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Investigations on the machine parts treatment by non-bound blast particles

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ABSTRACT

Purpose: of this paper is development of the mathematical models of the methods of treatment by non-bound blast particles. Analysis of non-bound blast particles behavior is carrying out for modeling. The operating factors such as geometrical parameters of a nozzle, distance to the treated surface, and pressure of compressed air and outlet factors such as level of strengthening, depth of hardened layer are determined. It is proposed to put into basis of the mathematical models the energy conception that permits the unification and simplification of mathematical description of the processes. The level of strengthening, and depth of hardened layer are estimated for the plain surfaces by means of created mathematical models.

Design/methodology/approach: The main methods used for the theoretical research are mathematical modelling, integral calculus, fundamentals of analytic geometry, probability theory, hydraulics of multiphase flow. The main methods used for the experimental investigations were conducted by receiving diagrams of surface roughness, microhardness of the oblique slices of the treated samples, speckle interferograms of the surfaces treated with the use of non bound blast particles.

Findings: Method of mathematical modeling for treatment by non-bound blast particles is developed based on the energy conception. Mathematical model is created that allows calculating the characteristics of surface quality depending on the technological modes of the treatment.

Research limitations/implications: It is planned to develop and improve the mathematical models in future research by extending them for the curvilinear treated surfaces, which has movement relative to the nozzle.

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 the treatment.

Originality/value: It is pioneered receiving functional dependences between the depth of hardening layer, changing of microhardness, degree of hardening and the parameters of equipment, blast, and working medium. Created functional dependences takes into account the distribution of characteristics of working medium (mass and velocity) all along the cross-sections of the blast.

Keywords: Surface treatment; Non-bound blast particles; Strengthening; Model; Shot-peening; Hopper; Abrasive blasting; Nozzle

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1. Introduction

Machine parts performances are formed on the finishing operations of their manufacturing process and significantly depend on the state and surface and subsurface layer properties. The correct choice of methods and modes of treatment for these operations provides performance design requirements that relate to machine parts, and has a decisive influence on their quality and appearance.

The desire to get high quality products parameters and processing to ensure maximum productivity while minimizing labor and material costs and reducing harmful effects on the environment during manufacturing processes has led to a large number of advanced methods of finishing. To ensure the required roughness and quality of machine part surfaces, a large number of advanced technological processes has been designed. These include finishing of machine parts with the effect of shock-pulse action on the surface of the non-bound blast particles. The necessity to reduce the price of machining, promote its productivity and efficiency, and also dissociate a metal-cutting tool from tool holder, carriage and machine-tool to avoidance heating and vibrations, brought to the creation of operations of forcibly propelling a steam of working medium, in which an instrument does not have mechanical connection with a machine-tool. During such processing the surface plastic deformation occurs and provides necessary physical and mechanical properties of machine parts surface layers. Especially it can increase fatigue strength and crack resistance of machine parts, hardness of surface layers, effectively cleans the surface of the scale, traces of corrosion and provides an attractive appearance.

The application of the operations of forcibly propelling a steam of non-bound blast particles as finishing operations while manufactured products, including molds and dies several times reduces labor costs, improves performance and extends tool life. However, a broad introduction into the production process is hindered due to the imperfect method for determining the optimum processing.

Such treatment is applied in aircraft, automobile, instrumental, repair industries of machine-building for grinding and polishing of details that have the especially complicated configuration (stamps, press-forms, blades of pumps, shaped casting, and others like that), and also at a necessity the receipt of clean surface without the directed tracks of treatment, increase of springs durability and teeth of cog-wheels, increase of tool piece firmness, receipt of surfaces with a high capillarity and increase of their wear resisting property, improvement of antirust properties and adhesion with galvanic coating and paints, delete of dross, corrosion, removal of rough edges after tooling. Processing is possible both simple surfaces (flat, cylinder) and formed surfaces of the wares. The efficiency of using different kinds of the non-bound blast particles treatment grows with the increase of size and complication extent the configuration of details.

The operations of forcibly propelling a steam of working medium are considered in [1-4]. The main approaches to the investigation of blast processing, as the process of mechanical and chemical cutting of metal are described in [1]. In [2] a mathematical model of contact interaction between a single particle and the treated surface is proposed. The machine planned experiments carried out with this model allow to investigate the change of roughness and linear dimensions of surfaces during processing. The generalized model of abrasive micro-cutting at high pressures (up to 300 MPa), which describes the fracture mechanics of solid bodies, proposed in [3]. Foreign scientists investigating treatment of forcibly propelling a steam of working medium usually relied on experiments and its impact on physical and mechanical properties of individual groups of metals and alloys [4].

According to Google search, thousands of enterprises from different countries, including Ukraine, USA, Canada, UK, Germany, Italy, produce equipment and accessories for the operations of forcibly propelling a steam of working medium. Scientific and technical literature analysis indicates that both in Ukraine and abroad, a large number of experimental studies were held in the field of the operations of forcibly propelling a steam of working medium in order to solve applied problems. In [5] based of experimental data, the authors noted that hydroabrasive surface treatment improves the adhesion properties between the base material and coating. The influence of technological process parameters on the residual compressive stress and roughness of processed surfaces at thermal abrasive blasting and sandblasting is considered in [6]. In [7,8] it was experimentally proved that fatigue strength of different materials increases after shot blasting process. In [9] the questions of creation of jet penetrations instruments are examined for superficial treatment (cleaning) of main pipelines. The structure of integrated stream-abrasive device of rotor type is presented.

2. Physical fundamentals of the operations of forcibly propelling a steam of working medium

The essence of the treatment consists in the blast of non-bound particles that impinge on the surface and during a collision execute work, changing the state of this surface, being sent with high speed (50...80 m/s) on the treated surface. As a rule, non-bound particles gather speed by means of the compressed air.

Every particle in a blast keeps a reserve of kinetic energy which grows into work of cutting and is sufficient for dissociating from the treated surface of chip. Thus a surface acquires an original kind, characteristic only for this process (Fig. 1).

Processes that use the effect of impinging loose solid balls at the treated surface will be realized in a number of different ways:

- an impact is actually carried out by the ball (mechanical shot-peening);
- an impact is carried out by a liquid jet or jet of the compressed air or jet of the steam which contains abrasive grains (air shot-peening, glass beads cleaning, sand blasting, abrasive blasting);
- the influence on the treated surface is carried out by slurry, which consists of the abrasive particles uniformly distributed in the special emulsion, and sprayed by compressed air with the use of blast nozzles (wet shot-peening, wet abrasive blasting).

Work mediums, which are used in industry are divided into:

- homogeneous material - jets consist of dry loose solid balls

(abrasive grains, shot, glass beads, crushed fruit pits, dry ice granules);
- two phase-materials - abrasive liquid jets or jets of compressed air or steam containing abrasive grains;
- multiphase materials - suspension, consisting of uniformly distributed in a special emulsion of abrasive and sprayed with compressed air with ejector nozzles.

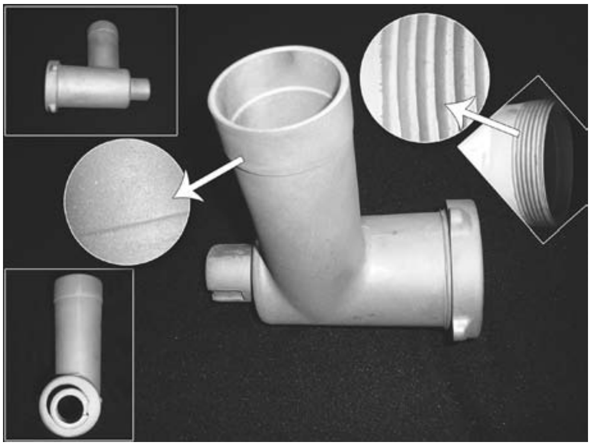


Fig. 1. Components treated by the blast of angular abrasive

It can give products the desired properties by changing the composition of the working medium and technological modes. Processing with loose solid balls is applied for obtaining clean surfaces without any directed traces, grinding and polishing of sophisticated shape parts (dies, molds, pump blades, casting), increasing the springs and gear teeth strength, improving the stability of the cutting tools, obtaining surfaces with high capillarity and increasing their endurance, improving the corrosion properties and adhesion to plated surfaces and colors, removing scale and burrs after machining. It can be processed as simple surface shapes (flat, cylindrical, spherical), so complex curved surfaces.

Processes flow that modify the microrelief and structure-surface stress state during the treatment such as:
- microcutting, traces of which can be seen in photographs of treated surfaces;
- brittle fracture caused by repeated shot impulse action of solid balls on the surface;
- plastic deformation, in which the superior compressive stress state is formed on the treated surface;
- hydro-molecular destruction as a manifestation of Rebinder effect, during penetration of the liquid components in highly developed microcracks on the treated surface.

Removing material from the treated surface is due to microcutting, i.e. the simultaneous metal removal from the surface by a large number of abrasive grains. Mass grains action forms a highly developed matt surface on the product covering a large area without processing traces and good capillary properties.

The action of cutting edges of a single abrasive grain on the workpiece surface is short-lived and has shock pulse character. Entering the abrasive grain peak into workpiece surface material depends on the attached load, the radius of peaks rounding, physical and mechanical properties of the workpiece. Grain rounded peaks provide high mechanical strength and large cutting angles. The cutting angles value depends on the depth of abrasive grains impinging in the metal and the radius of rounded peaks.

These angles become so large for small values of abrasive grain impinging on the metal that make the cutting process virtually impossible. In consequence, there is only elastic or elastic-plastic deformation of the surface layer. It is increasing the metal volume that undergoes plastic deformation, as in front of abrasive grains, and on the sides and below the cutoff line with increasing abrasive grain peak impinging in the metal. At a certain critical value of grain peak impinging depth, the abrasive grain movement is accompanied by chips removal. Investigations have shown that the process of removing chips becomes possible at stresses that occur along the line of shear resistance and excess ultimate strength of material. In other words, the effect on the treated surface may be in the form of elastic deformation, plastic deformation, and shear deformation, depending on the actual ratio between the abrasive grain impinging depth and the radius of surrounding its peak [1,2].

The predominance of one or another type of deformation depends on the mutual location of unmoved jet apparatus and the treated surface.

During processing by shock jet when impinging angle is right $\beta = 90º$ the bulk of the loose solid balls kinetic energy is used for the surface layer and solid balls deformation, i.e. the mechanism of surface plastic deformation is determinant. Processing shock jet should be used to strengthen the product surfaces. During processing by sliding jet when impinging angle is equal $\beta = 0º$ the kinetic energy spent to improve the sliding speed of solid balls across the surface. In both cases, the shear strain is small. It will be maximum if the blast impinging angle is $\beta = 45º$. In this case, microcutting is the predominant mechanism for the microrelief and structural-stress state formation on the treated surface.

Scheme of the blast that runs out from the nozzle with circular cross-section is shown on Figure 2. In the scheme the non-bounded blast is presented as a cone of working medium without breaks in him. Solid component of the blast are modeled as the balls with diameter equal to that of abrasive or shot grains of basic fraction. At the creation of mathematical model not separated balls, but packages of working medium, which have certain mass and speed and, accordingly, kinetic energy, are considered. Treated surface is broken on separate areas, and accepted that on every area of the surface for time unit gets one package of working medium, which has kinetic energy and executes work on the change of characteristics of the surface.

