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Determination of the stress state in the deformation zone under local loading

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Abstract Based on the theory of small elastoplastic deformations and the finite element method, a mathematical model of local loading was created using the ANSYS application program, which allows determination of the stress state in the deformation zone and residual stresses in the hardened part. Paper studies the influence of various factors on the stress state: ball diameter, penetration depth and the cylindrical sample diameter. The results show that using the finite element method in the analysis of technological processes of hardening gives a deeper understanding of the stress development that occurs during the deformation of the workpiece. The process in question can be implemented without the use of environmentally hazardous lubricating cooling technological means, which makes it possible to attribute it in the future to one of the types of green mechanical processing technologies.

1. Introduction

The processing of parts by surface plastic deformation (SPD) is one of the main ways to improve the reliability of machine parts. Currently, there is a large variety of SPD methods, which are classified in accordance with GOST 18296–72 [1]. Among the deformation methods of hardening machine parts, the local ones were widely adopted: running in with a ball, roller, disc, and smoothing with a diamond indenter. A characteristic feature of these methods is the stability of the shape and size of the source of deformation. The intensity of plastic deformation of the surface layer depends on the technological factors of processing: the strength, shape and size of the deforming element, the feed, the properties of the material being processed [2, 3]. The stress state that occurs in the deformation zone during the flow of metals is a complex process and has not been studied to date.

The quality assessment of the hardened layer after the SPD has been the subject of many studies, in particular [4, 5]. The influence of SPD on the roughness and waviness of the surface, the depth of hardening,

the values of residual stresses, contact stiffness and endurance was established. It should be noted that experimental studies were carried out mainly "around" the center of plastic deformation. For the study of the center of change, mainly indirect methods were used: flow lines (current), long grids, slip lines, the polarization-optical method, etc. [6, 7]. Important results for science and practice have been obtained, but they are mostly qualitative in nature, since the deformation zone remains a "black box".

Currently, methods SPD exhausted their technological capabilities. There is a search for new loading schemes and energy sources to solve the set tasks [8, 9]. To assess the capabilities of new technologies, it is necessary to compare the stress-strain state with simple well-known loading schemes with a local tool [10, 11].

The aim of the work is to study the stress and residual states of the surface layer of parts when a rigid ball is pressed into the cylindrical surface of an elastoplastic body.

2. Simulation of the local loading

The numerical solution of the elastoplastic problem for an inhomogeneous material is performed using the ANSYS program, based on the finite element method and designed to calculate stresses and strains in a loaded body. Consider the effect of the depth of the ball penetration, the diameter of the ball and the scale factor on the stress state of the surface layer of a cylindrical part.

Formation of the computational domain geometry was performed according to scheme qi-cylindrically sample loading surface hard ball, shown in figure 1 together with a model
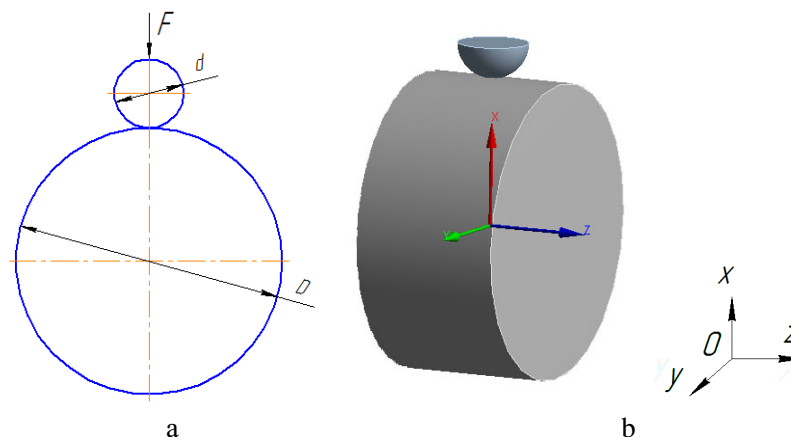

Figure 1. Scheme (a) and model (b) of loading a cylindrical specimen with a rigid ball.

Characteristics of a cylindrical sample: surface shape - cylindrical ($D = 15$ mm); material - steel 45 - elastic-plastic, hardening; elastic modulus $E = 2 \cdot 10^5$ MPa; Poisson's ratio $\mu = 0,3$; material deformation diagram - bilinear, described by yield strength $\sigma_m = 360\ MPa$, elastic modulus E and hardening module $E_\text{т} = 1,45 \cdot 10^3$ MPa.

Indenter characteristics: type - ball; material - VK8 alloy; elastic modulus $E = 6 \cdot 10^5$ MPa; Poisson's ratio $\mu = 0,3$.

