DOI: 10.1002/srin.200900094 steel research int. 81 (2010) No. 3

Development and Validation of a Numerical Model of Rolling with Cyclic Horizontal Movement of Rolls

A. Milenin[1), F. Grosman[2), L. Madej[1)*, and J. Pawlicki[2)

[1) Akademia Górniczo-Hutnicza, Mickiewicza 30, 30-059 Kraków, Poland, lmadej@agh.edu.pl
[2) Politechnika Śląska w Katowicach, Poland
* Corresponding author

The development of a numerical model capable of simulating the forming processes characterized by additional reversible movement of tools is the subject of this paper. The major assumption of this process is the introduction of additional shear stresses into the material in order to induce the strain path change effect. The scope of the problem is very broad, so the focus in the present work is on the process of flat rolling with additional oscillatory movement of rolls along their axes. Due to the sophisticated nature of this process particular attention is paid to the reduction in computational time by minimizing the number of required finite elements. The developed model is used to study differences in material behaviour during rolling with different roll velocities. A detailed description of the developed numerical model and examples of obtained results are presented in this paper. A comparison with experimental analysis is presented, as well.

Keywords: finite element model, rolling process with cyclic horizontal movement of rolls

Submitted on 25 May 2009, accepted on 23 September 2009

Introduction

Recent scientific investigations have revealed close relationships among changes in the strain path during deformation and material structure and formability [1–3]. The development of shear bands was identified as one of the main mechanisms that control material flow during deformation path change. It has been proven that detailed control of the shear banding phenomena may lead to reduction in applied rolling force. This is the basis of the proposed Structure Based Design of Metal Forming Operations (SBDMFO) [4], which has eventually led to the development of new types of industrial forming operations (i.e. KOBO type forming) [5]. It has been observed that certain process conditions (e.g., change in temperature or strain path) may lead to an increase in the forming capabilities of many materials that are difficult to form by conventional metal forming operations. This is one of the main advantages of the processes which benefit from the strain path change during deformation, i.e. extrusion with rotational oscillations of dies or compression with cyclic tool rotation (**Figure 1**).

Experimental research conducted over the past several years has proven the mentioned advantages provided by these two processes [1, 2]. However, to reduce the costs of laboratory or industrial trials, which are necessary to investigate material as well as tool behaviour during such complex deformation processes, a numerical model that supports this investigation is needed. Approaches to create FE models capable of simulating the extrusion and compression processes with rotational movement of tools can be found in the literature [6].

Rolling is a commonly used industrial process, and a question that has recently arisen is whether this process can be modified in order to provide similar advantages as the processes presented in Figure 1. This approach could be applied to rolling of new difficult-to-form materials. A lot of research from the experimental point of view has already been performed by the authors of this paper and can be found in a report on a Polish national project [7]. The major assumptions and discussions about the advantages and limitations of this process are summarized in the following sections.

The main objective of this work is to create a numerical model to simulate rolling with cyclic horizontal movement of rolls, to validate the model by comparing the results with experimental findings and, finally, to develop a tool for the design of these processes. Numerical analysis based on the developed model will reduce the number and cost of laboratory trials required to design the rolling technology.

Laboratory Tests

Rolling equipment capable of imposing an additional horizontal movement of rolls was designed on the basis of the laboratory two-high rolling mill. The presented equipment was developed in the Silesian University of Technology in Katowice, Poland and is described in [7]. In this solution rolls have the capability of cyclic horizontal movement in opposite directions, which is schematically presented in **Figure 2**. Maximum movement of rolls is ± 2 mm and maximal value of frequency is up to 3 Hz. Rolling velocity can be changed within 0 – 20 rpm. The roll diameter can be set up between 60 and 100 mm. Horizontal movement of rolls is realized by the bar linkage and eccentricity mechanisms as shown in Figure 2.

Horizontal movement is transferred to the sample by grooved rolls, which are schematically presented in **Figure 3**.

