Rolling of a weld pad on a flat surface. One-dimensional problem

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Abstract. The analysis of modern welding methods shows that there are a number of factors in the weld pad, which together lead to a significant reduction in the wear resistance of the applied metal plating of the parts: a considerable variation of mechanical properties; Presence of inclusions and metallurgical defects; heterogeneity of structure and irregularity of surface solids in the length of the part; presence of unfavourable tensile stresses; reduction of fatigue of the parts on board; difficulty of mechanical treatment. The article solved the one-dimensional problem of non-responsive deformation of the weld pad at rolling and presented the main results of the work on the mathematical substantiation of the processes of rolling up the weld pad. One of the stages of the surfacing technological process was selected for the study, in particular, plastic deformation of the weld pad by rolling in a hard roller at elevated temperatures. Finishing processing by plastic deformation methods is accompanied by hardening of the surface layer, which is very important to increase the reliability of the parts. In the process of deformation, metals create a product shape and provide certain properties.

1. Introduction
Improving the quality of metal coating and the wear resistance of refurbished parts is an important task in repair works of construction and road engineering. Increasing the wear resistance of the parts allows, in some ways, to solve the problem of increasing the durability of machines.

All the examples considered in different literature sources conclude that the structure and properties of the substance after deformation differ significantly from its structure and properties prior to deformation.

Thus, the relevance of the topic is due, on the one hand, to the practical significance and the prospect of widespread use of plastic deformation of the weld pad (PDWP) by the rollers of hot metal weld parts, and on the other hand, the insufficient amount of scientific information about the possible effects of PDWP rollers on metal coating of parts, production methods for rational and effective use in practical repair.

2. Analytical solution of the problem
The object of the study is a metal coating applied to the surface of the part by an automatic electric arc pad of wires under a flux layer with hardening rollers for processing using the heat of the welding arc.

The principal possibility of studying the processes of the metamorphosis of rheonomic bodies is shown in the writings of A.A. Ilyushin, A.Yu. Ishlinsky and G. Genki. Material condition at elevated temperatures to be described on the basis of rheological models [1-3].
Rheological models for the study of the technological problems of plastic metal forming have been used in the writings of G. Genki, A. A. Ilyushin, A. Yu. Ishlinsky, N. N. Malinin, K. I. Romanov, O. Zenkovich, N. Kristescu, S. Tang, D. Durban and others [4-6].

In the writings of N.N. Malinin and his collaborators [7-9], the calculations of technological processes of metal processing are based on equations of state reflecting the rheonomic properties of metals — on equations of technical creep theories.

The technological problems of hot forming metal equation of state of the material should be taken on the basis of the theory of creep [8,10-12]. Of the simplest of the creep theory, the most acceptable is the hardening theory, which describes well the creep of steels and alloys in a wide range of temperatures.

3. Calculation model of the plastic deformation of the weld pad

Rolling of the weld pad ranks a technological processes of metal forming. Calculations of metal processing processes are usually based on one of the plasticity theories of body models (most often rigidly perfectly plastic, sometimes elastic, perfectly plastic or rigidly toughened body).

Models for describing the technological problems of plastic forming of metals are used in the writings of [5,6,13] G. Genki, A.A. Ilyushin, A.Yu. Ishlinsky, N.N. Malinin, K.I. Romanov, O. Zenkovich, N. Christescu, S. Tang, D. Durban and others.

The first attempts to use the equations of rheonomic bodies for solving technological problems belong to A.A. Ilyushin, A.Yu. Ishlinsky, G. Genki. This direction was further developed in the writings of N.N Malinin et al. [7,8,14], in which technological problems were solved on the basis of technical creep theories, such as flow and hardening theories, as well as using the equation of state of nonlinearly viscous body. The principal possibility of studying the processes of rheonomic bodies is shown in the writings of A.A. Ilyushin [4], A.Yu. Ishlinsky [5] and G. Genki [9], in which the equation of deformation of a viscoplastic body is used.

\[
\sigma_e = \sigma_T + \gamma \dot{\varepsilon}_e
\]  

where \( \sigma_e \) and \( \dot{\varepsilon}_e \) - equivalent stress and equivalent strain rate, respectively; \( \gamma \) - constant, proportional to the viscosity of the material; \( \sigma_T \) - yield stress (\( \sigma_T \) and \( \gamma \) are experimentally described; while \( \sigma_e < \sigma_T \) medium does not experience deformation).

The plasticity condition in the deformation zone is recorded using the so-called forced yield strength in the form of:

\[
K = \beta \sigma_T
\]

In here \( \sigma_T \) - is a base yield strength, \( \beta = 1 - 1.5 \) is a Lode coefficient.

