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FEM SIMULATION OF RESIDUAL STRESSES IN COLD ROLLED STRIPS

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ABSTRACT

Finite elements method (FEM) was used for investigation and analysis of longitudinal residual stresses in cold rolled strips. FEM simulation of residual stresses and conditions of their balance was done by using model of equivalent outside loading. Experimental research was undertaken with the method of deflection. Good agreement of experimental results and simulation for stress-strain state confirm the reliabilility of FEM simulation**.**

Key words: residual stresses, elastic line, deflection, FEM

INTRODUCTION

Residual stresses in cold rolling strips provoke their irregular shape [1,2]. Longitudinal stresses have the dominant influence on the shape of strips. When these stresses are symmetrically balanced with cross section, the defect of the shape could not be avoided, and the potential instability may appear in the next stage of processing [2-4].

For analysis of residual stresses we can apply the Finite Elements Method (FEM) [5,6]. Application of this method is particularly important for simulation of effects which produce disturbance of balance, which necessitates a high correlation of real and calculated values of residual stresses.

Results of measured residual stresses were reported in this paper. Optimization of starting parameters of FEM was performed with the idea to obtain aimed a high correlation of calculated and measured values of longitudinal residual stresses.

EXPERIMENTAL

Alloy AlMg4.5Mn with the following chemical composition (wt.%): 4.23%Mg, 0.42%Mn, 0.26%Fe, 0.015%Cu, 0.02%Zn, was selected for the investigation.

The investigated material was a polished sheet with thickness H_0=1.28mm. Strips with length 20, 40 and 60mm were cut from this sheet, and in the next step cold rolled on a laboratory rolling stand with the reduction ratio of 15÷50 %. Samples of the final length of 82mm were cut from deformed strips. In order to disturb the balance of stress, samples were evenly damaged on one side by immersing into the 20% solution of NaOH. The rest of the sample was covered with the stable protection layer.

RESULTS AND DISCUSSION

Model of residual stresses. The positio of residual stresses, which appear in the cold rolled sheet was horizontal, with main components in the longitudinal and transversal direction. Longitudinal stresses have a dominant influence on the properties and the appearance of sheets. Their profile includes a complete cross section, and the maximum of stresses is to be located on the surface (Fig 1a).

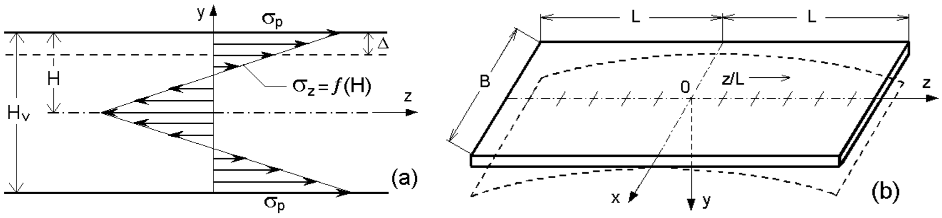

Fig. 1. Diagram of longitudinal residual stresses (a) and shematic presentation of elastic bending in cold rolled strips under the influence of residual stresses (b)

Based on conditions that the stresses have a linear distribution along the thickness of the sheet and that they constant along the width [2], the balance diagram can be shown by the equation:

$$\sigma_z = \sigma_p \left[A_1 h_r + A_2 \right] \qquad (1)$$

where: σ_z i σ_p –longitudinal stresses on cross section and surface; h_r – relative thickness (y/H); A_1, A_2 - coefficients which determine boundary conditions.

The estimate of residual stresses is based on measurement of elastic bend of sample. Elastic bend is the result of the unsymmetrical distribution of stresses along the section or of the disturbance of balance of stresses. This resulted in the bending of sample moment of loading until a new balance is established. In both cases loading stresses are constant along the length and depth of sample, as well as moment bending. This model of loading corresponds to the bending of a cantilever whose elastic line can be expressed by the equation:

$$y = a \cdot z_n^2 \qquad (2)$$

where: a – coefficient (maximal bend); z_n – relative longitudinal distance(z/L).

Horizontal rolled samples have a symmetrical distribution of longitudinal residual stresses (Fig. 1a) and a balanced moment of bending with regard to longitudinal axis. However, with induced damage a layer is removed from one side the sample (thickness Δ), balance is disturbed and the sample is bending in the shape shown in Fig. 1b. In accordance to bending by cantilever, the bend is symmetrical with regard to transversal x-axis. Measurement of bending and approximation by equation (2) can be done for both segments of the sample. This means that the zero point is located exactly in the middle of length 2L, which corresponds to the place of constrain, whereas the right and the left branches correspond to the positive and the negative segment variable z_n (z/L).