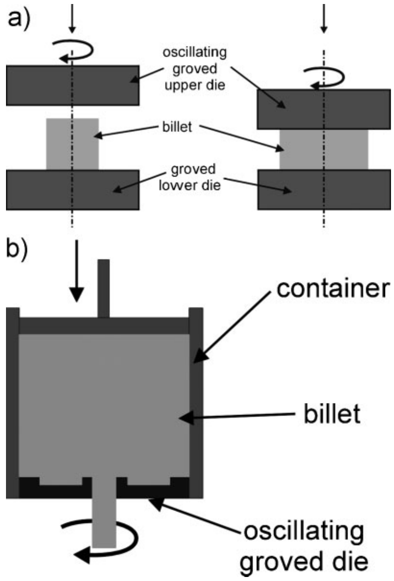

Figure 1. (a) Compression with cyclic tool rotation. (b) Extrusion with rotational oscillations of dies.

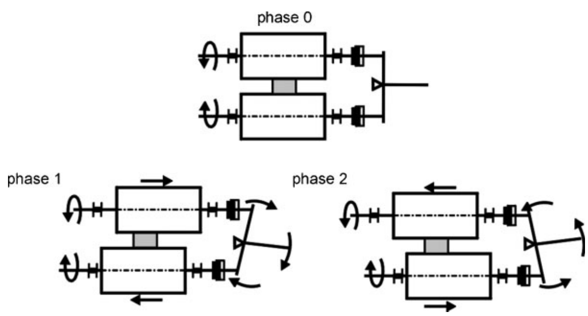

Figure 2. Kinematical scheme of rolling mill with additional cyclic horizontal movement of rolls.

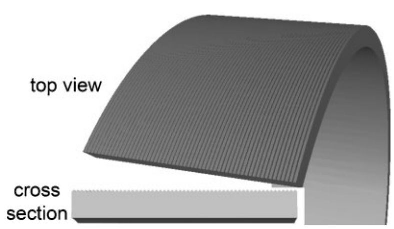

Figure 3. Rolls with a set of groves used to transfer horizontal movement from the rolls into the sample.

Due to its nature, this process is called a MEFASS rolling (Metal Forming Aided by Shear Stresses). The developed laboratory equipment is presented in **Figure 4** and is used to study material behaviour under various stress states. Different roll velocities, frequencies and amplitudes of oscillations and their various combinations were investigated to completely understand the mechanisms responsible for material deformation modes. An investigation of metal flow during the MEFASS process with different roll

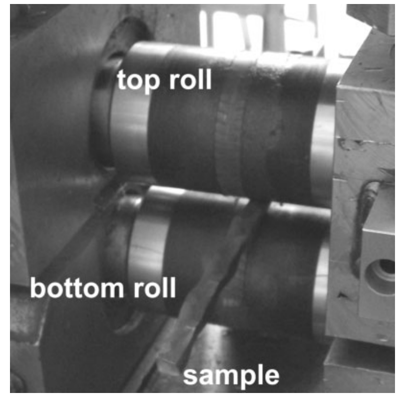

Figure 4. Picture of the laboratory rolling mill capable of imposing strain path change on the material.

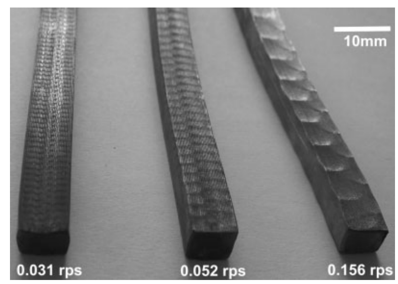

Figure 5. Geometry obtained after MEFASS with different roll velocities 0.031, 0.052, 0.156 rps, respectively.

velocities was performed as a case study for the purposes of the present work.