3. Simulation results

Consider the influence of the main parameters of the deformation process on the stress state in the deformation zone and the residual equivalent stress after unloading.

- Influence of the depth of the ball (d = 10 mm).

Figure 2 shows examples of the distribution of temporary stresses under the fingerprint of the axis at various depths of its introduction t = 0.1; 0.2 mm. As can be seen from fig. 2, an increase in the depth of penetration of the ball leads to an increase in temporal stresses, and the residual stresses increase to a maximum value and then decrease (in the case under consideration at t = 0.1 mm). This is explained by the existence of an optimal depth of penetration, above which a depletion of plasticity occurs and the surface layer is over-clipped, which results in a decrease in residual stresses.
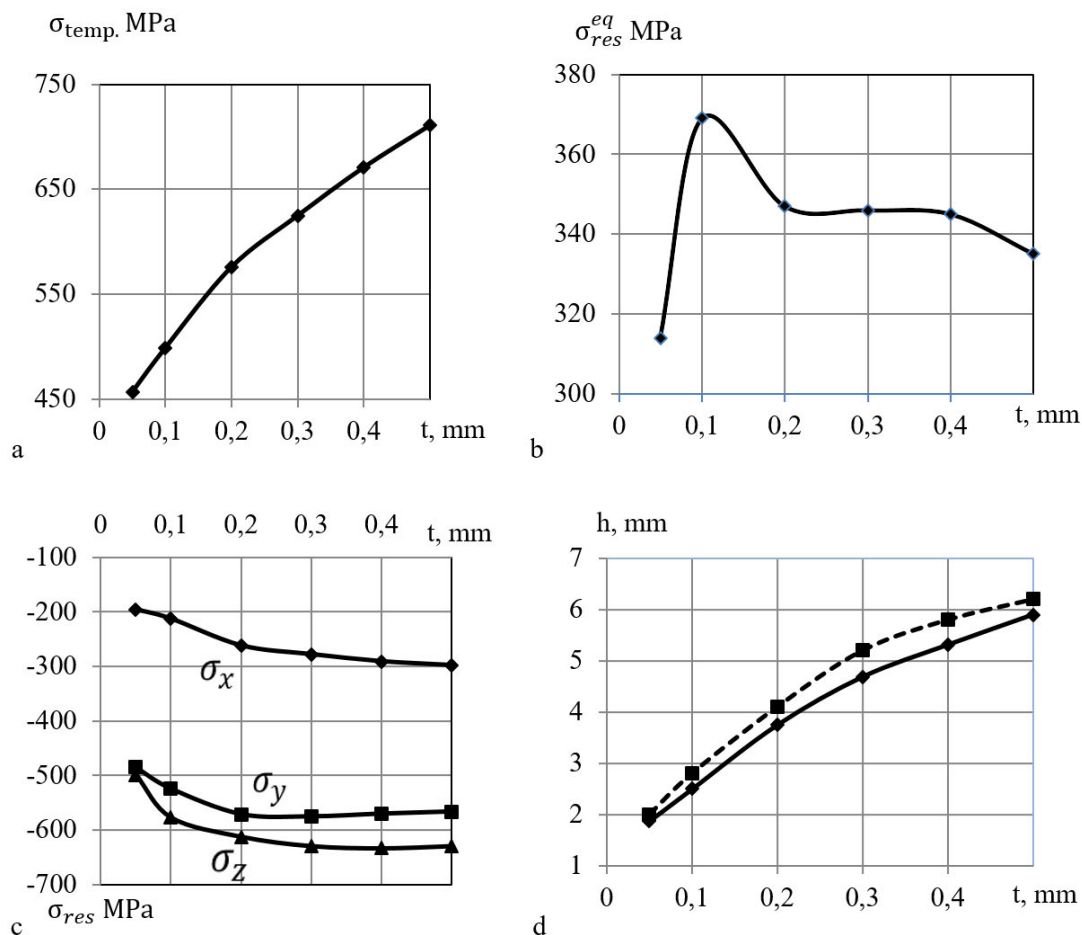

Figure 2. Dependence of equivalent temporary stress σ_{temp}^{eq} (*a*), maximum equivalent residual stress σ_{res}^{eq} (b), components $\sigma_{x,res}, \sigma_{y,res}, \sigma_{z,res}$ of maximum residual stress (c) and the depth h of hardened layer (d) under the imprint depth t of the ball penetration into the cylindrical surface ($-----$ experimental results [10]).

Slight discrepancy between tangential $\sigma_{y,res}$ and axial $\sigma_{z,res}$ maximum residual stresses when loading the cylindrical surface is explained by the round shape of the sample.

