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ИЗВЕСТИЯ

РОО «НАЦИОНАЛЬНОЙ
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NAS RK is pleased to announce that News of NAS RK. Series of geology and technical sciences scientific journal has been accepted for indexing in the Emerging Sources Citation Index, a new edition of Web of Science. Content in this index is under consideration by Clarivate Analytics to be accepted in the Science Citation Index Expanded, the Social Sciences Citation Index, and the Arts & Humanities Citation Index. The quality and depth of content Web of Science offers to researchers, authors, publishers, and institutions sets it apart from other research databases. The inclusion of News of NAS RK. Series of geology and technical sciences in the Emerging Sources Citation Index demonstrates our dedication to providing the most relevant and influential content of geology and engineering sciences to our community.

Қазақстан Республикасы Ұлттық ғылым академиясы «ҚР ҰҒА Хабарлары. Геология және техникалық ғылымдар сериясы» ғылыми журналының Web of Science-тің жаңаланған нұсқасы Emerging Sources Citation Index-те индекстелуге қабылданғанын хабарлайды. Бұл индекстелу барысында Clarivate Analytics компаниясы журналды одан әрі the Science Citation Index Expanded, the Social Sciences Citation Index және the Arts & Humanities Citation Index-ке қабылдау мәселесін қарастыруда. Webof Science зерттеушілер, авторлар, баспашылар мен мекемелерге контент тереңдігі мен сапасын ұсынады. ҚР ҰҒА Хабарлары. Геология және техникалық ғылымдар сериясы Emerging Sources Citation Index-ке енуі біздің қоғамдастық үшін ең өзекті және беделді геология және техникалық ғылымдар бойынша контентке адалдығымызды білдіреді.

НАН РК сообщает, что научный журнал «Известия НАН РК. Серия геологии и технических наук» был принят для индексирования в Emerging Sources Citation Index, обновленной версии Web of Science. Содержание в этом индексировании находится в стадии рассмотрения компанией Clarivate Analytics для дальнейшего принятия журнала в the Science Citation Index Expanded, the Social Sciences Citation Index и the Arts & Humanities Citation Index. Web of Science предлагает качество и глубину контента для исследователей, авторов, издателей и учреждений. Включение Известия НАН РК. Серия геологии и технических наук в Emerging Sources Citation Index демонстрирует нашу приверженность к наиболее актуальному и влиятельному контенту по геологии и техническим наукам для нашего сообщества.

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DEVELOPMENT OF A METHOD FOR CALCULATING THE ONE-DIMENSIONAL PROBLEM OF PLASTIC DEFORMATION OF THE DEPOSITED LAYER DURING THE RESTORATION OF FLAT SURFACES OF PARTS

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Abstract. Currently, the problem of increasing the operational properties of machine parts and mechanisms operating under variable loads or subject to abrasion is very relevant. Surface plastic deformation treatment using rolling of the surface of parts with steel cylindrical rollers is the most effective way to increase the durability of parts. With this method of finishing and hardening treatment, metal deformation is characterized by a significant influence of strain rates on stresses. This necessitates the calculation of stresses and deformations based on the equation of state of rheonomic bodies.

In the article, taking into account Coulomb's law of friction on the contact surface, the formulation of a one-dimensional problem of longitudinal running-in of a deposited layer by a cylindrical roller is considered. The solution of the problem involves calculating the stress-strain state in the deformation site based on the creep-hardening theory. A numerical solution of a one-dimensional nonlinear problem has been performed and the components of stresses and force factors of the technological process have been determined using modern numerical analysis systems, comparatively general formulas have been obtained for calculating the stress-strain state, pressure and friction forces on the contact surface, forces and moments acting on the roller.

The results of the study are applicable in repair production to solve actual practical problems of restoring the operational properties of machine parts.

Keywords: surface plastic deformation, stress, one–dimensional problem, creep-hardening theory, deposited layer, recovery, running-in, stress-strain state, cylindrical rollers, contact surface.

