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Theoretical Studies of Laws Nanostructuring and Heterogeneous Hardening of Steel Samples by Wave Intensive Plastic Deformation

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Theoretical studies and calculations, allowing to define the required parameters of the wave deformation hardening, are performed in order to obtain heterogeneous hardened surface layer in steel samples. The conditions for the effective use of impact energy for elastic-plastic deformation of the processed material and the establishment of a deep hardened surface layer are revealed.

Keywords: Impact energy, Plastic deformation, Pressure, Surface layer, The wave deformation.

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1. INTRODUCTION

One of the main parameters of obtaining nanocrystalline structure methods is a pressure, applied to the workpiece surface. For methods of surface plastic deformation, depending on the application, there are the following recommendations for the pressure, generated in the deformation [1, 2]:

– finishing-calibrating processing is carried out at pressures less 1,5σ_m (where σ_m – deformable material yield stress of);

– for finishing- strengthening processing operating pressure ranges from 1,5σ_m up to 3σ_m;

– hardening and a forming processing is carried out at pressures more than 3σ_m.

Since for grinding of the crystal structure to nanoscale its intensive plastic deformation is necessary, then during hardening by wave deformation it is necessary to select such parameters, that generate a pressure not less than 3σ_m [3].

2. DESCRIPTION AND ANALYSIS OF RESULTS

The pressure at the center of the deformation zone p_0, during hardening by a shock wave of deformation, can be defined as [4]:

$$p_0 = \frac{3}{2}\frac{A_{e-p}}{\pi ab\alpha}, \tag{1}$$

where $A_{e\text{-}p}$ – impact energy expended on elasticiplastic deformation, j.;

a – major semiaxis of the ellipse, along which the contact of the tool and the workpiece surface is carried, mm;

b – semiminor axis of the ellipse, along which the contact of the tool and the workpiece surface is carried, mm;

α – elastic-plastic deformation of the loaded metal, mm.

semiaxes of print, resulting by elastic-plastic deformation, are determined [6]:

$$\begin{aligned} a &= \sqrt{R_{11}\left(2\alpha_a + \alpha_e\right) - \alpha_a^2}, \\ b &= \sqrt{R_{21}\left(2\alpha_b + \alpha_e\right) - \alpha_b^2}; \end{aligned} \tag{2}$$

$$\begin{aligned} \alpha_a &\approx \frac{\pm 2R_{12}\alpha_p - R_{11}\alpha_e}{2\left(R_{11} \pm R_{12}\right)}, \\ \alpha_b &\approx \frac{\pm 2R_{22}\alpha_p - R_{21}\alpha_e}{2\left(R_{21} \pm R_{22}\right)}, \end{aligned} \tag{3}$$

where α_a, α_b – distances, measured along the line of action of the contact load, from the level of the center of residual dent to the most distant from it (without the influx) contour points of elliptical contact area, mm;

α_p – plastic deformation of the heated metal, mm;

α_e – elastic deformation under elastic-plastic contact, mm;

R_{11}, R_{21} – profile tool radius mm;

R_{21}, R_{22} – radii of curvature of the loaded surface, mm;

Plastic deformation of the loaded metal (plastic indentation depth), formed under the influence of dynamic load, can be represented as

$$\alpha_P = \sqrt{\frac{A_{e-p}\varphi}{2\pi R_r}}, \tag{4}$$

where φ – plasticity coefficient, adopted from the range 0,93-0,98 depending on the hardness of the reinforcing material;
ND – plastic metal hardness, MPa;

$$DN = \left(\frac{HB}{1.96}\right)^{1/0.89}, \tag{5}$$

where HB – hardness, measured according to Brinell, MPa;

R_r – reduced radius of curvature of the tool and load surface contact, mm;

$$R_r = \frac{0.511}{B}\left(\frac{A}{B}\right)^{-0.46}, \tag{6}$$

$$\begin{aligned} A &= k_{11} + k_{12} = \frac{1}{R_{11}} \pm \frac{1}{R_{12}}; \\ B &= k_{21} + k_{22} = \frac{1}{R_{21}} \pm \frac{1}{R_{22}}, \end{aligned} \tag{7}$$

where A, B – the principal curvatures of the contact surfaces, 1/mm.

