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EXPERIMENTAL AND NUMERICAL INVESTIGATION OF COLD ROLLING OF FERRITIC-PEARLITIC STEELS

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Abstract

Four steels with different chemical compositions were analysed during the cold rolling process on the basis of experimental and numerical investigation. Experiments provided input data for development and validation of conventional numerical model of cold rolling. The conventional model due to short computational times is oriented on industrial applications. Experimental investigation revealed influence of microstructure morphology containing different amount of phase components on deformation inhomogeneities. Model validation performed for all investigates steels was based on comparison of loads measured and calculated using finite element software. Comparison proved good predictive capabilities of the numerical solution.

Key words: cold rolling, conventional material model, industrial application

1. INTRODUCTION

Expectations from the automotive industries regarding new metallic materials with exceptional properties are the driving force of innovative experimental and numerical research. Thus, dynamic development of modern steel grades has been observed during recent years. As a result, various generations of Advanced High Strength Steels (AHSS) (Hofmann et al., 2009; Matlock & Speer, 2009) were proposed. These steels are considered the key materials for automotive body construction.

The major advantage of these steels is that they provide a possibility of reducing the automobile weight (increase of the fuel efficiency), while maintaining or even increasing their safety under exploitation conditions (crash worthiness). Particular focus in the present research is put on the DP (*Dual Phase*) steel, as a representative of the AHSS group. It is expected that by the end of 2020 modern car body will contain around 200kg of components made from the DP steels in comparison to the present level of approx. 60kg (Gorecki et al., 2014). That is the reason why intensive research is carried on in this area.

The DP steels are characterized by a combination of high strength, good formability, high bake hardenability and crash worthiness. These properties are the result of the properly designed microstructure consisting of ferrite matrix (around 70-90%) and hard martensitic islands. The DP ferritic-martensitic structures are obtained during the continuous annealing process. The technology of this process is composed of heating of the steel to the intercritical ferrite-austenite ($\alpha+\gamma$) two-phase region, followed by two-stage or three-stage controlled cooling, causing transformation of the remaining austenite into martensite (Bayram et al., 1999). Due to this complexity, experimental design of the process is time consuming and expensive.

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That is why a lot of attention has been recently put to the development of accurate numerical models that can support mentioned experimental investigations. Such models can be used to support design of efficient manufacturing cycles, which allow obtaining required morphology of the DP steel microstructures. However, industry is usually interested in an accurate, but at the same time fast, numerical models. Modern advanced multi scale numerical approaches can provide detailed information on material behaviour from various length scales. These models are promising from industrial point of view, however, long computing time still limits their wide applications. Thus, to meet industrial expectations authors searched for a conventional finite element model for fast and efficient modelling of industrial rolling. This work is focused on numerical simulation of one of the stages of the DP steel manufacturing cycle, which is cold rolling of ferritic-pearlitic strips. The main aim of this research was to perform experimental evaluation of various steels behaviour during cold rolling and to develop mentioned reliable numerical model.

2. EXPERIMENT

Primary rolling experiments are described by Madej et al. (2013). In the present work a wider spectrum of steel compositions was considered. Four steel grades with different chemical compositions were selected and ingots were casted (table 1). These ingots were forged into the square shaped samples, and hot rolled to obtain 2.5 mm strips. After hot rolling strips were slowly cooled to room temperature and two phase ferritic-pearlitic microstructure was obtained. The increase in carbon and alloying element content in the experimental steels resulted in the more complex microstructures containing also certain amount of bainite (table 2). Increase of bainite volume fraction directly influences mechanical properties.

Table 1. *Chemical composition of the investigated steels, wt%.*

	C	Si	Mn	P	S	Al	Cu	Cr	Ni	Mo	V
S243	0.09	0.10	1.42	0.011	0.010	0.053	0.03	0.35	0.01	0.005	0.001
S244	0.13	0.10	1.50	0.011	0.011	0.026	0.02	0.23	0.02	0.005	0.001
S245	0.08	0.12	1.74	0.010	0.010	0.028	0.04	0.56	0.02	0.01	0.001
S246	0.08	0.12	1.74	0.009	0.010	0.025	0	0.23	0	0.43	0.001

To evaluate mentioned properties, a series of tensile tests of the samples cut out from the strips in the longitudinal direction, as well as hardness measurements, were performed. Comparison of obtained results is presented in figure 1.