If we deal with the impact blast ($\beta = 90º$), most of the kinetic energy of non-bound particles is used for deformation of the surface layer and a non-bound particle, i.e. the mechanism of surface plastic deformation is predominant. The impact blast should be used to strengthen the surfaces. Sliding blast $\beta = 0º$ energy spent to improve the speed of sliding the particles across the surface. In both cases, the shear strain are small. They are maximal when the blast guiding angle $\beta = 45º$ to the machined surface. It will be maximum if the blast impinging angle is $\beta = 45º$. In this case, the predominant mechanism for the microrelief and structural-stress state formation on the treated surface is microcutting.

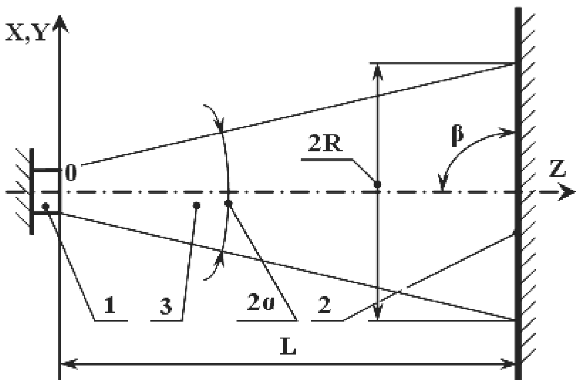


Fig. 2. Scheme of the blast that run out from the nozzle with circular cross-section: 1 - nozzle; 2 - surface; 3 - blast; 2α - cone angle; β - impinging angle; R - the blast trace radius on treated surface; L - the perpendicular length between treated surface and the end of the nozzle

Therefore, a wide modeling of processing has an actual task to improve the handling process, it is cheaper and recommended for process automation.

Classification of the operations of forcibly propelling a steam of working medium

The operations of forcibly propelling a steam of working medium are related to advanced technologies and can be used in production to solve diverse tasks. These tasks include the following:

- cleaning surfaces of dirt and scale;
- decorative surface treatment;
- increase fatigue strength of machine parts;
- machining of complex surface profile with removing small allowances;
- cutting of sheet material with an abrasive jet obtaining products with curved and complex contours.

The operations of forcibly propelling a steam of working medium are classified in Figure 3.

Technological surface destruction when it is processed by non-bound blast particles is determined plenty of the controlled and uncontrolled parameters. Their interrelations and influence on the surface forming is represented on Figure 4.

The initial parameter of treatment by non-bound blast particles that can serve as criteria for optimization, in most cases is formed by the physical and mechanical properties of surfaces.

Microrelief and roughness. The surface microrelief after treatment is characterized by chaotic arrangement of various peaks and hollow configurations. After processing by multiple impacts acute-angled abrasive particles highly developed matt surface with a large area without any dashes directed, which gives it valuable properties formed on the materials. Electron microscopic images of surfaces confirm a high degree of dispersion of microrelief. Depending on the materials used for the operations of forcibly propelling a steam of working medium, surface acquires a different nature and degree of roughness. Roughness measurement and recording profilogram showed that matt surface are of higher density profile, compared to surfaces treated with blade tools, which is obviously an advantage [2].

Corrosion resistance. High capillary surfaces treated blast, characterized by high corrosion resistance. During wet abrasive blasting by slurry with the addition of sodium nitrite and caustic soda passivation film are formed on the surface, which prevents corrosion. Corrosion resistant matt surfaces of the machine parts, obtained by abrasive blasting are excellent during long-term exploitation and storage [1].

Surface strengthening and endurance. During the surface treatment of non-bound blast particles fatigue strength and wear resistance of steel increase. It is explained by the fact that cold working layer is created on the surface after treatment and that small, uniformly distributed hollows resulting from shock-cutting action of abrasive particles are not sharp stress concentrators. During the forced mode of processing, depending on the compressed air pressure and abrasive particles size, depth of cold working layer reaches 20 ... 50 microns. The hardness of this layer is by 20 ... 25 % higher than the hardness of the base metal.

Uniformity of processing. The process of removing material occurs during processing. Typically, it is necessary to maintain a uniform process of removing a thin layer of material for rough handling and finishing of machine parts. Uniform removal of material, shape and topography of traces left by a blast on the surface of parts can be estimated upon the results of experimental studies conducted on flat samples of steel U9, which were still attached to the device [1]. Slurry was blasted through nozzles of round section fixed ejector-type apparatus ($d_{nozzle} = d_{air\ injector}$ = 12…14 mm). Research conditions and results are shown on Figure 5.

Mechanisms of microrelief and structural-stress state formation on the treated surface

Determining mechanisms which substantially influence on physical and mechanical properties of the treated surfaces and evenness of removal of the material is microcutting and surface plastic deformation. Therefore the operations of forcibly propelling a steam of working medium will be considered in two ways - as a process of dimensional and material processing, and as a process of surface-plastic deformation.

Removing material from the treated surface is due microcutting, i.e. the simultaneous metal removal from the surface by a large number of abrasive particles. Mass particles action forms on the product highly developed matte surface of large area without processing traces with good capillary properties.

The action of cutting edges of a single abrasive grain on the workpiece surface is short-lived and has shock pulse character. Entering the abrasive grain peak into workpiece surface material depends on the attached load, the radius of peaks rounding, physical and mechanical properties of the workpiece. Grain rounded peaks provide high mechanical strength and large cutting angles. The cutting angles value depends on the depth of abrasive grains impinging on the metal and the radius of rounded peaks. The values of cutting angles γ_i and δ_i depend on the depth of the non-bound blast particles intrusion into the metal surface h and on the rounded peak radius ρ (Figure 6).

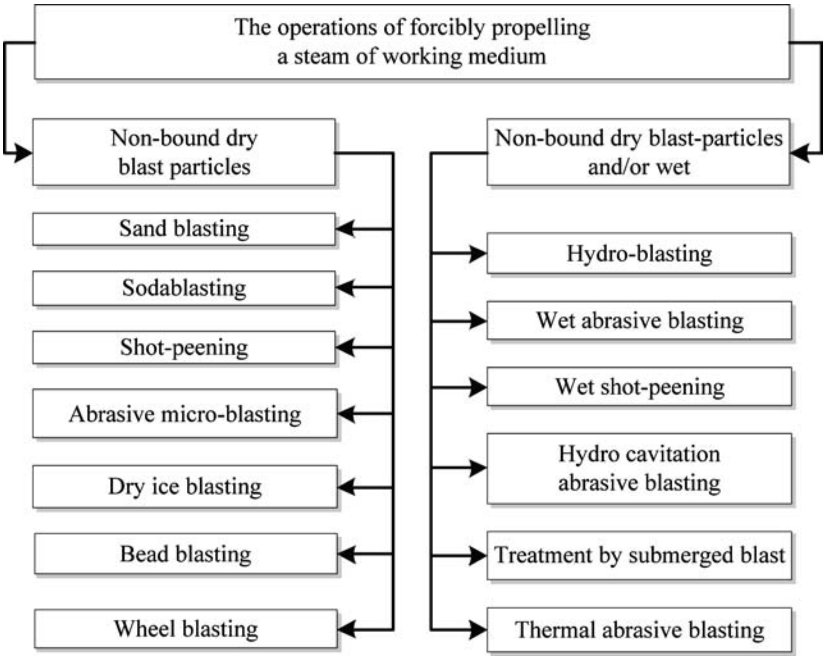


Fig. 3. The operations of forcibly propelling a steam of working medium

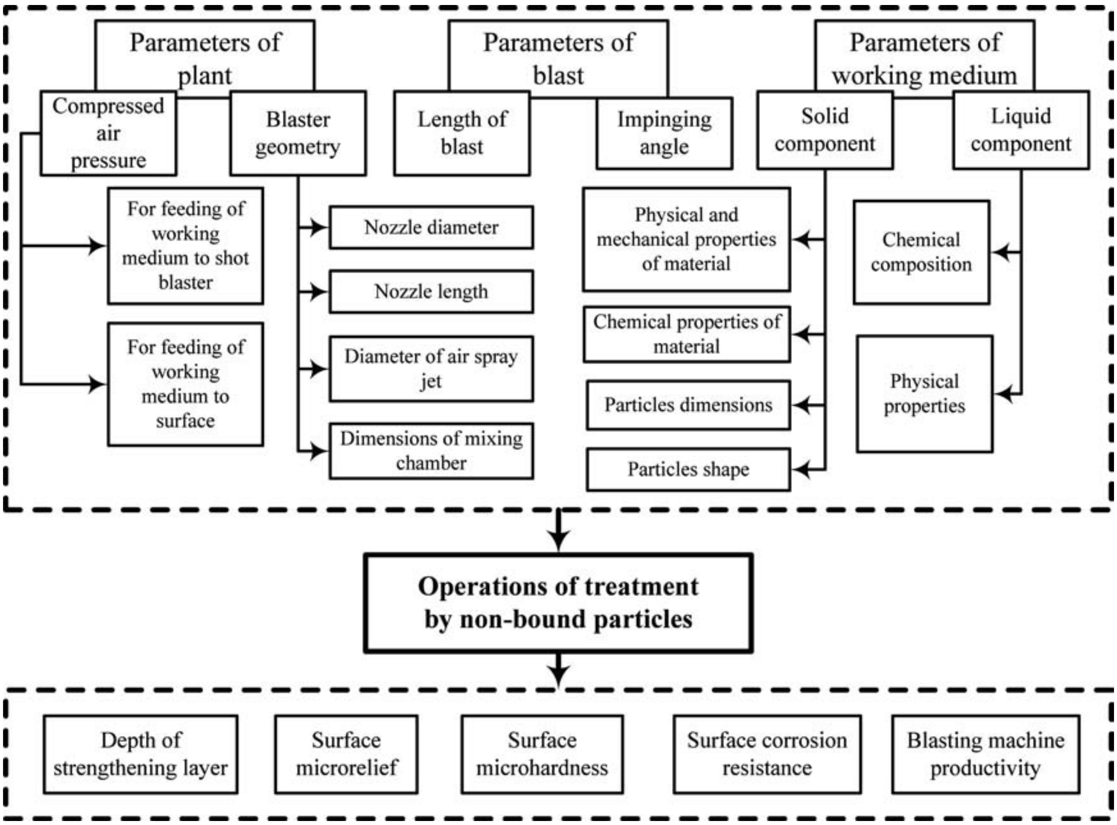


Fig. 4. Parameters of treatment by non-bound blast particles, and quality characteristics of the machine parts surfaces

a) b)

