EXPERIMENTAL ANALYSIS OF STRESS CONDITIONS DURING ROLLING

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Abstract

Strains and stress conditions during shape rolling of experimental billets were analyzed. Photoplasticimetry, the theoretical basis of which is briefly described, was applied as the experimental evaluation method. This method is advantageous for evaluating stress and strain conditions since it enables to determine directions of the main strain in each point of the deformed material in the real deformation zone, as well as differences between them. The obtained data can subsequently be also used to solve other issues of static conditions of equilibrium by applying the methods of shear stress differences and successive approximation.

Keywords: Stress analysis, strain analysis, photoplasticimetry, shape rolling

1. INTRODUCTION

The final mechanical properties of a deformed material, as well as its formability during the forming process, depend on various processing parameters. Among those having the most significant influences are especially chemical composition, thermodynamic conditions and strain and stress conditions in the real deformation zone. The knowledge of the stress and strain fields during the particular forming process is necessary for successful forming of any material without its failure.

The influence of processing parameters and geometry of forming processes can be predicted using several methods, from which the most important are numerical [1] and mathematical [2] modelling. While numerical modelling is mostly used to predict behavior of materials in the region of plastic [3-5], as well as elastic [6] deformation under specific conditions (however these conditions can be varied once the basic assembly is constructed), mathematical modelling is mostly used to create more general models and equations for behavior of materials [7,8].

Both these approaches have been extensively used for examinations of conventional, as well as non-conventional deformation technologies. Nevertheless, methods for experimental measurement of stress-strain conditions during the particular forming process, such as photo-plasticity method, have also been developed. Particularly this method has already successfully been applied to measure stress-strain condition during several forming technologies, e.g. rotary forging [9] and accumulative roll bonding [10].

The aim of the study described in this contribution was to outline an analytical solution of the stress-strain conditions during rolling in an enclosed shape die. Considering rolling, the strain and stress conditions are influenced mainly by the rolling gap geometry and friction conditions between the rolled billet and rolls. The paper features evaluation of the experimental results using photo-plasticity method and calculations of the stress and strain fields using a proposed hybrid method.

2. METHODS AND CALCULATIONS

In this experiment, we consider the process of rolling. Since this is a forming process during which the material experiences plastic deformation, it is necessary to involve a theory of plasticity in our calculations. To analytically solve the stress and strain fields during rolling we selected a hybrid method - we supplemented the theory of plasticity with results of observations performed experimentally using photo-plasticity method.

The principle of the photo-plasticity method is in examination of two types of interference lines, which form under polarized light. These types include isoclinic lines, the behavior of which can be used to determine the ε_1 and ε_2 directions, and isochromatic lines enabling the determination of the (ε_1 - ε_2) difference. The difference of the main strains can be determined on a quantitative basis via applying the Wertheim law (Eq. (1)) [11]. The proposed hybrid method then enables experimental determination of the directions of the main strains ε_1 and ε_2 and their differences (ε_1 - ε_2) in each point of the deformed material across the real deformation zone.

$$(\varepsilon_1 - \varepsilon_2) = n \frac{\lambda}{t\,.\,K} = n\,.\,f \tag{1}$$

where n is order of isochromatic line, λ is wavelength of penetrating light, t is thickness of optically active material, K is optical sensitivity of optically active material, f is value of order.

Since the distribution of deformation in the deformation zone during rolling is uneven, the elastic-plastic deformation theory was chosen to evaluate stress and strain fields. It also provides an advantageous approach for determination of shear stress and shear strain intensities. For the theory of elastic-plastic deformation, the following equation specifies the dependence between the stress deviator D_σ and the strain deviator D_ε (Eq. (2)) [12].

$$\boldsymbol{D}_\sigma = \frac{2S_\tau}{S_\gamma}\boldsymbol{D}_\varepsilon \tag{2}$$

where S_τ is intensity of shear stresses and S_γ is intensity of shear strains.

Equation (2) can subsequently be used to determine the above mentioned shear stress and shear strain intensities within the proposed hybrid method. The intensity of shear stresses S_τ and the intensity of shear strains S_γ are then defined by the following relationships (Eq. (3) and Eq. (4)):

$$S_\tau = \sqrt{-I_2(\mathbf{D}_\sigma)} = \sqrt{\frac{1}{6}\left[(\sigma_1-\sigma_2)^2 + (\sigma_2-\sigma_3)^2 + (\sigma_3-\sigma_1)^2\right]} \tag{3}$$

$$S_\gamma = 2\sqrt{-I_2(\boldsymbol{D}_\varepsilon)} = \sqrt{\frac{2}{3}\left[(\varepsilon_1-\varepsilon_2)^2 + (\varepsilon_2-\varepsilon_3)^2 + (\varepsilon_3-\varepsilon_1)^2\right]} \tag{4}$$

where $I_2(D_\sigma)$ is second invariant of the stress deviator and $I_2(D_\varepsilon)$ is the second invariant of the strain deviator.

