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CONSIDERATION THE INFLUENCE OF RESIDUAL STRESSES AND CREEP STRAINS ON ROLLING THE STEEL SHEETS

Обговорюється метод для врахування залишкових напружень, що виникають внаслідок пластичного деформування при прокатці, у визначенні напружено-деформованого стану при повзучості розтягнутих сталевих пластин. Надано математичну постановку задачі, яка включає рівняння стану, що побудовані за допомогою визначених анізотропних властивостей повзучості сталі, що розглядається. Описано схему технологічного процесу та його чисельне моделювання. Отримані залишкові напруження застосовано як початкові умови при розв'язанні початково-крайовій задачі, що виконано за допомогою розробленого двовимірного скінченноелементного програмного забезпечення. Обговорюються чисельні результати та рекомендації для організації безпечного технологічного процесу.

Ключові слова: процес прокатки, сталеві листи, залишкові напруження, повзучість, рівняння стану, анізотропія властивостей повзучості, напружено-деформований стан, скінченноелементний аналіз.

Обсуждается метод учета остаточных напряжений, возникающих вследствие пластического деформирования при прокатке, при определении напряженно-деформированного состояния при ползучести растянутых стальных пластин. Приведена математическая постановка задачи, включающая уравнения состояния, созданные с помощью определенных анизотропных свойств ползучести рассматриваемой стали. Описана схема технологического процесса и его численное моделирование. Полученные остаточные напряжения использованы в качестве начальных условий при решении начально-краевой задачи, проведенного с помощью разработанного двумерного конечноэлементного программного обеспечения. Обсуждаются численные результаты и рекомендации для организации безопасного технологического процесса.

Ключевые слова: процесс прокатки, стальные листы, остаточные напряжения, ползучесть, уравнения состояния, анизотропия свойств ползучести, напряженно-деформированное состояние, конечноэлементный анализ.

The method for considering the residual stresses which occur by plastic deformation during the rolling process in creep stress-strain state of steel plates in tension is discussed. The problem's solution is divided on two stages. First one presents the modeling of the problem of plasticity with consideration of finite strains. The rolling process of steel sheets with two rolling mills is regarded. The scheme of technological process and its numerical simulation are described. Obtained stress-strain field in a plate after rolling was considered as a residual for creep initial-boundary value problem, which presents the second stage of analysis. The mathematical problem statement including state equations are built by use of the determined anisotropic creep properties of considering steel 3 at room temperature is presented. The transition procedure from three dimensional to two dimensional stress strain state in considered plate is discussed. Creep problem solution was done by use of developed two-dimensional Finite Element Method codes which include time step integration schemes. The numerical results like stress and strain fields, dependencies between the traction values and maximum plate's displacements, deformed shape of the plate edge as well as the recommendations for safety conditions of technological process are presented.

Keywords: rolling process, steel sheets, residual stresses, creep, state equations, anisotropy of creep properties, stress-strain state, finite element analysis.

Introduction. The processes of metal forming present the complex mechanical problems. Modern state of art of them is characterized by strong mathematical statements considering the plastic flow of the material and finite strains [1-3]. Due to the complexity of the problem as well as initial and boundary conditions practically only the numerical methods are used for simulation. In this way the Finite Element Method (FEM) in combination with numerical step integration methods were wide spread [4−5]. During last twenty years the approach was realized in special commercial software like *LS Dyna* [6].

As it can be analysed from the literature [1-3], the basic amount of works concentrate their attention on the character of complex stress-strain state during plastic flow of rolling material. However, there are a significant number of materials with essential creep behavior in room temperatures [7]. During the long-lasting action of the force of sheet pulling in the technological process of rolling the above force can cause the creep deformation in a sheet.

The level of creep strains limits the values of the force, the velocity of gripper motion etc. The problem can be solved by solution of general creep problem with consideration of residual stresses as well as the anisotropy of creep properties in a metal sheet after rolling.

This way demands the use of problem-oriented FEM software in which the possibility of anisotropic creep description is realized.