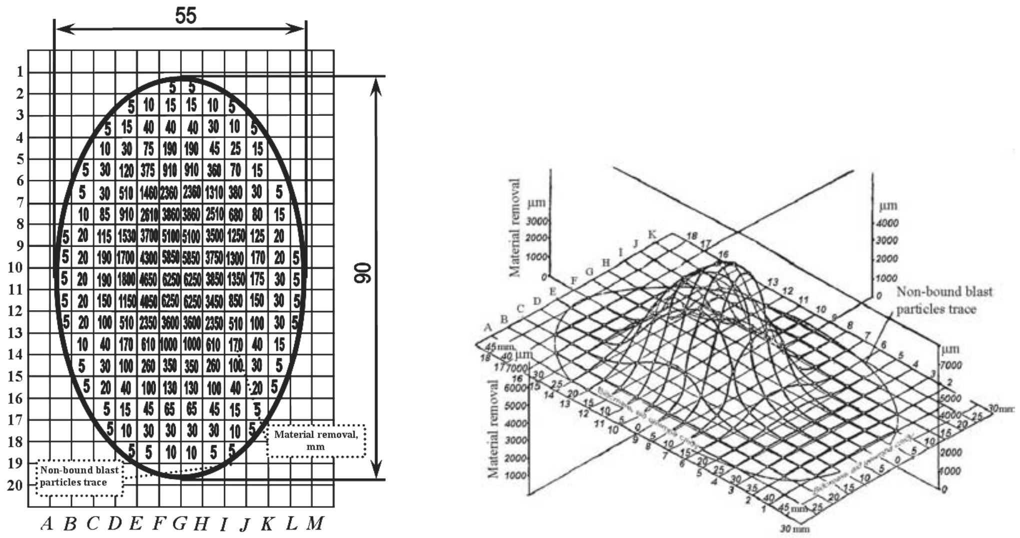


Fig. 5. a) material removal after abrasive blasting: compresses air pressure p = 0.5 MPa, processing time - 120 s, grid size - 60, the ratio of solid components in blast to liquid components - 1 : 4, impinging angle - 45º; b) trace shape and topography after treating flat unmoved surface with the stationary blast apparatus

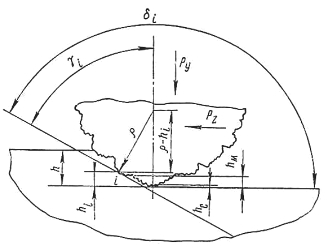


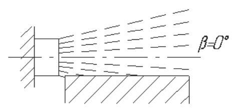
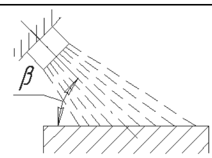
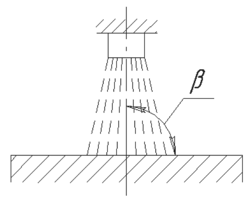
Fig. 6. Scheme of interaction between the non-bound particle and the surface

These angles become so large for small values of abrasive grain impinging on the metal *h* that make the cutting process virtually impossible. Then there is only elastic or elastic-plastic deformation of the surface layer. It increases the metal volume that undergoes plastic deformation, as in front of abrasive grains, and on the sides and below the cutoff line with increasing abrasive grain peak impinging on the metal. At a certain critical value of grain peak impinging depth, the abrasive grain movement is accompanied by chips removal. Investigations have shown that the process of removing chips becomes possible at stresses that occur along the line of shear resistance and excess ultimate strength of material. In other words, the effect on the treated surface may be in the form of elastic deformation, plastic deformation, and shear deformation depending on the actual ratio between the abrasive grain impinging depth and the radius of surrounding its peak [1,2].

The predominance of one or another type of deformation depends on the mutual placement of unmoved blast apparatus and the treated surface.

During processing by shock blast when impinging angle is equal β = 90º the bulk of the non-bounded blast particles kinetic energy is used for the surface layer and the particles deformation, i.e. the mechanism of surface plastic deformation is determinant. The processing shock blast should be used for strengthening the product surfaces. During processing by sliding blast when impinging angle is equal β = 0º the kinetic energy spent to improve the sliding speed of the particles across the surface. In both cases, the shear strain is small. It will be maximum if the blast impinging angle is β = 45º. In this case, the predominant mechanism for the microrelief and structural-stress state formation on the treated surface is microcutting (Table 1).

Table 1.
Types of the treatment by non-bound blast particles

Type of the treatment	Impinging angle β	Scheme
Sliding blasting	0°	
Inclined blasting	0° < β < 90°	
Impact blasting	90°	

3. Mathematical modelling the operations of forcibly propelling a steam of working medium

The basic scientific approaches of theoretical description and research of processes of treating with loose solid balls were laid in scientific work [2]. Functional dependence which allows approximately to estimate interrelation between the size of linear removal of material and the parameters of the treatment was offered to them. The simulation of interaction between the single ball and the treated surface was conducted for research changing of the linear sizes of the surface and roughness during abrasive blasting with usage of angular abrasive. The various structures of the nozzles and heads were described, and a form and properties of blast formed by them was analyzed. In their monography [9] the authors conducted a sophisticated and deep analysis of processes of micro abrasive blasting with the use of extra high pressure, and new complex approach was offered in the theory of micro abrasive cutting that consists in the positional control of a cut groove to achieve lower energy costs of the implementation process and significantly improve the quality of treatment; and basic principles of constructing micro abrasive cutting equipment were expounded. In [4,10] fundamental investigations of shot-peening are presented, especially by methods of finite elements.

The analysis of research conducted in this branch allows to draw the following conclusions:

- the parameters obtained, usually with just one of the mechanisms involved in the formation of geometrical and physical characteristics of the treated surface, are under consideration. An integrated approach and building flexible mathematical models with the ability to easily adapt them to specific production conditions will take into account the parameters obtained on the surface due to the different mechanisms, namely microcutting, hydromolecular effect, brittle fracture and plastic deformation, and will allow to describe much better the dynamics of forming surfaces when treatment of forcibly propelling a steam of working medium is applied;
- the known mathematical models do not consider distribution characteristics of the working medium in the blast cross-sections. For subsonic blasts in which the calculation processing modes of incorporation of this distribution will significantly improve the accuracy of calculations. It is important to take account of the distribution and processing using treatment of forcibly propelling a steam of working medium for cleaning surfaces;
- the models that describe treating with loose solid balls for curved surfaces are not developed;
- the proposed model does not take into account patterns of interaction between one or more blasts with the treated surface depending on its geometry.

For modeling and diagnostics of machine parts surfaces after processing and to understand the phenomena that occur during the process, a detailed research is conducted and the mathematical descriptions of the products surface quality formation mechanisms are made. This is the basis for the technological support to the wide implementation and the use of non-bound blast particles treatment operations in industry, providing optimized technological modes for reducing environment pollution and improving the process control, thus recommending the process automation. [13-17].

The energy concept, after which energy, given to the working medium by the nozzle, except the losses at different stages of the treatment, transfers the change of form and stress state of treated surfaces into work, is formulated in virtue of the mathematical models of non-bound blast particles treatment.

To apply the energy concept, we should take into account the mass distribution of working medium in blast. The authors proposed a universal mathematical model of the mass distribution.

$$M_{ij} = Q_m \cdot \int_0^t \int_{x_i}^{x_{i+1}} \int_{y_j}^{y_{j+1}} f(x,y)\,dy\,dx\,dt \tag{1}$$

where Q_m - the blasting machine productivity (working medium flow rate) shown in $kg\cdot s^{-1}$; t - duration of the treatment; f (x,y) - density of mass distribution of in a point (x, y); x_i, x_{i+1}, y_j, y_{j+1} - coordinates of ij-area on treated surface.

Its universality lies in the fact that depending on the design of blast apparatus, blast equipment parameters, blasting conditions of the working medium, the integrand function can take different form and general structure model is not changed. To take into account processing scheme sufficient to adjust the limits of integration.

The mathematical modeling proposed allows to receive the theoretical relationship of the mass distribution of working medium in the blast cross-sections according to (1). It is necessary to establish the relationship between blasting machine productivity Q_m by weight and the characteristics of the blast apparatus (dimensions, compressed air pressure) and choose the integrand function of the mass distribution in the blast cross-sections.

Relationship between blasting machine productivity and the characteristics of the blast apparatus

Determining the blasting machine productivity is different for different working medium. Methods of determination of productivity if the working medium is slurry - a mixture of solid components with liquid components, as is the case with hydroabrasive treatment will differ from the methods of determining productivity, if the working medium is dry non-bound blast particles, as is the case with sand-blasting and shot-peening.

Let us consider the case where the environment is a slurry. To calculate the productivity through the nozzle by [1] recommended to use the formula:

$$Q_v = \mu \cdot S \sqrt{\frac{2 \cdot \Delta p}{\rho_c}} \tag{2}$$

of which: Q_v - the blasting machine productivity, $m^3\cdot s^{-1}$; μ - coefficient of working medium flowrate; S - cross sectional area of blast nozzle; Δp - vacuum in the blast nozzle; ρ_c - slurry density.

The coefficient of working medium flowrate μ depends from vacuum in the blast nozzle Δp, temperature and working medium properties, and on the geometric characteristics of the nozzle. It is determined experimentally [18]. The relationship between Q_v and Q_m is as follows:

$$Q_m = Q_v \cdot \rho_c \tag{3}$$

Substituting the values from (2) to (3) and conveying the slurry density ρ_c through solid component and liquid component density and the ratio between liquid and solid phases, and cross-sectional area through its nozzle diameter, we obtain the final formula for determining the blasting machine productivity for round nozzle section:

$$Q_m = \left(\frac{5 \cdot \pi}{2}\right) \cdot \mu \cdot d_s^2 \cdot \sqrt{\frac{2 \cdot \Delta p \cdot \rho_T \cdot \rho_P}{x_T \cdot \rho_P + \rho_T \cdot (100 - x_T)}} \tag{4}$$

of which: d_s - nozzle diameter, x_T - solid components in %; ρ_T - solid components density; ρ_P - liquid components density.

As seen from (4) the blasting machine productivity depends on the nozzle diameter, vacuum in the blast nozzle, and slurry properties.

The experimental relationship between the blasting machine productivity and the nozzle diameter for wet abrasive blasting, is shown in Figure 7. The diagram is built for typical technological characteristics of abrasive blasting treatment [1]. As solid fraction of the working medium using quartz sand (ρ_T = 2400 kg/m^3), as liquid component - water (ρ_P = 1000 kg/m^3). Solid components in slurry is x_T = 37.5%.

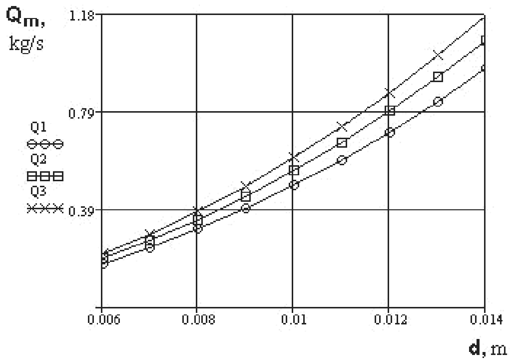


Fig. 7. The relationship between the blasting machine productivity Q_m and the nozzle diameter d_s: Q_1 - for Δp = 0,04 MPa; Q_2 - for Δp = 0,05 MPa; Q_3 - for Δp = 0,06 MPa

With increasing the nozzle diameter and the vacuum in the nozzle the blasting machine productivity increases.

