Abstract
In this study, the authors present the results of their theoretical and experimental analysis of the rolling process of bimetallic rods in stretching passes. The bimetallic rods had different ratios of the yield stress between components. The original rods were round (21.7 mm diameter) steel and aluminium rods, covered with 2.8 mm copper layer. A numerical model for hot stretching passes rolling was proposed. In the model, the deformation of a bimetallic material was analysed by three-dimensional rigid-plastic finite-element method. The model simulated metal flow during rolling of bimetallic rods in round-oval series. The results of the experiments were compared with the finite-element calculations of the stress distribution and spread of Cu-steel and Cu-Al rods in the deformation zone. The analysis demonstrated that an appropriate selection of shape and size of oval pass allows production of even distribution of the copper layer in the bimetallic roll products. The results of comparison of calculated spread and experimental data confirmed good ability of proposed mathematical model, that is recommended for roll pass design at rolling of bimetallic rods.

Keywords: Bimetallic rods; Elongating grooves; FEM; Stress distribution

1. Introduction
The dynamic development of computing machines creates possibilities of improving models that describe phenomena occurring during plastic working. The most common method used for modelling plastic working processes is presently the finite-element method. It enables the determination of strain fields, deformation rates, the velocities and directions of material flow, temperature distribution, and stresses formed in the material under the effect of elastic and plastic strains.

The processes of rolling in grooves are characterised by a spatial state of deformation and, due to their complexity, are difficult for detailed characterisation. Specifically, the pattern of metal flow in particular grooves is particularly difficult to determine. In order to perform computer simulations of these processes, it is necessary to employ mathematical models that utilise the complete three-dimensional solution made by the finite-element method [1,2,7–9,12,14], or models relying on the generalised flat state of deformation [4,5].

Computer modelling is the cheapest of the possible ways of process analysis and, at the same time, it provides a huge amount of information impossible to be acquired by other methods. The purpose of carrying out computer simulations is the verification of technologies being designed for rods of different shapes and of different materials in the real technical conditions of a rolling mill, prior to their implementation. The present paper describes the method of developing an automated computer program and the practical use of three-dimensional modelling for predicting the flow of metal during rolling homogeneous and bimetallic rods in elongation roll grooves.

2. Characterisation of materials used for investigations
The correctness of computations using a computer program is dependent on the properties of materials used for examinations. Experiments undertaken were aimed to establish the effect of deformation parameters on the value of yield stress for the St3S steel and the PA6 aluminium alloy.

The experimental examination of the properties of the St3S steel and PA6 aluminium alloy were carried out at the Institute of the Modelling and Automation of Plastic Working Processes of the Technical University of Częstochowa using a dilatometer-plastometer, type DIL 805A/D. Plastometric tests were performed using deformation rates of 1.0, 5.5 and 10 s⁻¹ and the temperatures of plastometric tests were, respectively: 700, 800, 900 and 1000 °C for St3S steel.

For PA6 aluminium alloy plastometric tests were performed...
using deformation rates of 0.1, 1.0 and $10 \text{s}^{-1}$ and the temperatures of plastometric tests were, respectively: 400, 500 \degree C and for M1-E copper plastometric tests were performed using deformation rates of 0.1 and 2.5 $\text{s}^{-1}$ and the temperatures of plastometric tests were, respectively: 400, 500, 600, 700, 800 and 900 \degree C. The results of plastometric tests of investigated M1-E copper were taken from the literature [4,5]. Figs. 1–3 show the results of plastometric tests in the form of flow curves for the St3S steel, PA6 aluminium alloy and M1-E copper, respectively.

In order to obtain a mathematical relationship making the value of yield stress, $\sigma_s$, dependent on deformation parameters ($\epsilon, \dot{\epsilon}, t$), the results of the performed tests were approximated with a functional relationship described with Eq. (1).

The flow stress $\sigma_s$ dependence of strain intensity $\epsilon$, strain rate $\dot{\epsilon}$ and temperature $t$ for the St3S steel, the PA6 aluminium alloy and the M1-E copper is approximated by Henzel–Spittel formula expressed as [6]:

$$\sigma_s = A_1 \epsilon^{A_2} \dot{\epsilon}^{A_3} \exp(-tA_4) \tag{1}$$

The coefficients $A_1$, $A_2$, $A_3$, $A_4$ of the St3S steel, the PA6 aluminium alloy and the M1-E copper are given in Table 1.