With a certain geometry of the deforming tool, the depth of hardening increases almost in direct proportion to the depth of the ball penetration into the cylindrical surface. The results of computer simulation correspond to the experimental data given in [12, 13].
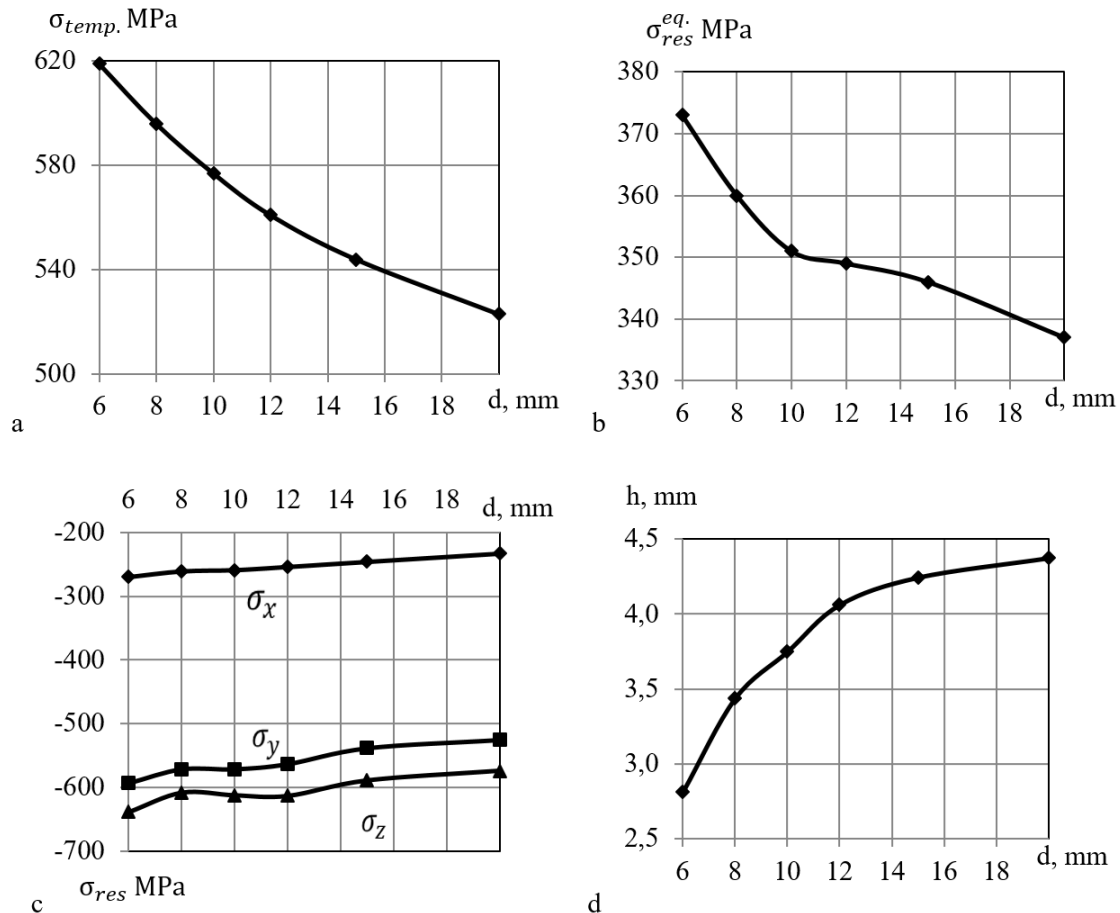
- Influence of the ball diameter (t = 0,2 mm).

Figure 3. Dependence of equivalent temporary stress σ_{temp}^{eq} (a), maximum equivalent residual stress σ_{res}^{eq} (b), components $\sigma_{x,res}$, $\sigma_{y,res}$, $\sigma_{z,res}$ of maximum residual stress (c) and the depth h of hardened layer (d) under the imprint of the ball with diameter d.

Analysis of the simulation results showed that the defining parameter affecting the magnitude of residual compressive stresses is the diameter of the ball used in the processing of SPD. On the curves resulted on figure 3, it can be concluded that at a constant depth of the ball penetration with an increase in the diameter of the deforming tool, the contact surface increases. This reduces the stresses that shift the front of the metal, as well as temporary and residual with their components. This is explained by the fact that with small diameters of the balls beneath them, when inserted into a cylindrical surface, an elastoplastic wedge is formed, the effect of which on the stress state in the deformation zone spreads more than with large diameters of balls [14, 15, 16]. At constant penetration depth, an increase in the ball diameter leads to an increase in the depth of hardening.