The theoretical value of the blasting machine productivity, calculated by the (4) agree well with experimental data presented in [1].

If the environment is dry non-bound blast particles, the blasting machine productivity of cyclic blasting system defined by the formula:

$$Q_m = \frac{M_Z}{t} \tag{5}$$

of which: M_Z - shot mass in the hopper of shot-blasting system; t - time of the full use of the shot mass.

The blasting machine productivity can be performed by changing the pressure in the hopper. Experimental relationship between medium mass consumption Q_m and pressure p in hopper of wet abrasive peening cyclic system, is shown on Figure 8 [19].

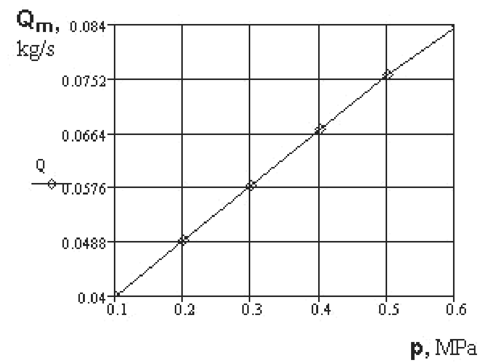


Fig. 8. The relationship between the blasting machine productivity Q_m and pressure p in the hopper of wet abrasive peening cyclic system

With increasing pressure in the hopper the blasting machine productivity increases in direct proportion.

Choice of mass distribution law in the blast cross-sections

As shown by experimental studies, the relationship between the mass distribution in the blast cross section and a radius of the considered cross-sectional area is probabilistic characteristics, which is non-linear [20]. Therefore coming from physical maintenance of the process and experimental information, shown in [1], for the nozzle with circular cross-section as a subintegral function is accepted normal law of mass distribution in plane XOY that is perpendicular to the axis of the blast:

$$f(x, y) = \frac{1}{2 \cdot \pi \cdot \sigma_x \cdot \sigma_y} e^{-\frac{(x-a_x)^2}{2 \cdot \sigma_x^2} - \frac{(y-a_y)^2}{2 \cdot \sigma_y^2}} \tag{6}$$

where a_x, a_y - centers of dispersion (mathematical hopes) on axes OX and OY, accordingly; σ_x, σ_y - standard deviations.

In the geometric interpretation a_x and a_y represent a shift of the center blast apparatus according to the axes OX and OY from the center of coordinates. Choosing one or another law of motion of the blast apparatus or treated surface and using expressions (1) and (6), we can calculate the mass distribution of arbitrary cross-section of the blast under certain laws of the blast apparatus motion.

In formula (6) standard deviations that depend on the parameters of the blast should be identified.

To round nozzle section as average, and the main probable deviation equal to each other:

$$\sigma_x = \sigma_y = \sigma,$$

$$E_x = E_y = E,$$

because the blasting conditions are similar to axes OX and OY. The circle with a radius equal to 4E covers an almost all scattering on the plane XOY. Therefore, this radius can be taken equal to the radius of the blast trace on the treated surface R:

$$R = 4 \cdot E \tag{7}$$

where $E = \rho \cdot \sqrt{2} \cdot \sigma$.

Radius of the blast trace on the treated surface determined from geometrical considerations (Figure 9).

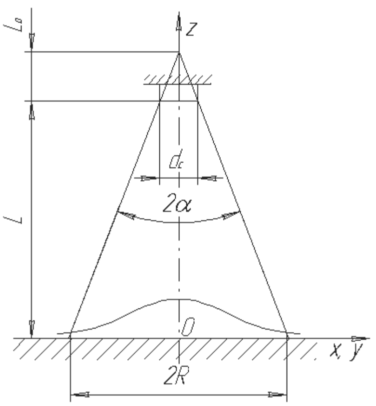


Fig. 9. Scheme for determining standard deviation for mass working medium distribution

$$R = (L + L_o) \cdot tg\alpha \tag{8}$$

where L_o - distance from the center of the blast to the end of the nozzle; L - the perpendicular distance between treated surface and end of the nozzle; α - cone angle of the blast, (rad). The perpendicular length between treated surface and end of the nozzle determined by (8):

$$L_o = 0.145 \cdot \frac{d_s}{a} \tag{9}$$

where α - coefficient of the blast turbulence: α = 0.07-0.14 [19].

It is recommended to determine the cone angle of the blast α experimentally, immediately before the processing.

Based on the above considerations, we write the expression for determining the standard deviation in the plane perpendicular to the axis of the blast for round section nozzle:

$$\sigma = \frac{(L + 0.145\frac{d_s}{a}) \cdot tg\alpha}{4 \cdot \rho \cdot \sqrt{2}} \tag{10}$$

Expression (10) allows to set technological modes equidistant from the nozzle surfaces of the processing one blast apparatus.

Substituting the values from (4) and (6) in (1) obtain a mathematical model of mass distribution of non-bound mass blast particles in the blast cross-section for round section:

$$M_{ij} = \left(\frac{5 \cdot \pi}{2}\right) \cdot \mu \cdot d_c^2 \cdot \sqrt{\frac{2 \cdot \Delta p \cdot \rho_T \cdot \rho_P}{x_T \cdot \rho_P + \rho_T \cdot (100 - x_T)}} \cdot$$
$$\cdot \Delta t \cdot \int_{x_i}^{x_{i+1}} \int_{y_j}^{y_{j+1}} \frac{1}{2 \cdot \pi \cdot \sigma^2} e^{-\frac{(x^2+y^2)}{2 \cdot \sigma^2}} dydx \tag{11}$$

The authors propose an algorithm, based on which a program is implemented to calculate the mass distribution of non-bound blast particles by means of (11). The program is written in the engineering calculation software MathCAD.

By using the engineering calculation software the 3D-mass distribution after non-bound blast particles treatment is received in a blast cross-section (Figure 10).

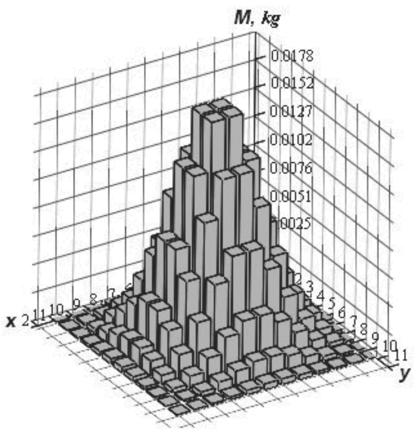


Fig. 10. The mass distribution after non-bound blast particles treatment

The mass distribution is received for the following technological modes:

- the nozzle diameter d_s = 0.01 mm;
- vacuum in the blast nozzle Δp = 0.05 MPa;
- the perpendicular distance between treated surface and end of the nozzle L = 0.1 m;
- the cone angle of the blast α = 10°;
- the solid components density ρ_T = 2400 kg/m^3;
- the liquid components density ρ_P = 1000 kg/m^3;
- the solid components in slurry x_T = 37.5 %.

Having analyzed the mass distribution, calculated by (10) and (11) for different values of technological modes, make the following conclusions. With increasing the perpendicular distance between treated surface and end of the nozzle L, nozzle diameter d_s and cone angle of the blast α standard deviation increases, i.e. the mass distribution curve becomes more flat, which leads to better uniformity of treatment while reducing its intensity. With increasing vacuum Δp in blast apparatus mixing chamber and coefficient of working medium flow rate μ, which depends on the geometrical parameters of mixing chamber and nozzle, the mass flow increases, thus increasing the kinetic energy of the blast and processing performance.

Initial parameter that describes the treatment by non-bound blast particles, as a process of resizing by cutting, and can be used to assign optimal allowances is the depth of the removed layer of material from the workpiece surface. Initial parameters that describe the treatment by non-bound blast particles, as s process of changing physical and mechanical properties of the surface, and can be used to predict structural and stressed state, is the hardness of the treated surface and the depth of cold working layer obtained on the treated surface after processing. These parameters are determined by the work carried non-bound blast particles in their interaction with the treated surface. It should be noted that the blast consists of a large amount of particles that simultaneously interact with the treated surface, and the interaction of each individual non-bound particle are unpredictable, while the results of the total interaction of a large number of non-bound blast particles with machined surface are predictable, and can be checked experimentally and described by mathematical expressions. So assume that the total work to change the dimensions and structure-stress state of the treated surface carry individual packets of the particles, the density of which is regulated by the concentration of solid components of working medium in the liquid. Work to change the shape and properties of the treated surface is due to the transformation of energy which are particles at the start of the interaction with the surface.

General energy balance of the operations of forcibly propelling a steam of working medium

Each non-bound blast particle at the outlet of the nozzle blast apparatus has stock of the kinetic energy which is determined by the equation:

$$E_k = \frac{m_i \cdot V_i^2}{2} \tag{12}$$

where m_i - mass; V_i - velocity.

The mass and velocity of the non-bound particles distribution in blasts is the subject of separate studies described here.

All the energy, except for loss turns to work on changing the size and structural and stressed state of the treated surface. Formula general energy balance for the blasting written as:

$$E_k = E_{kop} + E_{vtr} \tag{13}$$

where E_{kop} - energy, which turns to work on changing the size and structural and stressed state of the treated surface; E_{vtr} - energy loss.

Energy E_{kop} is divided into energy which is converted to work on the elastic-plastic deformation of the treated surface and energy wasted on the shear deformation and shear surface layer that becomes a work of cutting:

$$E_{kor} = E_{pld} + E_{prd} + E_{riz} \tag{14}$$

where E_{pld} - energy that is converted to work on the plastic deformation of the treated surface; E_{prd} - energy that is converted to work on the elastic deformation of the treated surface; E_{riz} - energy which is converted to work of cutting.

Energy which is converted to work on the elastic deformation of the treated surface E_{prd}, returns the particles during rebound from the treated surface, which must be considered in determining the energy losses

The correlation between energies E_{pld} and E_{riz} depends on the predominant mechanism for the formation of microrelief and structural-stress state on the treated surface and is defined by the impinging angle.

Energy losses that occur for the processing can be divided into:

- loss for the transport of the particles to the treated surface:

1. to overcome air resistance E_{op};
2. to overcome friction of the working medium in streams E_{trs};

- loss associated with the presence of liquid components in the working medium:

1. to overcome the non-bound particles liquid film formed on the treated surface E_{rid1};
2. to overcome the forces of molecular cohesion of the liquid at particle rebounds E_{rid2};

- loss for the process of dry friction and to overcome the adhesion:

1. friction loss in the interface between non-bound particles and surfaces during the elastic deformation E_{tr1};
2. loss due to friction between non-bound particles and surfaces in introducing particles at the surface during plastic deformation E_{tr2};
3. loss due to break the temporary connection between particles and surfaces in the particles rebound from the treated surface E_{tr3};

- loss in the form of wave energy, which extends into the depth of the metal during elastic deformation E_{hv};
- loss of energy in the form of elastically strained metal, which is returned when particles rebound from the surface E_{pr}.

