Journal of Achievements in Materials and Manufacturing Engineering
VOLUME 43
ISSUE 1
November
2010

Ensuring uniformity of strengthening for machine parts surfaces by shot-peening

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Received 30.09.2010; published in revised form 01.11.2010

Manufacturing and processing

ABSTRACT

Purpose: of this paper is developing the mathematical models of shot-peening, in which is reflected moving shot-peening head or machine parts surfaces during treating that will achieve uniformity of treatment machine parts.
Design/methodology/approach: The main methods used for the theoretical research are mathematical modelling, integral calculus, fundamentals of analytic geometry, probability theory. It is used approved enough and well known numerical methods for calculations after mathematical models.
Findings: Method of mathematical modeling for shot-peening is developed based on the energy conception. Mathematical model in which is reflected moving shot-peened head or machine parts surfaces during treating is created. It allows forecasting the characteristics of surface quality depending on the technological modes of treatment.
Research limitations/implications: It is planned developing and improving the methods of shot-peening mathematical modeling in future research by extending theirs for the curvilinear treated surfaces, which has movement relative to the nozzle of shot-peening head after the different laws of motion, and for different kinds of materials, especially for metal joint endoprosthesis biomaterials.
Practical implications: has the applied software, elaborated on the basis of the models, that allows providing for automation of calculations of the characteristics of surface quality depending on the technological modes of treatment.
Originality/value: It is pioneered receiving functional dependences in which is reflected moving shot-peened head or machine parts surfaces during treating. Created functional dependences takes into account the distribution of characteristics of working medium (mass and velocity) all along the cross-sections of shot blast.
Keywords: Surface treatment; Shot-peening; Strengthening; Modelling

Reference to this paper should be given in the following way:
Z.A. Stotsko, T.O. Stefanovych, Ensuring uniformity of strengthening for machine parts surfaces by shot-peening, Journal of Achievements in Materials and Manufacturing Engineering 43/1 (2010) 440-447.

1. Introduction

On the modern stage of mechanical engineering industry the quality criteria of machine parts is not only their precision manufacturing and surface roughness but also physical and mechanical properties of surface layer, such as character and value of residual stresses, degree and depth of hardening, surface microrelief (tracks from cutting tools such as convexes or concavities radiuses, incisions amount and orientation). Therefore research and wide introduction in the technological processes of methods which give the machine parts surface and subsurface layers required physical and mechanical properties for their operational reliability is an actual task.

The methods of surface plastic deformation are refered to such methods. One of the most universal and simple in realization methods of surface plastic deformation there are methods of machine parts surface treatment by the jet of loose solid balls, which are characterized that an tool does not have mechanical connection with a plant. It enable to avoid heating and vibrations that occur in a closed system "plant-device-tool-detail". Appearance of surface treated with loose solid balls is typical only for this process (Fig. 1).

At a necessity forming in the machine parts subsurface layers of compressed residual stresses, strengthening of machine parts surfaces and increasing fatigue strength without the change of their geometrical shape and sizes one of the most effective methods of treatment by the jet of loose solid balls is shot-peening.

For the surfaces of sophisticated shape this method is, as a rule, by the unique method to provide necessary physical and mechanical properties for details subsurface layers.

The causes of metal hardening during shot-peening is growth under shot impacts of its crystal lattice defects - vacancies and dislocations, and grinding of metal crystals into separate fragments and blocks with significant distortion of crystal lattice on their borders.

Dislocation formation rate increases with the effort during the impact and duration of the shot action on the processed surface. Movement of dislocations in metal crystals occurs under the influence of striking effort. Dislocations which move meeting with obstacles (e.g., dislocations placed on another plane) are blocked, that is fixing them, which have high strength characteristics of the material (yield stress, ultimate stress, hardness) with simultaneous decrease of plasticity (relative elongation, relative narrowing, impact strength). For example, in the unstrained annealed carbon steels average density of dislocations has $10^6...10^8$ cm^{-2}. After surface plastic deformation their amount in the most strained layer increases by several orders to $5{,}52 \cdot 10^{11}...11{,}58 \cdot 10^{11}$ cm^{-2} for steel 45.

The density of vacancies in the subsurface layer of metal during treating also increased substantially. Agglomeration of vacansies can be sources for new dislocations.

