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COMPUTER SIMULATION IN THE MATHCAD PACKAGE OF PLASTIC DEFORMATION OF THE DEPOSITED LAYER ON THE FLAT SURFACE OF THE PART

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ABSTRACT

The one-dimensional problem of plastic deformation of the deposited layer on a flat surface was studied when a cylindrical roller was rolled in, including the Coulomb friction law on the contact surface. The equation of state of the material is selected on the basis of the theory of creep (hardening theory). An application program was developed in the mathematical editor Mathcad for the numerical analysis of a non-linear one-dimensional problem. In the course of computer simulation and subsequent experimental checks, it has been established that the stress-strain state in the deformation zone significantly depends on magnitude and on the friction coefficient on the surface of contact of the material with the roller. According to the results of computer simulation and field experiments, a method for calculating the deposited layer was proposed. The given technique can be used to determine the parameters of the technological process during the restoration of flat surfaces. The article demonstrates with a specific example that, since every year the interest of various enterprises in the mathematical modeling of technological processes of metal processing grows much faster than various databases of material properties are filled in specialized packages such as JMatPro, Forge, Finel, Abaqus, LS Dyna, Deform required for calculations and obtaining adequate results, modeling the properties of materials in such common programs as, for example, MathCad, can be an excellent solution for enterprises that do not have the opportunity to engage in expensive experimental research. It is shown that the solutions proposed in the article for the MathCad package that implement the mathematical model of plastic deformation of the deposited layer allows studying the processes of plastic deformation for a user who does not have programming experience and work with numerical methods for solving systems of ordinary differential equations.

Keywords: *Plastic Deformation, Computer Simulation, Non-Stationary Thermal Conductivity*

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1. INTRODUCTION

The introduction of automation in research and analysis of complex systems of various nature in the context of the rapid development of computer technology is an urgent task for any field of research. For example, such a problem often arises when studying the plastic deformation of a deposited layer on a flat surface of a part. Such studies, while of their undoubted relevance, are an extremely difficult task, both for experimental study and for mathematical modeling, since the plastic deformation of metals and alloys is a complex dynamic process. In return, the properties of this process are determined both by the properties of the deformable material and by the method of external influence on it. One of the most effective ways to describe complex systems is mathematical modeling and a computational experiment. Mathematical models that fully reflect the mechanisms of the occurrence of deformation defects, their motion and interaction, allows studying the phenomenon of plastic deformation in the entire range of product operating conditions. Various models [1–5] differ primarily in the set of deformation defects and the mechanisms of their formation under consideration.

When using mathematical models, including equations of balance of deformation defects, the researcher has to work with systems of ordinary differential equations (ODE), which, as a rule, are rigid, and their solution is a very nontrivial task.

The use of methods of mathematical modeling of processes of plastic deformation of metals allows to minimize the costs of development and debugging of new technologies, to improve and optimize the shape of the working tool. Among the well-known specialized packages and programs used to solve such problems, it is possible to distinguish such packages as: JMatPro, Forge, Finel, Abaqus, LS Dyna, Deform, QForm, SuperForge, Compass, etc. The essence of modeling using these software products about discretizing the workpiece volume and repeatedly automatic mesh restructuring of the finite element taking into account boundary conditions. The accuracy of solving plastic problems using the above programs is on the same level. However, note that the use of such highly specialized packages is not always advisable at the initial stages of the study. This is primarily due to the high cost of such software products and their narrow focus.

When using a computer to solve various problems in the field of mechanical engineering, the role of man and the purpose of ECM (electronic computing machine) in this process should be correctly determined. The functions performed by a person are the precise wording of the objective of research, preparation of initial equations, initial conditions, preparation of an algorithm and a calculation program, analysis of the results obtained, which forms the basis of mathematical modeling of objects described in the first chapter. The role of the computer is to perform calculations and present the result in an analytical, numerical or graphical form.

In terms of using a computer to perform calculations and conduct research using a mathematical model, two approaches can be distinguished. The first of them is traditional, based on the application of a calculation program compiled in one of the high-level algorithmic languages (BASIC, Pascal, C ++, C #, Java, etc.). Meanwhile, the user must not only understand the essence of the problem being solved, know the appropriate dependencies and have some idea of the general principles of programming, but also be quite fluent in any programming language. Combining these different knowledge and skills in one person is quite difficult for an ordinary engineer from production. Therefore, in practice, to solve serious research problems, a group is usually organized, including both specialists, for example, mechanical engineers, and programmers.

The second approach, which has become possible only in the last few years, is based on the use of modern special mathematical software packages such as Mathematica, Mathlab, Derive, MathCAD and etc.

Currently, there are a number of mathematical packages of general-purpose applications (Maple, Mathematica, MathCad, MATLAB, and others) that allow solving systems of differential equations. The software packages contain, as a rule, classical methods from the Runge-Kutta family methods, as well as specialized methods for solving rigid ordinary differential equations (ODE) systems. To conduct a comprehensive full-scale study of the laws of plastic sliding deformation using mathematical software packages, the user must have a sufficient understanding of the methods for solving ODE, as well as skills in working with the software

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package and, as a rule, programming in the internal language of the package.

Due to the fact that every year the interest of various enterprises in mathematical modeling of technological processes of metal forming and heat treatment grows much faster than various databases of material properties are filled in specialized packages such as JMatPro, Forge, Finel, Abaqus, LS Dyna, Deform, necessary for calculations and obtaining adequate results, modeling the properties of materials in such common programs as, for example, MathCad, can be an excellent solution for enterprises that don't have opportunities to study an expensive experimental research. And besides, it should be noted that software packages such as Abaqus, LS Dyna, Deform, Compass, SPFCC or the same are 5–7 times more expensive than the cost of MathCAD. And their capabilities in the commissioning of experimental studies of the properties of new materials are in demand only in a minimal amount.

In our opinion, it is MathCAD in the near future that will become the same indispensable tool for an engineer as the slide rule was in the 60s of the last century.

The most important task of engineering production is to increase the reliability and durability of machine parts. The solution of these issues directly depends on the creation and mastering of progressive resource-saving technological methods for improving the quality of parts and increasing their wear resistance, reducing costs, increasing productivity and improving working conditions. Many of these problems are difficult to solve without resorting to preliminary mathematical and computer modeling of parameters corresponding to technological processes. Such problems, in particular, include the problem of computer modeling of plastic deformations of the weld layer on the flat surface of parts. Note that by surfacing products are obtained with wear-resistant, heat-resistant, anti-friction, acid-resistant, and such. If in engineering production, surfacing is used to increase the wear resistance of rubbing surfaces, since it allows to significantly increase the service life of parts and reduce the cost of scarce materials for their manufacture, then in the repair industry – mainly for subsequent work to restore the location, shape and size of worn-out elements.