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БӨЛШЕКТЕРДІҢ ТЕГІС БЕТТЕРІН ҚАЛПЫНА КЕЛТІРУ КЕЗІНДЕ БАЛҚЫТЫЛҒАН ҚАБАТТЫ ПЛАСТИКАЛЫҚ ДЕФОРМАЦИЯЛАУДЫҢ БІР ӨЛШЕМДІ МӘСЕЛЕСІН ЕСЕПТЕУ ӘДІСІН ЖАСАУ

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Аннотация. Қазіргі уақытта ауыспалы жүктемелер жағдайында жұмыс істейтін немесе тозуға ұшырайтын машиналар мен механизмдердің бөлшектерінің пайдалану қасиеттерін арттыру мәселесі өте өзекті. Бөлшектердің бетін болат цилиндрлік роликтермен сынау арқылы беттік пластикалық деформация әдісімен өңдеу бөлшектердің беріктігін арттырудың ең тиімді әдісі болып табылады. Әрлеу және қатайту өңдеудің бұл әдісімен металдардың деформациясы кернеулерге деформация жылдамдығының айтарлықтай әсерімен сипатталады. Бұл реономикалық денелердің күй теңдеуіне негізделген кернеулер мен деформацияларды есептеу қажеттілігін талап етеді.

Мақалада контакт бетіндегі кулонның үйкеліс заңын ескере отырып, балқытылған қабатты цилиндрлік роликпен бойлық кесудің бір өлшемді мәселесін қою қарастырылады. Мәселені шешу жылжу – қатаю теориясы негізінде деформация ошағындағы кернеулі деформацияланған күйді есептеуді қамтиды. Бір өлшемді сызықтық емес есептің сандық шешімі орындалды және қазіргі заманғы сандық талдау жүйелерін қолдана отырып, технологиялық процестің кернеулері мен күш факторларының компоненттері анықталды, кернеудің деформацияланған күйін, жанасу бетіндегі қысым мен үйкеліс күштерін, роликке әсер ететін күштер мен сәттерді есептеу үшін салыстырмалы түрде жалпы формулалар алынды.

Зерттеу нәтижелері механизмдер мен машиналар бөлшектерінің пайдалану қасиеттерін қалпына келтірудің өзекті практикалық міндеттерін шешу үшін жөндеу өндірісінде қолданылады.

Түйін сөздер: беттік пластикалық деформация, кернеу, бір өлшемді тапсырма, сусымалы қатайту теориясы, балқытылған қабат, қалпына келтіру, сыну, кернеулі деформацияланған күй, цилиндрлік роликтер, жанасу беті.

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РАЗРАБОТКА МЕТОДА РАСЧЕТА ОДНОМЕРНОЙ ЗАДАЧИ ПЛАСТИЧЕСКОГО ДЕФОРМИРОВАНИЯ НАПЛАВЛЕННОГО СЛОЯ ПРИ ВОССТАНОВЛЕНИИ ПЛОСКИХ ПОВЕРХНОСТЕЙ ДЕТАЛЕЙ

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Аннотация. В настоящее время очень актуальна проблема повышения эксплуатационных свойств деталей машин и механизмов, работающих в условиях переменных нагрузок или подвергающихся истиранию. Обработка методом поверхностного пластического деформирования с использованием обкатки поверхности деталей стальными цилиндрическими роликами является наиболее эффективным способом повышения долговечности деталей. При этом способе отделочно-упрочняющей обработки, деформирование металлов характеризуется значительным влиянием скоростей деформаций на напряжения. Это диктует необходимость выполнения расчета напряжений и деформаций на основе уравнения состояния реономных тел.

В статье, с учетом закона трения Кулона на поверхности контакта рассмотрена постановка одномерной задачи продольной обкатки наплавленного слоя цилиндрическим роликом. Решение задачи включает расчет напряженно-деформированного состояния в очаге деформации на основе теории ползучести – упрочнения. Выполнено численное решение одномерной нелинейной задачи и определены компоненты напряжений и силовых факторов технологического процесса с использованием современных систем численного анализа, получены сравнительно общие формулы для расчета напряженно-деформированного состояния, давления и сил трения на поверхности контакта, усилий и моментов, действующих на ролик.