Shot-peening causes grinding crystals into separate fragments and blocks. The boundaries of the fragments and the blocks are impeding the free movement of dislocations in the material.

Therefore with the increasing number of the fragments and the blocks, and also with the rising degree of their disorientation in the material, the number of boundaries at which dislocations deployment delayed and the borders resistance for dislocations movement are grow. It further increases the metal resistance for deformation, causing the rise of strength and reduced plasticity.

It should be noted that the microdistorsions accumulation in the metal crystal lattice has the limit, reaching which exhausts the lattice ability to further plastic deformation. Further application of shock efforts will lead to the formation of cracks and fracture surface of detail [1].

Physical and mechanical properties of surface and subsurface layers of details formed by the joint action of the numerous technological factors that can lead to significant scattering parameters of details during the shot-peening. Therefore, analysis and research of shot-peening is reasonably performed on the basis of mathematical modeling using the basic methods of probability theory.

The basic scientific approaches of theoretical description and research of processes of treating with loose solid balls were laid in [2, 3]. The process of interaction between single loose solid ball and treating surface is under consideration from the point of dislocation theory and the theory of plasticity in [2]. Mathematical model of thermal processes that occur in the zone of interaction between single loose solid ball and treating surface is created. In [3] mathematical model of contact interacting single abrasive grain with treating surface for abrasive-jet cutting is proposed. Conducting machine experiments planned for this model allows to investigate the change of roughness and surface dimension during processing [3]. In [4-7] mathematical models of mass distribution, velocity and kinetic energy in loose solid balls jet, which allow to predict received after treating physical and mechanical characteristics of details subsurface layers for the case of fixed shot-peening head and fixed detail surface is developed. Research processes of treatment with jet of loose solid balls by foreign scientists is usually experimental and they investigate influence of treating loose solid balls to physical and mechanical properties of certain metals and alloys groups [8-11].

The analysis of theoretical and experimental research makes the following conclusions:

- models that consider moving shot-peening head or the detail surface during treating with loose solid balls is not developed;
- models that describe treating with loose solid balls for curved surfaces is not developed;

proposed model does not take into account patterns of interaction between one or more jets of loose solid balls with the treated surface depending on its geometry is not developed.

Therefore, the development of theoretical relations, which will be considered moving shot-peening head or a detail surface during treating is an actual task. The dependences allow to predict influence of technological process parameters on the treatment productivity and uniformity. Productivity is determined by the degree of surface hardening. Its value depends on the loose solid ball mass and velocity at which shot impact into the surface. Uniformity of treatment depends on the kinetic energy distribution along the surface of the working medium, and depends on the curve distribution shape. Uniformity of treating can be determined as a difference between degrees of strengthening for neighboring areas of the treated surface.

Partial case of mathematical models, which included moving shot-peening head or detail surface during treatment is the model of interaction between unmoved shot-peening head and a detail that performs rotary motion in one plane relative to the head. This model can be used as a base for a particular module of computer-aided calculation system for shot-peening technilogical process and to ensure uniformity of treatment for flat surfaces in placing their on the rotary plate, that is rotated or on the shot-peening plant rotary tables; will develop recommendations on the proper selection and control technological modes, will allow to improve processing.

2. Description of the approach

Energy conception, after which energy, given a working medium by the nozzle of shot-peening head, except for its losses on the different stages of the treatment, transfers into work on the change of form and stress state of the treated surfaces, is fixed in basis of the mathematical model of treating by loose solid balls [12].

