Experimental research of features of surface treatment using plastic deformation

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Abstract. This study is devoted to the processing of external cylindrical surfaces by surface plastic deformation. The slip-page of tapered rollers during rolling of cylindrical samples made of steel 35 and 45 has been studied. A diagram is presented for determining the slippage during treatment by surface plastic deformation, as well as a section of a diagram chart with signal recording. It is according to this section that the pulses from current collectors in contact with roller surfaces and workpieces assigned to a specific recording length have been counted. The depth of penetration of the deforming roller into the workpiece and its effect on the roughness of the treated surface have been determined. The results of experimental studies are presented as graphs of dependence of slippage change on self-feed and penetration angles, of roughness on deformation rate as well on penetration and self-feed angle. It has been shown that the deformation force remains practically unchanged at self-feed angles ranging from 0 to 3 degrees. Therefore, a decrease in surface roughness of the treated samples can be explained by the presence of slippage of the contacting surfaces of the rolled workpiece and the deforming roller. It has also been found that if one installs a tapered roller with a smaller base in the feed direction, the roughness is slightly reduced, compared to installing the same deforming element with the same base in the direction opposite to the feed.

1. Introduction

When treating external cylindrical surfaces, one of the most high-performance and cost-effective types of processing is surface plastic deformation (SPD), which is being increasingly used. As a result of SPD, the hardness of the surface layer increases, favorable residual stresses are formed, roughness decreases [1–3], and, in some cases, the accuracy of workpiece dimensions increases.[4–6]

SPD occurs due to the forced rolling of the deforming element in the form of a solid of revolution along the surface to be treated under the influence of deformation force applied to it. [1]

Depending on the necessary quality of the surface layer and the productivity of SPD, the deforming element may have various shapes and sizes. [5,6]

2. Objective

The dependence of the roughness change on the penetration angle and the presence of a minimum on the graph, when a certain penetration angle is reached, were previously known. Yu.G. Schneider [1] and E.G. Konovalov [2] explain this correlation between the change in roughness and the penetration angle by a change in the contact area. As the penetration angle increases, the contact area decreases. This causes an increase in contact stresses and a decrease in roughness. When a certain contact value is reached, rehardening takes place and the roughness increases. [7,8] This explanation is qualitative
and is not based on any calculated data or theoretical assumptions. Therefore, it is not the only possible or the complete one.

Experimental studies were carried out to use the slip-page phenomenon to explain the influence of the installation angles of deforming elements on the roughness of the treated surfaces. This may add to the explanation and reveal new features of SPD.

3. Materials and methods

When planning and preparing experimental studies, the required number of measurements was chosen for a given error, using a specific measurement method and a specific device. [9,10]

To conduct experimental studies of geometrical parameters of the contact zone, samples (Figure 1) were manufactured on a 1K62 screw-cutting lathe using steel 45 and 35. To increase the reliability of studies, preliminary and final processing of samples was carried out on the machine without reinstallation, which helped to eliminate the runout of samples. Roughness was measured using the TR200 profilometer.

The processing was carried out by an adjustable roller, which allows to set the penetration and self-tightening angles more accurately, as well as to use a deforming element of random configuration, installed between the track rollers, at a given position relative to an axis of a work-piece.

The effect of the penetration value, the relief angle, the self-tightening angle, as well as the size and configuration of the deforming element on roughness has been studied.

The depth of penetration of the deforming element into the treated surface is one of the main features. It includes formulas for determining the deformation force, geometric parameters of the contact pattern, contact stresses, etc. Today, there are no exact design dependencies that would make it possible to determine the depth of penetration of the deforming element into a surface through the deformation force, contact pattern parameters, etc. Therefore, the penetration depth was determined as follows. During the introduction of the deforming element into the treated surface, a 0.005 mm-thick sheet of carbon copy paper was placed. As a result, after load removal, two prints of different sizes have been obtained on the piece of paper and on the surface of the workpiece. The difference in sizes of these prints determined the elastic recovery of the treated surface.

The slippage of the deforming element relative to the surface of the rolled sample was determined as follows (Figure 1a). An insulated current collector 1 was fixed to the holder mounted on the tail stock of the 1K62 screw-cutting lathe. Current collector 2 was installed in the roller head and was in contact with the surface of the deforming element 5, which was not in contact with the rolled workpiece. If it is necessary to bring into contact the entire surface of the deforming element with the surface of the workpiece, for example, when the generatrix of the tapered deforming roller is parallel to the axis of the rolled workpiece, then the roller has a stepped shape, and the current collector 2 is in contact with the lower step of the roller. A thin layer of insulating material is applied to the surfaces of the deforming element and the rolled workpiece in contact with current collectors 1 and 2. During rotation of the workpiece, the insulating layer acts as a chopper. A voltage is applied to the current collectors, which is a signal with a frequency equal to the number of revolutions of the deforming element and the rolled workpiece. This signal is transmitted to a recorder which records readings on a chart tape. Then, the number of impulses received from the current collectors of the deforming element and the rolled workpiece, assigned to certain processing time, has been determined.