Thus, the creation of a set of programs for such widespread modeling packages as MathCad or Mathematica that implement a mathematical model of plastic deformation, in particular a deposited layer, will allow investigating the processes of plastic deformation to a user who does not have programming experience and working with numerical methods for solving ODE systems. This is all the more relevant since the laws of plastic deformation and the evolution of a deformation defective medium are substantially determined by the type and parameters of the action, the characteristics of the material and the hardening phases, etc.

All the above conditional makes the topic of our research relevant.

2. ANALYSIS OF LITERARY DATA AND PROBLEM STATEMENT

Analysis of the deposition methods shows [1, 2] that a number of factors are characteristic of the deposited metal, which together lead to a significant decrease in the wear resistance of the applied metal coating of parts: a significant variation in mechanical properties; presence of inclusions and metallurgical defects; structure heterogeneity and uneven surface hardness along the length of the part; the presence of adverse tensile stresses; reduction of fatigue strength of the deposited parts; difficulty machining. For the preliminary values of given parameters in [3, 4] it was proposed to use computer simulation methods. However, the authors do not take into account the capabilities of many specialized mathematical packages for computer modeling, for example, MatLab, MathCad, Maple.

Based on the works [5–7] on the basis of the well-known methodical approaches [8, 9], a number of computer solutions were obtained, which allow determining the temperature of the weld metal in plastic deformation zones. In the course of computer simulation and field experiments, the authors obtained the condition of plasticity in the deformation zone. The condition is written using the so-called forced yield strength in the form $K = \beta\sigma_T$, in here σ_T – base yield strength $\beta = 1 - 1{,}5$ Lode coefficient. Since in such a case, the equations of state do not include the strain rates, these analytical solutions do not reflect the speeds of movement of the deforming tool on the shaping efforts and the stress-strain state of the deposited layer. This effect is especially significant if the metal is deformed at high temperatures and stresses. In this case, despite the relatively short time of deformation, the viscosity of the metal is essential, and therefore the calculations of

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technological processes of metal processing should be based on the equations of state that contain the strain rates, i.e. on equations reflecting the rhomonomic properties of metals - on equations of the theory of creep.

In the works [10–12] it is shown that improving the quality of metal plating and wear resistance of restored parts is an important task at the repair enterprises of mechanical engineering. Increasing the wear resistance of parts allows, to a certain extent, to solve the problem of increasing the durability of machines. However, the authors [13–15] did not use modern computer technology to verify the adequacy of their calculations.

In the works [16, 17] it is shown that one of the stages of the technological process of surfacing is surface plastic deformation. Surface plastic deformation (SPD) is a type of hardening treatment, in which chips are not formed, but plastic deformation occurs on a thin surface layer of the workpiece, a common and effective way to increase the bearing capacity of metal machine parts. The use of SPD makes it possible to effectively influence the durability of parts operating under cyclic loads, friction, and exposure to corrosive media and having stress concentrators. The authors also minimally confirmed their findings with the results of a computer model.

As a result of the analysis, the relevant task of further development of the methods of theoretical, computer and experimental studies of plastic deformation of the weld layer are considered when restoring the flat surfaces of parts.

3. STATEMENT OF THE PROBLEM.

Development of methods for theoretical and experimental studies of plastic deformation of the deposited layer when restoring flat surfaces of parts

To achieve the goal of research it is necessary to solve the following tasks:

Perform a numerical solution of a one-dimensional non-linear problem and determine the stress components, the power factors of the technological process;

Perform simulation modeling for this task using the mathematical editor Mathcad and develop an application solution for calculating the stress-strain state and the power parameters of the technological process in the Mathcad system, which will simplify and automate complex engineering calculations;

Conduct an experimental research of the quality of the deposited layer in the restoration of a flat surface to confirm the results of simulation in Mathcad.

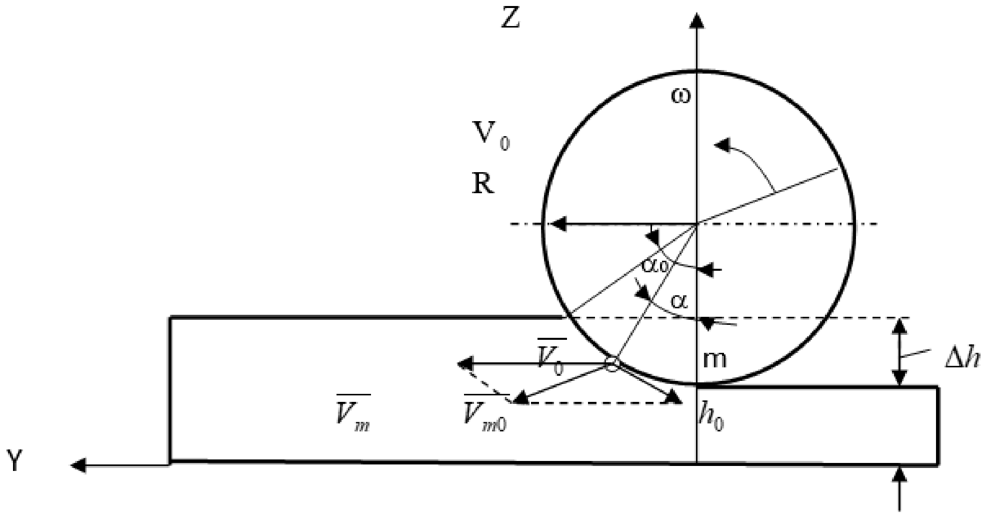
4. METHODS AND MODELS

The condition of the material is taken in the form:

$$\sigma_e = a\xi_e^m \kappa^n, \tag{1}$$

where $\kappa = \int \xi_e dt$ – Udquist parameter; σ_e –equivalent stress; ξ_e – equivalent strain rate; a, m, n – material constants at a certain temperature.

The deformation of the material under the action of an absolutely rigid cylindrical body (roller), which makes a plane-parallel motion in the plane of the drawing is being considered (Fig. 1). The deformable material is on a hard surface. Denote the speed of movement of the center of the roller through υ_0, and the angular velocity of rotation – ω. It is assumed that they are constant in time values.



R-roller radius, Δh -change of layer thickness, h_0 -thickness of the rolled layer, α_0 – maximum contact angle, α – the angular coordinate of the point m, ω -angular speed of rotation of the roller, $\overline{V_0}$ – the velocity vector of the center of the roller, $\overline{V_m}$ – the velocity vector of the point m on the contact surface, $\overline{V_{m0}}$ – vector of the rotation speed of point m relative to the center of the roller

Figure 1 : Driving scheme

The components of the speed of movement of any point on the surface of contact of the material with the roller in the deformation zone are shown in Fig. 1:

$$\upsilon_y = \upsilon_0 - \omega R \cos\alpha;$$
$$\upsilon_z = -\omega R \sin\alpha. \quad (2)$$

It is assumed that the stress-strain state of the material varies only along the coordinate y. Then the equilibrium equation of the elementary volume has the form:

$$\frac{d\sigma_y}{dy} + \frac{\sigma_y + p}{h} tg\alpha + \frac{q - q_1}{h} = 0, \quad (3)$$

$$\sigma_z = p - qtg\alpha, \quad (4)$$

where σ_y, σ_z – stress components, p, q – the pressure and intensity of the friction forces, respectively, on the surface of the contact of the material with the roller, q_1 – intensity of friction forces of a material with a hard surface.