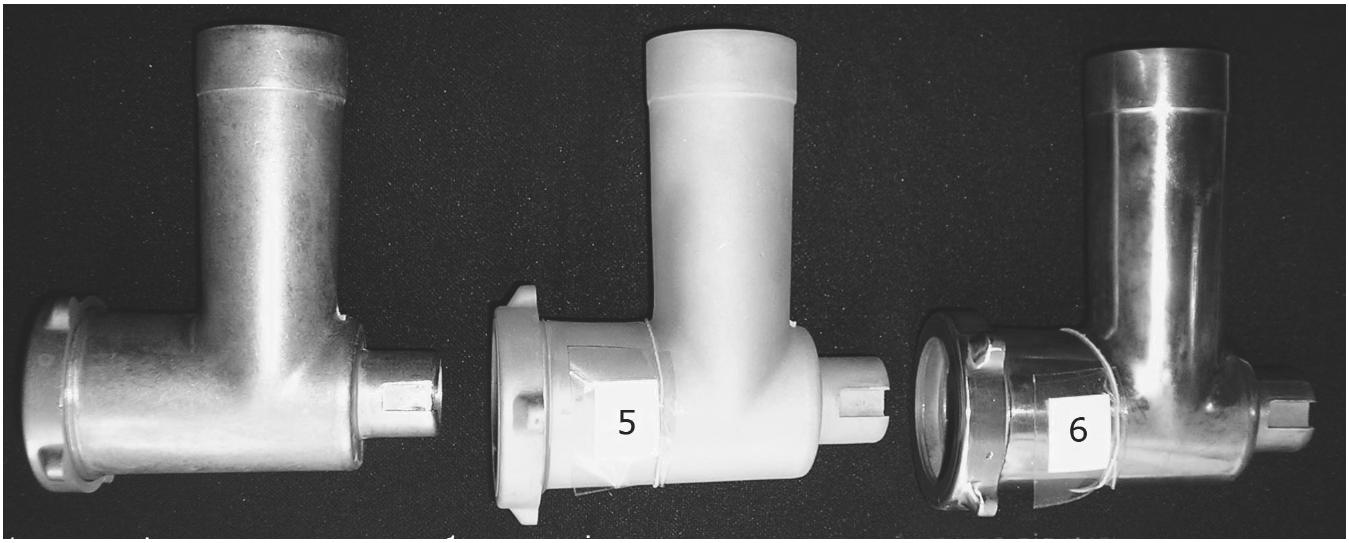

Fig. 1. Corps of electric meat cutter, treated after different technologies: from left to right - vibration treatment; shot-peening; shot-peening with post-polishing

Going out from general equalization of energy balance the simplified equalization which the simulation of the process is carried out on the basis of is got:

$$\frac{M\cdot V^2}{2}-\left(E_{op}+E_{tr.s}\right)=\frac{\left(A_{pl.d}+A_{ruyn}\right)}{\left(1-k_{vtr}\right)} \tag{1}$$

where M - mass distribution of the working medium on the treating surface, kg; V - velocity distribution of the working medium on the cross-section of the jet, which is congruent with treated surface, m/s; E_{op} - loss of energy by the jet on overcoming forces of air resistance, J; $E_{tr.s}$ - loss of energy on overcoming forces of friction in the jet, J; $A_{pl.d}$ - work, outlaying on the suface plastic deformation, J; A_{ruyn} - work, outlaying on destruction of the treated surface by microcutting, J; k_{vtr} = 0,1…0,15 - a coefficient of energy losses during interaction between the loose solid ball with the treated surface.

Each loose solid ball has a kinetic energy reserve that is transformed into the microcutting work and into the surfrace plastic deformation work, and therefore can serve as measure for the intensity of machine parts surface treatment. At the corner of a jet attack angle (angle of attack is the angle of jet axis to the surface being treated) equal to 90º kinetic energy of jet working medium is converted to the surface plastic deformation work, that is spent on strengthening the detail surface. It is introduced the assumption that the degree of the treated surface strengthening is proportional to kinetic energy of jet working medium:

$$\varepsilon = k\frac{M\cdot V^2}{2} \tag{2}$$

where ε - degree of strengthening; k - aspect ratio.

Estimating the degree of strengthening by (2) need to determine the mass working medium distribution and the velocity working medium distribution along the jet cross-section.

It was crossed the jet by plane XOY, that located on some distance from the nozzle of shot-peening head and match the surface being treated to investigate the mass working medium distribution along the jet cross-sections.

Rectangular area D was selected on the plane XOY (Fig. 2).