After having performed the substitution of equation (2) with deviator constituents in the orthogonal coordinate system, the formula determining the difference of the two main stresses in a specific location within the deformed work-piece can be expressed as follows [13] (Eq. (5)). This relationship is then a basis for the solution of the tensor stress and strain fields and will be used in the below described study.

$$(\sigma_1 - \sigma_2) = \frac{2S_\tau}{S_\lambda}(\varepsilon_1 - \varepsilon_2) \tag{5}$$

As for the model experimental material we used a low module optically active PS 4 epoxy resin fabricated by Vishay [14]. To obtain its material characteristics, we performed plastometric tests under various thermodynamic conditions. Based on these tests we were then able to determine properties of the material and its behavior in the region of plastic deformation. The obtained stress-strain curves can be used to determine the dependency between the shear stress intensity and the shear strain intensity. The following relationships for these intensities result from equations (3) and (4).

$$S_\tau = \frac{\sigma_1}{\sqrt{3}} \tag{6}$$

$$S_\gamma = \frac{2\varepsilon_1(1+\mu)}{\sqrt{3}} \tag{7}$$

To determine the dependency between both the intensities, we subsequently applied regression analysis and the minimum RMS (Root Mean Square) deviation method. Therefore the properties of the real material are eventually given by two material constants a and b according to equation (8).

$$S_\tau = a(S_\gamma)^b \tag{8}$$

3. RESULTS AND DISCUSSION

We experimentally performed a pass of shape rolling, during which the experimental billet changed its cross-sectional shape from original rectangle (before the pass) to final oval (after the pass). We evaluated stress and strain fields in six sections defined as I-VI, as is depicted in **Fig. 1**. The results of calculations for section II are presented below.

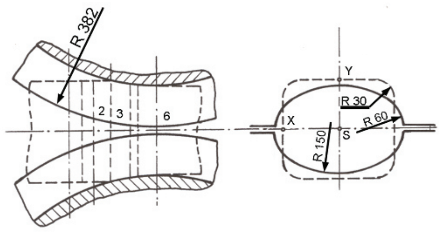

Fig. 1. Depiction of calculated areas during rectangle - oval shape rolling

The experimentally observed isochromatic lines can be seen in **Fig. 2**. These lines are constructed geometrically. They basically connect geometrical points in which the differences between two values are constant. This applies for main strains, as well as for main stresses. The same geometric construction approach can be used again to experimentally determine the isoclinic lines. These lines connect points in which the directions of the main strain and main stress are the same. These lines can finally be used while solving analytically strain and stress conditions during forming using the method of characteristics [15].

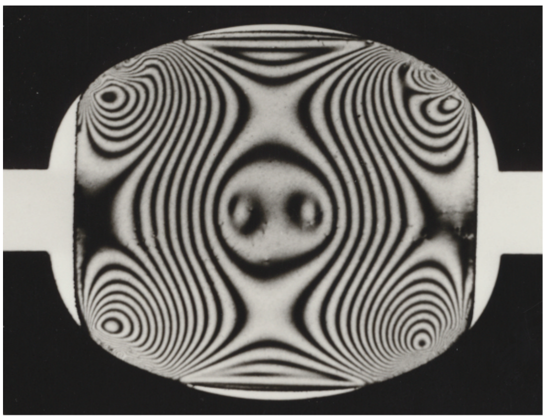

Fig. 2 Semi-orders isochromatic lines

Nevertheless, the experimentally obtained directions and differences of the main strains are not sufficient for determination of constituents of the strain and stress tensors. Therefore, it is necessary to use the static conditions of equilibrium and the relationships of the theory of plasticity to solve this issue. Since we considered a plane stress condition, the static condition of equilibrium in the x-axis direction can be described as follows (Eq. (9)):

$$\frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} = 0 \qquad (9)$$

In the partial differential equation (9), two unknown variables are present (i.e. σ_x and τ_{xy}). The following relationship (Eq. (10)) is then derived using the Mohr's circle for shear stress τ_{xy}:

$$\tau_{xy} = \frac{\sigma_1 - \sigma_2}{2} \sin 2\vartheta \qquad (10)$$

where ϑ is angle ensuing from the shape of the isoclinic lines.

