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THE INFLUENCE OF ASYMMETRY FACTOR AND DEFORMATION ON THE CRITERION OPTIMIZING THE RELATIVE FLOW RATE OF St3S+0H13J BIMETALLIC STRIP

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The design of new technologies of rolling bimetal plates poses a lot of problems with obtaining a uniform distribution of rolling reduction into the layers and a straight strip at the roll gap exit. This is the main cause to determine optimization criterion of relative flow rate. Computer analyses of the asymmetrical rolling process were performed in this study to optimize the conditions of production of bimetallic plates. A Finite Element Method-based program, Forge 2D, was used for computer simulation.

Key words: *optimization criterion, asymmetrical rolling, bimetallic sheet, FEM*

Utjecaj faktora asimetrije i deformacije na kriterij optimizacije relativne brzine toka bimetalne trake St3S+0H13J. Projektiranje novih tehnologija valjanja bimetalnih limova predstavlja mnogo problema glede ujednačene redukcije u slojevima ravne trake na izlazu između valjaka. Glavni razlog je određeni kriterij optimizacije relativne brzine protoka. U svrhu optimizacije uvjeta proizvodnje bimetalnih limova provedene su računske analize asimetričnog procesa valjanja. Za kompjutersku simulaciju se koristio program Forge 2D zasnovan na metodi konačnih elemenata.

Ključne riječi: *kriterij optimizacije, asimetrično valjanje, bimetalni lim, metoda konačnih elemenata*

INTRODUCTION

From numerous studies [1 - 6] on the process of asymmetrical rolling bimetallic sheets it has been found that the greatest problem arising when developing new technologies is non-uniformity of deformation of strip layers. A phenomenon of non-uniform flow of bimetallic strip layers appears both in the plane of exit and in the roll gap itself. The effect of this inhomogeneity is a bending of the bimetallic strip toward the layer with a greater deformation resistance (i.e. the hard layer) and flowing of the soft layer around it. This phenomenon often makes the continuation of the rolling process impossible, as the rolled sheet may enter into the roll gap and cause damage to the rolling mill and its equipment.

To counteract this phenomenon, an asymmetry of the peripheral speed of working rolls is introduced, among other things. By increasing the peripheral speed of the roll contacting with the hard layer, the velocity of flow of this layer at the roll gap exit increases. Thereby, the strip curvature reduces until a straight strip is obtained. The issue is to determine the optimal value of the asymmetry factor (i.e. the ratio of upper roll speed to lower roll speed). For this purpose, the introduced flow rate optimization criterion will allow the optimal value of the asymmetry factor, a_{vopt}, to be quickly determined based on numerical examination carried out.

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AIM AND SCOPE OF NUMERICAL ANALYSES

The study discusses the plastic flow of two-layer St3S+0H13J strip at the roll gap exit. To this end, a series of computer simulations were performed. The Forge 2D software was used for numerical examination, which utilizes the finite-element method for its computation. The investigation was carried out for sheet of a thickness of H_0 = 14 mm for three relative rolling reductions, namely: ε = 10 %, 20 % and 25 %, and for three different strip layer thickness ratios, H_T/H_M = 3/11, 5/9 and 6/8. The rolling process was conducted hot at a temperature of 1000 °C. Friction forces in the asymmetrical rolling process were modeled based on Tresci's solution and determined from Equation [7]:

$$\tau = -m\frac{\sigma_0}{\sqrt{3}}\frac{\Delta V}{\Delta v} \quad (1)$$

where:

τ - vector of unit friction forces,
σ_0 - base yield stress,
$\Delta V/\Delta v$ - parameter describing metal slip on the roll (ΔV- roll peripheral speed for a given time step, Δv velocity of metal slip on the surface of contact with the tool),
m - friction factor.

For numerical examination, an average friction factor value of $m = 0,4$ was taken, thus relating the friction forces with the value of yield stress, the temperature of each layer, and rolling speed. The value of friction forces in the roll gap was automatically determined in the Forge 2D program for particular surfaces of contact of the sheet with the rolls from relationship (1).

The parameters of work-hardening curves for the steel + steel bimetal pairs making up the bimetallic sheet were determined, as dependent on temperature and deformation velocity, from the Arrhenius equation:

$$K(T,\bar{\varepsilon}) = K_0 \cdot (\bar{\varepsilon} + \bar{\varepsilon}_0)^n \cdot e^{-\beta T} \quad (2)$$

where:

$\bar{\varepsilon}_0$ - vector of regulated deformation for successive steps,
$\bar{\varepsilon}$ - vector of total deformation,
K_0, n, β - parameters of the work-hardening curve.