Expression was recorded to determine the losses and it grouped homogeneous elements:

$$E_{vtr} = \left(E_{op} + E_{trs}\right) + \left(E_{rid1} + E_{rid2}\right) + \left(E_{tr1} + E_{tr2} + E_{tr3}\right) + E_{hv} + E_{pr} \tag{15}$$

Analyzing the resulting equation for the loss processes of wet abrasive blasting and sandblasting, it should be noted that the presence of liquid components in the working medium (wet abrasive blasting) takes additional energy to overcome liquid film, but significantly reduced the loss on the process of dry friction and adhesion forces. Therefore, it can be concluded that the introduction of liquid components in the medium can reduce energy loss and thus improve the performance of processing.

Substituting expressions (3) and (4) to (2), it was obtained a detailed view of the energy balance equation for the process:

$$E_k = (E_{pld.} + E_{prd} + E_{riz}) - (E_{op} + E_{trs}) - (E_{rid1} + E_{rid2}) - (E_{tr1} + E_{tr2} + E_{tr3}) - E_{hv} - E_{pr} \quad (16)$$

Neglecting wave energy E_{hv} and taking into account that energy, which turns into a work of elastic deformation E_{prd} be returned particles during the rebound from the treated surface in the form of E_{pr}, rewrite equation (16) as

$$E_k = (E_{pld} + E_{riz}) - (E_{op} + E_{trs}) - (E_{rid1} + E_{rid2}) - (E_{tr1} + E_{tr2} + E_{tr3}) \quad (17)$$

The loss of energy on non-bound particle impact at work surface is 10-15% of the value of energy has in reserve a particle [22]. So finally

$$E_k = \frac{(E_{pld} + E_{riz})}{0{,}85} \quad (18)$$

Expression (18) establishes the relationship between the kinetic energy of non-bound blast particles and work, which should spend to achieve the desired values of output parameters of the process that is both optimization criteria. This expression is the base for developing a mathematical models of the process.

Distributions of the working medium velocity

To apply (18) should theoretically receive and analyze the distribution of the working medium velocity in the blast cross-section, which is one of the stages of developing universal mathematical models of blast processing based on the previously proposed energy conception.

Blast that flows for the round cross-section nozzle is presented on Figure 11.

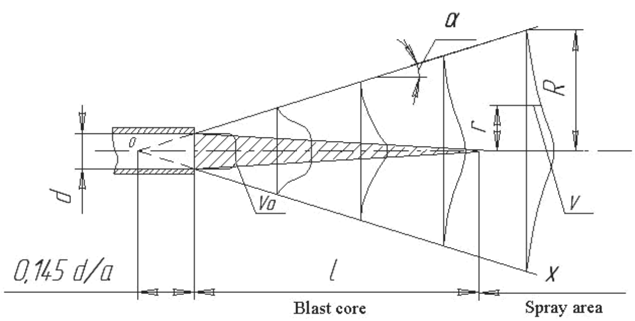


Fig. 11. Blast that flows for the round cross-section nozzle

The blast of working medium is conditionally divided into two areas: blast core, in which velocity is equal to the initial velocity, and the spray area, in which the axial velocity decreases with increasing distance from the nozzle. As seen from the diagram presented in Fig. 11, the velocity along the blast cross sections, except section which coincides with the end face of the blast apparatus nozzle is changed. To describe the change in velocity along the blast cross section it was used the following dependency:

$$V = V_L \left(1 - \left(\frac{r}{R}\right)^{1.5}\right)^2 \quad (19)$$

where V_L - velocity at blast axis at a distance L from the end face of the nozzle; r - distance from the blast axis to the point of the considered cross-sectional; R - maximum radius of the blast, i.e. the distance from the blast axis to the points with zero velocity.

Blast velocity distribution that was calculated by using (19), is presented on Figure 12.

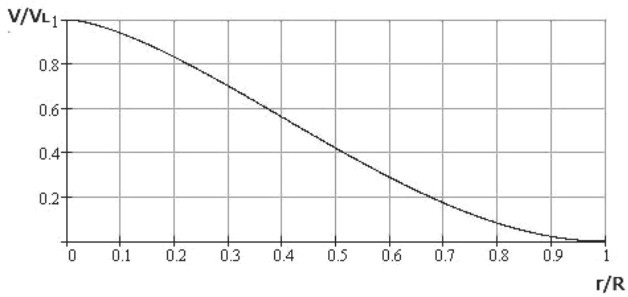


Fig. 12. Blast velocity distribution

Equation (19) adequately describes the velocities distribution in the cross-sections for the spray area, for which the velocity curves are similar. To describe the distribution of velocities in the cross-sections for the blast core amend (19). For this (19) will be written in general terms, replacing the constant coefficients of variables.

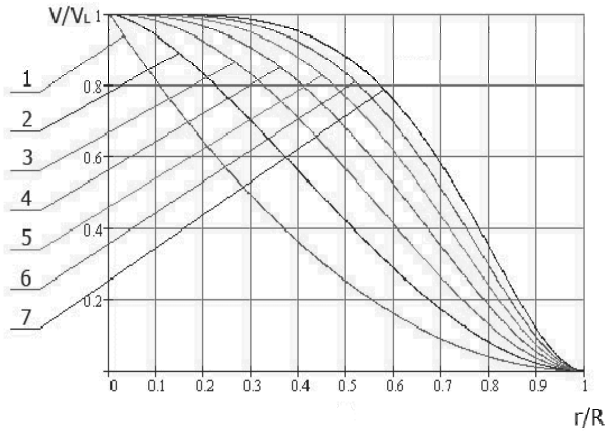
$$V = V_L \left(1 - \left(\frac{r}{R}\right)^{k_1}\right)^{k_2} \quad (20)$$

Therefore it is possible to analyze how changing the coefficients k_1 and k_2 affects the blast velocity distribution. For this purpose the blast velocity distributions for different values k_1 and k_2 (Figure 13) were obtained using MathCad.

While increasing the coefficient k_1 the velocity distribution becomes more convex, appears and extends area of the plot with constant values of velocity in the central part of the distribution. With increasing velocity coefficient k_2 the velocity distribution becomes more concave, and extends peripheral area of the plot.

Thus, changing the values of k_1 and k_2 leads to reshape the velocity distribution plot, allowing to make it more concave or convex, to form the areas with a constant value of velocity in the central part of the plot or in the periphery. It can adequately describe the distribution of velocities in the blast cross-sections by selection values of coefficients k_1 and k_2.

a)



b)

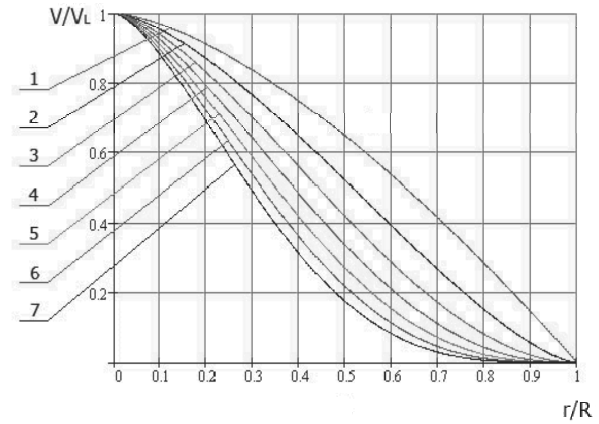


Fig. 13. Blast velocity distributions:

a) for different k_1 if $k_2 = 2$

1 - $k_1 = 1$; 2 - $k_1 = 1{,}5$; 3 - $k_1 = 2$; 4 - $k_1 = 2{,}5$;
5 - $k_1 = 3$; 6 - $k_1 = 3{,}5$; 7 - $k_1 = 4$

b) for different k_2 if $k_1 = 1{,}5$

1 - $k_2 = 1$; 2 - $k_2 = 1{,}5$; 3 - $k_2 = 2$; 4 - $k_2 = 2{,}5$;
5 - $k_2 = 3$; 6 - $k_2 = 3{,}5$; 7 - $k_2 = 4$

The transformation (19) in the general equation (20) gives an opportunity to use it for describing the distribution of velocities in different parts of the blast and provides flexibility in adapting the general mathematical model of the operations of forcibly propelling a steam of working medium to real operating conditions. To determine the velocity of the blast axis at a distance *L* from the end face of the blast apparatus nozzle the following empirical equation is introduced:

$$V_L = V_0 \frac{0{,}96}{\frac{2aL}{d_c} + 0{,}29} \qquad (21)$$

where V_0 - the velocity of the blast axis on the end face of the blast apparatus nozzle.

Substituting the values from equation (21) in (20), a general equation for determining the velocity distribution in the blast is obtained:

$$V = V_0 \frac{0{,}96}{\frac{2aL}{d_c} + 0{,}29} \cdot \left(1 - \left(\frac{r}{R}\right)^{k_1}\right)^{k_2} \qquad (22)$$

For receiving the distribution of velocities in the blast in a view similar to the mass distribution, an algorithm to calculate the velocity distribution V_{ij}, is developed with elementary non-bound mass of the particles in each of the areas studied region XOY, limited abscissas x_i and x_{i+1} and ordinates y_j and y_{j+1}. The investigated area XOY coincides with the treated surface, which is normal to the blast axis OZ. For each of the investigated areas the velocity values are averaged, taking as the basic values, velocity at the intersection of the diagonals of the rectangular area D. Based on these considerations, the distance from the blast axis to point of the considered cross-section *r* writes through the point coordinates x_i and x_{i+i}, y_j and y_{j+1} (Figure 14):

$$r = \sqrt{\left(\frac{x_i + x_{i+1}}{2}\right)^2 + \left(\frac{y_j + y_{j+1}}{2}\right)^2} \qquad (23)$$