Three different velocities were used: (i) 0.156 rps, (ii) 0.052 rps, (iii) 0.031 rps. These differences in roll velocities directly influence the number of additional oscillations that are induced into the material along the roll gap. Roll velocity was set up to obtain one, three and five additional oscillations while the material was in the deformation zone. All the remaining process parameters, such as frequency or amplitude, were constant and equal to 3 Hz and 1.4 mm, respectively. The copper samples with initial dimensions at the cross section 8×8 mm were subjected to oscillatory cold rolling with relatively small rolling reduction $\Delta h = 0.8$ mm.

Examples of the obtained experimental samples after rolling are shown in **Figure 5**. The large differences in the shapes of the final samples were obtained after rolling with different roll velocities. A detailed investigation of the state of the deformed material can be performed in two different ways. The first solution is to perform metallographic analysis to study the microstructure. The second solution is to use numerical modelling approaches which can give a quick and detailed overview of the character of metal flow during rolling.

However, one of the major problems occurring during numerical simulations of these kinds of processes is excessive computational time, which is due to the large number of required finite elements. As presented in Figure 3, a series of narrow grooves was introduced at the surface of the rolls to transfer additional reversible oscillation into the deformed material. Highly refined FE meshes should have been used in the numerical model to accurately transfer the shape of these grooved rolls into the deformed sample; however, this eventually leads to long computational times. One of the solutions to eliminate this problem is to apply anisotropic friction conditions instead of using grooved dies. This cannot be done using commercially available FE packages. That is why the authors of this work decided to use an in-house code and to introduce modifications that give the possibility to reduce the computational time. Details of the developed model are presented in the following chapter.

Mathematical Model of Metal Deformation during Rolling

To create a numerical model with the capability to simulate cyclic horizontal movement of rolls, several major modifications to the in-house Rolling3d code were introduced. The main principles of the basic FE code are described in [8, 9]. Examples of possible applications of the Rolling3d code to solve different problems in the development of rolling shape technology were published in [10, 11]. The main principles of the developed FE code are described below.

The theory of non-isothermal plastic flow of incompressible non-linear viscous medium was applied to solve the problem. Boundary conditions were taken into account by the method proposed in [9]. The essential idea of this method involves application of the penalty function to calculate metal-tools interaction in a complex spatial configuration. The solution is derived from the stationary condition of the modified Markov functional [12]:

$$J = \frac{1}{2}\int_V \mu \dot{\varepsilon}_i{}^2 dV + \int_V \sigma \dot{\varepsilon}_0 dV + K_\tau \int_F (v_\tau)^2 dF + K_n \int_F (v_n - w_n)^2 dF \quad (1)$$

where:

$$K_\tau{}^{(p)} = \frac{\tau^{(p-1)}}{v_\tau{}^{(p-1)}}, \quad (2)$$

$$\mu^{(p)} = \frac{\sigma_s{}^{(p-1)}}{\dot{\varepsilon}_i{}^{(p-1)}}, \quad (3)$$

where:

p – iteration number
v_τ – metal slip velocity with respect to the tool (m/s)
v_n – metal velocity normal to the tool surface (m/s)
w_n – normal component of the velocity of the tool surface (m/s)
τ – friction stress (according to the law $\tau = m\sigma_s$, where m – friction factor)
σ_s – yield stress (MPa)
σ – mean stress (MPa)
$\dot{\varepsilon}_i$ – effective strain rate (s^{-1})
$\dot{\varepsilon}_0$ – strain rate in the triaxial compression test (s^{-1})
K_τ – the penalty coefficient accounting for the metal slip velocity over the tool computed based on the data from the previous iteration ($p-1$)
K_n – the penalty coefficient for the metal penetration into the tool
μ – effective metal viscosity computed from (3) by the method of hydrodynamic approaches (MPa s)
V – volume (m^3)
F – contact surface (m^2).

If the penalty coefficient K_τ increases, the metal slip over the contact surface is hampered. $K_\tau = 0$ corresponds to frictionless metal slip.

In the present model the friction anisotropy was introduced, which provides the possibility to transfer the horizontal movement of rolls into the material without usage of the grooved rolls. Major assumptions of this approach have already been explained.