Equivalent Stress σ_e approximately calculated as:

$$\sigma_e = \sigma_y - \sigma_z. \quad (5)$$

To simplify the decision, it is assumed that the friction on the surface of the contact of the material with the roller obeys the Coulomb's law $q = \mu p$, moreover the proportionality

Coefficient μ is constant over the entire contact surface. The intensity of the friction forces on the contact surface of a material with a rigid surface is assumed to be proportional to the maximum tangential stress

$$q_1 = \chi\tau_{\max} = \chi(\sigma_y - \sigma_z)/2 = \\ = \chi\sigma_e/2, \quad (6)$$

where χ – constant coefficient of proportionality. With χ =1 sticking takes place.

After simple transformations, differential equation (3) is presented in the form:

$$\frac{d\sigma_y}{d\alpha} + \psi_1(\alpha)\sigma_y = \psi_2(\alpha), \quad (7)$$

where entered the notation:

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$$\psi_1(\alpha)=\frac{1}{h_0/R+1-\cos\alpha}$$
$$(\sin\alpha+\frac{\sin\alpha+\mu\cos\alpha}{1-\mu tg\alpha}),$$
$$\psi_2(\alpha)=\frac{1}{h_0/R+1-\cos\alpha}\cdot \tag{8}$$
$$\cdot(\frac{\sin\alpha+\mu\cos\alpha}{1-\mu tg\alpha}+\frac{\chi}{2}\cos\alpha)\sigma_e.$$

To integrate equation (7) we have the boundary condition: $\alpha=0,\sigma_y=0.$ Then the solution of the equation is written as follows:

$$\sigma_y=\exp(-\int_0^\alpha\psi_1 d\alpha)\int_0^\alpha\psi_2\exp(\int_0^\alpha\psi_1 d\alpha)d\alpha \tag{9}$$

For the strain rate in the longitudinal direction and the equivalent strain rate there is:

$$\xi_y=\omega tg\alpha,\xi_e=2\omega tg\alpha/\sqrt{3}. \tag{10}$$

Udquist parameter, taking into account the ratio $dt=d\alpha/\omega$. has the form: $\kappa=-2\ln|\cos\alpha|/\sqrt{3}$.

In this case, the equivalent voltage is calculated by the formula:

$$\sigma_e=a(2/\sqrt{3})^{m+n}\omega^m tg^m\alpha(-\ln|\cos\alpha|)^n.$$

The pressure on the surface of contact of the material with the roller is determined by the ratio $p=(\sigma_y-\sigma_e)/(1-\mu tg\alpha)$. The deformation in the longitudinal direction is equal to:

$$\varepsilon_y=\int_0^t\xi_y dt+\varepsilon_y^0= \tag{11}$$
$$=-\ln|\cos\alpha|+\varepsilon_y^0,$$

where ε_y^0- residual deformation after surfacing.

In order to completely eliminate residual longitudinal deformations, the condition must be fulfilled $\ln|\cos\alpha|=\varepsilon_y^0$. Corresponding contact angle:

$$\alpha_0=\arccos[\exp(\varepsilon_y^0)]. \tag{12}$$

On the other hand, the maximum contact angle (Fig. 1)

$$\alpha_0=\arcsin\left[2\sqrt{\Delta h/(2R)}\right], \tag{13}$$

where $\Delta h-$ reduced layer thickness.

Comparing formulas (12) and (13):

$$\Delta h=R[1-\exp(2\varepsilon_y^0)]/2. \tag{14}$$

If the value of the residual longitudinal welding strain is known, then the maximum contact angle of the material with the roller by formulas (12) and (14) and the deformation $\varepsilon_z=\Delta h/h$ by thickness of the element in the zone of the running layer are determined.

The moment of forces per unit length in the direction perpendicular to the drawing, assuming that the moment of contact pressure forces relative to the center of the roller can be neglected, is equal to

$$M=\mu R^2\int_0^{\alpha_0}p d\alpha.$$

The projection on the vertical axis of the force per unit length in the direction perpendicular to the drawing:

$$P_z=R\int_0^{\alpha_0}(p\cos\alpha-q\sin\alpha)d\alpha.$$

The projection on the horizontal axis of the force per unit length in the direction perpendicular to the drawing:

$$P_y=R\int_0^{\alpha_0}(p\sin\alpha+q\cos\alpha)d\alpha.$$

In the above formulas, the integrals are calculated numerically. For this, dimensionless values are entered:

$$\bar{\sigma}_e = \frac{\sigma_e}{a\omega^m},$$

$$\bar{\sigma}_{y,z} = \frac{\sigma_{y,z}}{a\omega^m}, \quad \bar{q} = \frac{q}{a\omega^m},$$

$$\bar{p} = \frac{p}{a\omega^m}, \quad \bar{v}_{y,z} = \frac{v_{y,z}}{\omega R},$$

$$\bar{M} = \frac{M}{a\omega^m R^2},$$

$$\bar{P}_{y,z} = \frac{P_{y,z}}{a\omega^m R},$$

$$\bar{\psi}_2(\alpha) = \psi_2(\alpha)/(a\omega^m),$$

$$\bar{\xi}_{e,y} = \frac{\xi_{e,y}}{\omega}$$

$$\Delta\bar{h} = \frac{\Delta h}{R}, \lambda = \frac{h_0}{R}.$$

As an example, the deformation of the material was calculated for the following values of constants: $m = 0,147; n = 0,157; \mu = 0,3; \chi = 1; h_0 / R = 0,1$. The magnitude of the permanent deformation was taken ε_y^0=-8,7×10^{-3}. Magnitude $\Delta h / R = 8,7 \times 10^{-3}$.

The study also considers the two-dimensional problem of plastic deformation of the deposited layer during rolling with a cylindrical roller, which performs a plane-parallel in-plane displacement (x, z). A rectangular coordinate system is used x, y, z. The plane deformation is considered and it is assumed that the stress-strain state does not depend on the coordinate y. The components of the velocity of movement in the deformation zone: $v_z = v_z(x,z), v_x = v_x(x,z), v_y = 0$. Stress tensor components $\sigma_{ij} = \sigma_{ij}(x,z); i,j = x,y,z; \tau_{zy} = 0, \tau_{xy} = 0$. Creep deformations are taken for total deformations.