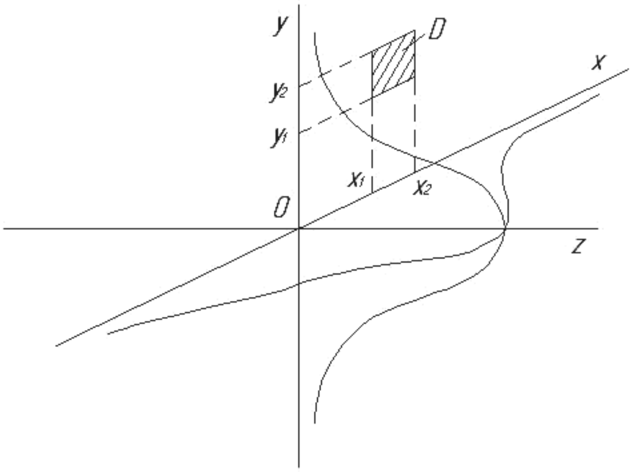

Fig. 2. Scheme for determining the mass working medium distribution in jet

Hit of the loose solid ball in the rectangle area D, limited abscissas x_i and x_{i+1} and ordinates y_j and y_{j+1},, can be interpreted as a random hit of the point (X, Y) in the given area D of the plane XOY, characterized by some distribution function and density distribution of two random variables f (x, y). It can be used "mechanical" interpretation of the two random variables distribution, as a single mass distribution on the plane XOY. In that case function f (x, y) represents the density distribution of mass at the point (x, y), and P(D(x, y)) is the probability of hit a random variable in the area D.

Mass of loose solid balls, which falls at the area D, limited abscissa x_i and x_{i+1}, ordinates y_j and y_{j+1}, during time Δt is equil:

$$M(D) = M(\Delta t) \cdot P(D(x, y)) \tag{3}$$

where M(Δt) - mass of loose solid balls, that escape from the nozzle of shot-peening head during time Δt, kg; P(D(x, y)) - probability of hitting a random variable on the area D.

Mass of loose solid balls M(Δt) is equil:

$$M(\Delta t) = \frac{Q \cdot \Delta t}{(x_{i+1} - x_i) \cdot (y_{j+1} - y_j)} \tag{4}$$

Geometrically probability of hitting a random variable P(D(x, y)) on the area D is equil:

$$P(D(x, y)) = \int_{x_i}^{x_{i+1}} \int_{y_j}^{y_{j+1}} f(x, y) dydx \tag{5}$$

where f(x, y) - the density distribution function; x_i i x_{i+1} - abscissas of the area D; y_j i y_{j+1} - ordinates of the area D.

As shown by experimental studies, the mass working medium distribution in the jet cross-section can be described by a normal distribution law. If the center of the shot-peening head nozzle is combining with the start point coordinate system for the same conditions of shot spraying along the axis, which is characteristic for the round nozzle section, the density distribution function of the normal law be written as:

$$f(x, y) = \frac{1}{2\pi\sigma^2} e^{-\frac{x^2}{2\sigma^2} - \frac{y^2}{2\sigma^2}} \tag{6}$$

where σ - standard deviation, mm.

Standard deviation for the nozzle with circular cross-section are determined, following a rule of “three sigma” and going out from the geometrical reasonings (Fig. 3):

$$\sigma = \frac{2 \cdot L_t \cdot \mathrm{tg}\alpha + d_c}{6} \tag{7}$$

where α - cone angle of jet, rad; L_t - perpendicular distance between surface being treated and the nozzle end, m.

$$M = \frac{Q \cdot \Delta t}{2\pi\sigma^2 (x_{i+1} - x_i)(y_{j+1} - y_j)} \cdot \int_{x_i}^{x_{i+1}} \int_{y_i}^{y_{i+1}} e^{-\frac{x^2}{2\sigma^2} - \frac{y^2}{2\sigma^2}} dydx \tag{8}$$

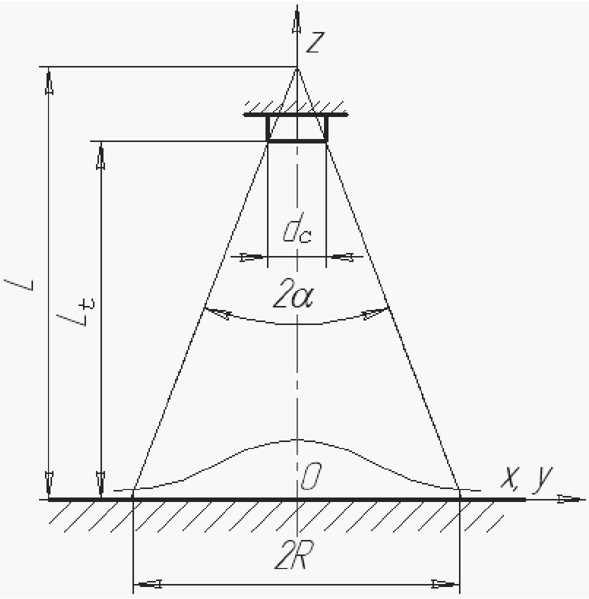

Fig. 3. Scheme for determining standard deviation for mass working medium distribution