The full tangential slip metal velocity over the tool is a sum of the two components:

$$v_\tau^2 = v_1^2 + v_2^2 \quad (4)$$

where 1 an 2 are axes of the local coordinate system in a current contact point in directions tangential to the contact surface. The local axis marked as 2 in this case is equivalent to an elongation direction *Y*. Therefore, the friction part of (1) is described as:

$$\int_F \left(K_{\tau 1} v_1^2 + K_{\tau 2} v_2^2\right) dF, \quad (5)$$

where:

$$K_{\tau 1}^{(p)} = \frac{m_1 \sigma_s}{v_\tau}, \quad (6)$$

$$K_{\tau 2}^{(p)} = \frac{m_2 \sigma_s}{v_\tau} \quad (7)$$

where m_1 and m_2 are friction factors in directions 1 and 2, respectively.

The horizontal velocity of rolls (in direction *Y*) was accounted for during the simulation by implementation of the following function:

$$v_2 = \frac{\pi U_{wy}}{\tau_{wy}} \sin\left(2\pi \frac{\tau}{\tau_{wy}}\right) \quad (8)$$

where:

$\tau_{wy} = \frac{1}{f}$ - time of roll movement in direction *Y* during one oscillation
τ - rolling time, U_{wy} - movement amplitude in direction *Y*.

The phenomena of contact loss between rolls and the sample during horizontal movement of rolls was observed experimentally (Figure 5) and was taken into account in the proposed model. This was done by an additional boundary condition:

$\sigma_n \geq 0,$

where σ_n is normal stress calculated in the current point at the contact surface.

The model developed in the present project is capable of transferring additional horizontal movement of rolls to the material not via the grooved rolls but via anisotropic friction conditions. This significantly reduces the computational time. Another important issue is temperature change during MEFASS rolling. Deformation heating is extremely important as it is one of the mechanisms leading to load reduction. In order to simulate temperature changes, the following heat transfer equation was solved:

$$c_{eff}(t)\rho(t)\frac{dt}{d\tau} = \mathrm{div}[k(t)\mathrm{grad}(t)] + q_{def}, \tag{9}$$

where:
$\rho(t)$ – metal density (kg/m^3)
t – temperature (K)
τ – time (s)
$k(t)$ – heat conductivity coefficient (W/m K)
$c_{eff}(t)$ – effective specific heat (J/kg K)
$q_{def} = 0.9\sigma_s\dot{\varepsilon}_i$.

The 3D solution of the temperature field distribution along the sample was built upon the subsequent solutions of the plane tasks, which correspond to the location of the sample cross-section during rolling. To solve Equation (9) the variational problem formulation based on minimization of function J was applied:

$$J = \int_V \frac{1}{2}\left[k(t)\left(\frac{\partial t}{\partial x}\right)^2 + k(t)\left(\frac{\partial t}{\partial y}\right)^2 - c_{eff}(t)\rho(t)\frac{dt}{d\tau}t + q_{def}t\right]dV + \int_F \frac{\alpha}{2}(t - t_\infty)^2 dF, \tag{10}$$

where:
α– coefficient of heat exchange (W/m^2 K)
t_∞ – temperature of the air or roll (K).

Finally, the temperature derivative with respect to time was calculated implicitly by equation:

$$\frac{dt}{d\tau} = \frac{t_\tau - t_{\tau-\Delta\tau}}{\Delta\tau}. \tag{11}$$

The coupled thermal mechanical solution was performed in simulations of rolling. Examples of the numerical analysis of the MEFASS process are shown below.

Numerical Analysis

The objective of the simulations was to supply data for comparison with experimental observations and to validate the model, which can be further used for the optimization of process parameters. A series of numerical simulations without horizontal movement of rolls was performed first to give the basis for evaluation of the scale of the effect caused by oscillations of the rolls. The results obtained along the measurement line located at the sample cross section (**Figure 6**) for monotonic rolling with three different roll velocities are presented in **Figure 7**. Simulations of rolling with roll oscillations were performed next. Predicted shapes of the samples after rolling (**Figure 8**) can be qualitatively compared with the shapes from the experiments shown in Figure 5, and good agreement is observed.