The components of deformation rates in this case are calculated by the formulas:

$$\xi_x = \partial v_x / \partial x, \xi_z = \partial v_z / \partial z, \xi_y = = 0, \eta_{xz} = \partial v_x / \partial z + \partial v_z / \partial x. \quad (15)$$

The condition of material incompressibility is:

$$\partial v_x / \partial x + \partial v_z / \partial z = 0. \quad (16)$$

The equivalent deformation rate and the Udquist parameter are:

$$\xi_e = 2/\sqrt{3} \times \sqrt{(\partial v_x / \partial x)^2 + (\partial v_x / \partial z + \partial v_z / \partial x)^2 / 4},$$

$$\kappa = \int \xi_e / v_x dx \ . \quad (17)$$

The components of the stress tensor are calculated by the dependencies of Saint-Venant-Levi-Mises: $\sigma_{ij} = \sigma_0 \delta_{ij} + 2\sigma_e \xi_{ij} / (3\xi_e)$, where: $\sigma_0 -$ medium stress $\sigma_0 = \sigma_{ii}/3; \delta_{ij} -$ Kronecker symbol.

Differential equilibrium equations have the form:

$$\left(\frac{\partial v_x}{\partial z} + \frac{\partial v_z}{\partial x}\right)\frac{\partial^2}{\partial z^2}\left(\frac{\sigma_e}{\xi_e}\right) + + \frac{\sigma_e}{\xi_e}\left(\begin{array}{l} \frac{\partial^3 v_x}{\partial z^3} + \frac{\partial^3 v_z}{\partial x \partial z^2} - \\ -\frac{\partial^3 v_x}{\partial x^2 \partial z} - \frac{\partial^3 v_z}{\partial x^3} + \\ +4\frac{\partial^3 v_x}{\partial z \partial x^2} \end{array}\right) - \left(\frac{\partial v_x}{\partial z} + \frac{\partial v_z}{\partial x}\right)\frac{\partial^2}{\partial x^2}\left(\frac{\sigma_e}{\xi_e}\right) + +4\frac{\partial^2}{\partial z \partial x}\left(\frac{\sigma_e}{\xi_e}\right)\frac{\partial v_x}{\partial x} = 0,$$

$$\frac{\partial \sigma_0}{\partial x} + \frac{2}{3}\frac{\partial}{\partial x}\left(\frac{\sigma_e}{\xi_e}\right)\frac{\partial v_x}{\partial x} + +\frac{1}{3}\frac{\sigma_e}{\xi_e}\left(2\frac{\partial^2 v_x}{\partial x^2} + \frac{\partial^2 v_x}{\partial z^2} + \frac{\partial^2 v_z}{\partial x \partial z}\right) + +\frac{1}{3}\frac{\partial}{\partial z}\left(\frac{\sigma_e}{\xi_e}\right)\left(\frac{\partial v_x}{\partial z} + \frac{\partial v_z}{\partial x}\right) = 0 \quad (18)$$

The equations in system (18), taking into account the equation of state (1), dependencies (17), are nonlinear partial differential equations with respect to the speeds of displacement and the average normal voltage.

For the integration of differential equations there have the boundary conditions:

$z=0, v_z=0; v_x=0$. On the surface of the contact of the material with the roller, the speed of movement is:

$$(z,x)\in L;$$
$$v_z=\omega R\sin\alpha, v_x=,$$
$$=v_0-\omega R\cos\alpha,$$

where L – arc of a circle with a central angle α_0, $0\le\alpha\le\alpha_0; R$ – the radius of the roller. On the side surfaces $x=0, x=a$ there is the condition that the total force is zero in the direction of the axis x, $\int\sigma_x dz=0$.

The integration of nonlinear partial differential equations with boundary conditions must be carried out by numerical methods. Difference methods are common. A central finite-difference scheme is applied using an iterative process. The zero for the speed of movement is set v_z (or v_x), from the condition of incompressibility the speed of movement v_x (or v_z), the equivalent strain rate are determined, the Udquist parameter, and from the equilibrium equations the average normal stress and displacement velocity v_z (or v_x) are found. The specified and obtained values of the velocity of movement at each iteration step are compared.

For the numerical solution of the problem, the above dimensionless quantities are used, as well as magnitude $\bar{x}=x/h_0, \bar{z}=z/h_0$ (h_0 - height of the deposited layer to deformation). The components of deformation rates, the equivalent deformation rate, the Udquist parameter and the equation of state in dimensionless quantities have the form:

$$\bar{\xi}_x=\frac{1}{\lambda}\frac{\partial\bar{v}_x}{\partial\bar{x}},$$
$$\bar{\xi}_z=\frac{1}{\lambda}\frac{\partial\bar{v}_z}{\partial\bar{z}},$$
$$\bar{\eta}_{xz}=\frac{1}{\lambda}\left(\frac{\partial\bar{v}_x}{\partial\bar{z}}+\frac{\partial\bar{v}_z}{\partial\bar{x}}\right),$$
$$\bar{\xi}_e=2/(\lambda\sqrt{3})\times$$
$$\times\sqrt{(\partial\bar{v}_x/\partial\bar{x})^2+(\partial\bar{v}_x/\partial\bar{z}+\partial\bar{v}_z/\partial\bar{x})^2/4},$$

$$\bar{\kappa}=\lambda\int\bar{\xi}_e/\bar{v}_x d\bar{x},\ \bar{\sigma}_e=\bar{\xi}_e^m\bar{\kappa}^n. \quad (19)$$

The designation $\psi=\bar{\sigma}_e/\bar{\xi}_e$ is entered. Using relations (19) for the function ψ there are:

$$\psi=\left(\frac{2}{\sqrt{3}}\right)^{m+n-1}\lambda^{1-m}\Big[\Big(\frac{\partial\bar{v}_x}{\partial\bar{x}}\Big)^2+\frac{1}{4}\Big(\frac{\partial\bar{v}_x}{\partial\bar{z}}+\frac{\partial\bar{v}_z}{\partial\bar{x}}\Big)^2\Big]^{\frac{m-1}{2}}\Big\{\int\Big[\Big(\frac{\partial\bar{v}_x}{\partial\bar{x}}\Big)^2+\frac{1}{4}\Big(\frac{\partial\bar{v}_x}{\partial\bar{z}}+\frac{\partial\bar{v}_z}{\partial\bar{x}}\Big)^2\Big]^{\frac{1}{2}}/\bar{v}_x d\bar{x}\Big\}^n \quad (20)$$

To calculate the integral on the right-hand side of equation (20), the notation is entered:

$$\varphi(\bar{x},\bar{z})=$$
$$=\int\Big[\Big(\frac{\partial\bar{v}_x}{\partial\bar{x}}\Big)^2+\frac{1}{4}\Big(\frac{\partial\bar{v}_x}{\partial\bar{z}}+\frac{\partial\bar{v}_z}{\partial\bar{x}}\Big)^2\Big]^{\frac{1}{2}}/\bar{v}_x d\bar{x}. \quad (21)$$

For function $\varphi(\bar{x},\bar{z})$ there is a differential equation:

$$\frac{\partial \varphi}{\partial \bar{x}} = [(\frac{\partial \bar{v}_x}{\partial \bar{x}})^2 + \frac{1}{4}(\frac{\partial \bar{v}_x}{\partial \bar{z}} + \frac{\partial \bar{v}_z}{\partial \bar{x}})^2]^{\frac{1}{2}} / \bar{v}_x. \tag{22}$$