Результаты исследования применимы в ремонтном производстве для решения актуальных практических задач по восстановлению эксплуатационных свойств деталей механизмов и машин.

Ключевые слова: поверхностное пластическое деформирование, напряжение, одномерная задача, теория ползучести-упрочнения, наплавленный слой, восстановление, обкатка, напряженно-деформированное состояние, цилиндрические ролики, поверхность контакта

Introduction. The most effective way to increase the strength of parts is the method of finishing and hardening using the technology of testing the surface of parts with rollers. This method provides a low roughness of the surface of the parts by depositing metal along the thickness in the seam area to create plastic tensile deformations in the longitudinal and transverse directions, residual compressive stresses in the surface layers and the formation of fine grain of the structure. The testing process with steel cylindrical rollers ensures the complete elimination of residual deformations, provided that the plastic tensile deformations in the layer and adjacent parts of the base metal formed as a result of the tests are equal to the residual plastic compression deformations in these areas. At the same time, the residual longitudinal stresses may be close to zero (Grechnikov, 2021; Smelyansky, 2005; Sherov, et al, 2022).

In order to properly account for the deposition effect by the thickness of the heated material, to assess changes in residual stresses and deformations, it is necessary to study the stress-strain state of the metal layer, on the basis of which the deformation force and total power are calculated. It is advisable to calculate the technological processes of high-temperature metal processing on the basis of the equations of state of the simplest theories. In this regard, the most common is the theory of hardening. In this case, unlike the usual rolling process between rotating drive rolls, the deforming roller performs a flat parallel movement, and the contact surfaces have different friction conditions. The deformation of metals in the process of high-temperature processing is characterized by a significant influence of the deformation rate on stresses. This requires the calculation of stresses and deformations based on the equation of state of rheonomic bodies.

Materials and basic methods.

To determine the relationship between deformations, stresses, their rate of change and time in the simplest conditions of uniaxial stretching, a flowability theory is needed that allows describing deformations of the material, in general, time-varying stresses and deformations, on the basis of the simplest tests of the material, as well as providing the definition of the law of deformation change in accordance with a given law.voltage changes and vice versa. In an exceptional case, the theory of crawling allows you to build relaxation curves from serial curves. The simplest, but the best way to test the theory of creep is to compare the results of an experimental study of relaxation under constant deformation with data from the theory of creep.

The purpose of this work is to develop a method for calculating the one-dimensional problem of plastic deformation of the deposited layer during the restoration of flat surfaces of parts, to obtain relatively general formulas for calculating the stress-strain state, pressure and friction forces on the contact surface, forces and moments acting on the roller.

The research in the article will be based on the work of authors from near and far abroad in the field of finishing and hardening treatment by methods of surface plastic deformation of parts operating under wear conditions under high loads using steel cylindrical rollers. The research database contains information on the research activities of research institutes and centers of applied experimental research involved in solving urgent problems of improving the performance properties of machine parts and mechanisms operating under variable loads or subjected to abrasion. Empirical and theoretical research methods are used in writing the paper: review, synthesis, numerical analysis, modeling.

Results.

Nowadays, simple creep theories of materials are increasingly used to describe the creep processes of metals. The application of elementary theories in metalworking issues makes it possible to achieve reliable results with minimal labor and time. There are three simple theories: aging, currents, and hardening. As is known, the theory of aging does not correspond to the results of experimental studies in comparison with the theory of flow and hardening and does not better reflect the creep process under sharply varying loads. It should also be noted the theory of structural parameters of Yu.N. Rabotnov, a special case of which is the theory of flow and the theory of hardening. Studies show that the theory of hardening is in better agreement with experimental data (Oteniy, et al 2006; Akhmedov, et al, 2020). Therefore, to study the technological problem of testing the molten layer, we use the equation of state of the material based on the theory of hardening. The construction of the creep theory is usually performed for the simplest case of uniaxial stretching, and then for the general state of an inhomogeneous stress state.