From a quantitative point of view, the amplitude of the surface waviness was compared, which also showed reasonable agreement (**Table 1**). FE simulations slightly overestimate the amplitude, which may be related to the lack of ability of this numerical model to demonstrate micro shear band development.

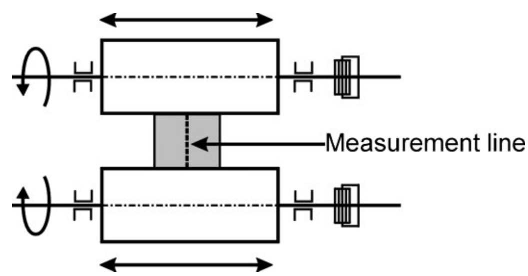

Figure 6. Measurement line at the sample cross section at the exit of the deformation zone.

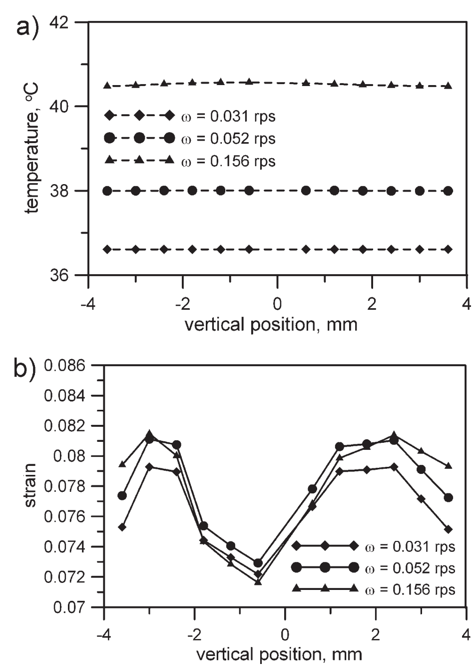

Figure 7. Temperature profile (a) and equivalent strain (b) along the vertical line of symmetry at the exit section of the sample during conventional rolling.