Taking into account the expression (21) the function ψ takes the form:

$$\psi = (\frac{2}{\sqrt{3}})^{m+n-1} \lambda^{1-m} \times [(\frac{\partial \bar{v}_x}{\partial \bar{x}})^2 + \frac{1}{4}(\frac{\partial \bar{v}_x}{\partial \bar{z}} + \frac{\partial \bar{v}_z}{\partial \bar{x}})^2]^{\frac{m-1}{2}} \times \varphi^n(\bar{x}, \bar{z}). \tag{23}$$

Using the above notation, differential equations (18) are written in the form:

$$\frac{\partial \bar{\sigma}_0}{\partial \bar{x}} + \frac{2}{3\lambda} \frac{\partial \psi}{\partial \bar{x}} \frac{\partial \bar{v}_x}{\partial \bar{x}} + \frac{1}{3\lambda} \psi \left(2\frac{\partial^2 \bar{v}_x}{\partial \bar{x}^2} + \frac{\partial^2 \bar{v}_x}{\partial \bar{z}^2} + \frac{\partial^2 \bar{v}_z}{\partial \bar{x} \partial \bar{z}} \right) + \frac{1}{3\lambda} \frac{\partial \psi}{\partial \bar{z}} \left(\frac{\partial \bar{v}_x}{\partial \bar{z}} + \frac{\partial \bar{v}_z}{\partial \bar{x}} \right) = 0. \tag{24}$$

The construction of a difference scheme for solving partial differential equations is based on the introduction of a grid in the space under consideration (Fig. 2). Grid nodes are calculated points.

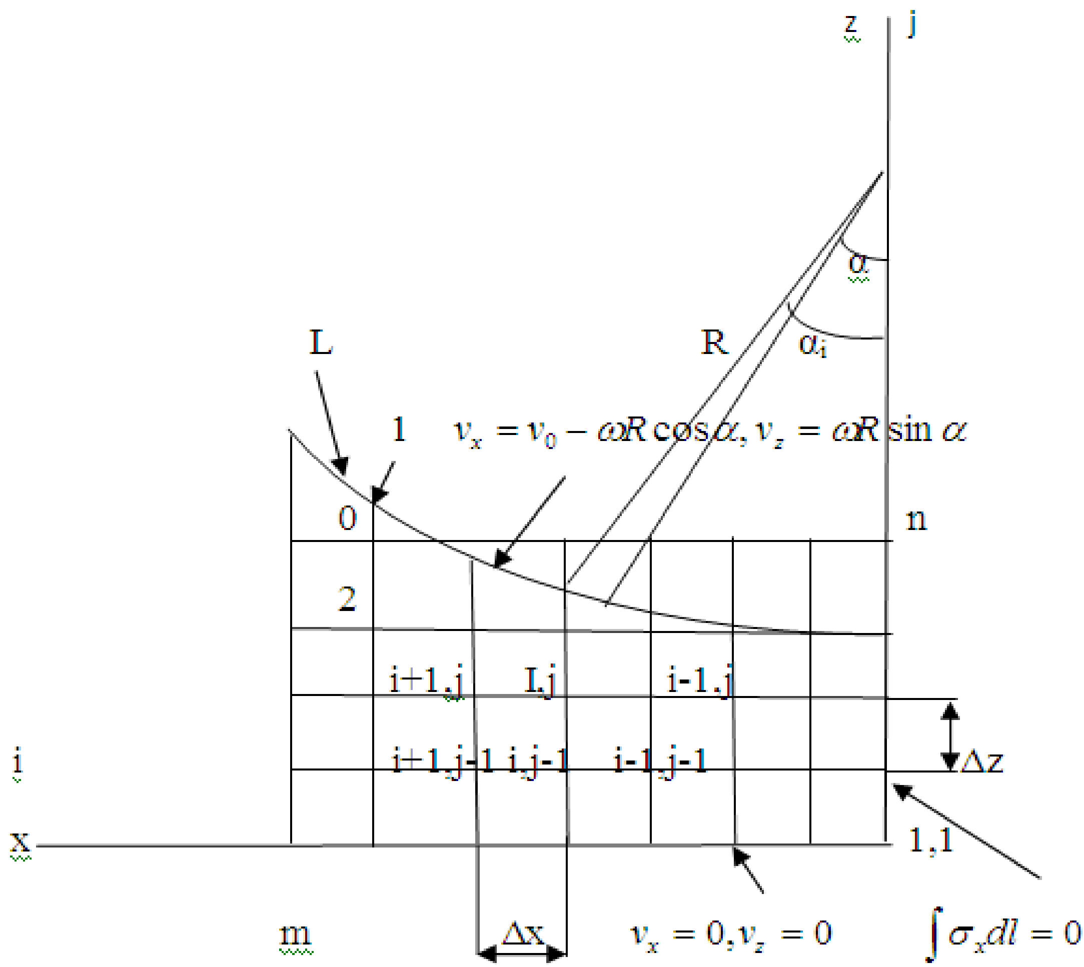

Figure 2 : Rectangular grid area of integration

The basic equations in finite differences are:

$$\varphi_{i,j} = \varphi_{i-1,j} + \Delta\bar{x}[(\frac{\bar{v}_{xi+1,j} - \bar{v}_{xi-1,j}}{2\Delta\bar{x}})^2 +$$

$$+\frac{1}{4}(\frac{\bar{v}_{xi,j+1} - \bar{v}_{xi,j-1}}{2\Delta\bar{z}} +$$

$$+\frac{\bar{v}_{zi+1,j} - \bar{v}_{zi-1,j}}{2\Delta\bar{x}})^2]^{\frac{1}{2}} / \bar{v}_{xi,j},$$

$$\psi_{i,j} = (\frac{2}{\sqrt{3}})^{m+n-1}\lambda^{1-m}$$

$$[(\frac{\bar{v}_{xi+1,j} - \bar{v}_{xi-1,j}}{2\Delta\bar{x}})^2 + \frac{1}{4}(\frac{\bar{v}_{xi,j+1} - \bar{v}_{xi,j-1}}{2\Delta\bar{z}}$$

$$+\frac{\bar{v}_{zi+1,j} - \bar{v}_{zi-1,j}}{2\Delta\bar{x}})^2]^{\frac{m-1}{2}}\varphi^n_{i,j} \quad ,$$

$$\bar{v}_{xi,j} = \{\frac{\bar{\sigma}_{0i+1,j} - \bar{\sigma}_{0i-1,j}}{2\Delta\bar{x}} + \frac{1}{6\lambda\Delta\bar{x}^2}(\psi_{i+1,j} - \psi_{i-1,j}) \times (\bar{v}_{xi+1,j} - \bar{v}_{xi-1,j}) + \frac{\psi_{i,j}}{3\lambda}[2\frac{\bar{v}_{xi+1,j} + \bar{v}_{xi-1,j}}{\Delta\bar{x}^2} + \frac{\bar{v}_{xi,j+1} + \bar{v}_{xi,j-1}}{\Delta\bar{z}^2} + \frac{1}{4\Delta\bar{x}\Delta\bar{z}}(\bar{v}_{zi+1,j+1} - \bar{v}_{zi-1,j+1} - \bar{v}_{zi+1,j-1} + \bar{v}_{zi-1,j-1})] + \frac{1}{12\lambda}\frac{\psi_{i,j+1} - \psi_{i,j-1}}{\Delta\bar{z}} \times \frac{(\frac{\bar{v}_{xi,j+1} - \bar{v}_{xi,j-1}}{\Delta\bar{z}} + \frac{\bar{v}_{zi+1,j} - \bar{v}_{zi-1,j}}{\Delta\bar{x}})\}}{[\frac{2}{3\lambda}\psi_{i,j}(\frac{2}{\Delta\bar{x}^2} + \frac{1}{\Delta\bar{z}^2})]},$$