Table 2. *Volume fractions of subsequent phases in investigated steel grades.*

	S243	S244	S245	S246
Ferrite	74.74	69.59	72.94	23.14
Pearlite	19.92	25.16	12.56	2.12
Bainit 1	0.61	2.06	6.53	74.74
Bainit 2	4.73	3.19	7.97	-

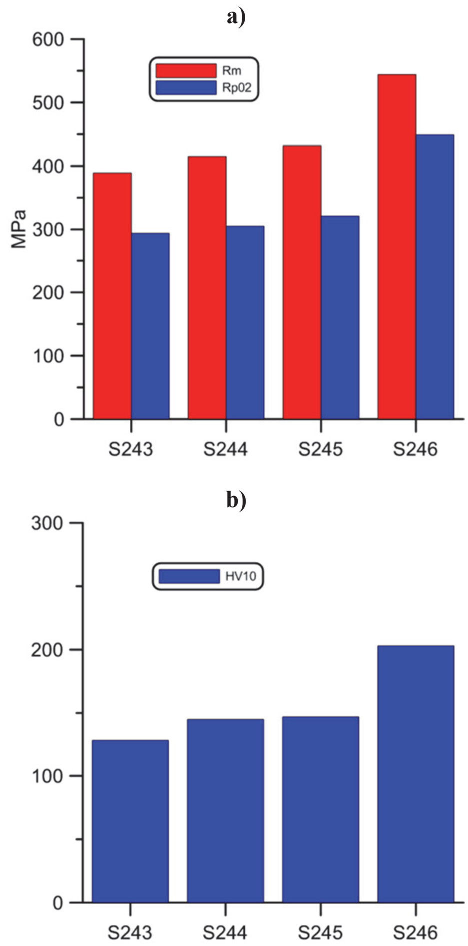

Fig. 1. *Properties of the investigated steel samples obtained after a) tensile test and b) hardness measurements.*

The hardening behaviour was investigated with a series of axisymmetrical compression tests. Tests were performed on the Gleeble 3800 at the temperature 20°C and constant strain rates of 0.1, 1 and 10 s^{-1}. The dimensions of the samples were ϕ10×12 mm. Forces recorded from all the tests were used as input for the inverse analysis realized with the algorithm described by Szeliga et al. (2006). Selected example of obtained result in the form of stress-strain curves is presented in figure 2. Details on the performed plastometric tests can be found in Madej et al. (2013).

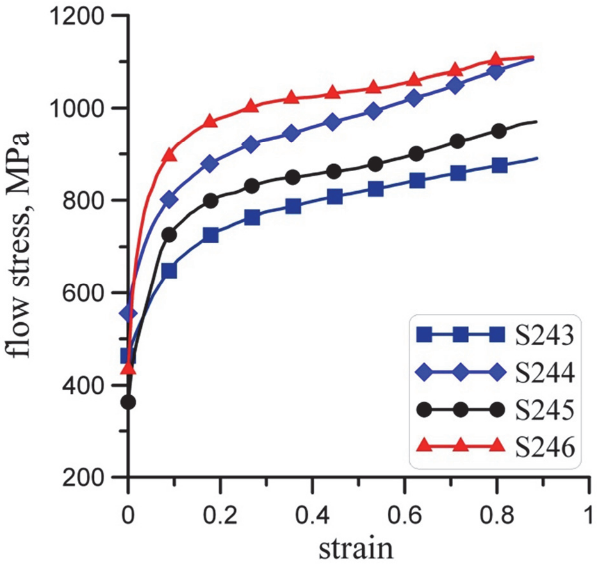

Fig. 2. *Comparison of flow stress of the investigated steel grades determined using inverse analysis for the strain rate 1s^{-1}.*

Table 3. *Parameters of the rolling process for the steels S243 and S244.*

S243				S244			
Pass	*h*, mm	*r*	F_m, kN	Pass	*h*, mm	*r*	F_m, kN
0	2		-	0	2.65	-	-
1	1.87	0.065	70.2	1	2.55	0.0378	30.7
2	1.682	0.101	92.9	2	2.42	0.051	63.1
3	1.53	0.09	79.8	3	2.175	0.101	91.9
4	1.395	0.088	82.5	4	1.83	0.159	126.2
5	1.195	0.143	104	5	1.673	0.0858	85.1
6	1.02	0.146	110.3	6	1.363	0.185	136.8
7	1.015	0.005	47.5	7	1	0.266	179.4
8	0.875	0.138	101.7				

Finally, samples obtained after hot rolling, were subjected to multi pass cold rolling in order to obtain 65% height reduction. The laboratory two high rolling mill was used during the experimental research. Work roll diameter was D_w = 59 mm and back up roll diameter D_b = 150 mm. Rolling velocity was set up to v = 0.05 m/s to prevent occurrence of deformation instabilities. The initial dimensions of the investigated samples were: thickness h_0 = 2.0 mm; 2.65 mm; 2.62 mm; 2.36 mm for the steel grades S243-S246, respectively, width b = 40 mm and length l = 300 mm. The rolling schedules for all steel grades, as well as recorded maximal load values, are given in tables 3 and 4. Thickness is an average value of three measurements in different locations along the strip length.