According to the theory of solidification, it is assumed that there is a certain relationship between the rate of bulk deformation, stress and bulk deformation at a given temperature:

$$\xi(\varepsilon)^{\beta} = f(\sigma), \qquad (1)$$

moreover, it is assumed that $f(0) = 0$. Different expressions have been proposed for the stress function.

Dependence is widely used to study technological problems (Zaides, et al; 2017; Barshay, et al, 2003):

$$f(\sigma) = \alpha\sigma^{\nu}, \qquad (2)$$

where: α, β, ν - coefficients for a certain material, depending on the temperature. Obviously, at a certain temperature, these coefficients are constant.

Often, dependencies (1) and (2) are represented as:

$$\sigma = a\xi^{m}\varepsilon^{n}, \qquad (3)$$

where: *a, m, n* - the constants of the material at a certain temperature.

For an inhomogeneous stress state, the dependence (3) has the form:

$$\sigma_e = a\xi_e^{m}\kappa^{n}, \qquad (4)$$

where: $\kappa = \int \xi_e \, \mathrm{dt}$ - Udquist parameter, σ_e - equivalent voltage , ξ_e - equivalent strain rate.

As a special case, the hardening theory implies the equation of a nonlinearly viscous body, which is widely used in the analysis of flow in a state of super plasticity:

$$\xi_e = K\sigma_e^{\nu}, \qquad (5)$$

where: *K, ν* - the constants of the material at a certain temperature.

For a uniaxial stress state, equation (5) has the form:

$$\xi = K\sigma^{\nu}. \qquad (6)$$

From equation (4), as a special case (when m=0), an equation is obtained that is used to study the deformation of purely plastic materials, including an ideally rigid plastic material (when $m = 0, n = 0$).

For numerical calculations of the stress-strain state of the layer in the deformation focus, it is necessary to know the values of constant materials at the temperature of the shape change. The material constants (parameters of the equation of state) are determined by processing creep curves. The equation of state (3) describes creep curves with a pronounced hardening section (the first section) and the equation of state (6) describes creep curves on which there is no hardening section and a fixed creep section is clearly expressed (the second section).

Discussion.

Methods for determining the parameters of the equation of state are given in (Feldstein, et al, 2005; Skvortsov, et al, 2016; Stepanova, et al, 2009). The degree of coincidence of experimental and theoretical creep curves depends on the accuracy of determining the parameters of the equation of state (material constants). The reliability of the calculation of the stress-strain state and the power parameters of the technological process depends on the accuracy of the material constants. Consider the deformation of the material under the action of an absolutely rigid cylindrical body (roller), which performs a plane-parallel motion in the plane of the drawing (Fig.1). The deformable material is located on a rigid surface. Denote the speed of movement of the center of the roller by υ_0, and the angular velocity of rotation - ω. It is believed that they are constant values in time. Components of the velocity of movement of any point on the contact surface of the material with the roller in the deformation focus (Fig.1):

$$\upsilon_y = \upsilon_0 - \omega R\cos\alpha; \upsilon_z = -\omega R\sin\alpha. \qquad (7)$$

Suppose that the stress-strain state of the material changes only along the y coordinate.