(25)

$$(\frac{\bar{v}_{xi,j+1} - \bar{v}_{xi,j-1}}{2\Delta\bar{z}} + \frac{\bar{v}_{zi+1,j} - \bar{v}_{zi-1,j}}{2\Delta\bar{x}}) \times (\frac{\psi_{i,j+1} - 2\psi_{i,j} + \psi_{i,j-1}}{\Delta\bar{z}^2} - \frac{\psi_{i+1,j} - 2\psi_{i,j} + \psi_{i-1,j}}{\Delta\bar{x}^2}) + \frac{1}{2\Delta\bar{x}^2\Delta\bar{z}}(\bar{v}_{xi+1,j} - \bar{v}_{xi-1,j}) \times (\psi_{i+1,j+1} - \psi_{i+1,j-1} - \psi_{i-1,j+1} + \psi_{i-1,j-1}) + \psi_{i,j}[\frac{\bar{v}_{xi,j+2} - 2\bar{v}_{xi,j+1} + 2\bar{v}_{xi,j-1} - \bar{v}_{xi,j-2}}{2\Delta\bar{z}^3} - \frac{\bar{v}_{zi+2,j} - 2\bar{v}_{zi+1,j} + 2\bar{v}_{zi-1,j} - \bar{v}_{zi-2,j}}{2\Delta\bar{x}^3} + \frac{\bar{v}_{zi+1,j+1} - \bar{v}_{zi-1,j+1} - 2\bar{v}_{zi+1,j} + 2\bar{v}_{zi-1,j} + \bar{v}_{zi+1,j-1} - \bar{v}_{zi-1,j-1}}{2\Delta\bar{x}\Delta\bar{z}^2} + \frac{3}{2\Delta\bar{x}^2\Delta\bar{z}}(\bar{v}_{xi+1,j+1} - \bar{v}_{xi+1,j-1} - 2\bar{v}_{xi,j+1} + 2\bar{v}_{xi,j-1} + \bar{v}_{xi-1,j+1} - \bar{v}_{xi-1,j-1})] = 0$$

Border conditions:

$$\bar{v}_{xi,j} = 0; \bar{v}_{zi,j} = 0;$$
$$(i = 1,2,...,m;\ j = 1),$$
$$\bar{v}_{xi,j} = \bar{v}_0 - \cos\alpha_i,$$
$$\bar{v}_{zi,j} = \sin\alpha_i; (i, j \in L),$$
$$\int \sigma_x dl = 0; (i = 1, j \in [1,...,n]).$$

The questions of convergence, approximation and stability of a difference scheme are considered.

5. SIMULATION MODELING MATHCAD

To test the workability of the mathematical model, simulation was carried out in the Mathcad package. Accordingly, an applied solution was developed for the calculation of the stress-strain state and the power parameters of the technological process in the Mathcad system, which will simplify and automate complex engineering calculations [18].

In fig. 3 shows the distribution of the dimensionless quantities of the stress components and the equivalent stress in the deformation zone. As can be seen from fig. 2, in the axial direction, the stresses are positive, so the residual tensile stresses after welding will increase when the seam is rolled.

In fig. 4 shows the change of residual strain in the longitudinal direction, and fig. 5 – distribution of the dimensionless magnitude of the contact pressure. The magnitude of the force factors acting on the roller are equal to: $\bar{P}_y = 4.1\times10^{-3}$, $\bar{P}_z = 0.011$, $\bar{M} = 3.4\times10^{-3}$.

In fig. 6 shows the graphs of the change of dimensionless values of forces and moment depending on the angle of contact. Using these graphs, the values of the force and moment of deformation can be set up and determine the required power of the process equipment.

Calculations show that the parameters μ and λ can be chosen so as to significantly reduce stresses in the direction of the axis y (fig. 7). At certain values λ, friction force q change direction in a small area of the contact surface.

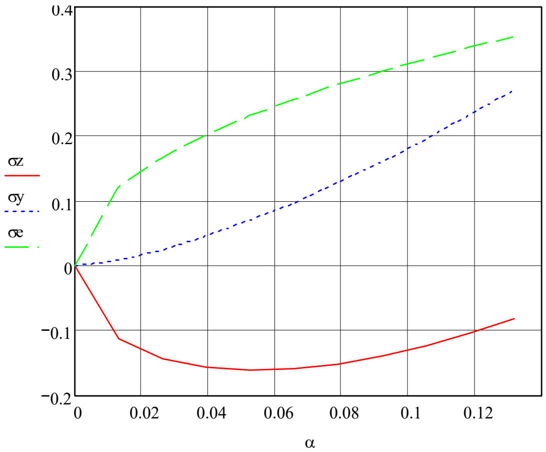

Figure 3: Distribution of stress components and equivalent stress in the deformation zone