In order to establish connection between the conditions of bending and residual stresses, it is necessary to realize relation for their moment of loading. The equation for estimation of longitudinal residual stresses is obtained from equality of moments of bending of cantilever and moment bending from residual stresses [3,4]:

$$\sigma_p = \frac{8\,E\,(H - \Delta/2)^3\,f}{H^2\,L^2\left[6(\Delta/H) - 6(\Delta/H)^2 + (\Delta/H)^3\right]} \tag{3}$$

As it can be seen from the equation (3), stresses can be estimated, if the following parameters are known: elastic moduli of materials, thickness of the removed layer (Δ) and dimension of elastic bend (f). These parameters for chosen dimensions of samples and reduction ratio are shown in Table 1. Calculated values of stresses are shown in the Table 2.

Table 1. Dimension,reduction ratio,elastic bend and FEM parametars of selection samples

Sample 1		Dimension 1,01x20x82		Reduct. ratio ε=21.1 %		Thick. lay. rem. Δ=322 μm		Max.bend f=2,446 mm		FEM-/number/
z, mm	-38	-28	-23	-13	0	10	20	30	38	eleme.	node
y, mm	1.84	0.99	0.67	0.21	0	0.12	0.49	1.13	1.88	12324	16000
Equation of leastic line: $y = 1{,}823 \cdot z_n^2$											
Sample 2		Dimension 1,005x40x82		Reduct. ratio ε=21.5 %		Thick. lay. rem. Δ=331 μm		Max. bend f=2,243 mm		FEM-/number/	
z, mm	-38	-28	-23	-13	0	10	20	30	38	eleme.	node
y, mm	1.54	0.87	0.60	0.19	0	0.08	0.43	1.03	1.70	25596	32800
Equation of leastic line : $y = 1{,}622 \cdot z_n^2$											
Sample 3		Dimension 1,001x60x82		Reduct. ratio ε=21.8 %		Thick. lay. rem. Δ=365 μm		Max. bend f=2,742 mm		FEM-/number/	
z, mm	-38	-28	-23	-13	0	10	20	30	38	eleme.	node
y, mm	2.13	1.17	0.80	0.26	0	0.12	0.49	1.17	1.95	43344	55245
Equation of leastic line: $y = 2{,}012 \cdot z_n^2$											

FEM simulation. In the presence of residual stresses cold rolled strips change their geometry and properties. These changes can be identified by the support of experimental measurements of stresses. Also, changes of FEM can be performed by simulation of residual stresses. Accuracy of simulation was estimated based on the value of stress on the surface, shape of distribution and shape of the distortion model.

FEM simulation was performed with the help of the outside load which is equivalent to the disturbed balance of residual stresses (Fig. 1a), with intention to confirm the effect on stress-strain state. In this regard a half of the sample was separated as equivalent cantilever with:

- position of constrain along transversal x-axis;
- couple forces of outside loading opposite direction in regard to Fig. 1a.

The simulation was done on the three chosen samples by using program MSC NASTRAN. Parameters of FEM (Table 1) and equivalent outside loading were chosen with the aim to satisfy starting hypothesis and to attain a high correlation with experimental results.

By simulation on a half of the length of the sample, fields of values of components tensor of stresses on the space model were obtained as well as fields of values move on y-z surface. Values of longitudinal stresses and distribution with the cross-section are shown in Fig. 2. Lengths of 34, 30 and 26 mm can be separated in samples 1, 2, 3 respectively and on these samples a constant value of normal stresses σ_{zz} was obtained. In that way the initial bending condition was satisfied showing that the longitudinal stresses, i.e. the moment of bending, is constant along the length and the width of the strip.

