Influence of relative rolling reduction and thickness layers bimetallic plate at the non-uniformity of the strain after rolling process

D Rydz\textsuperscript{1a}, G Stradomski\textsuperscript{1a}, H Dyja\textsuperscript{1a}

\textsuperscript{1}Technical University of Czestochowa, Faculty of Production Engineering and Materials Technology Armii Krajowej 19, 42-200 Częstochowa, Poland, Institute of Plastic Forming Processes and Safety Engineering,

e-mail: rydz@wip.pcz.pl

Abstract. In the article were made numerical and laboratory tests of two-layers rolling process sheet composed of Al99.8 + M1E. Laboratory tests made with use of 150 mm diameter working rolls mill. To the modeling of the bimetallic plate rolling were taken the FEM Forge 2D software based on the theory of plasticity and MathCad program (in which to the rolling process modeling were used the mathematical model developed in the work \cite{5} based on the theory of viscoelasticity). The aim of study was to determine the influence of layer thickness $H_T/H_0$ and relative deformation $\varepsilon$ on the uneven distribution of steel sheet deformation after rolling process. Calculations based on the theory of viscoelasticity allowed additionally take into account the impact of the delayed effects of the variation of viscoelastic deformation of layers of the bimetallic plate rolling process.

Keywords: bimetallic plate, rolling process, viscoelastic

1 Introduction

This paper will focus on the analysis of the second stage is a two-layer metal rolling process initially joined by explosive welding. Previous numerical studies were mainly based on calculations made using commercial software based on the theory of plasticity. In this paper we proposed to carry out modeling of two-layer metal rolling process based on plasticity theory and the theory of viscoelasticity. In the modeling process, bilayer sheet rolled taken to analyze the problem of uneven deformation of the layers in the double-layer plate according to the ratio of the layer thicknesses $H_T/H_0$ (the ratio of the layer thickness of less resistance to deformation Al99.8 thickness of greater deformation resistance M1E) and the value of the relative $\varepsilon$ deformation. In addition, the numerical researches based on the theory of viscoelasticity will determine the influence of the delayed effects on the variation of viscoelastic deformation of bimetallic plate layers during the rolling process. As a result, during rolling process of the two-layer sheet rolling the deformation of the individual layers are different, this cause the effect of bending on the exit of deformation gap \cite{1,5,7}. The direction of bending depends on the location of the layer with higher deformation resistance (hard), the bent appear toward to this layers.
2 Description of the kinematic model of the rolling process of double layer viscoelastic bodies

In this paper it was assumed that the x and y axis directions are the principal directions of strains. Most of materials pairs forming a bimetallic sheet during the rolling process are nonuniform deformed, which causes bending of the rolled band after leaving the roll gap. In the present work for the analysis of the bimetallic sheet layers deformation during the rolling process is adopted the rheological Jeffreys model \(3, 4\). It allows taking into account the dynamics of the rolling process for both homogeneous and composite sheet. In addition to the analysis of the bimetallic plate rolling process in this paper is used the Boltzmann’s theory of bodies. Another assumption made in this work, is the adoption to the present analysis the incompressibility condition \(\rho(r)=\rho=0.5\). It results that the analysis assumes a flat state of stress and strain. Based on the assumptions were developed schematic kinematic model of two-layer metal rolling process, which is shown in Figure 1.

The rolling process of two-layer materials is a complex process, which is often accompanied by uneven deformation of the two layers of a bimetallic band. This is caused by different deformation resistance due to the different layers forming the bimetal \([1, 2, 5 \div 7]\). Soft layer deforms more and it can be written as:

\[
\varepsilon_M > \varepsilon > \varepsilon_T
\]

where:

\(\varepsilon_T\) – Relative deformation of layers with higher plastic deformation resistance,
\(\varepsilon\) – Total relative bimetallic band deformation,
\(\varepsilon_M\) – Relative deformation of layers with minor plastic deformation resistance.