Load on both working rolls was measured during the process to provide data for numerical model validation stage (figure 3). After each pass, part of the sample was cut off for metallographic investigation as seen in figure 4.

Examples of microstructures obtained using light optical microscopy prior and after 65% deformation are presented in figure 5. Severely deformed-elongated ferrite grains, as well as hard constituents, are clearly visible. Mentioned hard constituent in sheets from steels S243, S244 and S245 are deformed approximately to the same degree as ferrite grains. In the case of S246 steel, the rolling process provided more irregular microstructure that contains well developed subgrain structure.

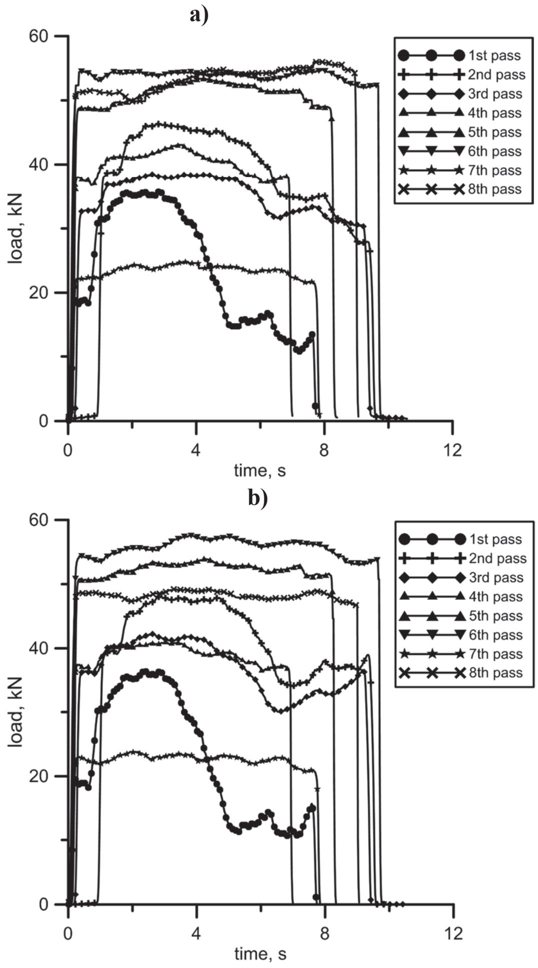

Fig. 3. *Load measured at the a) left and b) right gauge during 8 passes of rolling of S243 sample.*

Table 4. *Parameters of the rolling process for the steels S245 and S246.*

S245				S246			
Pass	*h*, mm	*r*	F_m, kN	Pass	*h*, mm	*r*	F_m, kN
0	2.62		-	0	2.36	-	-
1	2.5	0.046	63	1	2.18	0.0763	100.6
2	2.08	0.168	132	2	1.895	0.131	149.1
3	1.81	0.13	121.3	3	1.675	0.116	138.5
4	1.71	0.055	76.9	4	1.55	0.0746	129.9
5	1.515	0.114	123.6	5	1.45	0.0645	104.9
6	1.325	0.125	120	6	1.31	0.0966	127.3
7	1.145	0.136	120.7	7	1.21	0.0763	139.1
8	1.04	0.092	120.8	8	1	0.174	163.0

Fig. 4. *Example of S243 samples cold rolled after 3rd, 6th and 8th pass.*

Presented data were used during subsequent stages of numerical model development and validation. The basic equations of the proposed approach are summarized below.