- Influence of the sample diameter (t = 0,2 mm).

The intensity of stresses in the deformation zone depends not only on the tension, the size of the deforming tool, but also on the diameter of the sample (workpiece). From figure 4, and it can be seen that the small temporary diameters D of the billet correspond to large temporary stresses, but as the diameter increases,

the voltage smoothly decreases and, beginning with D = 60 mm, practically ceases to vary. With the same depth of indentation of the ball with an increase in the diameter of the sample, the temporal stresses gradually decrease, and the residual stresses increase. With a diameter D> 60 mm, their values practically do not change. With a constant ball size and penetration depth with increasing sample diameter, the depth of hardening increases to a certain value (figure 4, d).
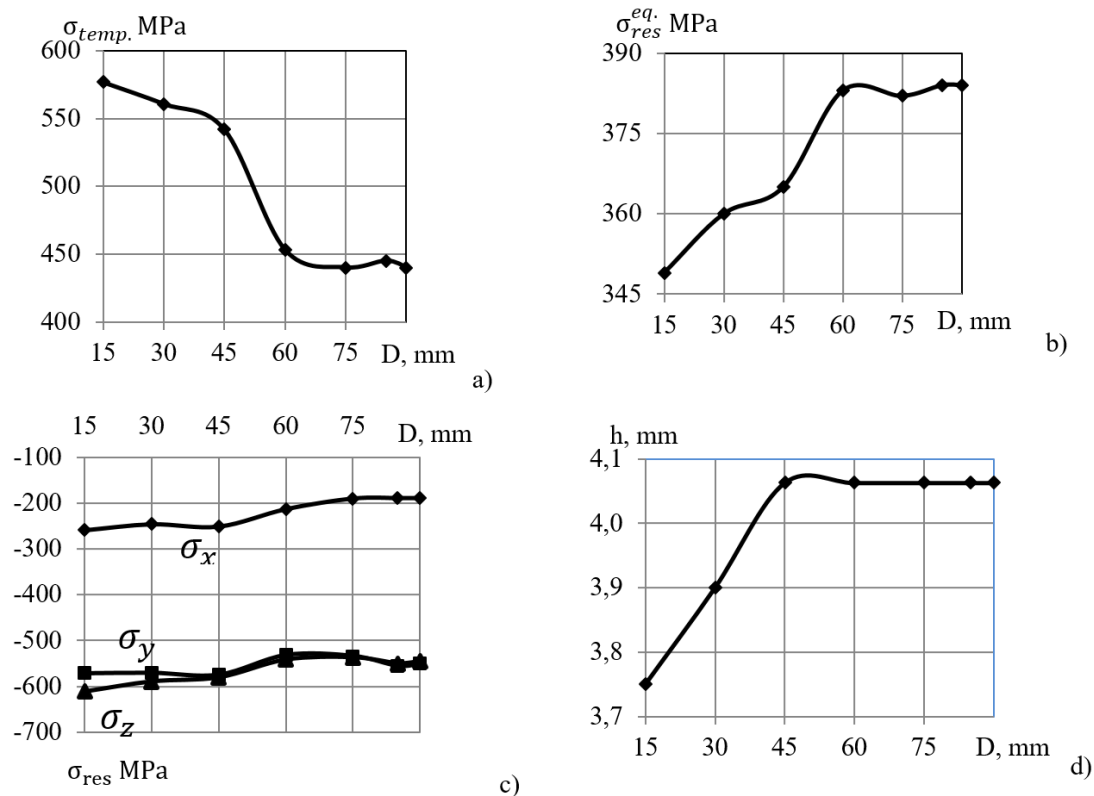

Figure 4. Dependence of equivalent temporary stress σ_{temp}^{eq} (*a*), maximum equivalent residual stress σ_{res}^{eq} (b), components $\sigma_{x,res}, \sigma_{y,res}, \sigma_{z,res}$ of maximum residual stress (c) and the depth *h* of hardened layer (d) under the imprint of the sample with diameter *D*.

4. Conclusions

Based on the finite element method, a computational mathematical model of the process of pressing a ball into an elastoplastic body has been developed, which allows determining the stress state in the deformation process and the residual stress state under local loading.

The effect of the introduction depth of the deforming tool diameter and of the scale factor on the stress state of the part:

- there is an optimal value of the depth of the ball at which the maximum compressive residual stresses are formed (in this case, t = 0.1 mm);
- an increase in the diameter of the deforming ball leads to a decrease in the magnitude of the residual stresses;

- with increasing diameter of the cylindrical sample to a certain value (in this case, D = 60 mm) of the stresses remain practically unchanged.

Acknowledgments

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