The relative deformation of each bimetal’s sheet layer can be represented by the following formula \([5]\):
\[ \varepsilon_r = \frac{H_{T_0} - H_T}{H_{T_0}} \]
\[ \varepsilon_M = \frac{H_{M_0} - H_M}{H_{M_0}} \]  
(2)

where:
\[ H_T = 2 \left( \frac{H_{T_0}}{2} + R - \sqrt{R^2 - x^2} \right) \]  
\[ H_M = 2 \left( \frac{H_{M_0}}{2} + R - \sqrt{R^2 - x^2} \right) \]  
\[ H_{T_0} = 2 \left( \frac{H_{T_0}}{2} + R - \sqrt{R^2 - x_{T_0}^2} \right) \]  
\[ H_{M_0} = 2 \left( \frac{H_{M_0}}{2} + R - \sqrt{R^2 - x_{M_0}^2} \right) \]  
(3)

After substituting the equations (4 and 5) to equation (3) and assuming that \( x \leq R \), the relationship (3) can be simplified to the form:
\[ \varepsilon_r = \frac{x^2 - x_{T_0}^2}{R H_T + x_{T_0}^2} \]
\[ \varepsilon_M = \frac{x^2 - x_{M_0}^2}{R H_M + x_{M_0}^2} \]  
(5)

where:
\( R \) – roll radius,
\( x_{T_0}, x_{M_0} \) – the length of the rolling gap for the hard and soft layer,
because then it can be written with some approximation that the thickness of the individual layers are:
\[ H_{T_0} \approx \left( H_T + \frac{x^2}{R} \right) \]
\[ H_{M_0} \approx \left( H_M + \frac{x^2}{R} \right) \]  
(6)

The model takes into account the occurrence of late viscoelasticity effects, as a factor affecting directly the value of the deformation and indirectly on the curvature of bimetallic rolled sheet layers.

3 Modeling of the rolling process of bimetallic sheet in the program Forge 2D

The numerical investigations were made for three different ratios of the layer thicknesses \( H_{M_0}/H_{T_0} = 0.2, 0.6 \) and 1.0, and three values of the relative deformation \( \varepsilon = 5\%, 10\% \) and 15\%. Numerical investigations were made for cold process in the ambient temperature. The comparison of results of laboratory tests and computer simulation show problem of uneven layers deformation in the bimetallic sheet rolling process. The effect of non-uniform deformation of sheet layers is the cause of bimetallic bending after leaving the roll gap. Strengthening curve parameters of tested materials were determined on the basis of chemical composition and set of from the Archenius equations [1]:
\[ K(T, \varepsilon) = K_0 \cdot (\varepsilon + \varepsilon_0)^n \cdot e^{-\beta/\mu} \]  
(7)

where:
\( \mathbf{e}_0 \) – controlled deformation vector for next steps,
\( \mathbf{\varepsilon} \) – total strain vector,
\( K_0, n, \beta \) - Strengthening curve parameters.

Frictions during the rolling process were modeled on the basis of the Tresca solutions and were determined from the equation [1]:

\[
\tau = -m \frac{\sigma_0 \Delta V}{\sqrt{3} \Delta v}
\]

where
\( \tau \) – unity vector of friction forces,
\( \sigma_0 \) – base yield stress,
\( \Delta V/\Delta v \) – parameter describing the slip of metal on the roll,
\( m \) – friction factor.

Numerical research made in the program 2D Forge were performed for the corresponding laboratory tests.

4 Material selection and the range of tests

The double-layer sheet rolling process was carried out on the duo laboratory rolling mill with work rolls diameter D = 150mm and \( V_w \) = velocity of 100 mm/s on samples after direct explosive welding connection method.

The experimental and numerical tests were made for bimetal sheet complex of Al99.8 and M1E layers.

Chemical compositions of the tested materials are shown in Table 1.

Table 1. The chemical composition M1E (PN-87/H-82120) i Al99.8 (PN-79/H-82160).

| Material | Cu    | Al  | Zn    | Sn    | As    | Sb    | Si    |
|----------|-------|-----|-------|-------|-------|-------|-------|
| M1E      | 99.9  | -   | max 0.003 | max 0.002 | max 0.002 | -     |
| Al99.8   | max 0.02 | 99.8 | max 0.05 | -     | -     | -     | max 0.13 |

Modeling and laboratory research were performed for three sets of samples with the following dimensions:
- I set: \( H_0 = 12 \) [mm], \( L_0 = 150 \) [mm] and \( H_{T0}/H_{M0} = 2/10 \),
- II set: \( H_0 = 8 \) [mm], \( L_0 = 150 \) [mm] and \( H_{T0}/H_{M0} = 3/5 \),
- III set: \( H_0 = 8 \) [mm], \( L_0 = 150 \) [mm] and \( H_{T0}/H_{M0} = 4/4 \),

where:
\( H_{M0} \) – the initial thickness of the layer (soft) with lower strain resistance,
\( H_{T0} \) – the initial thickness of the layer (hard) with higher strain resistance,
\( H_0, L_0 \) – accordingly height and length of bimetallic plates.