And explosive welding of the copper tube, with the diameter of 24 mm and wall thickness of 2.5 mm with the steel and aluminium rod with the diameter of 16 mm was performed after mechanical cleaning and degreasing. An explosive material called Amonal, which contained 98\% of ammonium nitrate and 2\% of aluminium powder was used [3].

### 3. Rolling of homogeneous and bimetallic rods

The process of rolling bimetallic rods in elongation grooves is characterised by great inequality of deformation of rolled billet across its width. This may be the cause of occurring numerous defects, such as non-uniform distribution of the cladding layer, incorrect filling of rolling grooves, structural and chemical inhomogeneity and the inhomogeneous state of stresses in particular layers of the bimetallic rod.

Bimetallic rods with an outer diameter of 21.7 mm covered with 2.8 mm copper layer, after explosive welding, were rolled on a D 320 three-stand two-high shape mill. The stock material was round St3S steel and PA6 aluminium rod covered with an M1-E copper layer. Heating of the bimetallic stock of an initial length of 250 mm was carried out in a chamber furnace. Rods heated up to a temperature of 960 \degree C (for the St3S steel and the Cu-steel bimetallic rods) and 550 \degree C (for the PA6 aluminium and the Cu-aluminium rods) were cooled down (only for the Cu-steel bimetallic rods) before being fed to the first roll groove. Owing to this,
no delamination of layers occurred. Rolling speed was approximately 0.45 m/s. As a result of rolling in six passes, rods of a diameter of about 14.0 mm were obtained. Six elongation grooves were used in the horizontal oval–vertical oval–horizontal oval–round system (Fig. 4). After each pass, the billet was tilted by an angle of 90°. During rolling, the copper layer thickness decreased by 1–4% compared with rods after explosive welding. The view of all cross-sections is shown in Fig. 5. In this figure, a deformation of the copper layer can be seen.

As can be seen from Fig. 5, the widening of the bimetallic band depends on the material of which its core is made. For the copper-steel bimetal rods (Fig. 5b), the widening is smaller compared to the homogeneous steel rod (Fig. 5a), while for the copper-aluminium bimetal rods (Fig. 5d), the widening is greater than that of the homogeneous aluminium rod (Fig. 5c). Experimental tests of rolling bimetallic rods have confirmed that the elongation and widening of the bimetallic band has an effect on the resistance of plastic flow ($\sigma_s$) of the core. In bimetallic rods, where core $\sigma_s$ more...
than cladding layer $\sigma_s$, the widening is greater compared to a homogeneous rod rolled from the metal of which the core is made. On the other hand, for bimetallic rods for which core $\sigma_s$ less than cladding layer $\sigma_s$, the widening is smaller.

The initial positioning of rolls for rolling bimetallic specimens was made on steel and aluminium specimens. During rolling steel specimens, a slight overfill occurred in the sixth pass (oval–round), Fig. 5 a. By using the results of theoretical studies [1,2,13] on the effect of tensile stresses on the widening and elongation of (copper-steel) bimetal specimens compared to homogeneous steel specimens, the rolling of the bimetal was conducted without changing the positioning of rolls in this pass, despite a slight fin that occurred during rolling steel specimens. During rolling copper-aluminium bimetal specimens, an overfill appeared in the second pass (Fig. 5 d). During rolling copper-aluminium bimetal specimens, the initial positioning of rolls in the second pass had to be corrected.

The rolling of copper-steel bimetal specimens has confirmed that the rolling can be conducted in the same passes as those in which homogeneous materials are rolled, while obtaining a larger widening compared to homogeneous aluminium rods.

The correctly chosen roll pass design and rolling process parameters eliminated the phenomenon of soft layer “flowing off”, the delamination of layers and possible lapping of the soft copper layer. Thus, it is possible to obtain a finished product of the desired share of the copper layer in the bimetallic rod cross-section, slightly differing from the share of the copper layer in the stock material.