The aim of the study was to determine the optimal value of asymmetry factor a_{vopt} based on the criterion of optimization of the relative flow rate of two-layer strip.

For this purpose, a series of computer simulations of the process of asymmetrical rolling St3S+0H13J bimetallic sheets was conducted. From these simulations, the effect of the asymmetry factor on the plastic flow of strip leaving the roll gap was established. As the optimization criterion, the flow rate of bimetallic strip layers was taken after work [1], which is represented by the relationship below:

$$\psi = \int_0^h \left(v_{wy} - v_{śr}\right)^2 \mathrm{d}v \rightarrow \min \quad (3)$$

where:

v_{wy} - flow rate of metal particles along the height at strip exit from the roll gap,
$v_{śr}$ - average flow rate of metal particles in the plane of strip exit from the roll gap,
ψ - criterion of optimization of strip flow rate.

INVESTIGATION RESULTS AND THEIR ANALYSIS

This study uses the term of relative flow rate defined as the ratio of the flow rate of clad sheet layers at the roll gap exit to the constant speed of the upper roll.

The distribution of flow rate of bimetallic strip along its height in the plane of roll gap exit depends on the distribution of the total deformation into particular clad sheet layers. Increasing the deformation of the hard layer in an asymmetrical rolling process entails a reduction of differences in the flow velocities of layers at the exit for the roll gap. To obtain a perfectly flat product, it is necessary to determine the optimal value of asymmetry factor a_{vopt}, for which the behaviour of relative flow rate distribution in the plane of roll gap exit is as much close to linear as possible. Figures 1. through 3. show examples of bimetallic strip relative flow rate distributions depending on the values of reduction ε and ratio a_{vopt}. The bimetallic strip height has been divided according to the number of nodes.

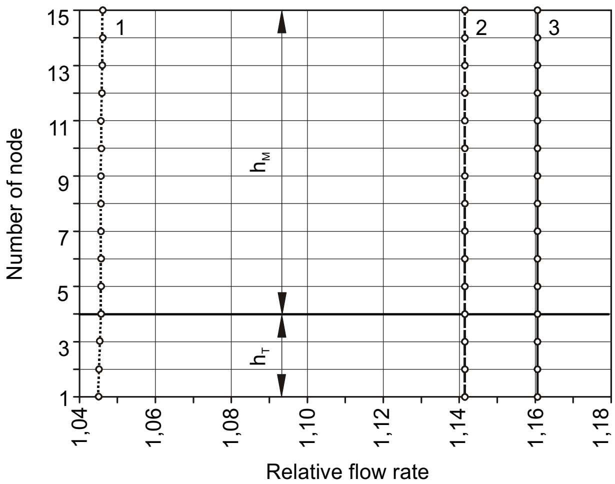

Figure 1. **Distribution of relative flow rate along the strip height in the roll gap exit plane for St3S+0H13J strip with H = 14 mm for optimal conditions of: 1) ε = 10 %, a_{vopt} = 0,957; 2) ε = 20 %, a_{vopt} = 0,86; 3) ε = 25 %, a_{vopt} = 0,78**

Slika 1. **Raspored relativne brzine protoka duž visine trake u otvoru valjaka na izlaznoj ravnini za traku sastava St3S+0H13J s visinom trake H = 14 mm za optimalne uvjete od: 1) ε = 10 %, a_{vopt} = 0,957; 2) ε = 20 %, a_{vopt} = 0,86; 3) ε = 25 %, a_{vopt} = 0,78**

It can be seen from the data in Figures 1. to 3. that, for the optimal conditions of the asymmetrical rolling process, the distributions of relative flow rate in the plane of roll gap exit are linear in character. The value of the abso-