5 The results and analysis

On the basis of laboratory and numerical studies, was determined the effect of layer thicknesses \( H_{T0}/H_{M0} \) and relative deformation \( \mathbf{\varepsilon} \) on the value of the deformation of bimetallic plate forming layers fig. 2 and 3.
Figure 2. Influence of layer thicknesses and relative deformation on the value of hard layer deformation M1E a bimetal sheet a) according to the theory of plasticity, b) according to the theory of viscoelasticity c) the results of laboratory tests.

Figure 3. Influence of layer thicknesses and relative deformation on the value of soft layer deformation Al99.8 a bimetal sheet a) according to the theory of plasticity, b) according to the theory of viscoelasticity c) the results of laboratory tests.
On the basis the results of research presented on Figures 3 and 4, it can be concluded that both the solutions based on the theory of plasticity and viscoelasticity properly reflect the influence of layer thicknesses and relative deformation on the non-uniformity of bimetallic sheet layers deformation. Nevertheless, taking into account the delayed viscoelastic effects in the modeling of bimetallic plate rolling process allows to define more precisely the strain of hard and soft layers of M1E Al99.8.

Presented in Figures 3 and 4 results allow to conclude that the increase in layer thicknesses ratio \( H/T \) decreases the deformation value of a hard layer M1E, while increasing the strain value of the soft layer Al99. Moreover, based on the numerical studies it can be concluded that the increase in relative deformation \( \varepsilon \) increases the uneven deformation of layers forming bimetallic plate.

Presented in the paper comparing the calculation results obtained using the model with the theory of plasticity and viscoelasticity theory and its experimental verification confirms the correctness of the results. It should be noted, however, that taking into account the effect of expansion of the material after leaving of the roll gap in the theory of viscoelasticity model makes the results of the calculations more exact and with less error.

6 Summary and Conclusions

The paper presents a theoretical and experimental analysis of double-layer sheet rolling process. For numerical studies based on the theory of plasticity was applied Forge 2D program, based on the finite element method. Numerical calculations based on the theory of viscoelasticity were performed in Mathcad program on the base of developed in the work [1] mathematical model. In this work, calculations were based on assumptions of the theory of small deformations and the adoption of the principle of superposition of Boltzmann, which is a heuristic law. Implementation of numerical calculations for bimetal sheet layers allowed to determine the value of deformation in the roll gap and delayed viscoelastic effects. Experimental verification of the results of calculations were performed on the basis of laboratory tests on laboratory duo mill with 150 mm work rolls diameter.

On the basis of numerical research results and experimental verification can be drawn the following conclusions:
- With the increase layer thicknesses ratio \( H/T \) of bimetallic plate and with an increase in the relative deformation \( \varepsilon \) uneven distribution of strain on the layer grows,
- Taking into account the delayed viscoelastic effects can increase the accuracy of the calculation. These effects cause affect on the value of the layers permanent deformation after rolling process of bimetallic plate.

References

[1] Dyja H., Mróz S., Rydz D.: „Technologia i modelowanie procesów walcowania wyrobów bimetalowych” Seria Metalurgia Nr 33, Prace Naukowe Wydziału Inżynierii Procesowej, Matematyki i Fizyki Stosowanej, Częstochowa 2003,
[2] Dyja H., Pietrzyk M.: On the theory of the process of hot-rolling of bimetal plate and sheet, Journal of Mechanical Working Technology, Volume: 8 Issue: 4, p. 309-325, 1983
[3] Nowacki W.: Teoria pełzania, Warszawa, Arkady 1963
[4] Schiessel H., Metzler R., Blumen A., & Nonnenmacher T. F. Generalized viscoelastic models: Their fractional equations with solutions. Journal of Physics A: Mathematical and General, n.28, 1995,
[5] Rydz D.: Analiza procesu walcowania blach bimetalowych w oparciu o rozwiązania dla ciał lepkosprężystych, seria monografia nr 152, Politechnika Częstochowska, Wydawnictwo Politechniki Częstochowskiej, Częstochowa 2009,
[6] Skalmierski B., Rydz D.: Zastosowanie rozwiązań lepkosprężystych do opisania procesu walcowania blach, Seria: Metalurgia nr 39, V Międzynarodowa sesja naukowa: Nowe Technologie i Osiągnięcia w Metalurgii i Inżynierii Materiałowej, Częstochowa 2004,
[7] Skoblik R., Rydz D., Stradomski G.: Analysis of Asymmetrical Rolling Process of Multilayer Plates, Solid State Phenomena (JCR) Vol. 165 2010 p. 348-352 © Trans Tech Publications, Switzerland.