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FORMATION OF GRADIENT NANOSTRUCTURES ON THE SURFACE OF PARTS BY SHOT BLASTING

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Abstract A theoretical model predicting nanostructured layer thickness in shot blasting is developed, linking technological parameters (pressure, shot size, angle) with material yield strength. Derived from contact mechanics and validated against experimental data, the model shows thickness is proportional to $\sqrt{\text{pressure}}$ and inversely proportional to $\sqrt{\text{yield strength}}$. This provides a practical tool for optimizing surface hardening to enhance fatigue strength and wear resistance in critical machine components..

Keywords: shot peening, gradient nanostructured layer, analytical model, yield strength, plastic deformation, contact problem, theoretical prediction, hardening thickness, railway carriage.

Анотація Розроблено теоретичну модель, що дозволяє прогнозувати товщину наноструктурного шару при дробеструйній обробці, пов'язуючи технологічні параметри (тиск, розмір дробу, кут) з межею текучості матеріалу. Модель, отримана на основі механіки контакту та перевірена експериментальними даними, показує, що товщина пропорційна $\sqrt{\text{тиску}}$ та обернено пропорційна $\sqrt{\text{межі текучості}}$. Це є практичним інструментом для оптимізації поверхневого зміцнення з метою підвищення втомної міцності та зносостійкості критичних деталей машин.

Ключові слова: дробеструйне зміцнення, градієнтний наноструктурний шар, аналітична модель, межа текучості, пластична деформація, контактна задача, теоретичне прогнозування, товщина зміцнення, залізничний вагон.

Introduction

Improving the performance and service life of machine parts is a key task. An effective method of surface strengthening is shot peening, which is based on the phenomenon of cold plastic deformation of the surface layer from the impact of a stream of shot. This leads to the formation of a gradient nanostructured layer. To obtain the desired layer characteristics in a controlled manner, a quantitative model is needed that links the technological parameters to the properties of the material. The development of such a model is a relevant scientific and applied task [1,2].

Research results

Method for determining the hardened (nanostructured) layer.

To analyse this process, a classical solution of elasticity theory for a half-space loaded by a concentrated force was applied [3]. The corresponding calculation model is shown in Fig. 1.

Let the plane $z = 0$ be the edge of a semi-infinite solid body, and let a concentrated force P act on this plane along the z -axis. In the literature, this problem is called the Bussinescu problem.

The action of a concentrated force on the boundary of a semi-infinite array (Bussinesk's problem) For radial stress, we can take as a first attempt the formula [4]:

$$\sigma_R = -kP \frac{\cos \theta}{l^2} \quad (1)$$

where P is the impact force,

Moving to cylindrical coordinates, according to the conversion formulas, we should obtain

$$\left. \begin{aligned} \sigma_z &= \sigma_R \cos^2 \theta \\ \tau_{rz} &= \frac{1}{2} \sigma_R \sin 2\theta \end{aligned} \right\} \quad (2)$$

Replacing $\cos \theta = \frac{z}{l}$, $\sin \theta = \frac{r}{l}$, $\frac{1}{2} \sin 2\theta = \frac{rz}{l^2}$ и $l^2 = z^2 + r^2$, we have:

$$\sigma_z = -kP \frac{z^3}{l^5}, \quad (3)$$

$$\tau_{rz} = -kP \frac{z^2 r}{l^2}. \quad (4)$$

To determine the displacements, we use equation (2). The displacement component along the radius r

$$u = \varepsilon_{\theta} r = \frac{r}{E} [\sigma_z - \mu(\sigma_r + \sigma_z)]. \quad (5)$$

After substituting (5) into expressions (2) and transformations, we obtain

$$u = \frac{P}{4\pi G} \left[\frac{rz}{l^3} - (1 - 2\mu) \frac{r}{l^2 + lz} \right] \quad (6)$$

For vertical displacements of points on the boundary plane $z = 0$ for the so-called "day surface" we obtain the expression:

$$w_{z=0} = \frac{P(1 - \mu^2)}{\pi E r}. \quad (7)$$

Thickness of nanostructured layer (basic formula)

From (19) the layer thickness is expressed as the width of the contact zone: δl

$$\delta = l = \sqrt{\frac{2}{3} \frac{P}{\pi \sigma_T}} \quad (8)$$

The impact force of one pellet

$$P = p_0 \pi R^2 \sin \alpha \quad (9)$$

where is the pressure in the air jet with the shot, p_0

R – radius of the grain,

α – the angle between the jet and the surface of the part.