The paper presents the example of the complex investigations in which the initial distribution of stresses obtained after the rolling process is considered in creep calculations for steel sheet in extension by the technological pulling forces. The plates from steel 3 which is widely used in industry and demonstrate substantial creep behavior at room temperatures [8] was selected for the analysis. The program complex *FEM CREEP* [9], designed by authors for FEM numerical simulation of two-dimensional problems, was used in creep calculations.

Preliminary analysis of plastic stress-strain state after rolling. Let us regard the simple cold rolling machine which action chart is presented on Fig. 1. The plane steel metal billet passes through the mill and pulls by the action of traction is distributed on its front edge.

The sheet dimensions are:

width: $a = 0.12$ m; length of the first part $l_1 = 0.64$ m; length of the second part $l_2 = 0.36$ m; thicknes $h_1 = 0.006$ m;

The bottom of the sheet is located on the unmoveable rectangular basis. The rolling mills are characterized by the distance between them $h_2 = 0.0038$ m; The mill's hight $b = 0.18$ m, its radius $R = 0.5$ m.

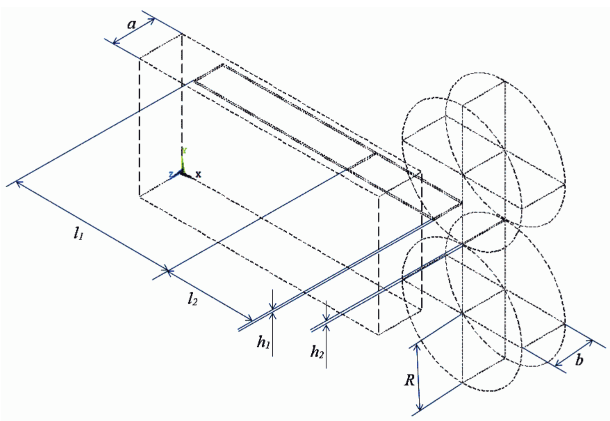

Figure 1 – The model of the rolling mill

For the determining of the residual stress-state after rolling the engineering FEM program complex was used. The basis and mills were considered as rigid. The calculations were performed in 3d statement with use of the FE mesh with 55800 elements for the aggregate model.

The stress-strain diagram with linear hardening was obtained experimentally [8].

The different velosities of sheet's motion were numerically analysed. Let us regard the example with $v = 1$ m/s. The von Mises strain redistribution after rolling is presented on the Fig. 2.

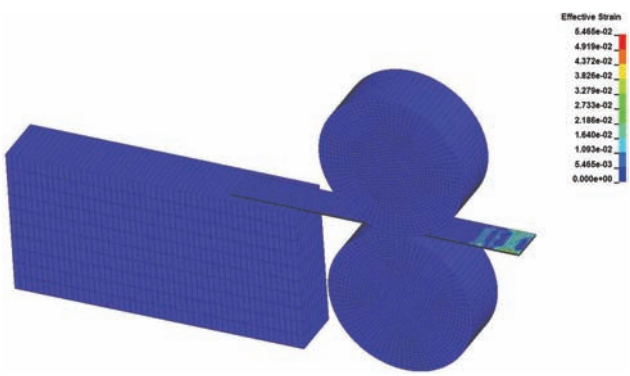

Figure 2 – Von Mises strains in the plate after rolling

The analysis of numerical data shows that the plate becomes thinner after the rolling process and the inhomogeneous stress-strain distribution was obtained.

Mathematical model for creeping plate with residual stresses after rolling. From the mechanical point of view the problem will be formulated as following: it is necessary to found the evolution of stress-strain state in the rectangular plate with initially obtained stress and strain distribution caused by plastic deformation through rolling. The small strains as well as plane stress state will be considered.