Then from the equilibrium condition of the elementary volume of the body we have the following equations (Fig.2.):

$$\frac{d\sigma_y}{\mathrm{dy}} + \frac{\sigma_y + p}{h}\mathrm{tg}\alpha + \frac{q - q_1}{h} = 0, \qquad (8)$$

$$\sigma_z = p - \mathrm{qtg}\alpha, \qquad (9)$$

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

In technological problems of this kind in a one-dimensional formulation, the equivalent voltage σ_e is approximately calculated as (Bulekbayeva, et al, 2023):

$$\sigma_e = \sigma_y - \sigma_z \tag{10}$$

To simplify the solution, we assume that the friction on the contact surface of the material with the roller obeys Coulomb's law $q = \mu p$, moreover, the proportionality coefficient is constant over the entire contact surface. The intensity of the friction forces on the contact surface of the material with a rigid surface is assumed to be proportional to the maximum tangential stress:

$$q_1 = \chi\tau_{\max} = \chi(\sigma_y - \sigma_z)/2 = \chi\sigma_e/2, \tag{11}$$

where: χ - constant coefficient of proportionality. By =1 there is sticking.

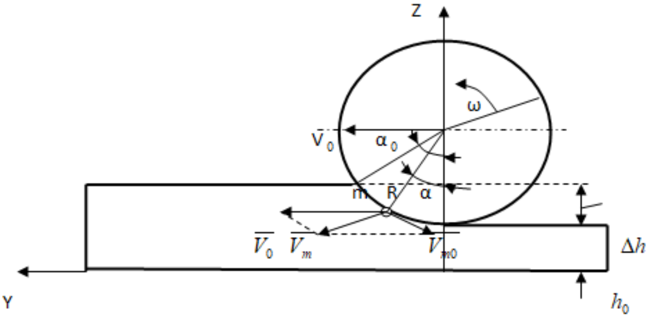

Figure 1 - Cylindrical roller running-in scheme:
R- roller radius, Δ*h*- changing the layer thickness, h_0- thickness of the rolled layer, α_0 maximum contact angle, α- angular coordinate of the point m, ω- angular rotation speed of the roller, $\bar{V}_0$ – velocity vector of movement the center of the roller , $\bar{V}_m$ - the velocity vector of the point m on the contact surface , $\bar{V}_{m0}$ - the vector of the rotation speed of the point m relative to the center of the roller.

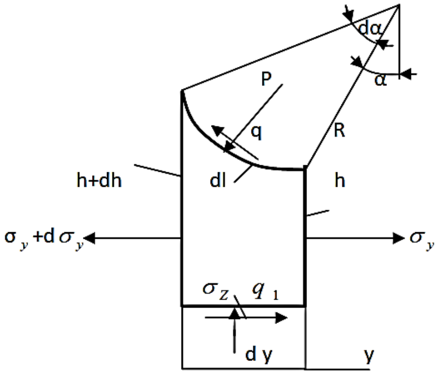

Figure 2 - To the derivation of the equilibrium equation of the element

It is obvious from Fig. 2 that $h = h_0 + R(1 - \cos\alpha)$, $\mathrm{dy} = R\cos\alpha d\alpha$. Considering in equation (8) the relations (9), (10), (11), as well as the last equalities, after simple transformations, a differential equation is obtained:

$$\frac{d\sigma_y}{d\alpha} + \psi_1(\alpha)\sigma_y = \psi_2(\alpha), \tag{12}$$

where are the designations introduced:

$$\psi_1(\alpha) = \frac{1}{h_0/R + 1 - \cos\alpha}\left(\sin\alpha + \frac{\sin\alpha + \mu\cos\alpha}{1 - \mu \mathrm{tg}\alpha}\right)$$

$$\psi_2(\alpha) = \frac{1}{h_0/R + 1 - \cos\alpha}\left(\frac{\sin\alpha + \mu\cos\alpha}{1 - \mu \mathrm{tg}\alpha} + \frac{\chi}{2}\cos\alpha\right)\sigma_e \tag{13}$$

Stress-strain state of the layer and power parameters of the technological process

To integrate equation (12), we have the boundary condition: $\alpha = 0, \sigma_y = 0$. Then the solution of the equation will be written as follows:

$$\sigma_y = \exp\left(-\int_0^\alpha \psi_1 d\alpha\right)\int_0^\alpha \psi_2 \exp\left(\int_0^\alpha \psi_1 d\alpha\right) d\alpha \tag{14}$$