Final calculation formula for layer thickness

After substitution into formula (20): P

$$\delta = R \sqrt{\frac{2}{3} \frac{p_0 \sin \alpha}{\sigma_T}} \quad (10)$$

where: δ – thickness of the nanostructured surface layer,

R – radius of the grain,

p_0 – pressure in the jet,

α – angle of incidence of the jet,

σ_T – yield strength of the material of the workpiece.

Based on calculations according to formula (10), the following table of calculated values of the thickness of the nanostructured layer (δ) can be compiled depending on the yield strength of the material (σ_T) and the pressure in the jet (p_0).

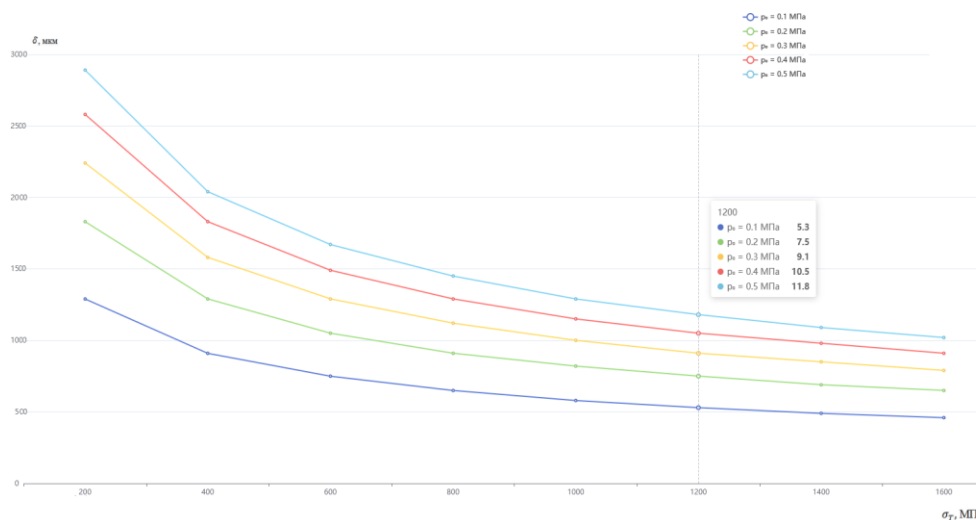
Initial data for calculation:

Particle radius, $R = 10^{-4}$ m (0.1 mm)

Angle of incidence of the jet, $\alpha = 30^\circ$

$\sin(30^\circ) = 0.5$

Figure 2: Dependence of the thickness of the nanostructured layer of the processed material on the yield strength based on calculations [3]



1 – $p_0 = 0.1$ MPa; 2 – $p_0 = 0.2$ MPa; 3 – $p_0 = 0.3$ MPa, 4 – $p_0 = 0.4$ MPa, 5 – $p_0 = 0.5$ MPa

Fig. 2. Dependence of the thickness of the nanostructured layer of the processed material on the yield point:

Based on the solution of the Boussinesq problem, analytical expressions for the stress-strain state in the near-surface layer were obtained. The Mises plasticity criterion was used to describe the transition to the state of plastic deformation.

Conclusions

Based on the model, a numerical analysis was performed for typical conditions. The dependence of the layer thickness δ was calculated for materials with a yield strength of 200–1600 MPa at a pressure of 0.1–0.5 MPa, a grain radius of 0.1 mm and an angle of incidence of 30°. The results are presented in the table and graph. The analysis showed that the layer thickness is in the range of ~4.6–28.9 μm. It was established that the layer thickness is inversely proportional to $\sqrt{\sigma_T}$ and directly proportional to $\sqrt{p_0}$. For stronger materials, more intensive processing modes are required. The results are consistent with experimental data on the depth of hardening.

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