4. Model of the rolling process

The mathematical model for the three-dimensional flow of bimetallic rods during rolling in grooves of any arbitrary shape has been developed based on principles published in works [1,12], by employing the finite-element method. The solution was sought for from the Markov functional $J$ [10]:

$$J = \frac{1}{2} \int_V \mu \dot{\varepsilon}^2_i dV + \int_V \sigma \dot{\varepsilon}_0 dV - \int_S \sigma_{tu} dV$$

(2)

where $\mu$ is the apparent metal viscosity determined from the equation

$$\mu = \frac{\sigma_s(\dot{\varepsilon}_s, \varepsilon_s, t)}{\dot{\varepsilon}_s}$$

(3)

where $\sigma_s(\dot{\varepsilon}_s, \varepsilon_s, t)$ is the dependence of yield stress $\sigma_s$ on strain rate intensity $\dot{\varepsilon}_s$, strain intensity $\varepsilon_s$ and temperature $t$; $V$ the deformed medium volume; $\dot{\varepsilon}_0$ relative volume change rate; $\sigma$ the mean stress; $u_t$ the velocity of slip of metal relative to the tool; $S$ the metal–tool contact surface area; $\sigma_t$ the stress of friction at the metal–tool interface, where

$$\sigma_t = \frac{m \sigma_s}{\sqrt{3}}$$

(4)

$m$ the friction factor.

The method of taking boundary conditions into account is described in detail in [12]. This uses penalty function method for solving contact problems, namely for the prevention of material permeation into the tool and for accounting for the effect of friction forces.

The model has been substantiated experimentally and a good agreement between the measured and calculated strain fields was observed [2,12].
4.1. Automatic generation of a finite-element grid

To obtain the numeric solution of functional (2), prismatic elements of order 2 were used. The automatic generation of the grid of elements of a deformed body is composed of the following four stages, as illustrated in Fig. 6:

(a) reading in cross-section contours for the groove and the feedstock (i.e. core + cladding layer), prepared in a CAD program (such as AutoCAD);
(b) generating a two-dimensional grid of triangular elements;
(c) creating a three-dimensional grid from the obtained two-dimensional grid. While doing this, the principle of elongation of individual triangular elements in the rolling direction, and for the rolls, the principle of rotation of flat elements around the axes of corresponding rolls are applied;
(d) arranging the initial position of the feedstock and the rolls.

5. Results and discussion

A theoretical analysis of the process of rolling homogeneous steel and aluminium rods and copper-steel and copper-aluminium bimetal rods in the first pass (where the deformation was maximal) has been performed in the study. The initial stock temperature for homogeneous and bimetallic rods was taken based on measurements made by using an IG8 pyrometer manufactured by IMPAC, then the time of cooling before the successive pass was given, which ranged from 5 s for homogeneous steel and aluminium rods and copper-aluminium bimetal rods, to approximately 30 s for copper-steel bimetal rods.

The following input data were taken for simulation:

- stock temperature of 940 °C—for steel rods and Cu-steel bimetal rods;
- stock temperature of 560 °C—for aluminium rods and Cu-PA6 rods;
- tool (upper and lower roll) temperature of 60 °C;
- ambient temperature of 20 °C;
- friction factor, \( m = 0.8-0.85 \);
- coefficient of heat exchange between the material and the tool, \( \alpha = 3000 \text{ W/K mm}^2 \);
- coefficient of heat exchange between the material and the air, \( \alpha_{\text{pow}} = 100 \text{ W/K mm}^2 \).

The comparison of billet shape and dimensions, respectively, obtained from computer simulations and measured is shown in Figs. 7 and 8.

The data shown in Figs. 7–8 indicate that the shape and dimensions of steel and aluminium bands and copper-steel and copper-aluminium bimetal bands after performed simulation are in agreement with the shape and dimensions of the passes used and with the shape and dimensions of templates taken after rolling. In no case, any difference between pass height and the height obtained from simulation was noticed.

The results of the theoretical studies have confirmed that bimetallic band widening depends on the resistance of plastic flow of particular its components and differs from the
widening of the rod rolled from the metal of which the core is made. Table 2 compares band widening results obtained after rolling in the oval pass.

5.1. Analysis of the distribution of stresses in the roll gap

In order to explain the differences in widening values obtained from simulation, the analysis of the distribution of stresses in the roll gap was performed. Figs. 9 and 10 illustrate the distribution of longitudinal stresses, $\sigma_x$ (in the rolling direction), during rolling homogeneous steel and aluminium rods and copper-steel and copper-aluminium bimetal rods after the first (circle–oval) pass.