Let us write the total system of motion equations of solid Ω with border Γ with standard description of unknowns: stress σ, total strain ε with plastic p and creep c components :

$$\sigma_{ij,j} = \rho \ddot{u}_i; \quad \sigma_{ij} n_j = t_{ri}(x); \quad x \subset \Gamma_2;$$

$$\varepsilon_{ij} = \frac{1}{2}\left(u_{i,j} + u_{j,i}\right); \quad x \subset \Omega; \quad u_i\big|_{\Gamma_1} = \tilde{u}_i; \quad x \subset \Gamma_1; \; i = 1,2; \quad (1)$$

$$\sigma_{ij} = C_{ijkl}\left(\varepsilon_{ij} - p_{ij} - c_{ij}\right);$$

$$u_i(x_i,0) = u_i^0(x_i); \sigma_{ij}(x_i,0) = \sigma_{ij}^0(x_i);$$

$$\varepsilon_{ij}(x_i,0) = \varepsilon_{ij}^0(x_i); c_{ij}(x_i,0) = 0.$$

Here n is outer normal vector, ρ is the material density. The addition of strains is considered. Zero subindex denotes the initial distribution of the value.

The experimental investigations are presented in [8] shows that this steel 3 is characterized by creep at room temperatures. It was shown here, that elastic properties are isotropic but creep ones are orthotropic.

Let us briefly present the state equations. The plastic strains are considered by Huber-Mises plasticity condition with Prandl-Reuss flow rule [7]:

$$dp_{ij} = \frac{3}{2}\frac{d\bar{p}_i}{\sigma_i} s_{ij}, \quad (2)$$

where s_{ij} presents the deviatoric stress components σ_I is von Mises equaivalent stress.

Experiments [8] show the essential creep hardening in specimen made from steel 3 at T=20 C. Therefore the following creep state equations (3) were used

$$\dot{c}_{ij} = \tilde{B} c_{vM}^{-\alpha} \sigma_V^{n-1} \left[B\right] \sigma_{ij}, \quad (3)$$

where $\left[B\right]$ is the matrix of the creep constants, σ_v is equivalent stress , built by use the creep constants of material, c_{vm} is von Mises equivalent strain, $\left((\alpha+1)\tilde{B}\right)^{\frac{1}{\alpha+1}} = 3.166 \cdot 10^{-31}$ (10 МПа)$^{-m}$/h, $n = 97.35$, $\alpha = 4.32$ [8].

Results of FEM numerical simulations. The problem (1-3) was solved by use of combination of FEM with plane triangle element and direct numerical integration of initial problems.

Let us regard the metal sheet by use the calculation scheme of the thin plate 0.36x0.12 m, which is fixed in one edge and loaded by different values by traction t_r.

By use of special designed code the part of FE mesh with 864 elements and 481 nodes with subsequent stress-strain component distributions was imported into the *FEM CREEP* program complex [9].

The top layer of 3d elements was selected for import. The values here are equal to the bottom layer's values and are greater than inner ones. Due to smallness of y–displacements in 3d model, the y coordinates in 2d model had not changed. x-coordinates were increased on 2.5 mm due to the results of 3d calculations.

The values of stress tensor components for 2d model were obtained by re-calculation procedure, in which longitudinal normal components were the same, and other values were obtained due to principle of equality of the stress tensor invariants – von Mises equivalent stresses in each elements.

This von Mises equivalent stress distribution is presented in Fig. 3. The map shows its inhomogeneous character after the rolling process.

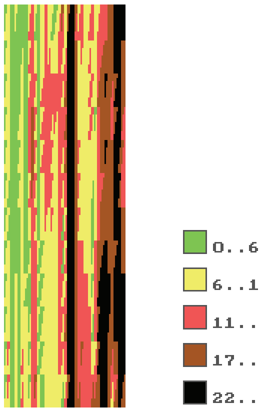

Figure 3 – Von Mises equivalent stress distribution in a plate after rolling, MPa 10^{-1}

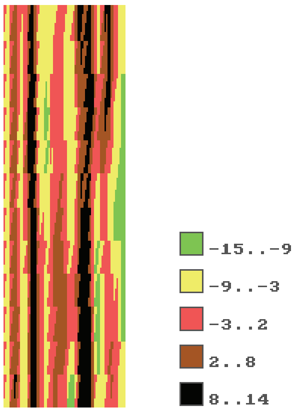

Figure 4 – Distribution of normal stress σ_x in a plate, MPa 10^{-1}

Fig. 4 contains distribution of the normal stress σ_x in a plate. As one can see, the considerable areas of compression after rolling are presented.