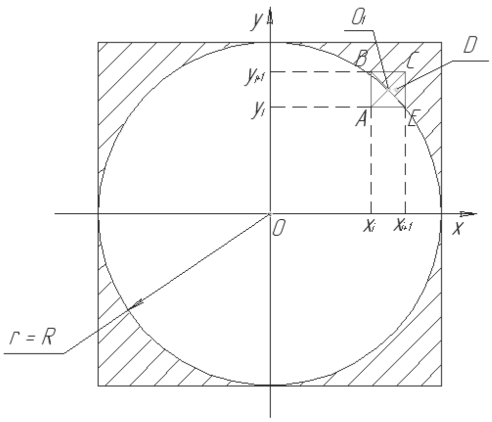


Fig. 14. Scheme for calculating blast velocity V_{ij}

After substituting the values r from (23) to (22):

$$V_{ij} = V_0 \frac{0{,}96}{\frac{2aL}{d_c} + 0{,}29} \cdot$$

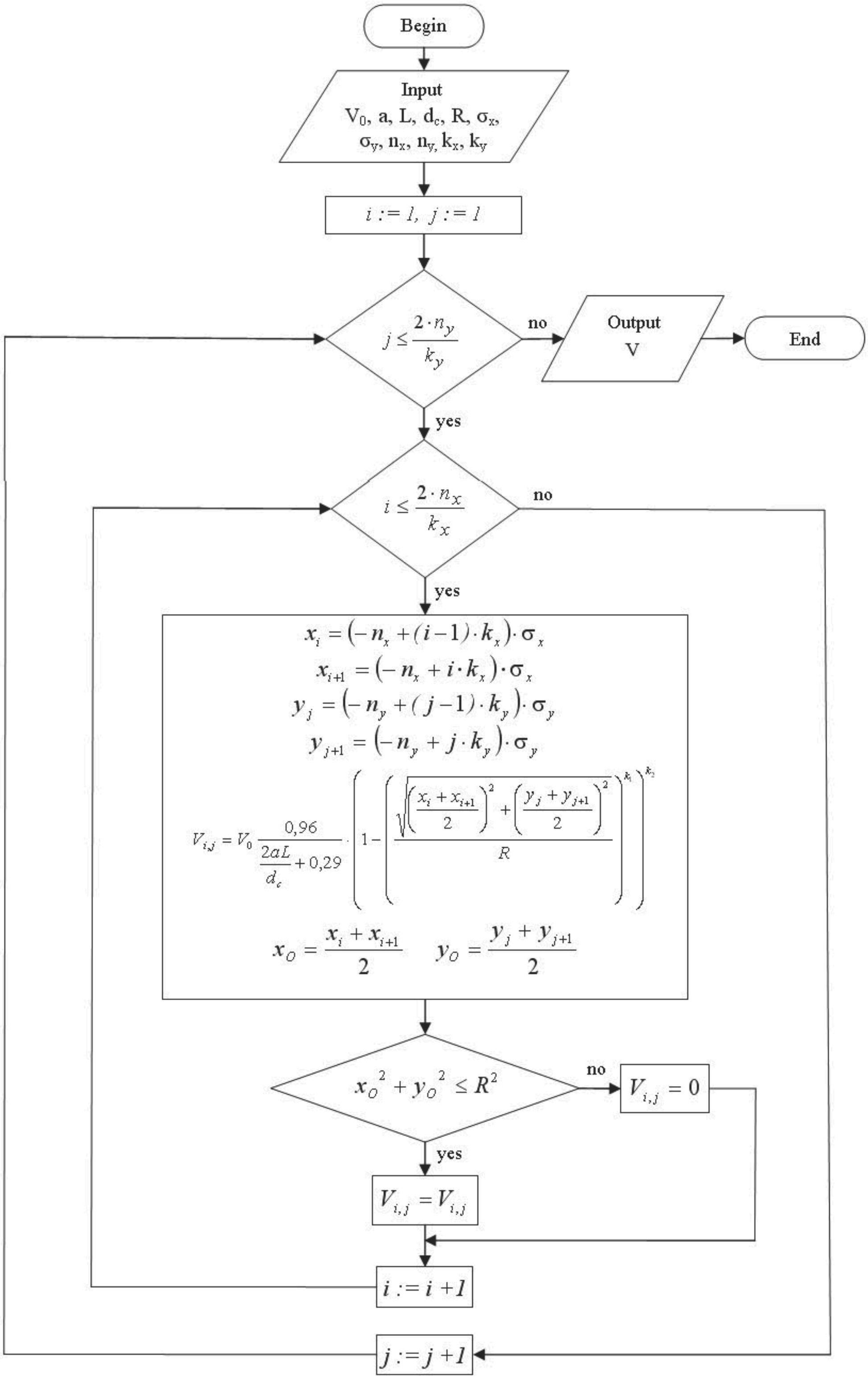


Fig. 15. Flowchart for blast velocity distribution calculations V_{ij}

$$\cdot\left(1-\left(\frac{\sqrt{\left(\frac{x_i+x_{i+1}}{2}\right)^2+\left(\frac{y_j+y_{j+1}}{2}\right)^2}}{R}\right)^{k_1}\right)^{k_2} \qquad (24)$$

Equation (24) is the base for creating an algorithm to calculate the velocity distribution packages of non-bound blast particles in an arbitrary point of the blast cross-section and investigations of processing curved surfaces and flat surfaces for different blast angles. Considerations in developing the algorithm to calculate the velocity distribution is similar to the considerations in developing the algorithm for calculating the mass distribution. The flowchart of the algorithm is shown in Figure 15.

The results of the calculation are displayed in a matrix form:

$$V=\begin{pmatrix} V_{11} & \dots & \dots & V_{1\left(\frac{2\cdot n_y}{k_y}\right)} \\ \dots & \dots & \dots & \dots \\ \dots & \dots & V_{ij} & \dots \\ V_{\left(\frac{2\cdot n_x}{k_x}\right)1} & \dots & \dots & V_{\left(\frac{2\cdot n_x}{k_x}\right)\left(\frac{2\cdot n_y}{k_y}\right)} \end{pmatrix}$$

According to the matrix data can plot the velocity distribution in the cross-section of the blast. To perform calculations using the algorithm proposed by the authors, the MathCAD program was developed. The results calculated for the blast cross-section are shown in Figure 16 as 3D histogram.

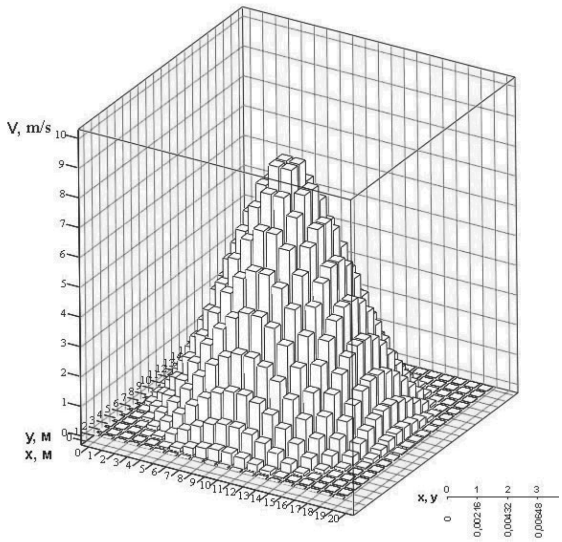


Fig. 16. Blast velocity distribution in a cross-section: d_s = 0.01 m; L = 0,1 m; $\Delta p = 0{,}5\times10^5$ Pa; $\alpha = \pi/18$; ρ_c = 1280 kg·m^{-3}; a = 0.14; k_1 = 1.5; k_2 = 2; ξ = 1

Having analyzed the velocities distribution for different values, calculated by (24), it is found that with increasing the nozzle diameter and the compressed air pressure in the system for air supply, axial velocity at increasing distance from the nozzle increases, which leads to the intensification of the processing. With increasing the coefficient of the blast turbulence and density of the working medium axial velocity at increasing distance from the nozzle decreases, leading to a decrease in the intensity of treatment.

Distribution of the working medium mass and kinetic energy

For determination of the working medium mass distribution $M_{i,j}$, the “mechanical” interpretation is used. Distribution of system that consists of two random quantities is accepted as the distribution of single mass on the treated plane. The following equation is obtained:

$$M_{ij}=Q_m\cdot\int_0^t\int_{x_i}^{x_{i+1}}\int_{y_j}^{y_{j+1}} f(x,y)\,dydxdt \qquad (25)$$

Q_m - the blasting machine productivity (working medium flow rate) shown in kg·s^{-1}; t - duration of the treatment; f (x,y) - density of mass distribution of in a point (x, y); x_i, x_{i+1}, y_j, y_{j+1} - coordinates of ij-area on treated surface.

Substitution laws of motion as the coordinates ij-area allows for simulation of the processing by means of blast movable apparatus for different trajectories of its movement.

Based on the mathematical models application software is created. It allows for presenting the results of treatment in a family of curves for the case when the blast apparatus moves relative to the surface, or as three-dimensional histogram for unmoved blast apparatus and the treated surface.

The working medium mass distribution for case of uniform rectilinear moving blast apparatus along the fixed treated surface are presented on Figures 17, 18.

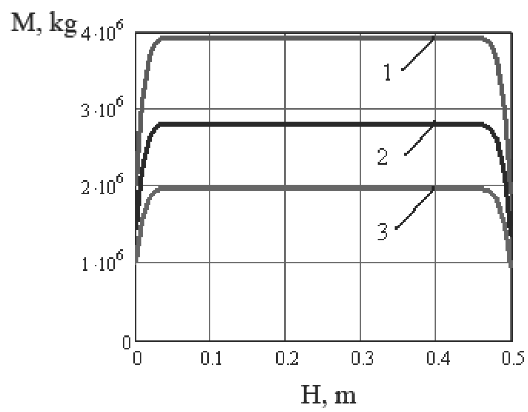


Fig. 17. Mass distribution along the treated surface trajectory for various velocities of its movement:
1 - V = 0.005 mps; 2 - V = 0.007 mps; 3 -V = 0.01 mps

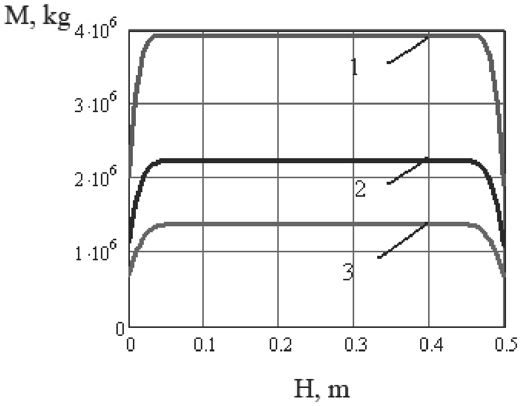


Fig. 18. Mass distribution along the treated surface trajectory for various distances between surface being treated and the nozzle 1 - L = 0.4 m; 2 - L = 0.5 m; 3 - L = 0.6 m

The kinetic energy working medium distributions along the radius of the rotary plate for case of uniform rectilinear moving blast apparatus is shown on Figs. 19, 20.

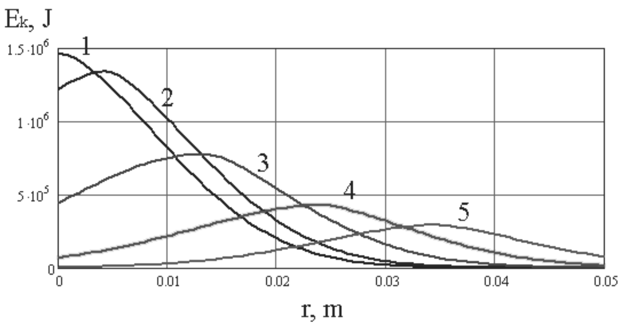


Fig. 19. Kinetic energy distribution along the radius of the rotary plate from eccentricity x_c:
1 - x_c = 0 mm; 2 - x_c = 5 mm; 3 - x_c = 15 mm;
4 - x_c = 25 mm; 5 - x_c = 36 mm

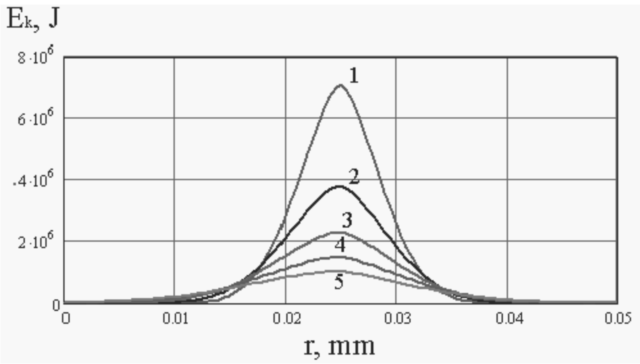


Fig. 20. Kinetic energy distribution along the radius of the rotary plate from perpendicular distance between surface being treated and the nozzle end for the eccentricity x_c = 25 mm:
1 - L_t = 0.15 m; 2 - L_t = 0.2 m; 3 - L_t = 0.25 m;
4 - L_t = 0.3 m; 5 - L_t = 0.35 m

Distribution diagram of hardening layer depth and change of microhardness for case of the fixed treating surface and the blast apparatus are shown on Figure 21.