3. FINITE ELEMENT MODEL OF COLD ROLLING

The finite element (FE) solution used in the present work is based on the rigid-plastic thermo-mechanical finite element approach proposed by Kobayashi et al. (1989). Detailed description of the algorithm and the program, which are used in this work, is given by Lenard et al. (1999). The solution assumes that the material obeys Huber-Mises yield criterion and associated Levy-Mises flow rule. The velocity field is calculated by searching for a minimum of the power functional:

$$J = \int_V \left(\sigma_i \dot{\varepsilon}_i + \lambda \dot{\varepsilon}_V \right) dV - \int_S \mathbf{f}^T \mathbf{v}_s dS \qquad (1)$$

where: σ_i - effective stress, which is equal to the flow stress σ_p, $\dot{\varepsilon}_i$ - effective strain rate, V - volume, S - contact surface, $\dot{\varepsilon}_V$ - volumetric strain rate, λ - Lagrange multiplier, $\mathbf{f}$ - vector of boundary tractions, $\mathbf{v}_s$ - vector of velocities.

In the flow theory of plasticity, strain rates are related to stresses by the Levy-Mises flow rule:

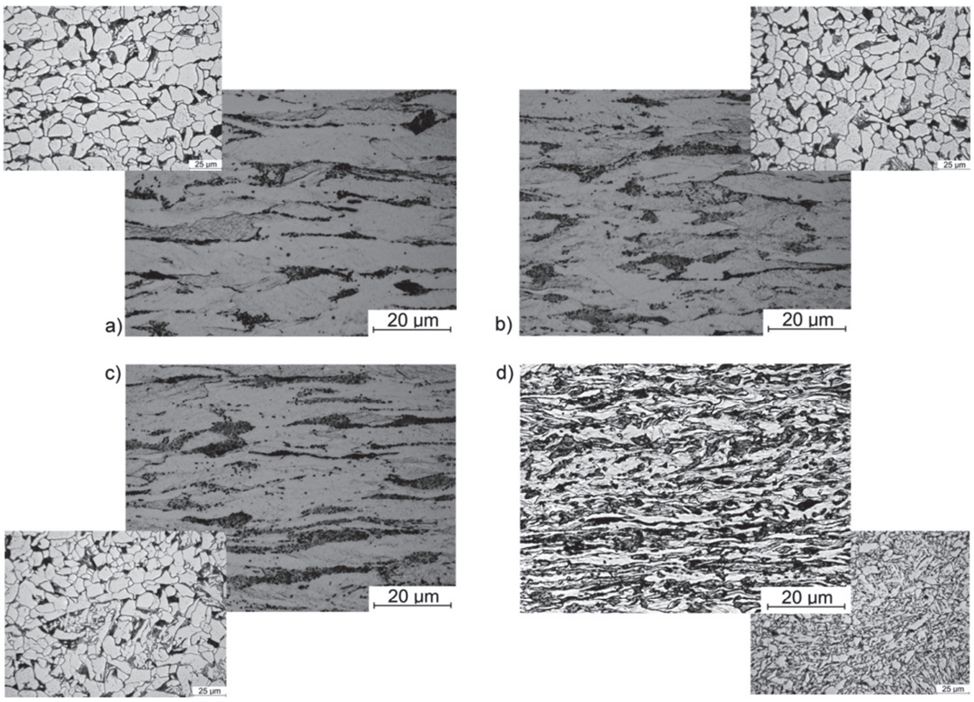

Fig. 5. *Comparison of the microstructures prior rolling and after cold rolling a) S243, b) S244, c) S245 and d) S246; degree of deformation during cold rolling ~ 65%. LOM.*

$$\boldsymbol{\sigma} = \frac{2}{3}\frac{\sigma_i}{\dot{\varepsilon}_i}\dot{\boldsymbol{\varepsilon}} \qquad (2)$$

where: $\boldsymbol{\sigma}$ – vector of stresses, $\dot{\boldsymbol{\varepsilon}}$ – vector of strain rates.

Discretization of equation (1) and differentiation with respect to the nodal velocities and to the Lagrange multiplier yields a set of non-linear equations, which is usually solved by the Newton-Raphson linearization method. Linearization gives:

$$\mathbf{p} = \mathbf{K}\begin{Bmatrix}\Delta\mathbf{v}\\ \lambda\end{Bmatrix} \qquad (3)$$

where:

$$\mathbf{K} = \begin{bmatrix}\dfrac{\partial^2 \mathbf{J}}{\partial \mathbf{v}^T \partial \mathbf{v}} & \mathbf{b}\\ \mathbf{b}^T & 0\end{bmatrix} \quad \mathbf{p} = \begin{Bmatrix}\dfrac{\partial J}{\partial \mathbf{v}^T}\\ \mathbf{b}^T\hat{\mathbf{v}}\end{Bmatrix} \quad \mathbf{b} = \int_V \mathbf{B}^T \mathbf{c}\, dV$$

$\hat{\mathbf{v}}$ - vector of nodal velocities calculated in the previous iteration, $\Delta\mathbf{v}$ – vector of increments of nodal velocities, $\mathbf{c}$ – matrix, which imposes the incompressibility condition $\dot{\boldsymbol{\varepsilon}}_V = \mathbf{c}^T\dot{\boldsymbol{\varepsilon}}$, $\mathbf{B}$ – matrix of derivatives of shape functions.