Elastoplastic deformation of the loaded metal is defined as:

$$\alpha = \alpha_p + \alpha_e , \tag{8}$$

where α_e – elastic deformation of the loaded metal under elastoplastic contact, mm.

$$\alpha_e = \frac{\alpha_0}{\sqrt[3]{1 + \dfrac{2\alpha_p}{\alpha_i}}} , \tag{9}$$

α_0 – elastic deformation of the loaded metal at a a purely elastic contact mm.

In purely elastic force contact the indenter convergence with a loaded surface is described by the Hertz equation:

$$\begin{aligned} &\alpha_0 = \frac{n_\delta}{2}\sqrt[3]{\frac{9\pi^2}{4}P^2\eta_e^2\sum k};\\ &\eta_e = k_i + k_m = \frac{1-\mu_i^2}{E_i} + \frac{1-\mu_m^2}{E_m};\\ &\sum k = A + B;\\ &n_\delta = 10^{0.0477+0.1788(\log(A/B))}, \end{aligned} \tag{10}$$

where P – contact load, N.

In the case of elastic-plastic loading of material by a shock wave of deformation, contact load during purely elastic contact will be equal to the static load, required for pre-kick compression of the waveguide with the tool to the loading surfaces, ie. $P = P_{st}$ [5].

Static load component in the wave deformation hardening of plane surfaces is defined as:

$$P_{\text{st}} = 0,1P_i, \tag{11}$$

where P_i – the amplitude of impulse, suitable for processed metal after hitting by the striker (the impact force)

$$\begin{aligned} &P_i = \frac{C_1C_2}{C_1 + C_2}v\\ &C_1 = \rho_1 a_1 F_1; \quad C_2 = \rho_2 a_2 F_2\\ &F_1 = \frac{\pi d_1^2}{4}; \quad F_2 = \frac{\pi d_2^2}{4}, \end{aligned} \tag{12}$$

C_1, C_2 – the acoustic stiffness of the striker and the waveguide, respectively, kg;

ρ_1, ρ_2 – the density of the material, of the striker and the waveguide, respectively, kg/m^3;

a_1, a_2 – speed of the shock wave propagation, respectively, in the striker and the waveguide, m/s;

v – speed of kick, m/s

$$v = \sqrt{\frac{2A_g}{m_1}} , \tag{13}$$

$$m_1 = \rho_1 L_1 F_1 , \tag{14}$$

m_1 – striker weight, respectively, kg;

A_g – impact energy of the pulse generator, J;

Determination of impact energy, expended on elastoplastic deformation $A_{i\text{-}ep}$ is carried as follows.

Resistance coefficient to introduction k is calculated:

$$\begin{aligned} &k = 2\pi R_r N D n_d \phi^{-1}\\ &n_d = 0.5\left(1 - 137\frac{v}{ND} + \sqrt{1 + 2250\frac{v}{ND}}\right), \end{aligned} \tag{15}$$

The energy of the impulse head portion $A_{k\,h}$ is calculated for an interval of $0 \le t \le T$, for $I = 1 \dots n$.

$$\begin{aligned} &T = \frac{2L_1}{a_1};\\ &b = \frac{k}{E_2F_2}; \quad \Delta = e^{-ba_2t}; \quad \psi = 1 - 2\Delta,\\ &R_0^* = \frac{r'-1}{r'+1}, \quad r' = \left(\frac{d_1}{d_2}\right)^2,\\ &P_{ki}^I = P_u\left(\psi R_0^*\right)^{i-1}\left(1+\psi\right),\\ &A_{ki}^I = \frac{P_{ki}^{I^2}}{2k},\\ &A_{kh}^I = \sum_{i=1}^{n} A_{ki}^I, \end{aligned} \tag{16}$$

where T – the duration of the shock impulse, s;

t – time coordinate, s;

I – the serial number of impulse, appropriate to the deformation zone in a given period of time;

Δ – coefficient component of passing shock impulse in the interaction of deformation wave with the elastic-plastic boundary;

ψ – the reflection coefficient of shock impulse in the interaction of deformation wave in the contact section of the waveguide with the elastic-plastic boundary;

E_2 – the elasticity modulus of the waveguide material, Pa;

R_0 – the reflection coefficient of the direct wave deformation;

r' – ratio of cross-sectional areas of the striker and the waveguide.

The resistance coefficient of introduction after action of the head portion impulse k_g is calculated.