Practically similar character of distribution along the plate length can be used for justifying the use of FE model dimensions.

Let us regard the results of numerical simulation of creep in plate. The values of traction are equal to 64, 128, 220, 230 та 250 MPa were used in calculations. The creep time 30 s was analysed.

Fig. 5 contains the total von Mises equivalent stress distribution in a plate, which is obtained by addition to initial stress field the value of traction t_r = 250 MPa. This distribution can be regarded as maximum possible, because the equivalent stress values in definite places are closer to the rupture stress 395.3 MPa.

As one can see, there are areas with equivalent stress vales 330-390 MPa, in which significant creep strains up 2.2 % occur in a plate material [8].

Fig. 6 illustrates the dependence between traction values and maximum longitudinal displacement in a plate. By this figure's analysis the border between 'safety' values of the traction without considerable creep can be determined. This value can be determined as 200 MPa. Even we think that the displacement of 0.5 mm is not so big, we must assume the irregular character of creep strain accumulation in a plate due to the irregular initial stress distribution. Fig. 7 contains the graphical illustration of plate's edge displacements in points along the plate width at t=30 s and t_r=250 MPa.

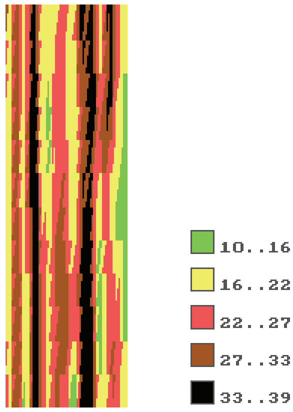

Figure 5 – Total von Mises equivalent stress distribution in a plate in the case t_r = 250 MPa, MPa 10^{-1}

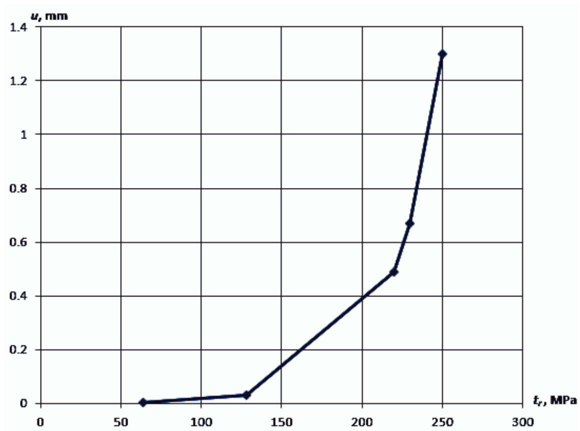

Figure 6 – Dependence between traction values and maximum longitudinal displacement in a plate

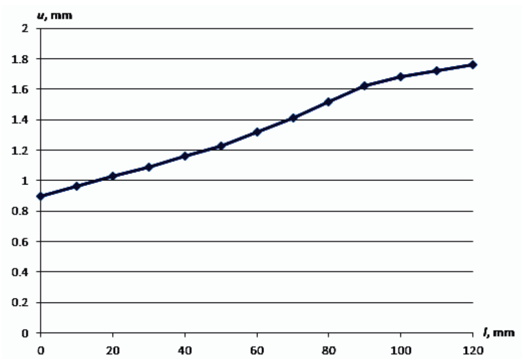

Figure 7 – Plate's edge displacements in points along the plate width at t = 30 s and t = 250 MPa

This non-symmetric character of displacement distribution can be justified by the non-symmetric character of initial stress field as well as strain compatibility conditions in creep process.

Conclusions. The paper contains the results of numerical modeling the creep process in thin plate, which models the steel sheet in tension during the rolling process. Preliminary deformation of the sheet in rolling mills is determined by numerical simulation of this technological process by use of the approach which includes the finite plastic strains consideration. Obtained stress-strain fields were used as initial conditions in creep process. It was determined, that these distributions had inhomogeneous character through the plate's width. Solutions show that after increasing the traction from the determined value is equal to 200 MPa, the significant non- symmetric distribution of displacements occurs in plate, which can be considered as invalid from the point of view of technology. Creep calculations of the described problem allow to find the 'safe' modes of extension, where the creep strains can be consider as negligible.

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