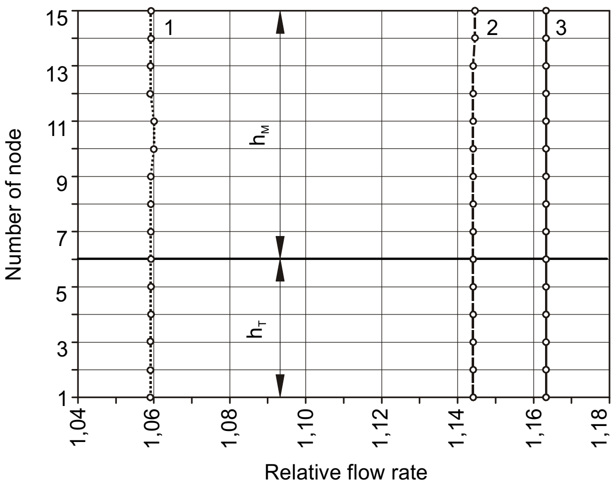

Figure 2. **Distribution of relative flow rate along the strip height in the roll gap exit plane for St3S+0H13J strip with H = 14 mm for optimal conditions of: 1) ε = 10 %, a_{vopt} = 0,868; 2) ε = 20 %, a_{vopt} = 0,33; 3) ε = 25 %, a_{vopt} = 0,311**

Slika 2. **Raspored relativne brzine protoka duž visine trake u otvoru valjaka na izlaznoj ravnini za traku sastava St3S+0HI3J s visinom trake H = 14 mm za optimalne uvjete od: 1) ε = 10 %, a_{vopt} = 0,868; 2) ε = 20 %, a_{vopt} = 0,33; 3) ε = 25 %, a_{vopt} = 0,311**

lute flow rate of strip layers is dependent on the value of asymmetry factor and technological parameters.

The distribution of strip flow rate is influenced both by the value of deformation ε and bimetallic strip layer

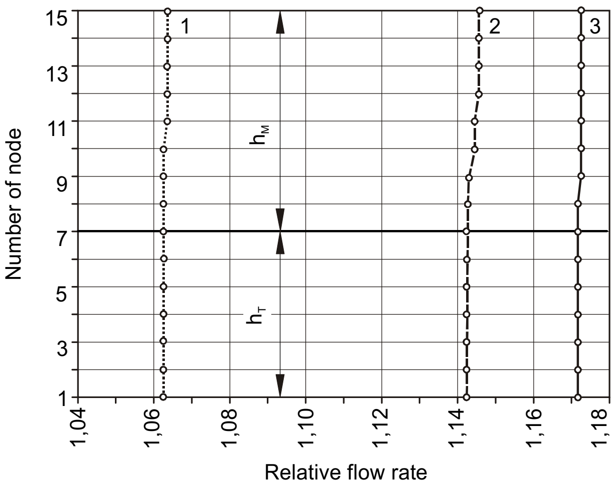

Figure 3. **Distribution of relative flow rate along the strip height in the roll gap exit plane for St3S+0H13J strip with H = 14 mm for optimal conditions of: 1) ε = 10 %, a_{vopt} = 0,86; 2) ε = 20 %, a_{vopt} = 0,3; 3) ε = 25 %, a_{vopt} = 0,25**

Slika 3. **Raspored relativne brzine protoka duž visine trake u otvoru valjaka na izlaznoj ravnini za traku sastava St3S+0H13J s visinom trake H = 14 mm za optimalne uvjete od: 1) ε = 10 %, a_{vopt} = 0,86; 2) ε =20 %, a_{vopt} = 0,3; 3) ε = 25 %, a_{vopt} = 0,25**

thickness ratio H_T/H_M. The distributions of the relative flow velocities of metal particles along the strip height were determined for a_{vopt}. The value of a_{vopt} was determined from the minimum value of optimization criterion. To obtain a straight two-layer strip after rolling, the function described by relationship (3) must attain the minimum value.

The dependence of optimization criterion values on relative reduction ε and asymmetry factor a_v for different layer thickness ratios H_T/H_M is illustrated in Figures 4. to 6.