The DC voltage supplied to the probes is transmitted as a stepwise signal, containing data on the roller and the workpiece speed, to a high-speed recording device and is recorded on a diagram chart (Figure 1b). After that, the number of impulses coming from roller probes and the workpiece, assigned to specific record length, is counted.
Figure 1. Experimental evaluation of slippage. (1, 2—current collectors, 3, 4—layer of insulating coating, 5—deforming element, 6—rolled workpiece); b) recording of a signal on a diagram chart.

The studies have been carried out to treat the outer surface of a 80 mm cylindrical workpiece by deforming element shaped as a 18 mm tapered roller at various penetration depths and penetration and self-tightening angles.

4. Results and Discussion
Based on the experimental data, dependence graphs of the difference between ratios of the number of deforming elements’ revolutions have been obtained experimentally (Figure 2).

Figure 2. Dependence of changes in slippage $\Delta n_r/n_d$ on the self-tightening angle $\alpha$ (a), penetration angle $\gamma$ (b), and penetration depth $h_m$ (c).
As can be seen from Figure 2a, as the self-tightening angle increases, slippage increases, but as the penetration angle increases, slippage decreases (Figure 2b). This is explained by the fact that when the deforming element is installed at the self-tightening angle, circumferential slippage occurs, which is directed opposite to the direction of rotation of the rolled workpiece. A decrease in the slip-page value with an increase in the penetration angle is explained by a decrease in the contact area of the deforming element and the rolled surface. As a result, total slippage also decreases. Slippage also increases as the depth of penetration of the deforming roller into the rolled surface increases (Figure 2c). This points to the fact that the material is being displaced from the contact zone to its less loaded areas in the direction of supply of the deforming element.

Then, roughness of rolled surfaces was measured using the TR220 profilometer. As a result, it was found that the angles of self-tightening and penetration of the deforming element relative to the workpiece axis have a significant effect on the roughness of the treated surface. Figure 3 shows graphs of dependence of changes in the roughness of the rolled surface on the change in penetration (Figure 3a) and installation angles of the deforming element (Figure 3b). It can be seen from the graphs that, as the angle of penetration increases, the roughness of the treated surface first decreases and, having reached the minimum value at an angle of 0.66 degrees, increases.

The decrease in roughness with an increase in the self-tightening angle (Figure 3b) can also be explained by the presence of slippage, since the change of the area of the contact pattern within the range of variable angles of self-tightening, is small. If we consider the graph representing changes of the slippage rate (Figure 3b) and compare it with the graph representing changes in roughness versus the self-tightening angle (Figure 3b), we can see their inversely proportional dependence. However, in [1] it is noted that the rolling speed hardly affects the roughness of the treated surface. This means that in order to determine the influence of slippage between the surfaces of the deforming element and the surface of the workpiece on the obtained roughness, it is necessary to identify discrepancies in smoothing and slipping during rolling.

The difference between slipping and smoothing, in addition to different values of sliding rates, lies in the direction of slipping. During rolling, slippage between the surfaces of the deforming element and the surface of the workpiece is directed towards the feed and perpendicular to the direction of rolling of the deforming element. During smoothing, the sliding of the surface of the indenter is directed around the circumference of the workpiece.

![Figure 3](image-url). Dependence of changes of the roughness of the treated surface on the penetration angle (a) and the self-tightening angle (b).
One more feature of sliding is a change in its value within the contact zone according to a certain dependence. With that in mind, the differences arising during the formation of the surface layer of the treated workpiece are determined by the nature of slippage of the deforming element relative to the rolled surface. To determine the effect of slippage on the surface roughness of deforming elements of various configurations, experimental studies have been carried out. In these studies, a deforming element shaped as a tapered roller was installed with larger and smaller bases in the feed direction at the same self-tightening and penetration angles. From the graphs obtained (Figure 3b), it can be seen that when installing a tapered roller with its smaller base in the feed direction, the surface roughness is lower than when installing the same roller with a larger base in the same direction. This phenomenon can be explained by the fact that, when a tapered roller is installed with its smaller base in the feed direction, its radius increases in the direction of that part of the contact where smoothing occurs. This leads to an increase in slippage.

5. Conclusion

Experimental dependences of changes in roughness of the treated surface on the angles of self-tightening and penetration, as well as the location of the roller relative to the workpiece, have been obtained. It was found that, with an increase in the self-tightening angle, the surface roughness of the treated samples decreases. In this case, the contact area and voltage, with a change in the self-tightening angle in the range from 0 to 3 degrees, changes insignificantly. Therefore, the decrease in roughness can be explained by the presence of slippage between the deforming element and the rolled workpiece.

Studying the phenomenon of slippage between the surfaces of the deforming element and the workpiece to explain the influence of penetration and self-tightening angles on roughness can complement the explanation and reveal new features of SPD.

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