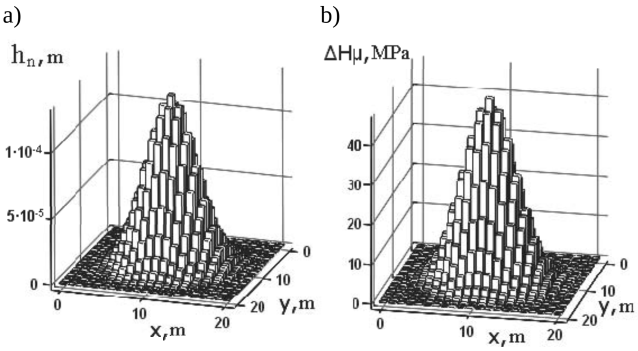


Fig. 21. Distribution diagram of quality characteristics on the surface after non-bound blast particles treatment: a) depth of hardening layer h_n, b) change of microhardness Δ Hμ

4. Experimental studies of the operations of forcibly propelling a steam of working medium

The plastic deformation mechanism and stressed the surface state treated with non-bound blast particles are investigated experimentally using laser speckle interferometry with the analysis of interference pattern by a computer automated system (Figure 22).

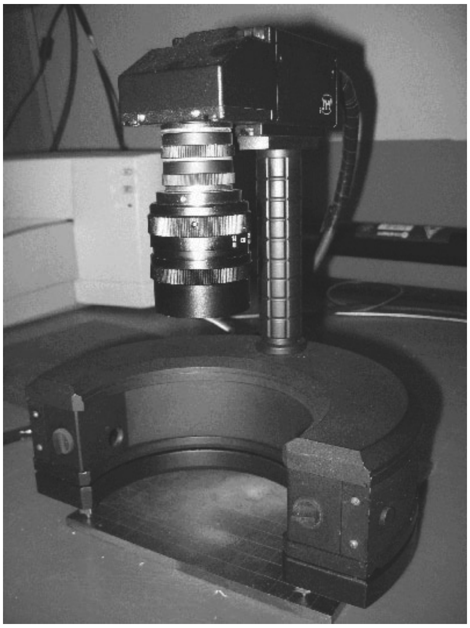


Fig. 22. Investigations of specimen plastic deformation as a result of non-bound blast particles treatment

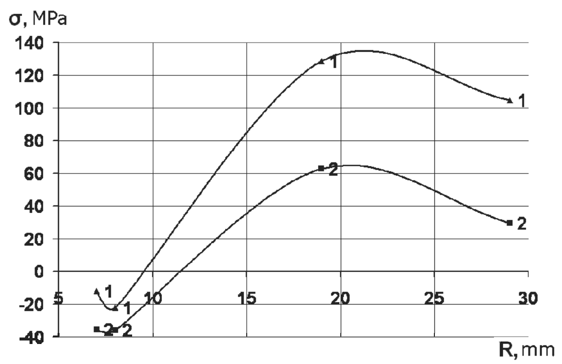
As the specimens used square plates made of carbon steel with a side length of 150 mm, thickness - not less than 5 mm, because there is a deformation of the plate after treating for a lower thickness, which significantly affects the measurement accuracy. The measuring bases on the plate were previously polished. It was found by using a set of probes, mould rulers and verification plate that the deviation from parallelism plate surfaces did not exceed 0.02 mm. For convenience of measurement the specimen’s surface was marked with 10 mm side squares [8].

An error of measuring is 6 % from fluidity limit of material during tensile deformation, that ± 15 MPa, and the results of measuring are shown in Fig. 23.

Zone with predominant compressive stresses is formed as a result of non-bound blast particles treatment on the surface. The maximum values of stresses are fixed in a center of the plates. They are equal σ_{xx} = - 11,82 MPa; σ_{yy} = - 35,43 MPa for duration of treatment t = 10 min; σ_{xx} = - 31,81 MPa; σ_{yy} = - 46,49 MPa for duration of treatment t = 20 min.

The material layer thickness removed non-bound blast particles from the flat specimen were measured to investigate microcutting surface after treatment (Figure 24).

a)



b)

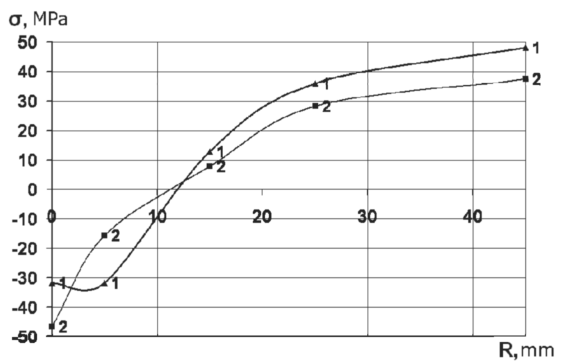


Fig. 23. Distribution diagram of residual stresses along the jet track on the treated surface: 1 - residual stresses σ_{xx}; 2 - residual stresses σ_{yy}: a) processing time - 10 min; b) processing time - 20 min

As a result of measurements it was found that for the impinging angle equal β = 90º removing material from the specimen surface is. The maximum removal is observed at the area, which lies on the jet axis, and is 0.844 mm for the duration of treatment 10 minutes, and 1.27 mm for the duration of treatment 20 minutes (Figure 25).

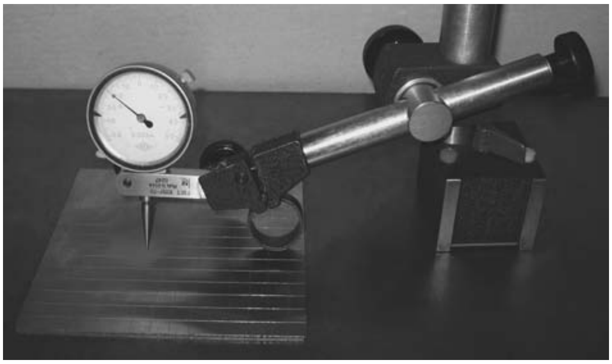
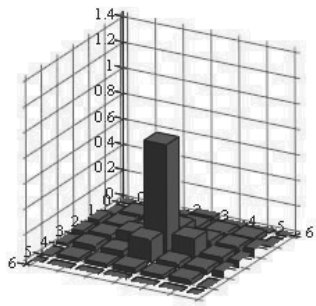


Fig. 24. Investigations of specimen microcutting as a result of non-bound blast particles treatment

a)



b)

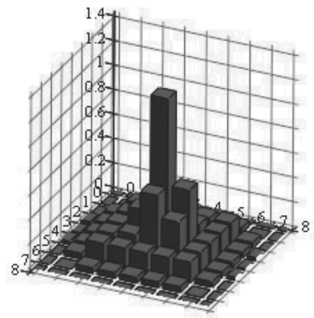


Fig. 25. The material layer thickness removed by wet abrasive jet from flat specimen distribution: a) processing time - 10 min; b) processing time - 20 min

Removing material from the surface in the case for a theoretically substantiated, that it should not be, because the abrasive grains that bounce off the surface after the impact, colliding with the grains, which move in the direction perpendicular to the surface and change the trajectory of their movement and angle interaction with the surface. This phenomenon should be considered in accurate diagnosis of the surface treated non-bound blast particles.

5. Designing of shot-peening cyclic system

One way to solve environmental problems and improve efficiency shot-peening is improving the management process and introduction of its automation. This can be achieved by means of design improvement of shot blasting units, including a change in the principle of transportation shot to the machine parts surfaces. Therefore, development of design of modernized shot blasting units and a method of calculating their geometric and process parameters are important scientific and applied tasks.

For its solution the shot hopper should enter in the design of shot-peening system. It is allowing to increase productivity and eliminate usage of compressed air to creating ejection.

The principle of operation of the shot-peening machine is that portion of shot falls from the conical bunker 7 in the hopper 2 by gravity. Compressed air is supplied through pipe 4 to the hopper. Compressed air turbulizes, captures the shot and transports it to the nozzle 7 on the hose 8.

Formed by means of the nozzle shot blast is transported to the machine part surface 5. Worked-out shot enters across the table-grid 6 the bottom of the conical bunker 7 for reuse. This machine belongs to injection-type shot-peening cyclic systems.

An important task during the design of injection-type shot-peening cyclic systems is to develop methods for estimation of the machine cycle for submitting the required number of shot to the treated surface per unit time (machine productivity), the geometrical dimensions of the shot hopper; pressure in the lines of compressed air to ensure desired velocity for shot, as well as automation of these calculations by using modern software.

Shot hopper of shot-peening ejection system is shown in Figure 26.

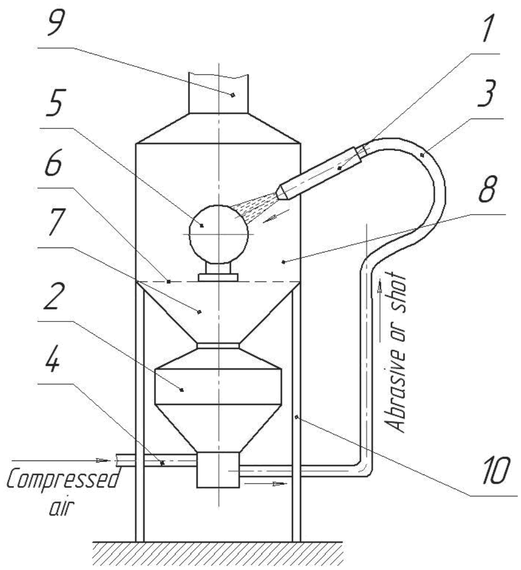


Fig. 26. Shot-peening system equipped by shot hopper: 1 - nozzle; 2 - hopper; 3 - hose; 4 - pipe for supplying compressed air; 5 - machine part; 6 - table; 7 - conical bunker; 8 - working chamber; 9 - incoming pipe cyclone; 10 - holders

Calculation of the machine cycle for injection-type shot-peening cyclic systems

The machine cycle of the system consists of a time for filling the hopper by shot and a time for emptying the hopper during processing the machine parts:

$$t_z = t_{zap} + t_{sp} \tag{26}$$

where t_{zap} - time for filling the hopper by shot; t_{sp} - time for emptying the hopper.