It can be stated by analysing the data in Fig. 9 that the band zone which is under the influence of longitudinal tensile stresses, $\sigma_x$, is small in the rod cross-section and varies from the entry plane to the exit plane. The small values of tensile stresses do not limit the widening. In the entry plane, the lateral band zones are under the effect of longitudinal tensile stresses, $\sigma_x$, which disappear in the plane of band exit from the rolls.

The analysis of Fig. 9b shows that the length of the band zone which is under the effect of longitudinal tensile stresses, $\sigma_x$, is much larger compared to the results obtained from rolling homogeneous steel rods. This provides evidence for the fact that these stresses and their diverse distribution on the rolled rod cross-section area resulting from the soft layer tending to more intensive elongation are the cause of the lesser band widening compared to that of the uniform steel rod. During rolling homogeneous steel rods tensile stresses, $\sigma_x$, are smaller than in copper-steel rods, therefore the widening of homogeneous rods is larger compared to bimetallic rods, with their elongation being smaller.

Table 2

<table>
<thead>
<tr>
<th>Rolling diagrams</th>
<th>Rod</th>
<th>Band dimensions (mm)</th>
<th>Band widening (mm)</th>
<th>Relative error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Before the rolling</td>
<td>After the rolling</td>
<td>Experimentally</td>
<td>Theoretically</td>
</tr>
<tr>
<td>Round–oval</td>
<td>Steel</td>
<td>21.7 21.7</td>
<td>12.8 31</td>
<td>9.3</td>
</tr>
<tr>
<td>Round–oval</td>
<td>Cu-steel</td>
<td>21.7 21.7</td>
<td>13.8 23.4</td>
<td>22.9</td>
</tr>
<tr>
<td>Round–oval</td>
<td>PA6</td>
<td>21.7 21.7</td>
<td>13.1 28.4</td>
<td>28.6</td>
</tr>
<tr>
<td>Round–oval</td>
<td>Cu-PA6</td>
<td>21.7 21.7</td>
<td>13.1 29.9</td>
<td>29.7</td>
</tr>
</tbody>
</table>

$h_0$—thickness prior to rolling; $b_0$—thickness after rolling; $b_0$—width prior to rolling; $b_1$—width after rolling; $\Delta b_0$—absolute spread experimentally; $\Delta b_1$—absolute spread theoretically.
When analysing the distributions of $\sigma_x$ stresses shown in Fig. 10a and b for homogeneous aluminium rods and copper-aluminium bimetal rods a different character of longitudinal stress distribution (Fig. 10b) from that of the copper-steel bimetal rod (Fig. 9a) can be found. It can be found from the analysis of Fig. 9b that the length of the band zone which is under the effect of longitudinal tensile stresses, $\sigma_x$, is much smaller compared to the results obtained from rolling homogeneous aluminium rods. This distribution of stresses on the cross-sectional area of rolled rod restricts a more intensive elongation of the soft layer, which is the cause of the larger widening of the band compared to the widening of the homogeneous aluminium rod.

It can be found from the analysis of stress distribution in the roll gap during the rolling of bimetallic rods that the elongation of the bimetallic band depends on the ratio of the resistance of plastic flow of particular components.

6. Conclusions

The investigation carried enables the following observation to be made and conclusions to be drawn:

1. During the rolling of a bimetallic rod, more intensive flowing out of the soft layer (the core of the cladding layer) is observed in zones located close to the surface of contact of the band with the rolls. During the rolling of a homogeneous steel or aluminium band this effect does not occur. The characteristic flow of bimetal is in agreement with the explanation proposed in [11], according to which the cause of such phenomena is a difference in the rheological properties of bimetal components.

2. During the rolling of a bimetallic rod, the magnitude of widening is either much larger (when core $\sigma_x$ is more than cladding layer $\sigma_x$) or much smaller (when core $\sigma_x$ is less than cladding layer $\sigma_x$) compared to the widening of a homogeneous rod rolled from the metal of which the core is made.

3. The developed computer program designed for the mathematical modelling of the spatial state of deformation of homogeneous and bimetallic rods during rolling is characterised by easy preparation of initial data and a short computation time compared with the existing commercial programs available on the market.

4. Computations carried out for the conditions of bimetallic rod rolling have shown that the model accurately reflects the conditions of rolling in elongation grooves. A correctly performed rolling process assures the bimetallic rod product to be obtained with bonding quality comparable with a stock material after explosive welding.

References


[12] A. Milenin, H. Dyja, L. Lesik, S. Mróz, Teoreticheskij i eksperimental-

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