Given equations (4) - (7), formula (3) be written as:

If the rectangular area D (x_1, x_2, y_1, y_2) lies on a flat surface that rotates, such as rotary plate, its coordinates change in time and motion are determined by law surface:

$$x_1 = x_c + r \cdot \cos(\omega \cdot t) \tag{9}$$

$$x_2 = x_c + r \cdot \cos(\omega \cdot t) + h_x \tag{10}$$

$$y_1 = r \cdot \sin(\omega \cdot t) \tag{11}$$

$$y_2 = r \cdot \sin(\omega \cdot t) + h_y \tag{12}$$

where x_c - distance between the center axis of the rotary plate and jet (eccentricity), m; r - radius in which the area D is located relatively to the rotary plate center, m; ω - angular velocity of the rotary plate, s^{-1}; h_x, h_y - length and width of the area D, m: $h_x = x_2 - x_1$, $h_y = y_2 - y_1$.

In Fig. 4 it is shows how the rotary surface can be placed relatively the jet of working medium. The rotary plate axis in this case is parallel to the axis of the nozzle.

During movement the surface being rotated from position A to position C the intensity of processing some area D varies. For determining the change of mass working medium distribution on the surface of the rotary plate, coordinates x_1, x_2, y_1, y_2 from (9) - (12) should be substituted in (8):

$$M = \frac{Q \cdot \Delta t}{2\pi\sigma^2 (x_{i+1} - x_i)(y_{j+1} - y_j)} \cdot \int_{x_c + r\cdot\cos(\omega\cdot t)}^{x_c + r\cdot\cos(\omega\cdot t) + h_x} \int_{r\cdot\sin(\omega\cdot t)}^{r\cdot\sin(\omega\cdot t) + h_y} e^{-\frac{x^2}{2\sigma^2} - \frac{y^2}{2\sigma^2}} dydx \tag{13}$$

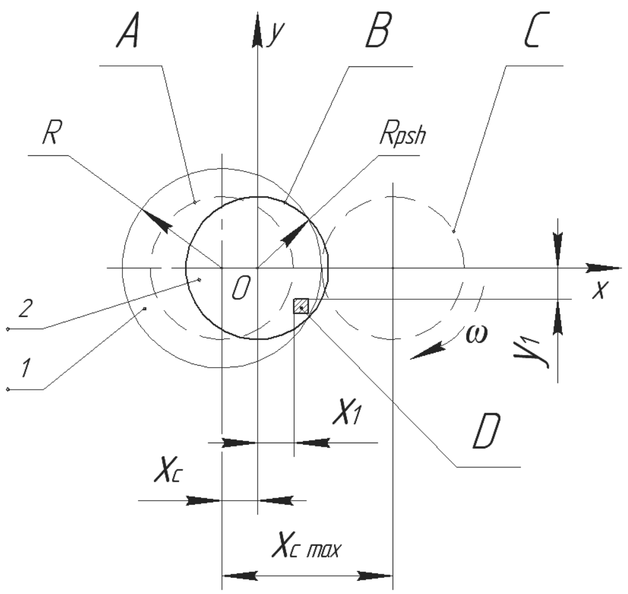

Fig. 4. Scheme of shot-peening for rotating surface (top view): 1 - cross-section of jet that match the surface being treated, 2 - rotary face; A - position of the rotary plate in which its center coincides with the center jet, B - intermediate position of the rotary plate, C - position of the rotary plate, after which the treating rotary surface is displaced beyond jet and its treating is terminated, D - investigated area; R - radius of the jet in the plane its contact with the rotary surface, R_{rsh} - radius of the rotary plane; $x_{c\ max}$ - the maximum possible eccentricity, after which the treating rotary surface is displaced beyond jet and its treating is terminated

It was used the dependence for unmoved jet given in [4] for investigating the velocity working medium distribution in the jet cross-sections. This dependence is converted to take into consideration eccentricity. For the case $r_i \leq x_c$ the velocity working medium distribution is equil:

$$V = \frac{0.96 \cdot V_0}{\frac{2aL}{d_c} + 0.29}\left(1 - \left(\frac{x_c - r}{R}\right)^{1.5}\right)^2 \qquad (14)$$

For the case $x_c < r_i$ the velocity working medium distribution is equil:

$$V = \frac{0.96 \cdot V_0}{\frac{2aL}{d_c} + 0.29}\left(1 - \left(\frac{r - x_c}{R}\right)^{1.5}\right)^2 \qquad (15)$$

де a - coefficient of jet turbulence; R - maximum radius of the jet or distance from the jet axis to the points with a zero velocity, m (Fig. 3).