The disadvantage of this work is that the equation (2) does not describe the dependence of the stress-strain state of the material in the deformation zone and the deformation force at elevated temperatures on the speed of the roller. Experimental studies of many authors [6,5,11] show that equation (2) does not describe the state of metals at elevated temperatures, and the calculation of technological processes must be based on a rheological model. The equation of state based on the theory of creepiness, the theory of strength of Ludwik - Nadai - Davenport [8] is relatively general.

4. Purpose and objectives of research

For the study, one of the stages of the surfacing technological process was selected, in particular, the plastic deformation of the weld pad by rolling in a hard roller at elevated temperatures. Rolling is used to process the weld in order to reduce the level of residual stress and improve the structure of the layer. The best effect is obtained by plastic deformation of the layer under isothermal conditions at a welding temperature.
Rolling is carried out by steel cylindrical rollers. The main characteristics of the process are: roller force, radius and width of roller working part, thickness of metal in the rolling zone, material condition parameters [6].

Experimental data show [5,8] that metal deformation during high temperature treatments is characterized by significant stress velocities. Therefore, the calculation of stresses and deformations should be based on the equation of the condition of the rheonomic bodies.

According to the theory of hardening, it is assumed that at a given temperature there is a certain ratio between the creep strain rate, stress and creep deformation.

\[ \xi(\varepsilon)^\beta = f(\sigma) \]  

and it is assumed that \( f(0) = 0 \). Different expressions have been proposed for the stress function. The dependence is widely used for the study of process problems [5,15-17]:

\[ f(\sigma) = a\sigma^\nu \]  

where \( \alpha, \beta, \nu \) -are coefficients for a specific material, depending on the temperature. Obviously, at a certain temperature, these coefficients are constant.

In experiments, a deformable material (Figure 1) is located on a rigid surface. We denote the speed movement of the center of the roller through \( \nu_0 \), and the angular velocity of rotation through \( \omega \). They are considered to be constant in time. The velocity moving components of any point on the surface of contact of the material with the roller at the point of deformation (Figure 1):

\[ \nu_y = \nu_0 - \omega R \cos \alpha; \nu_z = -\omega R \sin \alpha \]  

\[ \text{Figure 1. Rolling chart: } R \text{ - a roller radius, } \Delta h \text{ - a layer thickness change, } h_0 \text{ - a thickness of rolled layer, } \alpha_0 \text{ - a maximum contact angle, } \alpha \text{ - an angular coordinate of the point } m, \omega \text{ - an angular speed of rotation of the roller, } \vec{V}_0 \text{ - a vector velocity of the roller center, } \vec{V}_m \text{ - a vector velocity of the point } m \text{ on the contact surface, } \vec{V}_{m0} \text{ - a vector of the rotation speed of point } m \text{ relative to the center of the roller (Figure 2).} \]

Let’s assume that the stress-strain state of a material changes only along the coordinate \( y \). Then from the equilibrium condition of the elementary body volume we have the following equations (Figure 2):

\[ \frac{d\sigma_y}{dy} + \frac{\sigma_y + p}{h} \tan \alpha \pm \frac{q - q_1}{h} = 0, \quad \sigma_z = p - q \tan \alpha \]
where $\sigma_y$, $\sigma_z$ are stress components, $p$, $q$ are pressure and intensity of friction forces, respectively, on the contact surface of the material with the roller, $q_1$ is the intensity of the friction forces of the material with a rigid surface.

Figure 2. Withdrawal of the element equilibrium equation.

In technological problems of this kind in a one-dimensional formulation, the equivalent voltage $\sigma_y$ is approximately calculated as [11,18]:

$$\sigma_y = \sigma_y - \sigma_z$$  \hspace{1cm} (6)

To simplify the solution, we assume that the friction on the contact surface of the material with the roller obeys the Coulomb law $q = \mu p$, moreover the proportionality coefficient $\mu$ 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

$$q_1 = \chi r_{\text{max}} = \chi (\sigma_y - \sigma_z)/2 = \chi \sigma_z/2$$ \hspace{1cm} (7)

where $X$ is a constant coefficient of proportionality. When $X=1$ tends to sticking.