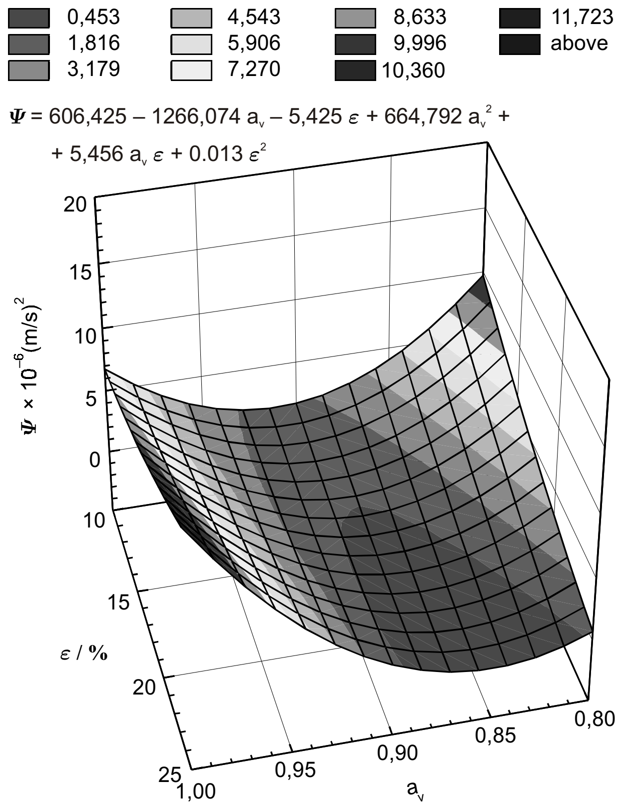

Figure 4. **Effect of relative rolling reduction and asymmetry factor on the value of criterion optimizing the flow rate of bimetallic sheet in the exit plane for σ_{pT}/σ_{pM} = 1,22 and H_T/H_M = 3/11**

Slika 4. **Utjecaj relativne redukcije valjanja i faktora asimetrije na vrijednost kriterija optimizacije brzine protoka bimetalne trake u ravnini izlaza za σ_{pT}/σ_{pM} = 1,22 i H_T/H_M = 3/11**

The minimum of the criterion of optimization of the flow velocities of layers in the exit plane determines the optimal value of roll speed asymmetry factor for a given rolling reduction value. The obtained function equations shown above the diagrams in Figures 4. to 6. are equations describing the shape of a plane obtained by the least squares method from the results of computer simulation.

The relationships illustrated in Figures 4. to 6. for a_v=1,0 show that with increasing ε the value of optimization criterion ψ increases. This behaviour imparts a significant effect on the value of asymmetry factor a_{vopt}, which decreases as deformation increases (i.e. the roll speed asymmetry is greater).

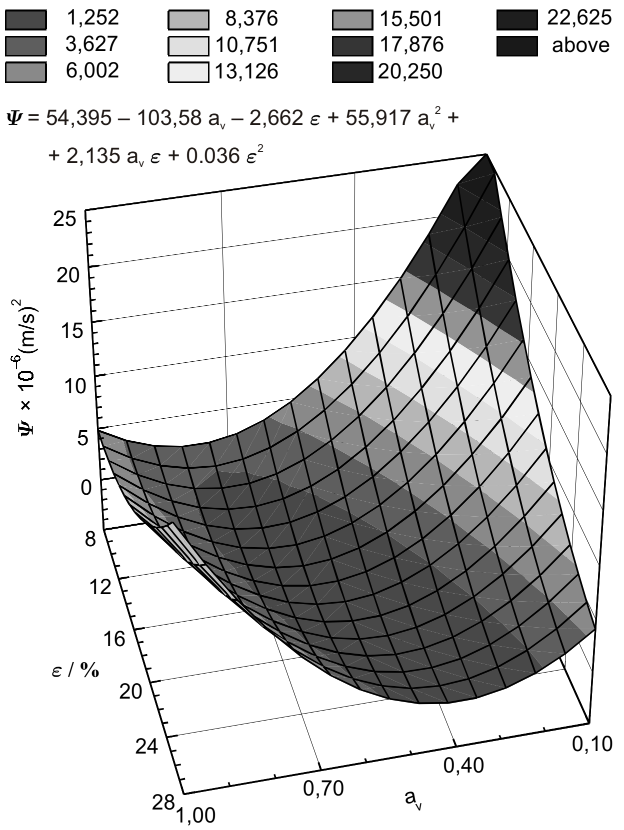

Figure 5. **Effect of relative rolling reduction and asymmetry factor on the value of criterion optimizing the flow rate of bimetallic sheet in the exit plane for σ_{pT}/σ_{pM} = 1,22 and H_T/H_M = 5/9**

Slika 5. **Utjecaj relativne redukcije valjanja i faktora asimetrije na vrijednost kriterija optimizacije brzine protoka bimetalne trake u ravnini izlaza za σ_{pT}/σ_{pM} = 1,22 i H_T/H_M = 5/9**

The distribution of optimization criterion varies depending on the layer thickness ratio, H_T/H_M, and the value of deformation, ε. The minimum of optimizing criterion value for a given reduction determines the location of the optimal value of asymmetry factor.