Substituting (13) - (15) into (2), obtain:

$$\varepsilon = \frac{k \cdot Q \cdot \Delta t}{4\pi\sigma^2 (x_{i+1} - x_i)(y_{j+1} - y_j)} \cdot \int_{x_c + r\cdot\cos(\omega\cdot t)}^{x_c + r\cdot\cos(\omega\cdot t) + h_x} \int_{r\cdot\sin(\omega\cdot t)}^{r\cdot\sin(\omega\cdot t) + h_y} e^{-\frac{x^2}{2\sigma^2} - \frac{y^2}{2\sigma^2}} \, dydx \cdot \left(\frac{0.96 \cdot V_0}{\frac{2aL}{d_c} + 0.29}\left(1 - \left(\frac{|x_c - r|}{R}\right)^{1.5}\right)^2\right)^2 \qquad (16)$$

Dependence (16) allows to simulate the kinetic energy distribution of the jet working medium on a plane surfaces of the rotary plate, and indirectly assess the intensity and uniformity of their strengthening.

3. Description of achieved results of own researches

Based on the developed mathematical model (16) in the mathematical editor MathCAD program is created for the numerical experiment and for the investigating influence of shot-peening technological modes on the kinetic energy working medium distribution along the surface of rotary plate, and thus it is obtained a theoretical framework for automation of shot-peening technological process.

In Fig. 5 it is shown schedules of mass, velocity, kinetic energy working medium distribution along the radius of rotary surface for such shot-peening technological modes:
productive capacity of shot-peening plant P = 0.8 kg/s; processing duration t = 60 s;
perpendicular distance between surface being treated and the nozzle end $L_t = 0.5$ m;
distance between the center axis of the rotary plate and jet (eccentricity) $x_c = 25$ mm;
diameter of the shot-peening head nozzle $d_c = 10$ mm;
angular velocity of the rotary plate $\omega = 0.2$ s^{-1};
radius of the rotary plate $R_{psh} = 50$ mm;
cone angle of jet $\alpha = \pi/36$ rad;
coefficient of jet turbulence a = 0.1;
length of the research rectangular area $h_x = 0.001$ m;
width of the research rectangular area $h_y = 0.001$ m.

Analyzing the schedule of kinetic energy working medium distribution allows to conclude that velocity of working medium more significantly than mass affects on the distribution, and hence the degree of strengthening and uniformity of treatment.

Schedules of kinetic energy distribution depending on the shot-peening technological modes are built and analyzed to study the influence of technological modes on uniformity of the surface hardened layer and productivity of processing (Figs. 6-8).
If it is shifting the rotary plate axis relatively to the nozzle axis, or in other words increasing the distance x_c is, uniformity of the hardened layer on the detail surface, located on the rotary plate increases, but productivity of treatment decreases (Fig. 6). Most even hardened layer for the studied technological modes is reached fo eccentricity $x_c \approx 25$ mm, when the center of the Gaussian curve is located approximately on the half of the rotary plant radius

