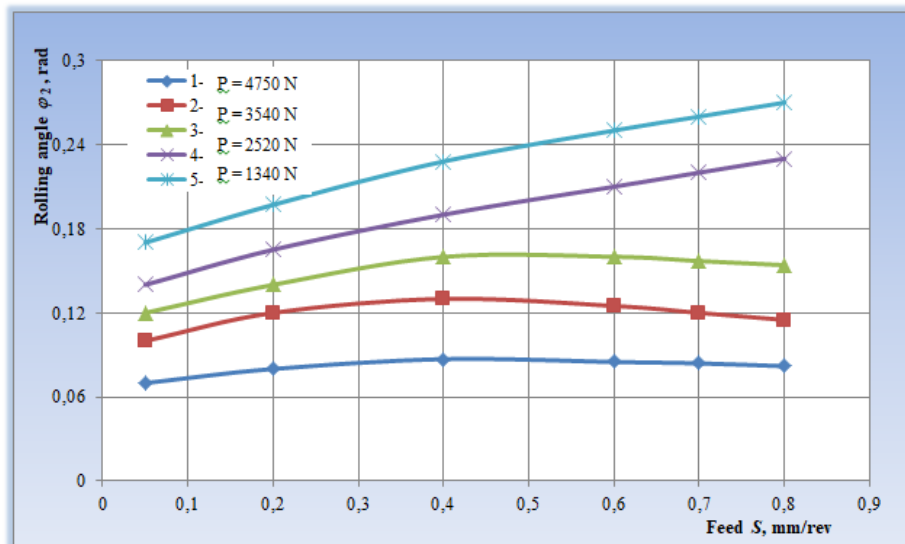

Fig. 5 Effect of the angle of coverage of the roller by the material of the part in the reverse direction φ_2 from feed S mm/rev

At high rolling forces, the dependence of the angle φ_2 on the feed will be nonlinear. A similar nonlinearity also occurs during rolling with low forces (730 ... 1340 N), but it is observed only at low feeds up to 0.27 mm /rev, a further increase in feed leads to stabilization of the angle φ_2 and the dependence graph becomes straight, parallel to the x-axis. The curve of the change in the metal wave angle behind the roller φ_2 will have a similar character: from feed during rolling with significant transverse conditions, only in this case stabilization of the angle φ_2 occurs at large feed values that go beyond the considered range of modes.

The fact that stabilization will occur follows from the physical essence of the processes occurring in the plastic deformation zone, since the considered angles of metal coverage of the part cannot decrease or increase indefinitely, and the size of the contact zone certainly has its limitations. Stabilization of the contact zone will apparently occur at the moment when the angles of coverage of the roller with the metal of the part in front of the roller and behind it become equal.

Analysing the entire feed interval under study, it can be noted that at low feeds, the flow of material occurs mainly from under the roller in the direction of feed, that is, in front of the roller, while the proportion of the metal wave angle in front of the roller in the total, total angle of coverage of the roller with the metal of the part with increasing feed decreases, and the fraction of the metal wave angle behind the roller increases. When rolling with a force of 500 N and above and at low feeds of 0.0 3 ... 0. 27 mm/rev, a significant wave of plastic flow of the metal is formed in front of the roller. The deformation of the surface layer of the part