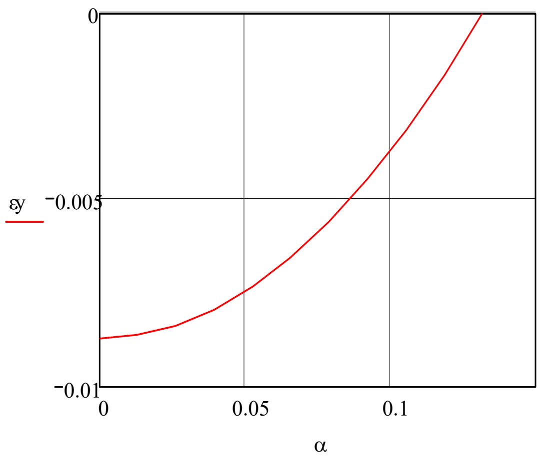

Figure 4 : Change of residual strain in the axial direction of the layer

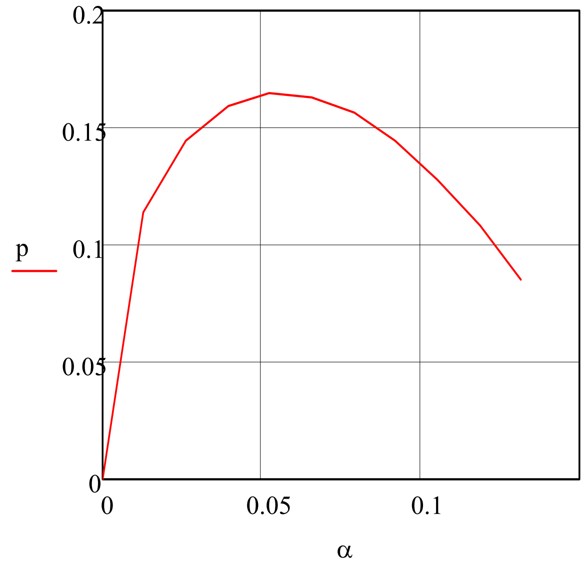

Figure 5 : Distribution of contact pressure on the roller

Note that the results obtained in the course of computational and field studies can give engineers the opportunity to more quickly fill out database information for more highly specialized programs. For example, the data obtained by us was initially entered into Excel, and then, as necessary, were transferred to the Compass, SPFCC programs, which are quite common at engineering plants in Kazakhstan, Ukraine, and other countries.

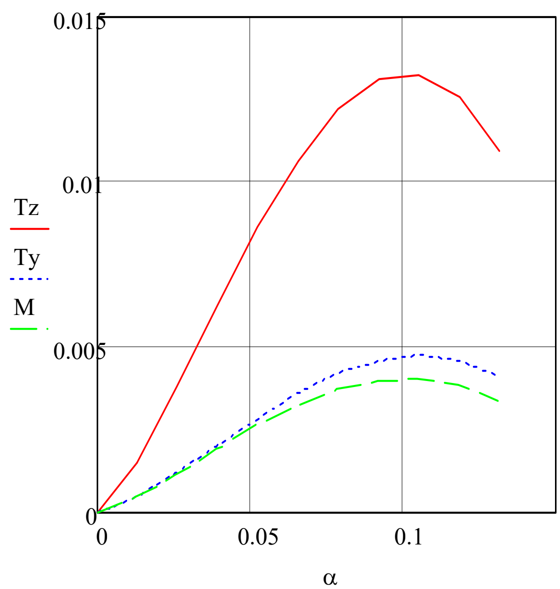

Figure 6 : Forces and moment acting on a roller

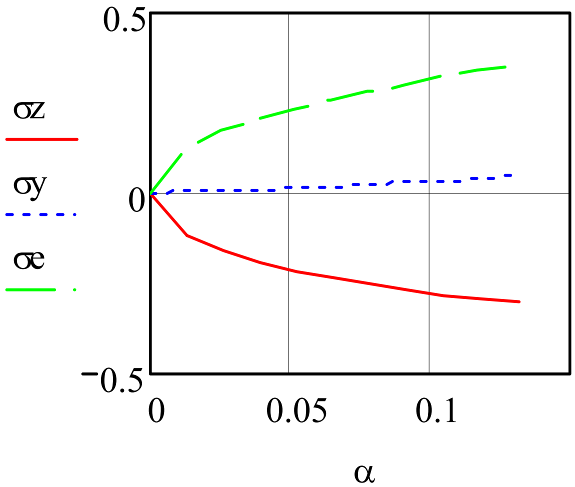

Figure 7 : Distribution of component voltages and equivalent voltages indeformation zone for values μ =0,3; λ =0,5.

Thus, in a one-dimensional formulation, comparatively general formulas were obtained for calculating the stress-strain state, pressure and friction forces on the contact surface, forces and moments acting on a roller.

6. FULL-SCALE EXPERIMENTS

As noted earlier, when restoring worn parts by welding, it is seek to obtain such surfaces, the wear resistance of which would be no less than that of new parts. However, this is not always possible, especially when restoring high-carbon and high-strength steels by surfacing. It is sometimes not possible to obtain a welded joint that is equally resistant to defect-free base metal, besides having high wear resistance.

There are many ways to avoid the appearance of defects such as cracks in a welded joint (preheating, post weld heat treatment, etc.). However, often, despite the efforts made, defects or pockets of their occurrence remain in the welded joint. After welding-cladding, various methods of relieving welding stresses and strains are often used, which at the same time strengthen the surface of the weld metal.

In this paragraph of study, ways to minimize the size, the number of defects such as cracks in a welded joint when restoring surfaces by welding, or ways to eliminate the sources of these defects by plastic deformation are considered.

Steel 45 and steel 60 were selected for research. When restoring the weld overlay for experimental studies, welding under a layer of flux was chosen as the best way to obtain high-quality weld metal. Welding materials – wire Sv-08HG2SMF and flux AN-348A, were selected taking into account the possibility of obtaining appropriate wear resistance and resistance to the formation of defects. In the course of the study, optimal modes and welding technology were established, in accordance with which it was planned to overlap the previous one with at least half of each subsequent roller, in order to reduce the share of the base metal in the weld metal and thereby increase the resistance to cracking.

Samples were deposited in one or two layers (fig. 8, 9). In the case of a two-layer weld metal, the number and size of the cracks were much smaller than the single-layer one (Fig. 10, 11) and the surface of the weld metal was more uniform.

Figure 8 : First layer of weld metal

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Figure 9 : Second layer of weld surface

Figure 10 : The number of cracks and their dimensions at single-layer steel surfacing.

Figure 11 : The number of cracks and their dimensions at double-layer steel surfacing.

In those places of the weld metal, where cracks were formed, samples of different sizes were cut for subsequent plastic deformation. For metallographic studies, samples were etched with 4% nitric acid.

The prepared samples were heated in a furnace to a temperature of phase transformations of 650-700^{0}C and the deposited surfaces were plastically treated with a hammer on the anvil. Experiments have shown that the cracks completely disappeared on some of the deposited specimens.

On single-layer and two-layer samples, where the number of passes exceeded eight, the cracks were not completely eliminated due to the large size of the samples and the decrease in temperature to 200^{0}C. However, their number significantly decreased. This was followed by the experiments on a laboratory rolling mill.

The results of computer and field experiments showed that the cracks were eliminated on all the prepared samples after plastic deformation (Fig. 12).

Figure 12 : Sample without cracking after plastic deformation

The microstructure of the first layer of deposited metal is troostite alloyed with ferrite, the second layer is sorbitol with coagulated cementite with a hardness of 285–330 HV, and the structure of the heat-affected zone is bainite with plastic sorbitol with a hardness of 290–340 HV. In some areas, a martensitic structure was observed.

The results showed that in samples heated to a temperature range of 650–700 650–700^{0}C and treated with plastic deformation on a rolling mill,

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the cracks were completely eliminated. The structure of their surface layer is favorable. The hardness of the weld metal showed that its wear resistance is much higher than that of steel 60. As for the samples treated with a hammer, the elimination of cracks in them depends on the area of the weld metal (on the sample size).