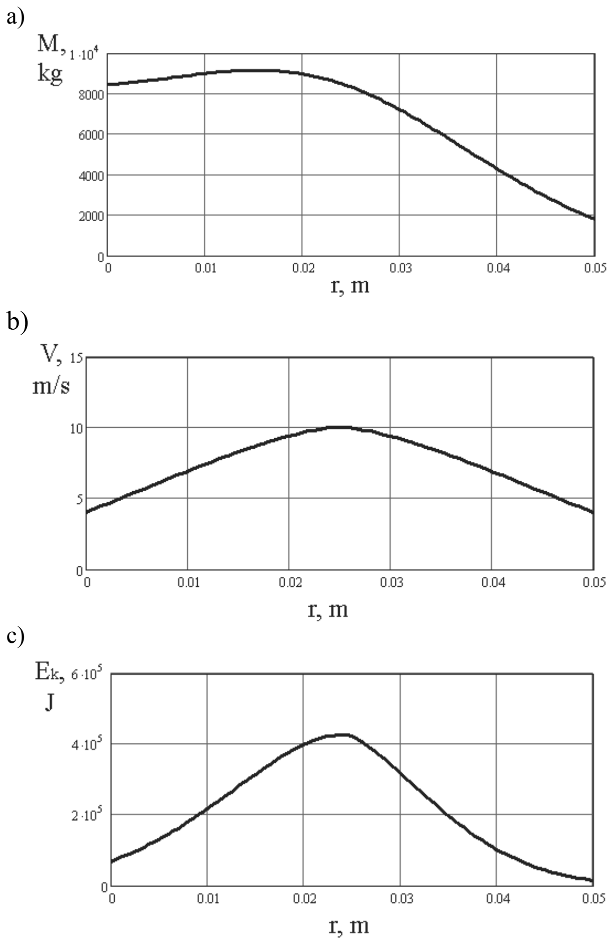

Fig. 5. Distribution mass (a), velocity (b), kinetic energy (c) of jet working medium along the radius of the rotary plate for the eccentricity x_c = 25 mm, and such technological modes: P = 0.8 kg/s; t = 60 s; L_t = 0.5 m; α = π/36 rad; d_c = 10 mm; ω = 0.2 s^{-1}; R_{psh} = 50 mm

If the perpendicular distance L_t between treated surface and the nozzle end is increasing, uniformity of hardened layer increase too, but productivity of strengthening drops. Fastest productivity of strengthening drop, almost 4 times, observed when changing the distance L_t from 0.15 m to 0.25 m, but the uniformity of treatment significantly increases (Fig. 7).

Increasing the diameter of the shot-peening head nozzle with 6 mm to 16 mm leads to a decrease in the uniformity of treatment while increasing the productivity of strengthening (Fig. 8). However, in this case, please note that the increase in nozzle diameter causes a reduction of primary nozzle jet velocity at nozzle outlet, so there is a need to increase shot-peening plant productivity.

Essential influence on hardened layer uniformity has the distance between surface being treated and the nozzle end and eccentricity of locating rotary plate axis, in other words its displacement relative to the nozzle axis. Shot-peening head must be moving so that the the nozzle end remained parallel the rotary surface for changing the eccentricity.

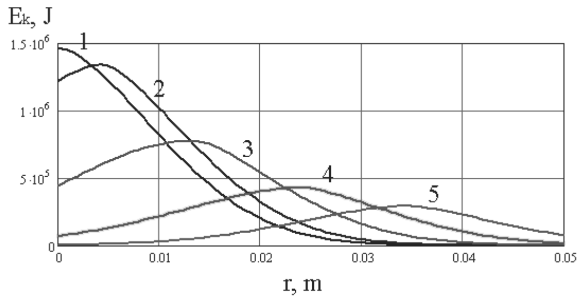

Fig. 6. Graphic dependence kinetic energy working medium distribution along the radius of the rotary plate from eccentricity x_c: 1 - x_c = 0 мм; 2 - x_c = 5 мм; 3 - x_c = 15 мм; 4 - x_c = 25 мм; 5 - x_c = 36 мм; other shot-peening technological modes - P = 0.8 kg/s; t = 60 s; L_t = 0,5 m; α = π/36 rad; d_c = 10 mm; ω = 0.2 s^{-1}; R_{psh} = 50 mm

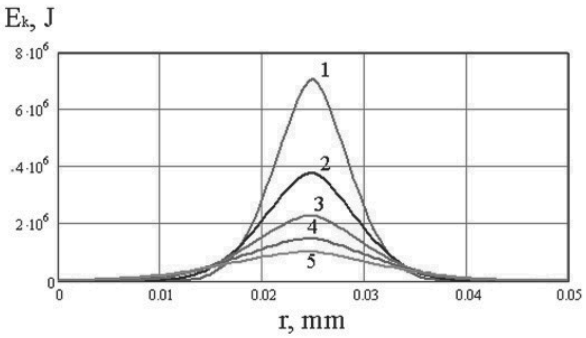

Fig. 7. Graphic dependence kinetic energy working medium distribution along the radius of the rotary plate from perpendicular distance between surface being treated and the nozzle end for the eccentricity x_c = 25 mm: 1 - L_t = 0.15 m; 2 - L_t = 0.2 m; 3 - L_t = 0.25 m; 4 - L_t = 0.3 m; 5 - L_t = 0.35 m; other shot-peening technological modes - P = 0.8 kg/s; t = 60 s; d_c = 10 mm; α = π/36 rad; ω = 0.2 s^{-1}; R_{psh} = 50 mm