under such conditions is of a completely different nature than when the roller is pressed into a stationary part with the same force, and the deformation pattern changes with increasing feed, and a redistribution of the metal occurs in the plastic deformation zone.
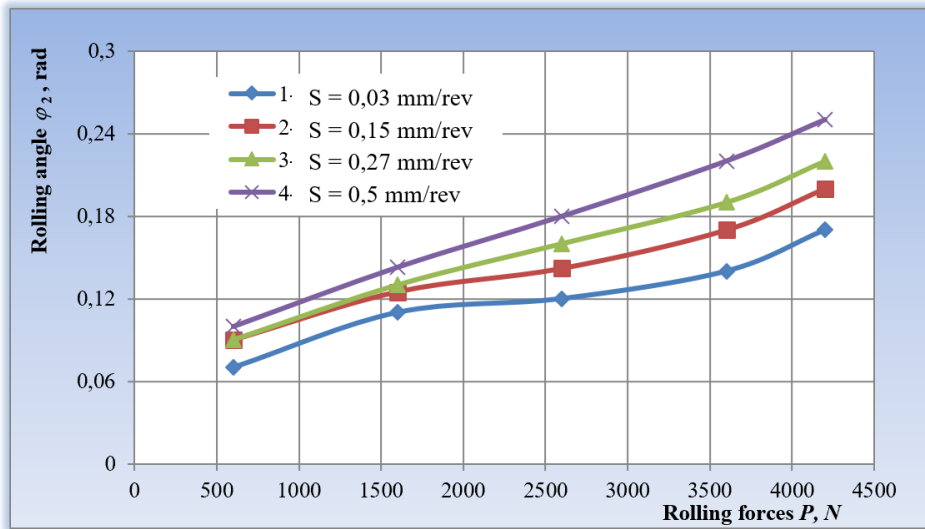

Fig. 6 Effect of the angle of coverage of the roller by the material of the part in the reverse direction φ_2 from the rolling force P, N

3. CONCLUSIONS

Based on the results of studies of the geometric parameters of the plastic deformation zone determined by the full-scale photographic method, it was established that the size of the zone itself, the distribution of metal in it, and the change in the angles of coverage of the roller with metal are determined by the ratio of processing modes. At small feeds, a metal wave of very significant height is formed from under the roller in the direction of feed. if the rolling process is interrupted, the presence of such a wave makes it possible to obtain significant surface roughness if the rolling process is interrupted. The relationship between the beginning of the destruction process and the characteristics of the process of deformation of the surface layer of the part is confirmed by the process of peeling of the contact surface, which causes wear to begin under certain modes, which are characterized by a certain size of the contact zone of the roller with the part. Additional studies of the deformation zone when rolling with a roller with a profile radius of 8 mm determined the dependencies angles of coverage of the roller with metal from the processing modes, differing in absolute value, and have a similar character as when rolling with a roller with a profile radius of 2 mm.

REFERENCES

[1]   LUKYANOV A.A., BOBROVSKY N.M., BOBROVSKY V.V., MELNIKOV P.A., EZHELEV A.V., 2013, *Directions of Development of Surface Plastic Deformation of Machine Parts,* International Scientific and Practical Conference – Modern Directions of Theoretical and Applied Research 2013, Odessa, Kuprienko, T.3, 1, 56–68.

[2]   BUI L-V., MAC T-B., NGUYEN D-T., 2023, *Surface Roughness Investigation Through Interplay of Cutting Speed and Thermal-Assisted Machining in High-Speed Machining of SKD11 Steel*, Journal of Machine Engineering, 23/4, 33–42, https//doi.org/10.36897/jme/170980.

[3]   PHAM H-T., ZH G., BULEKBAYEVA A.U., TABYLOV A.Z., BUKAYEVA N.B., et al., 2024, *Analysis of One-Dimensional Inelastic Deformation of the Clad Layer by Rolling for Restoration of Flat Surface Parts*, Journal of Machine Engineering, 24/1, 87-102, https://doi.org/10.36897/jme/185475.

[4]   CHEPA P.A., 1981, *Technological Foundations of Hardening of Parts by Surface Deformation*, Mn.: Science and Technology, 128.

[5]   BOBROVSKY N.M., BOBROVSKY I.N., EZHELEV A.V., MELNIKOV I.T., 2012, *Technology of Processing Parts by Surface Plastic Deformation Without the Use of Lubricating and Cooling Technological Means,* Samara Scientific Center of the Russian Academy of Sciences, Samara, 142.