As was described above by equation (8), the given dependency of the intensities S_τ and S_γ is non-linear in the area of plastic deformations. Therefore equation (9) is also a non-linear partial differential equation. The equation must be solved numerically to be eventually converted to the following form applicable for rolling conditions (Eq. (11)).

$$\sigma_{x,i} = \sigma_{x,o} \pm \sum_{1}^{i} \frac{\Delta \tau_{xy}}{\Delta y} \Delta x \qquad (11)$$

where $\sigma_{x,0}$ is a known value of normal stress σ_x in the initial point of integration.

Numerical integration begins on an unloaded surface of the rolled billet, in the point which is characterized with zero values of the parameters σ_x and τ_{xy}. The integration uses the shear difference method and successive approximation method. The evaluation process is described in detail in reference [16], while the successive approximation method is outlined in **Fig. 3**. The results of the integrations are constituents of the stress tensor in all the locations of the real deformation zone.

The strain and stress fields are tensor fields which cannot be depicted as simple scalar fields containing only one parameter. Therefore, these fields are mostly depicted using equiscalar levels of the scalar constituents of the strain and stress tensors. The equiscalar levels of tensors within the rectangle to oval shape rolling are plotted in **Fig. 4**, in which stress is depicted in the upper half and strain in the lower half of the schematic figure.

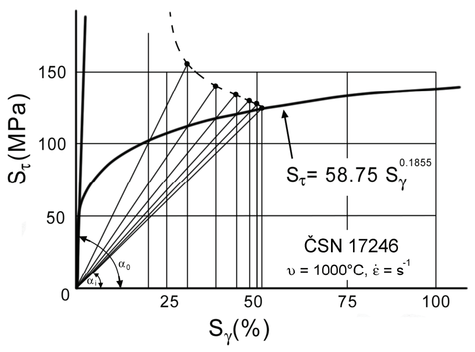

Fig. 3 Method of successive approximation

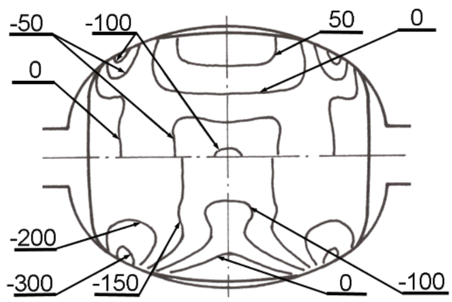

Fig. 4 Equiscalar levels of strain and stresses

The experimentally observed behavior of isochromatic and isoclinic lines imparts the supposition that deformation within a rolled billet is induced a relatively long time before the material enters the deformation zone. The maximum intensity of strain was detected in four points of the rolled billet within the exit rolling plane.

Comparison of **Fig. 2** and **Fig. 4** provides a reasonable similarity, i.e. correlation of calculated and experimentally obtained results. Using the theory of similarity, the results of our calculations based on laboratory experiments can subsequently be applied for real shape rolling conditions. However, to be able to make a conversion via the theory of similarity it is necessary to also determine the mechanical properties of the real material. This can favorably be done using plastometric tests, likewise to our study.

4. CONCLUSIONS

In the presented paper we propose and briefly describe the hybrid method, which we applied on an analysis of strain and stress conditions during shape rolling. The method basically consists of a combination of analytical calculations based on the theory of plasticity with subsequent experimental verification using the photo-plasticity method. The results of calculations showed that tensile stresses, which may cause rupture of the rolled billets especially in materials with low formability, were detected on the top and bottom surface of the rolled billet. The proposed method showed a good correlation of experimentally and analytically obtained results and can therefore be reproduced also for other forming processes. In the near future, we are planning to use the same hybrid method to calculate stress and stress fields in methods of severe plastic deformation, such as accumulative roll bonding (ARB) end equal channel angular pressing (ECAP).

ACKNOWLEDGEMENTS

We honor departed prof. Ing. Pavel Macura, DrSc. who was researching these methods for long time of his life. This work was supported by the European Regional Development Fund in the IT4Innovations Centre of Excellence project (CZ.1.05/1.1.00/02.0070) and the FRVS2015/75 project financed by the Ministry of education of the Czech Republic and the Faculty of Metallurgy and Materials Engineering, VSB - Technical University of Ostrava.

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