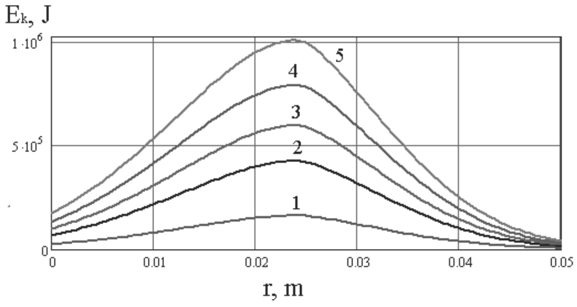

Fig. 8. Graphic dependence kinetic energy working medium distribution along the radius of the rotary plate from diameter of the shot-peening head nozzle d_c for the eccentricity x_c = 25 mm: 1 - d_c = 6 mm; 2 - d_c = 10 mm; 3 - d_c = 12 mm; 4 - d_c = 14 mm; 5 - d_c = 16 mm; other shot-peening technological modes - P = 0.8 kg/s; t = 60 s; L_t = 0,5 m; α = π/36 rad; ω = 0,2 s^{-1}; R_{psh} = 50 mm

Automation of these movements will allow to regulate the uniformity of strengthening for machine part placed on the rotary plate and improve controlling of shot-peening. For adjustment of productive capacity it is best of all to equip shot-peening plant with set of nozzles that has different diameters of outlet or shot-peening head, in which will be implemented automatically replace a nozzle. Productivity of strengthening can be increased by increasing the nozzle diameter, but it should be takes into consideration a necessity of simultaneous increasing air pressure and as result power of shot-peening plant.

4. Conclusions

Theoretical generalization is conducted and the scientific problem of technological ensuring the machine parts surface quality during shot-peening for the case of the shot-peening head relative movement and the detail surface during processing is solved. It is enables to introduce shot-peening into technological process as a alternative finishing operation, that provides high levels of the machine parts surface quality, including roughness, depth of hardened layer, the degree of hardening, microhardness, residual stress distribution.

Achieving uniformity of treating flat surfaces is possible by placing details on the rotary plate, and by automatically adjustment the distance between surface being treated and the nozzle end and eccentricity of locating rotary plate axis. Automatic adjustment of these parameters can be done by equipping shot-peening plants with computer-aided control systems, the base of development which can be assigned mathematical models. The advantage of the proposed mathematical models is that they considered the of work medium characteristics (mass and velocity) distribution along the jet cross-section and along the rotary plant surface.

Promising way to develop research in the field of treatment with loose solid balls is creating mathematical models of the process for the machine parts curved surfaces, involving the separation and analytical description of surfaces with different shapes (spherical convex and concave surfaces, convex and concave cylindrical surface, elliptic and hyperbolic paraboloids) that combinations can generate a wide range of curved surfaces, the following analytical description of a jet track in the curved surfaces being treated, attack angles of jet for each area of the surface, the kinetic energy working medium distribution, and thus allow to predict quality characteristics of the surfaces being treated.

Potential area of application for the treatment with loose solid balls can be endoprosthesis manufacturing, that is now rapidly developing [13, 14, 15].

Preview of development of metallic materials used as implants one may state that there were attempts to apply a vast majority of metals and alloys which displayed a satisfactory biotolerance, resistance to corrosion and as well as the appropriate physico-chemical and mechanical properties: strength, wear resistance, manufacturability [16]. Stainless steel alloys, titanium alloys are currently used for the metal endoprostheses. Such endoprostheses fixed in bone by cement.

Endoprosthesis manufacturing is a high precision industry. Endoprostheses pass multistage control and certification. For ensuring their quality it is proposed different methods for investigating properties of materials being used for endoprostheses and sophisticated method for their processing [17, 18]. Using methods of treating with loose solid balls for fastening parts endoprosthesis can allows to receives highly developed surfaces that can provide the best adhesion cement with metal base and, consequently, better fixation of the prosthesis to the bone.

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