[6]   LE M.T., VAN A-L., NGUYEN T.T., 2023, *Performance Optimization of Multi-Roller Flat Burnishing Process in Terms of Surface Properties*, Journal of Machine Engineering, 23/2, 159-173, https://doi.org/10.36897/jme/161661.

[7]   BOBROVSKY N.M., 2008, *Development of the Scientific Foundations of the Process of Machining Parts by Surface Plastic Deformation Without the Use of Lubricants*, Tolyatti, Tolyatti State University, 170.

[8]   KALISZ J., ZAK K., GRZESIK W., CZECHOWSKI K., 2015, *Characteristics of Surface Topography After Rolling Burnishing of EN AW-AlCu4MgSi(A) Aluminium Alloy*, Journal of Machine Engineering, 15/1, 71–80.

[9]   ZAIDES S.A., CUONG N.C., 2018, *The Influence of New Kinematics of the Rolling Roller on the Quality of the Hardened Layer Under Surface Plastic Deformation,* News of Higher Educational Institutions, Mechanical engineering, 2, 695, 58-67, https://doi.org/10.18698/0536-1044-2018-2-58-67.

[10]   SERGEEV N.N., SERGEEV A.N., KUTEPOV S.N., GVOZDEV A.E., AGEEV E.V., 2019, *Influence of Operating Modes of High-Temperature Thermomechanical Processing on Mechanical Properties of Reinforcing Bars,* Proceedings of the Southwest State University, 23/2, 29–52, https://doi.org/10.21869/2223-1560-2019-23-2-29-52.

[11]   KARAMYSHEV A.P., VICHUZHANIN D.I., NEKRASOV I.I., NESTERENKO A.V., PARSHIN V.S., SMIRNOV S.V., FEDULOV A.A., SHVEIKIN V.P., 2016, *Investigation of Strain Hardening and Damage of Billets from Heavy Tungsten-Based Alloys.* International Scientific and Technical Conference, Nano-technology of Functional Materials (NFM 16), Snkt-Petersburg, June 21–25, 148–154.

[12]   BULEKBAEVA G.Z., KIKVIDZE O.G., KIPIANI P.N., MINDADZE S.O., 2016, *Plastic Deformation as a Means to Eliminate Defects Such as Cracks in Welded Joints*, Kutaisi. Bulletin of Akaki Tsereteli State University, 1/7, 45–60.

[13]   KIKVIDZE O.G., TULEUGALIEVA G.B., BULEKBAEVA G.J., BEKENOVA A., BALASHOVA G., 2011, *Calculation of the Boundary Layer During Plastic Deformation of Surfaces*, Engineering News of Georgia, 4/60, 51–55.

[14]   CUONG N.C., ZAIDES S.A., QUANG L.H., 2018, *Hardened Layer Quality Evaluation at Surface Plastic Deformation by Rollers of Different Designs*, Mechanical Engineering and Machine Science, 22/1, 30–37, https://doi.org/10.21285/1814-3520-2018-1-30-37.

[15]   ZAIDES S.A., NGO K.K., 2017, *Increasing the Stress State in the Deformation Zone for Cylindrical Parts Under Surface Plastic Deformation*, Izvestie vysshikh uchebnykh zavedenii, Mashinostroenie, Proceedings of Higher Educational Institutions, Machine Building, 5, 52–59.

[16]   NESTERKIN G., KONKIN M., GOLINITSKY P., CHERKASOVA E., ANTONOVA U., 2023, *Justification of the Method of Surface Plastic Deformation to Strengthen the Surface of the Shaft Under the Cuff During Repair*, E3S Web of Conferences, 458, 10017, 1–7.

[17]   ZHAO P., WU Q., YANG Y.-L., CHEN Z., 2023, *Process Optimization of the Hot Stamping of AZ31 Magnesium Alloy Sheets Based on Response Surface Methodology*, Materials, 16, 1867, 1–14, https://doi.org/10.3390/ma16051867.