Based on the fundamentals of the mechanics of granular materials and recommendations [22] equation for calculation of time for filling the hopper by shot is received:

$$t_{zap} = \frac{4.472 \cdot m}{\pi \cdot \lambda \cdot \rho_{nd} \cdot d_{vp}^{2,5} \cdot g^{0,5}} \tag{27}$$

where m - shot consumption used for one cycle of treatment; g - free fall acceleration; λ - rate of material leakage from the hopper - for dry good free-flowing materials, that include shot λ = 0,6; ρ_{nd} - shot bulk density; d_{vp} - diameter of the hopper outlet.

Diameter of the hopper outlet d_{vp} (Figure 27) should be sufficient to ensure the required shot-peening machine productivity and to avoid the shot arch formation in the hopper during free-running shot to the hopper.

Diameter of the hopper outlet is chosen from the condition recommended in [22]:

$$d_{vp} \geq (4,0...5,5) d_{dr}^{max} \tag{28}$$

де d_{dr}^{max} - maximum diameter of shot, which is planned to use in shot-peening system.

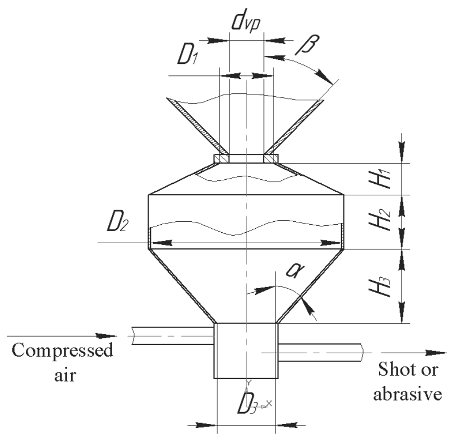


Fig. 27. Dimensions of shot hopper

Time of emptying of the hopper is defined as the ratio of the compressed air volume that is necessary in one processing cycle for transportation of shot mass, to the volumetric air flow of shot-peening machine.

Taking into the account the principles of the theory of granular materials pneumatic conveying [23], the equation to determine the emptying time of the hopper was obtained:

$$t_{sp} = \frac{4 \cdot m \cdot \rho_{pov}}{\pi \cdot d_s^2 \cdot V \cdot \mu} \tag{29}$$

where ρ_{pov} - air density, kg/m^3; d_s - diameter of the nozzle; V - compressed air speed in a line of the shot-peening system; μ - concentration of operating mix that consists of shot and compressed air.

Take into account (27) and (29), equation to determine the machine cycle of the shot-peening cyclic system was obtained:

$$t_z = \frac{4 \cdot m}{\pi} \cdot \left(\frac{1{,}107}{\lambda \cdot \rho_{nd} \cdot d_{vp}{}^{2,5} \cdot g^{0,5}} + \frac{\rho_{pov}}{d_s^2 \cdot V \cdot \mu}\right) \tag{30}$$

Thus, assuming that $Q = m/t_z$, the equation to determine the shot-peening machine productivity was obtained:

$$Q = \left(\frac{4}{\pi} \cdot \left(\frac{1{,}107}{\lambda \cdot \rho_{nd} \cdot d_{vp}{}^{2,5} \cdot g^{0,5}} + \frac{\rho_{pov}}{d_s^2 \cdot V \cdot \mu}\right)\right)^{-1} \tag{31}$$

Calculation of the hopper sizes for injection-type shot-peening cyclic systems

The initial parameter for calculating the hopper sizes is the shot consumption used for one cycle of treatment. The hopper volume consists of the volume, which is filled with shot, and volume of internal cavities, which should be left in the hopper to ensure air jet turbulization in it. On the basis of experience designing pneumatic type machines it should be at least 80% of the hopper volume.

Finally, the hopper volume is:

$$W = \frac{5 \cdot m}{\rho_{nd}} \tag{32}$$

Sizes for each of the hopper section (Figure 27) is chosen using geometric relationships to determine the volumes of cylindrical and conical bodies and rows of superior numbers [23]:

$$\begin{aligned} W_1 &= \frac{\pi}{12} \cdot H_1 \cdot (D_1^2 + D_1 \cdot D_2 + D_2^2) \\ W_2 &= \frac{\pi}{4} \cdot H_2 \cdot D_2^2 \\ W_3 &= \frac{\pi}{12} \cdot H_3 \cdot (D_2^2 + D_2 \cdot D_3 + D_3^2) \end{aligned} \tag{33}$$

where D_1 - diameter of the hopper upper orifice; H_1 - height of the hopper upper conical section; D_2 - diameter of the hopper cylindrical section; H_2 - height of the hopper cylindrical section; D_3 - diameter of the hopper lower orifice; H_3 - height of the hopper lower conical section.

The angle of the conical wall inclination of the hopper lower section α and angle of the conical bunker wall inclination β should be checked based on the condition of shot braking absence [22]:

$$\begin{aligned} tg\alpha &\geq f \\ tg\beta &\geq f \end{aligned} \tag{34}$$

where f - frictional coefficient between shot and the hopper wall; recommended ratio equal to f = 0,75…0,8 for moving the body to the metal surface.

Calculation of the pressure in the shot-peening system line

Compressed air pressure in a line of the shot-peening system is calculated by the known equation of the pneumatic [24]:

$$p = \frac{V^2 \cdot \rho_s}{2} \tag{35}$$

where ρ_s - averaged density of the operating mix that calculate by the following equation:

$$\rho_s = \frac{\rho_d \cdot \rho_{pov} (\mu + 1)}{\mu \cdot \rho_{pov} + \rho_d} \tag{36}$$

where ρ_d - shot density.

Taking into the account equations (26)-(36), an algorithm to calculate the hopper of shot-peening system is designed (Figure 28).

MathCAD applied program was developed for the automated calculations based on the algorithm. As an example, to input parameters presented in Table 2, calculations of shot-peening system operation period, the hopper geometric dimensions and the required compressed air pressure in a line were conducted.

To ensure productivity of modernized shot-peening system equipped by shot hopper not less than 48 kg/min and the velocity of the blast axis on the end face of the nozzle 100 m/s air pressure in the line of the shot-peening system shall be not less than 0.765 MPa. It is recommended to use a nozzle diameter of 0.01 m and the hopper volume 14 dm^3.

The calculated geometrical parameters of the hopper are:

- diameter of the hopper upper orifice D_1 = 200 mm;
- height of the hopper upper conical section H_1 = 30 mm;
- diameter of the hopper cylindrical section D_2 = 350 mm;
- height of the hopper cylindrical section H_2 = 70 mm;
- diameter of the hopper lower orifice D_3 = 130 mm;
- height of the hopper lower conical section H_3 = 112 mm;
- angle of the conical wall inclination of the hopper lower section $\alpha = 45^o$;
- diameter of the hopper outlet d_{vp} = 80 mm.

To reduce the environmental problems that arise during shot-peening treatment, and increase its effectiveness shot-peening system can be modernized by including the shot hopper in its design.

The proposed methodology for calculating the geometrical and technological parameters of cyclic shot-peening system equipped by shot hopper, can be used when designing ejection equipment and the basis for computer-aided design systems.

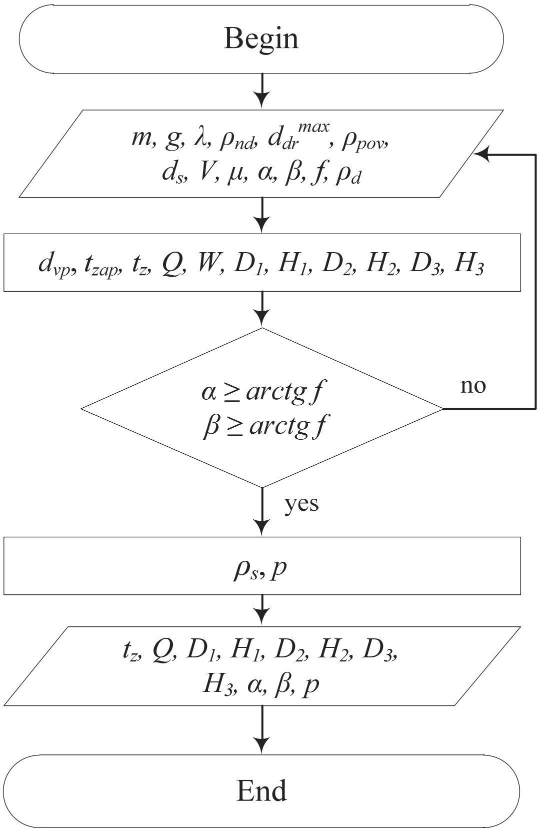


Fig. 28. Algorithm of shot hopper calculations

Table 2.
Input data for calculations of the shot-peening system

Characteristic	Value
Productivity (general shot consumption) Q, kg/min	48
Shot consumption used for one cycle of treatment m, kg	12
Mass ratio between shot and compressed air μ, kg/kg	120
Nozzle diameter d_s, m	0.01
Required compressed air speed in a line of the shot-peening system V, m/s	100
Shot density ρ_d, kg/m^3	7800
Shot bulk density ρ_{nd}, kg/m^3	4300
Air density ρ_{pov}, kg/m^3	1.29
Maximal shot diameter d_{dr}^{max}, m	0.005
Hopper outlet diameter d_{vp}, m	0.08
Coefficient of shot flow, λ	0.6

6. Conclusions

The operations of forcibly propelling a steam of working medium provide valuable operational properties of the machine part surfaces and subsurface layers. The effectiveness of its use especially increased during the treatment of shaped surfaces, and complying with optimal technological modes.

Purposeful controlled forming physical and mechanical surface and subsurface layers properties of the treated machine parts during processing and the possibility of diagnostics of the surfaces quality can be achieved by the introduction of automated production control, design and calculation process, the basis of which may be assigned the proposed mathematical models.

The mathematical model describes interaction between the technological modes of process and quality characteristics, obtained as a result of the treatment: depth of cold working layer, degree of hardening, change of microhardness, and take into the account the physical and mechanical properties of the treated surfaces, the design of blast apparatus and equipment, working medium properties, the scheme of interaction between non-bound blast particles and the treated surface depending on its geometry.

The practice of using the operations of forcibly propelling a steam of working medium confirms the feasibility of their implementation in the manufacturing of products for different purposes and with different materials. The special and potential area of application for the treatment with loose solid balls can be manufacturing of endoprostheses, a sector rapidly developing nowadays [25,26,27].

The review of reference literature indicates that metals and alloys presenting satisfactory biotolerance, resistance to corrosion and as well as the appropriate physical-chemical and mechanical properties: strength, wear resistance, manufacturability are used as implants for the human body [28]. Stainless steel alloys, titanium alloys are currently used for the metal endoprostheses. Such endoprostheses are fixed in bones with cement.

Endoprosthesis manufacturing is a high precision industry. Endoprostheses pass multistage testing inspections and certification. To ensure their quality different methods for investigating properties of materials being used for endoprostheses and sophisticated method for their processing are proposed [29,30]. Using methods of treating with loose solid balls for fastening parts, the endoprosthesis is provided with highly developed surfaces characterized with the best adhesion properties binding cement with metal base and, consequently, better fixation of the prosthesis to the bone.

Thus, the methods of treatment by non-bound blast particles may get another branch of extremely relevant and effective use.

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