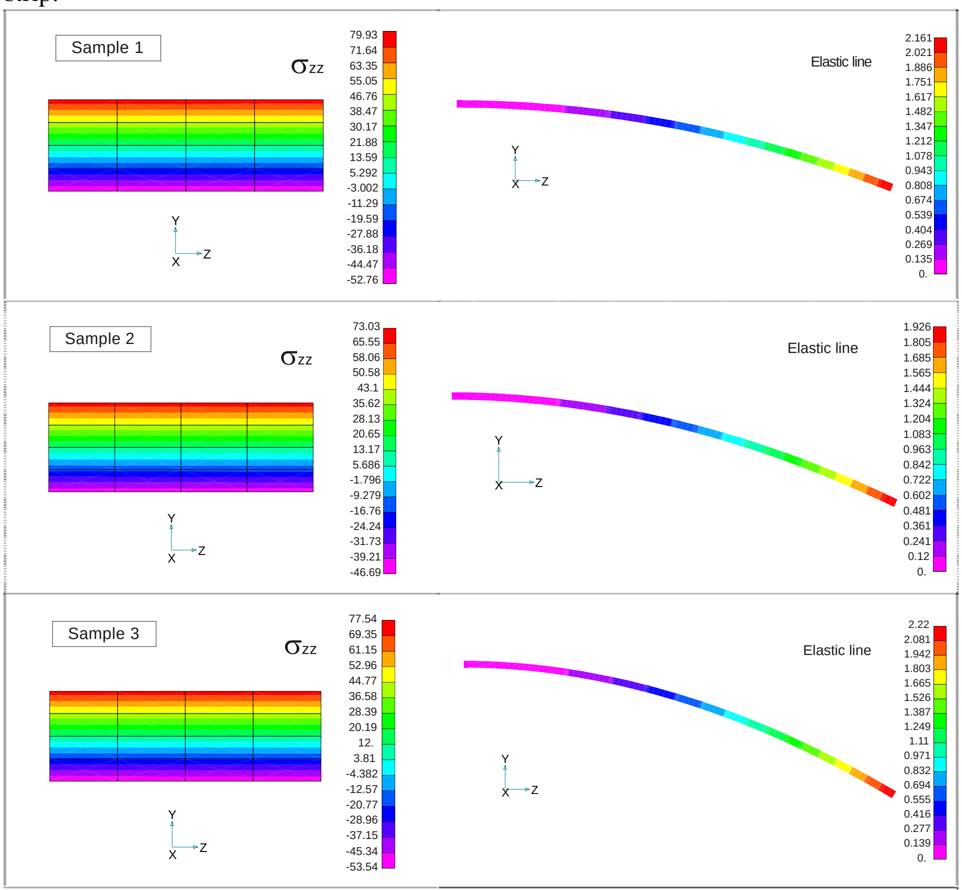

Fig. 2. FEM simulation of longitudinal residual stresses and elastic line for samples 1, 2 and 3

The stress σ_{zz} has linear distribution along thickness and in accordance with this a maximal value of the stress on the surface. Other normal stress σ_{xx}, as well as all shear stresses have a symmetric distribution with regard to longitudinal z-axis and low values compared to stress. Third normal stress was practically equal to zero. In agreement with previously mentioned, equivalent Von-Mises's stress is a dominant factor which is caused by the longitudinal normal stress. The present shade at Von-Mises's stress expresses differences in the layer, which in absolute amount are similar to maximal values of stresses σ_{xx}, σ_{xy}, σ_{yz} and $\sigma_{zx.}$ These differences increase with the increase of sample width and range to a maximum of 15MPa.

Significant index of simulation were also numerous values of longitudinal stresses on the surface. In the Table 2 these results were comparatively shown with the calculated values of stresses using the equation (3). Practically identical values of stresses σ_p and σ_{zz} were obtained for the sample 1, whereas for samples 2 and 3 the absolute differences were 3.75 MPa and 2.97 MPa, respectively. These differences were minimal in the program of investigation which included different dimensions of samples, a wide range of reduction ratio of cold rolling (15÷50%) and values of residual stresses (45÷85 MPa).

Table 2. Comparative results for longitudinal stresses on the surface and for maximal bend

Sample	**Deflection**		**FEM**	
	σ_p, (MPa)	f, (mm)	σ_{zz}, (MPa)	f, (mm)
1	79.04	2.446	79.93	2.161
2	69.28	2.243	73.03	1.926
3	74.57	2.742	77.54	2.220

Equivalent outside loading caused elastic bending in the y-z surface (Fig. 2). Comparing the moving obtained by FEM simulation with experimental results from Table 2, a good agreement may be noticed. Also, tests show that the moving obtained by FEM simulation can be precisely described by the equation (2). Maximal values of bend obtained in the experiment and by FEM simulation were also shown in parallel in Table 2. The highest difference obtained for the sample 3 and equals to 0.522mm. Notwithstanding the difference caused by unavoidable mistake of measurement of elastic bend of thin strips as well as the mistake of FEM, obtained coincidence for values of stress on the surface and elastic bend confirms the possibility of simulation by FEM on the selected model.

CONCLUSION

Residual stresses in cold rolled strips are unavoidable and they may cause defects of the shape. Selecting of equivalent outside load and parameters of FEM, it is possible with enough precision to perform simulation of residual stresses and predict the effects of their balance disturbance.

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