From figure 2 it is obvious that, $h = h_0 + R(1 - \cos \alpha)$, $dy = R \cos \alpha d\alpha$. Considering equation (7), and the last equality after simple transformations the differential equation is obtained:

$$\frac{d\sigma_y}{d\alpha} + \psi_1(\alpha)\sigma_y = \psi_2(\alpha)$$ \hspace{1cm} (8)

where the notation is introduced as follows:

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

$$\psi_2(\alpha) = \frac{1}{h_0 / R + 1 - \cos \alpha} \left(\frac{\sin \alpha + \mu \cos \alpha}{1 - \mu g \alpha} + \frac{X}{2} \cos \alpha\right)$$ \hspace{1cm} (9)

5. The stress-strain state of the layer and the power process parameters

To integrate equation (9), we have the boundary condition: $\alpha = 0, \sigma_y = 0$. Then the solution to the equation will be written as follows:

$$\sigma_y = \exp(-\int_0^\alpha \psi_1 d\alpha) \int_0^\alpha \psi_2 \exp(\int_0^\alpha \psi_1 d\alpha) d\alpha$$ \hspace{1cm} (10)
For small contact angles, the solution of differential equation (9) has the form of:

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

(11)

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

\[
\sigma_e = a \xi^m \kappa^n
\]

where \( a, m, n \) – constant material; \( \xi \) - equivalent strain rate; \( \kappa = \int_0^\alpha \xi \, dt \) – is an Udquist parameter.

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

\[
\xi_y = \frac{du_y}{dy} = \omega \sin \alpha \frac{d\alpha}{dy}
\]

In the case of a flat deformed state, the equivalent rate of deformation is [19,20] \( \xi_y = 2 \xi_y / \sqrt{3} \). If we take into account that (Figure 2) \( d\alpha/dy = dl/(Rdy) = 1/(R \cos \alpha) \), then for the strain rate and the equivalent strain rate we have [19]:

\[
\xi_y = \omega \sin \alpha, \xi_y = 2 \omega \sin \alpha / \sqrt{3}
\]

(12)

taking into account the second equality (2.17) and the ratio \( dt = d\alpha/\omega \), will take the form:

\[
\kappa = -\frac{2}{\sqrt{3}} \ln |\cos \alpha|
\]

(13)

If the formulas for the equivalent deformation and the Udquist parameter in the equation of state (10) are taken into account, the equivalent voltage is as follows:

\[
\sigma_e = a \left( \frac{2}{\sqrt{3}} \right)^{m+n} \omega^n \sin ^m \alpha \left( -\ln |\cos \alpha| \right)^n
\]

(14)

From formula (9), taking into account (10) and (13), we determine the pressure distribution on the contact surface of the material with the roller

\[
p = \frac{\sigma_y - \sigma_e}{1 - \mu g \alpha}
\]

(15)

Considering the first equation (12) deformation in the longitudinal direction is equal to:

\[
\varepsilon_y = \int_0^l \xi_y \, dt + \varepsilon^0_y = -\ln |\cos \alpha| + \varepsilon^0_y
\]

(16)

where \( \varepsilon^0_y \) – a residual deformation after welding.

In order to completely eliminate residual longitudinal deformations, it is necessary to fulfill the condition \( \ln |\cos \alpha| = \varepsilon^0_y \). Corresponding contact angle:

\[
\alpha_0 = \arccos [\exp (\varepsilon^0_y)]
\]

(17)
At the same time, the maximum contact angle (Figure 2.) is:

$$\alpha_0 = \arcsin \left( \sqrt{\frac{2\Delta h}{2R}} \right)$$  \hspace{1cm} (18)

where $\Delta h$ – decrease in the thickness of the weld pad.

Comparing the expressions (17) and (18) we find:

$$\Delta h = R[1 - \exp(2\varepsilon_0)]/2$$  \hspace{1cm} (19)

If the value of the permanent longitudinal welding deformation is known, the maximum contact angle of the material with the roller and the thickness $z = \varepsilon h$ of the element at the seam rolling area shall be determined according to formulas (17) and (19).

Force moment per unit length in a direction perpendicular to the drawing, assuming that the moment of contact pressure relative to the roller centre can be ignored, is equal to $M = \mu R^2 \int_0^{\alpha_0} p d\alpha$.

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

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

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

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

6. Findings

1. The calculations show that the stress-deformed state in the deformation centre depends substantially on the value $\lambda$, ($\lambda = h_0/R$; $h_0$, $R$ - thickness of the layer before deformation and the radius of the roller respectively) and on the friction coefficient on the surface of the contact of the material with the roller.

2. It has been established that, at certain friction values $\lambda$ friction changes direction on a small area of the contact surface. Contact pressure takes a maximum value at a point on the contact surface with an angular coordinate $\alpha = 0.05$, and then decreases. With values of $\lambda = 0.5$ and $\mu = 0.3$ the normal stress in the running direction decreases significantly and actually equals to zero.

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