Friction plays an important role in the inverse analysis of plastometric tests. The friction model suggested by Chen and Kobayashi (1978), is used in the present work:

$$\tau = m\sigma_p \operatorname{arctg}\frac{\Delta v}{a} \qquad (4)$$

where: m - friction coefficient, Δv - relative slip velocity, a - a constant, which is few orders smaller than an average slip velocity.

It was observed in the experiments that deformation heating causes significant increase of the sample temperature in the plastometric test. Proper prediction of the temperature increase is an inevitable condition for obtaining realistic results. Therefore, the flow formulation, which is the basis of the mechanical model in the present work, is coupled with the finite element solution of the Fourier heat transfer equation:

$$\nabla k \nabla T + Q = c\rho\frac{\partial T}{\partial t} \qquad (5)$$

where: k – conductivity, Q – heat generation rate due to deformation work, c – specific heat, ρ – density, T – temperature, t – time.

The following boundary conditions were used in the solution:

$$k\frac{\partial T}{\partial \mathbf{n}} = q + \alpha\left(T_a - T\right) \qquad (6)$$

where: α – heat transfer coefficient, T_a – surrounding temperature or tool temperature, q – heat flux due to friction, $\mathbf{n}$ – unit vector normal to the surface.

Discretization of the problem was performed in a typical finite element manner and cold rolling processes were performed.

Based on the stress strain data, obtained from mentioned uniaxial compression tests, flow stress model was developed using the simplified Hensel-Spittel equations:

$$\sigma_p = A\varepsilon^B\dot{\varepsilon}^C \qquad (7)$$

where: ε – strain, $\dot{\varepsilon}$ – strain rate, A. B, C, – coefficients

As mentioned, coefficients of equation (7) for the investigated steels were obtained as a result of the full inverse analysis (Szeliga et al., 2006) and they are given in table 5. These models were used as flow stress models incorporated into the fundamental Levy-Misses equation (2).

Table 5. *Coefficients determined using inverse analysis of plastometric tests.*

Steel	A	B	C
S243	908.2	0.137	0.0019
S244	1050.6	0.164	0.0015
S245	981.3	0.132	0.0018
S246	1113.6	0.089	0.0018

The developed finite element numerical model for cold rolling has properly defined initial and boundary conditions to reflect real process. Coulomb friction coefficient of 0.07 and heat exchange coefficient of 25 kW/m^2K (Pietrzyk et al., 1994) were assumed in the simulations. Graphical comparison of the measured and calculated rolling forces for these steels is shown in figure 6. The corresponding strain distributions through the thickness after each pass are shown in figure 7. Results are presented only for S243 as the trend is similar for other test cases. Coordinate $y = 0$ corresponds to the center of the strip.

In general, very good agreement between measurements and calculations was obtained. Some discrepancies occurred for very small reduction, e.g. pass 7 S243 and pass 4 for S245. Overestimation of