All the above material properties can be obtained experimentally, and until recently, this was the most common way that industrial enterprises followed in their scientific and production activities when introducing mathematical modeling. Despite the fact that the modeling approach presented in the article is simplified compared to the approach that is present in more expensive software products, such as LS Dyna, see Fig. 13, 14, it does not require significant financial costs and time consumption on experimental research and filling out the database of material properties with which the enterprise works.

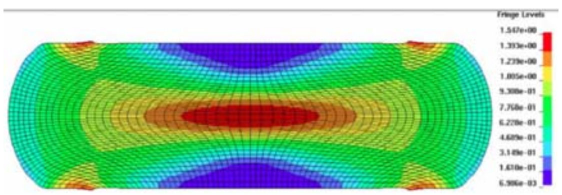

Figure 13 : Compression simulation example in LS Dyna package

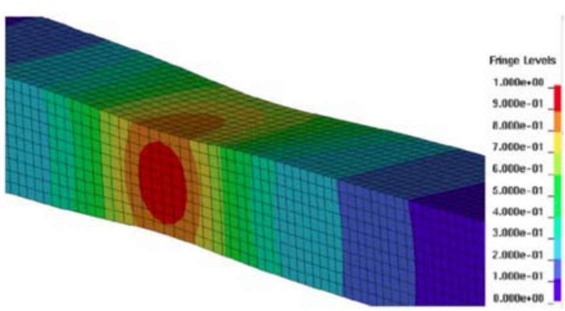

Figure 14 : Example of part modeling compression in LS Dyna package

One of the common ways to reduce the cost of experimental research is to fill in databases from open literature and search for analogues of materials. The main disadvantages of this path are the methods of obtaining various materials that change every year, which, without a doubt, affect their properties, the non-obviousness of the effect of the difference in the chemical composition of the material on the above properties in the case an analog, the difference in the initial conditions of the material with which the enterprise works, and of selecting the material in question in one or another literary source.

In addition to the packages JMatPro, Forge, Finel, Abaqus, LS Dyna, Deform mentioned at the beginning of the article, it may also be mentioned such universal engineering analysis systems as ANSYS, ABAQUS, MSC.NASTRAN, etc. These software products allow to solve a wide range of problems related to the modeling of physical fields of various nature: stresses and strains, thermal, electromagnetic, etc. The software products of this group have a design focus and provide the ability to simulate only elastic and minor plastic deformations. The meshing of finite elements in them is based on the Lagrangian approach. In this situation, these software products are not suitable for solving the specific problem considered in the article. We also note that the disadvantages of the latter are include the lack of automatic adaptive re-partitioning of the product model into finite elements with significant deformation, distorting the shape of individual elements more than a critical value.

Thus, it is impossible to adequately model fracture of materials with significant plastic deformation in these systems.

The LS-DYNA and MSC.Marc software packages can be distinguished into a special group of universal engineering analysis systems. These systems make it possible to study complex processes with significant plastic deformation and fracture, since they have the function of automatic adaptive re-partitioning of the finite element mesh, and the possibility of realizing a Lagrangian, Euler, and combined mesh. These software products have found application for scientific research in various fields of science and technology to solve the problems of collision, explosion, metal forming and cutting, etc. However, the cost of these packages is extremely high, and unlike the MathCad package we are considering, they require a fairly high qualification of the researcher.

Universal engineering analysis systems such as LS-DYNA and MSC.Marc have a limited set of criteria for the destruction of a deformable material. As such criteria in them, as a rule, the maximum allowable stresses or strains are used, upon reaching which the finite element is removed from the model [18–24].

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Unlike the existing work in the field of computer modeling of plastic deformation of metals, our survey clearly figures that at the initial stages of the study it is not necessary to use specialized software packages, in particular such as JMatPro, Forge, Finel, Abaqus, LS Dyna. Conventional packages can be used for mathematical modeling, for example, MathCad. Moreover, the correctness of the calculation depends more on the accuracy of the mathematical model, which determines the adequacy of the results.

In contrast to previous studies in this field, the emphasis is placed on cost reduction of mathematical and computer modeling of plastic deformation of metals, which is achieved by using inexpensive mathematical software packages, rather than specialized, expensive computer programs for such tasks.

The use of MathCad at the initial stage of the study, for example, in the task of computer simulation of plastic deformation of a deposited layer on a flat surface of a part, allows high-accuracy modeling of significant plastic deformation and fracture of products in many technological processes of product processing, without the use of additional user routines. Today, MathCad presents quite a lot of opportunities for modeling significant plastic deformations and fracture of solids from all low-cost software products on the market of Kazakhstan and Ukraine.

7. CONCLUSIONS

1. It is shown that, since every year the interest of various enterprises in the mathematical modeling of metal processing technological processes grows much faster than various databases of material properties are filled in specialized packages such as JMatPro, Forge, Finel, Abaqus, LS Dyna, Deform needed for calculations and obtaining adequate results, modeling the properties of materials in such common programs as, for example, MathCad, can be an excellent solution for enterprises that do not have the ability to get expensive experimental research. Using a specific example, during a computational experiment to study the deformation of a deposited layer, it is shown that the MathCAD package in the near future may become the same indispensable tool of an engineer as the slide rule was in the 60s of the last century.

2. It is shown that the proposed solutions for the MathCad package that implement the mathematical model of plastic deformation of the deposited layer will allow to study the processes of plastic deformation for a user who does not have programming experience and work with numerical methods for solving systems of ordinary differential equations. At the same time, the results obtained can give researchers and engineers the opportunity to more quickly fill out database information for more highly specialized programs, such as JMatPro, Forge, Finel, Abaqus, LS Dyna, Deform, QForm, SuperForge, Compass, SPFCC and others.

3. The one-dimensional problem of plastic deformation of the deposited layer on a flat surface was studied when a cylindrical roller was rolled in, including the Coulomb friction law on the contact surface. The equation of state of the material is selected on the basis of the theory of creep (hardening theory).

4. The mode of behavior of the workpieces at each stage of the processing cycle was studied in depth using modeling in the MathCad package.

5. An application program was developed in the mathematical editor Mathcad for the numerical analysis of a non-linear one-dimensional problem.

6. In the course of computer simulation and subsequent experimental checks, it has been established that the stress-strain state in the deformation zone significantly depends on magnitude λ ($\lambda = h_0 / R; h_0, R$ – layer thickness to deformation and roller radius, respectively) and on the friction coefficient μ on the surface of contact of the material with the roller. During simulation, it was also found that at certain values λ friction forces change direction in a small area of the contact surface. Contact pressure takes the maximum value at the point of the contact surface with the angular coordinate $\alpha = 0{,}05$, and then decreases. At values λ=0,5 and μ=0,3 the normal stress in the running direction decreases substantially and is actually zero.

6. With the help of the Mathcad package, the solution of nonlinear partial differential equations is obtained on the basis of the grid method.

7. According to the results of computer simulation and field experiments, a method for calculating the deposited layer was proposed. The given technique can be used to determine the parameters of the technological process

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during the restoration of flat surfaces.

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