For small contact angles, the solution of the differential equation (12) has the form:

$$\sigma_y = \frac{R}{h_0}\exp\left(-\frac{\mu R\alpha}{h_0}\right)\left[(1 + \mu^2)\int_0^\alpha \sigma_e \exp\left(\frac{\mu R\alpha}{h_0}\right)\alpha d\alpha + \left(\frac{\chi}{2} + \mu\right)\int_0^\alpha \sigma_e \exp\left(\frac{\mu R\alpha}{h_0}\right) d\alpha\right]. \tag{15}$$

As can be seen from the solutions obtained, in order to calculate the stresses, it is necessary to describe the state of the deformable material. Let’s take the equation of state according to the theory of hardening (4):

$$\sigma_e = a\xi_e^m \kappa^n,$$

where: a, m, n - permanent materials; ξ_e - equivalent strain rate; $\kappa = \int_0^t \xi_e \mathrm{dt}$ - the Udquist parameter.

The rate of deformation in the longitudinal direction, taking into account the ratios (7), is calculated as:

$$\xi_y = \frac{dv_y}{\mathrm{dy}} = \omega R \sin\alpha \frac{d\alpha}{\mathrm{dy}} \tag{16}$$

In the considered case of a plane deformed state, the equivalent rate of deformations (Bulekbayeva, et al, 2024; Pham, et al, 2024) $\xi_e = 2\xi_y/\sqrt{3}$. If we take into account that (Fig.2) $d\alpha/\mathrm{dy} = \mathrm{dl}/(\mathrm{Rdy}) = 1/(R\cos\alpha)$, then for the strain rate and the equivalent strain rate we have:

$$\xi_y = \omega \mathrm{tg}\alpha, \xi_e = 2\omega \mathrm{tg}\alpha/\sqrt{3} \tag{17}$$

Then the Udquist parameter, taking into account the second equality (17) and the ratio $\mathrm{dt} = d\alpha/\omega.$, will take the form:

$$\kappa = -\frac{2}{\sqrt{3}}\ln|\cos\alpha| \tag{18}$$

If we take into account the formulas for the equivalent strain and the Udquist parameter in the equation of state (16), then to calculate the equivalent stress we obtain:

$$\sigma_e = a(\frac{2}{\sqrt{3}})^{m+n}\omega^m \mathrm{tg}^m\alpha(-\ln|\cos\alpha|)^n \tag{19}$$

From formula (9), taking into account (10) and (19), we determine the pressure distribution on the contact surface of the material with the roller:

$$p = \frac{\sigma_y - \sigma_e}{1-\mu\mathrm{tg}\alpha} \tag{20}$$

Taking into account the first equation (17), the deformation in the longitudinal direction is equal to:

$$\varepsilon_y = \int_0^t \xi_y \mathrm{dt} + \varepsilon_y^0 = -\ln|\cos\alpha| + \varepsilon_y^0, \tag{21}$$

where: ε_y^0 – residual deformation after surfacing.

In order to completely eliminate the residual longitudinal deformations, it is necessary to fulfill the condition $\ln|\cos\alpha| = \varepsilon_y^0$. Appropriate contact angle:

$$\alpha_0 = \arccos[\exp(\varepsilon_y^0)] \tag{22}$$

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

$$\alpha_0 = \arcsin\left[2\sqrt{\Delta h/(2R)}\right]. \tag{23}$$

where: Δh – reducing the thickness of the deposited layer.

Comparing expressions (22) and (23) we find:

$$\Delta h = R[1 - \exp(2\varepsilon_y^0)\,]/2 \tag{24}$$

If the magnitude of the residual longitudinal welding deformation is known, then formulas (22) and (24) determine the maximum contact angle of the material with the roller and the deformation $\varepsilon_z = \Delta h/h$ by the thickness of the element in the rolling zone of the seam (Bulekbayeva, et al, 2024).

After determining the contact pressure and the intensity of the friction forces, the force and moment acting on the roller can be calculated.