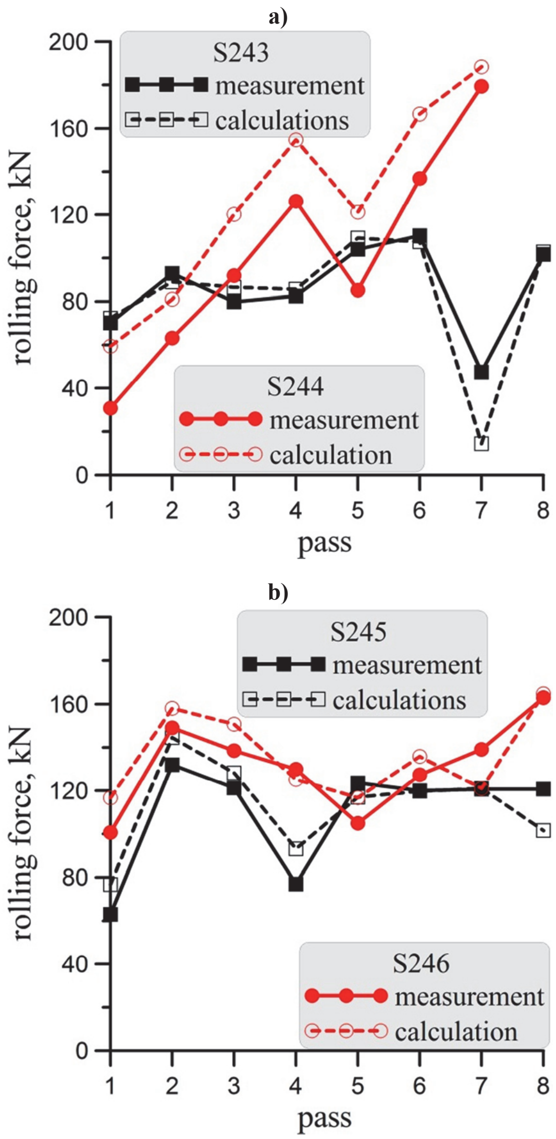

Fig. 6. Comparison of measured and calculated forces for the steels a) S243/S244 and b) S245/S246

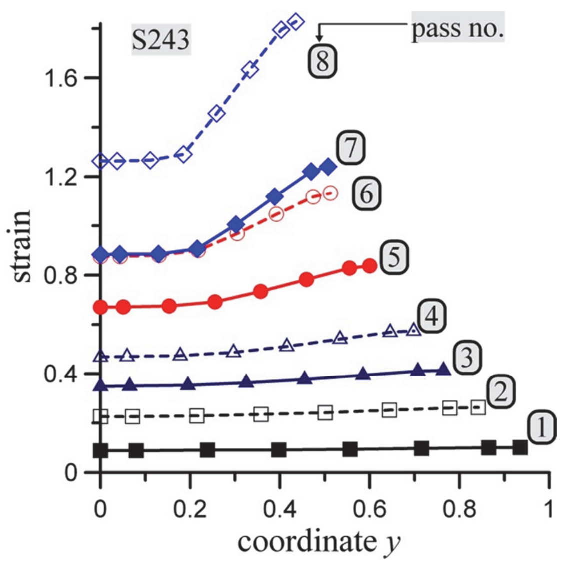

Fig. 7. Calculated strain distributions through the thickness after each pass during rolling of the S243 steel

the force in all passes is observed for the steel S244. The possible explanation of the discrepancies observed in case of S244 steel may be connected to the inhomogeneity of the microstructure in the hot rolled sheet. These data will be used during further research to develop multi scale finite element model based on digital material representation for detailed investigation of strain inhomogeneities.

4. CONCLUSIONS

Both experimental and numerical studies of the cold rolling of four ferritic-pearlitic steels were presented in the paper. Based on these studies it can be concluded that:

- despite the properly selected heat treatment due to the increase in carbon and alloying element content in the experimental steels more complex than only two phase microstructures were obtained,
- increase of bainite volume fraction directly influences microstructure morphology after deformation, obtained mechanical properties as well as loads recorded during the cold rolling,
- developed finite element model based on the rigid-plastic thermo-mechanical formulation accurately predicts material behavior during cold rolling,
- simplified Hansel-Spittel flow stress model can correctly predict material hardening under cold deformation conditions,
- the key element influencing accuracy of the simulation is proper identification of the selected flow stress model.

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EKSPERYMENTALNE I NUMERYCZNE BADANIE ZACHOWANIA SIĘ STALI FERRYTYCZNO-PERLITYCZNEJ PODCZAS WALCOWANIA NA ZIMNO

Streszczenie

W pracy badano zachowanie czterech stali o różnym składzie chemicznym podczas walcowania na zimno z wykorzystaniem badań eksperymentalnych oraz analizy numerycznej. Model reologiczny dla tych stali opracowano na z wykorzystaniem serii badań plastometrycznych i analizy odwrotnej. Zaproponowany model numeryczny walcowania został zweryfikowany przez porównanie wartości sił uzyskanych z pomiarów w procesie walcowania w walcarce laboratoryjnej. Dodatkowo poprzez badania metalograficzne wykazano wyraźny wpływ morfologii mikrostruktury o charakterze dwufazowym za niejednorodności odkształcenia. Ze względu na krótkie czasy obliczeń zaproponowane rozwiązanie numeryczne jest dedykowane praktycznym zastosowaniom przemysłowym, wspomagającym projektowanie procesów walcowania.

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