Obtaining a straight strip is only possible, when the function equations given above the diagrams in Figures 4. to 6. reach a minimum value. For all cases of rolling bimetallic sheets, it can be seen that the value of optimization criterion decreases for asymmetries from 1,0 to a_{vopt}, while further increasing asymmetry causes this parameter to increase again. It can be noticed from Equation (3) that the decrease in the optimization criterion value is associated with an increase in the uniformity of two-layer strip flow rate along the height in the roll gap exit plane. Hence, decreasing optimization criterion value results in straightening of the sheet.

Figures 4. through 6. show the influence of layer thickness ratio, deformation ε, and asymmetry factor a_v on the shape of the surface representing the value of optimization criterion. The flattest surface for a pair of materials with the ratio of σ_{pT}/σ_{pM} = 1,22 was obtained for the layer thickness ratio of H_T/H_M = 3/11. In the case of increasing layer thickness ratio H_T/H_M, the concavity of the planes shown in Figures 4. to 6. increases. The planes shown in

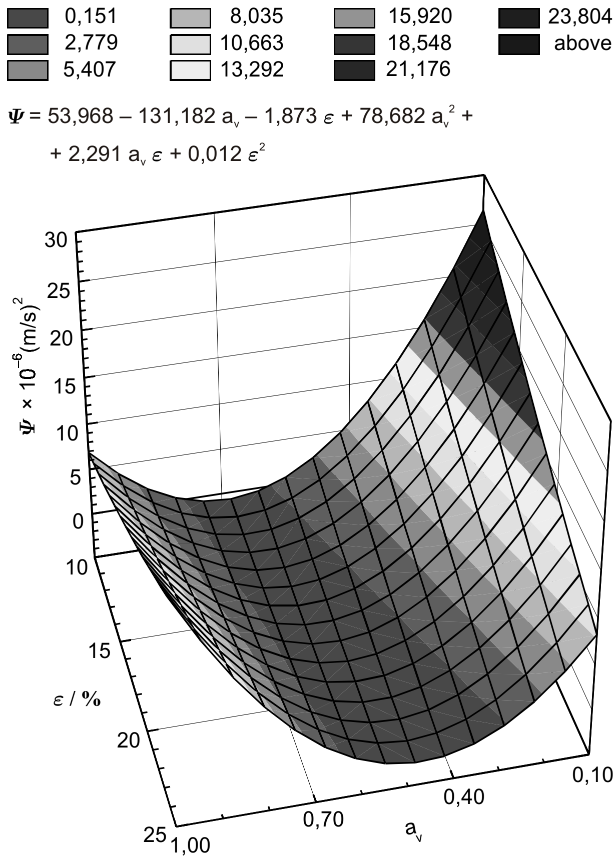

Figure 6. **Effect of relative rolling reduction and asymmetry factor on the value of criterion optimizing the flow rate of bimetallic sheet in the exit plane for σ_{pT}/σ_{pM} = 1,22 and H_T/H_M = 6/8**

Slika 6. **Utjecaj relativne redukcije valjanja i faktora asimetrije na vrijednost kriterija optimizacije brzine protoka bimetalne trake u ravnini izlaza za σ_{pT}/σ_{pM} = 1,22 i H_T/H_M = 6/8**

Figures 5. and 6. for H_T/H_M = 5/9 (0,56) and H_T/H_M = 6/8 (0,75) have a similar shape.

Comparison of the examination results represented in Figures 1. to 3. indicates that the minima of functions describing the shape of planes, determine an optimal value of roll peripheral speed asymmetry factor a_{vopt} for specified deformations.

SUMMARY AND CONCLUSIONS

Performed numerical analyses confirm that it is possible to control the flow rate of two-layer strip layers by using roll peripheral speed asymmetry. The presented investigation results can be summarized as follows:

- with increasing rolling reduction ε the value of criterion optimizing the flow rate of bimetallic strip layers increases, which entails a necessity of using an increasingly greater asymmetry of working roll peripheral speed in order to obtain straight sheet;
- with increasing layer thickness ratio H_T/H_M the value of criterion optimizing the flow rate of bimetallic strip layers also increases due to a greater share of the harder layer in the two-layer sheet;
- increasing the peripheral speed of the roll contacting with the hard layer results in a gradual straightening of the two-layer strip until straight sheet is obtained, which corresponds to the minimum of the function describing the criterion of optimization of the flow rate of two-layer strip;
- the criterion of optimization of bimetallic strip flow rate can be fully utilized when determining the optimal value of asymmetry factor a_{vopt}.

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