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:

$$M = \mu R^2 \int_0^{\alpha_0} \mathrm{p} d\alpha \qquad (25)$$

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

$$P_z = R \int_0^{\alpha_0} (p\cos\alpha - q\sin\alpha) d\alpha \qquad (26)$$

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

$$P_y = R \int_0^{\alpha_0} (p\sin\alpha + q\cos\alpha) d\alpha \qquad (27)$$

In the formulas obtained above, the integrals are calculated numerically. To do this, we introduce dimensionless quantities:

$$\bar{\sigma}_e = \frac{\sigma_e}{a\omega^m}, \bar{\sigma}_{y,z} = \frac{\sigma_{y,z}}{a\omega^m}, \bar{p} = \frac{p}{a\omega^m}, \bar{M} = \frac{M}{a\omega^m R^2}, \bar{P}_{y,z} = \frac{P_{y,z}}{a\omega^m R}, \ \ \bar{q} = \frac{q}{a\omega^m}, \bar{v}_{y,z} = \frac{v_{y,z}}{\omega R},$$

$$\bar{\psi}_2(\alpha) = \psi_2(\alpha)/(a\omega^m), \bar{\xi}_{e,y} = \frac{\xi_{e,y}}{\omega}, \Delta\bar{h} = \frac{\Delta h}{R}, \lambda = \frac{h_0}{R}.$$

The above basic equations in dimensionless quantities will take the form:

$$\bar{\psi}_2(\alpha) = \frac{1}{\lambda+1-\cos\alpha}\left(\frac{\sin\alpha+\mu\cos\alpha}{1-\mu\mathrm{tg}\alpha} + \frac{\chi}{2}\cos\alpha\right)\bar{\sigma}_e,$$

$$\bar{\sigma}_y = \exp\left(-\int_0^\alpha \psi_1 d\alpha\right) \int_0^\alpha \bar{\psi}_2 \exp\left(\int_0^\alpha \psi_1 d\alpha\right) d\alpha,$$

$$\bar{\sigma}_y = \frac{1}{\lambda}\exp\left(-\frac{\mu\alpha}{\lambda}\right)\left[(1+\mu^2)\int_0^\alpha \bar{\sigma}_e \exp\left(\frac{\mu\alpha}{\lambda}\right)\alpha d\alpha + \left(\frac{\chi}{2}+\mu\right)\int_0^\alpha \bar{\sigma}_e \exp\left(\frac{\mu\alpha}{\lambda}\right) d\alpha\right],$$

$$\bar{\xi}_y = \mathrm{tg}\alpha, \bar{\xi}_e = 2\mathrm{tg}\alpha/\sqrt{3},$$

$$\bar{p} = \frac{\bar{\sigma}_y - \bar{\sigma}_e}{1-\mu\mathrm{tg}\alpha}, \quad \bar{\sigma}_e = \left(\frac{2}{\sqrt{3}}\right)^{m+n}\mathrm{tg}^m\alpha(-\ln|\cos\alpha|)^n ,$$

$$\Delta\bar{h} = [1-\exp(2\varepsilon_y^0)]/2, \ \ \alpha_0 = \arcsin\left[2\sqrt{\Delta\bar{h}/2}\right].,$$

$$\bar{M} = \mu \int_0^{\alpha_0} \bar{p} d\alpha,$$

$$\bar{P}_z = \int_0^{\alpha_0}(\bar{p}\cos\alpha - \bar{q}\sin\alpha)d\alpha,$$

$$\bar{P}_y = \int_0^{\alpha_0}(\bar{p}\sin\alpha + \bar{q}\cos\alpha)d\alpha.$$

Conclusion. The creep theory, based on elementary tests of the material, provides an opportunity to describe the process of deformations of the material in the general case of time-varying stresses and deformations, and also provides a definition of the law of deformation change according to a given law of stress change. In a one-dimensional formulation, relatively general formulas are obtained for calculating the stress-strain state, pressure and friction forces on the contact surface, forces and moments acting on the roller.

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