Value of the contact force at any given time when $m \le n$, where $m = ta_2/(2L_2)$ (where m – the number of pulses, impacting on the work surface in a time t) is calculated:

$$\begin{aligned} &P_{kh} = \left(1+\psi\right)\left[\sum_{j=1}^{m}\sum_{i=0}^{m-j}\left(P_{uj}\Delta^{m-j-i}\left(\psi R_0^*\right)^i\right)\right] + \left(1+\psi\right)^2 R_0^*\Delta \times\\ &\times\left[\sum_{j=3}^{m}\sum_{i=0}^{m-j}\left(P_{uj-2}\Delta^{m-j-i}\left(\psi R_0^*\right)^i\right)\left(m-j-i+1\right)\left(i+1\right)\right] \end{aligned} \tag{17}$$

The value of the elastic-plastic introduction of tools under the influence of the head portion impulse is calculated:

$$\alpha_h = 10^3\sqrt{\frac{A_{kh}^I}{2\pi R_r N D}10^{-3}} . \tag{18}$$

The coefficient of introduction resistance under the influence of the tail part of shock impulse is calculated:

$$k_h = \frac{P_{kh}}{\alpha_h \cdot 10^{-3}} . \qquad (19)$$

The energy of the tail part of impulse A_{kt} is calculated for an interval of $T \le t \le 2T$, when $I = 1 \ldots n$.

At the beginning clarification of coefficients values are performed, based on the coefficient, calculated in the previous paragraph k_h [6]:

$$\begin{aligned} & b_h = \frac{k_h}{E_2 F_2}; \quad \Delta_h = e^{-b_\Gamma a_2 t}; \\ & \psi_h = 1 - 2\Delta_h \end{aligned} \qquad (20)$$

The energy of the tail part is composed of three parts.

The first part.

$$\begin{aligned} & A_{kt}^{II} = \sum_{i=1}^{n} A_{ki}^{II}, \quad A_{ki}^{II} = \frac{P_{ki}^{II^2}}{2k_h}, \\ & P_{ki}^{II} = P_u R_0^* \xi \left(\psi_h R_0^*\right)^{i-1} \left(1 + \psi_h\right) \end{aligned} , \qquad (21)$$

where ξ – the transmission coefficient of deformation wave of the free boundary of the striker,
R_0^* – the reflection coefficient of the backward wave.

The second part.

$$\begin{aligned} & A_{ki}^{III-I} = \frac{P_{ki}^{III-I^2}}{2k_h}; \\ & A_{kt}^{III-I} = \sum_{i=1}^{n} A_{ki}^{III-I}, \\ & P_{ki}^{III-I} = P_u \psi q^* \xi q \left(\psi_h R_0^*\right)^{i-1} \left(1 + \psi_h\right), \\ & q^* = \frac{2}{(r'+1) r'}; \quad q = \frac{2}{r'+1}; \quad \xi = -1, \end{aligned} \qquad (22)$$

where q – the transmission coefficient of the direct deformation wave;
q^* – the transmission coefficient of the backward wave;

The third part.

$$\begin{aligned} & A_{ki}^{III-II} = \frac{P_{ki}^{III-II^2}}{2k_h}; \\ & A_{kt}^{III-II} = \sum_{i=1}^{n} A_{ki}^{III-II}, \\ & P_{ki}^{III-II} = P_u \psi^2 R_0^* q^* \xi q \left(\psi_h R_0^*\right)^{i-1} \left(1 + \psi_h\right). \end{aligned} \qquad (23)$$

The energy of the tail part of shock impulse is determined:

$$A_{kt} = A_{kt}^{II} + A_{kt}^{III-I} + A_{kt}^{III-II} . \qquad (24)$$

As a result energy of blow, expended on elastic-plastic deformation $A_{e\text{-}p}$ is determined as:

$$A_{ki} = A_{kh}^{I} + A_{kt} . \qquad (25)$$

3. CONCLUSIONS

On the basis of these dependences it was made up algorithm for calculating the required impact energy, generated by the pulse generator A_e depending on the hardness of the deformable metal material, and the curvature of the deforming tool.

Yield strength of 45 steel is not less than 360 MPa. Studies have shown, that in strengthening by shock deformation waves, pressure in the deformation zone is more than three yields strength when energy of hits is 15 J or higher, for rod roller in diameter of 10 mm and a width of up to 6 mm.

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