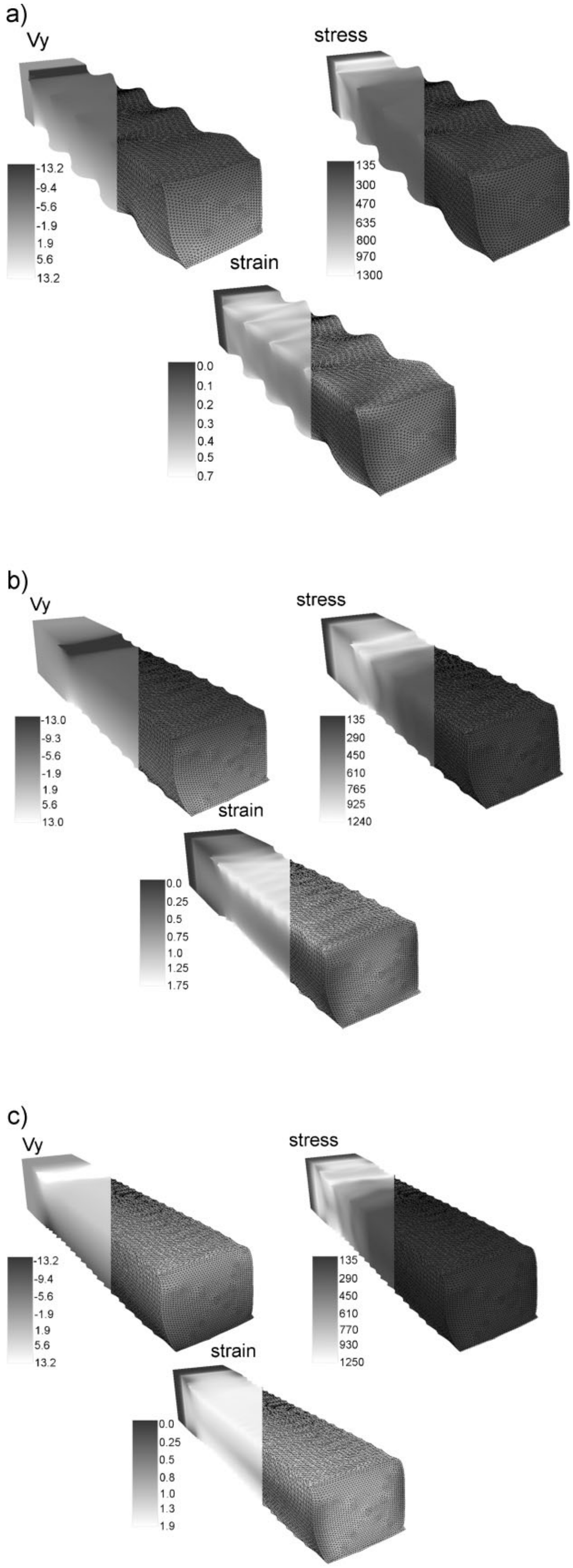

Figure 8. Distribution of the V_y component, equivalent strain and equivalent stress obtained for MEFASS with different roll rotational velocities of (a) 0.156, (b) 0.052 and (c) 0.031 rps.

Table 1. Amplitude of the surface waviness measured after experiment and FE simulation.

Roll rotational velocities rps	FE simulation mm	Experiment mm
0.031	1.69	1.02
0.052	2.37	1.93
0.151	4.89	4.57

Since deformation heating is one of the major mechanisms influencing the load reduction during the FE simulation, particular attention was paid to the changes in the temperature measured during rolling. Temperature profiles at the exit from the roll gap obtained along the vertical line at the sample cross section for the three considered cases are presented in **Figure 9a**. A similar comparison was performed for the effective strain profiles, and the results are presented in Figure 9b.

A large increase in temperature was observed at the lowest roll velocity. That is the case when rolls perform five oscillations while material is going through the roll gap. As seen in Figure 9, when the contribution of oscillations decreases, the temperature decreases as well. The same situation is observed when strain values are considered. Additional oscillations result in large strain accumulations in the material. When the conventional rolling process without additional oscillations is considered, the increase in

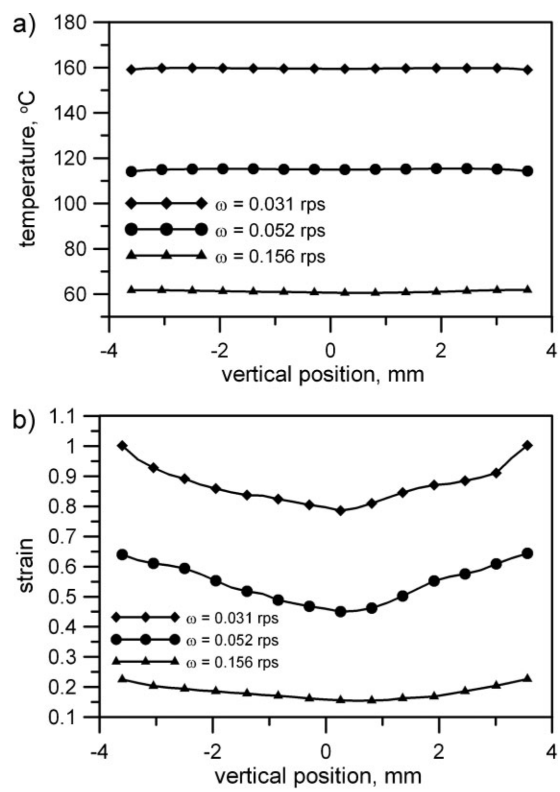

Figure 9. Temperature profile (a) and equivalent strain (b) along the vertical line of symmetry at the exit from the roll gap during the MEFASS process.

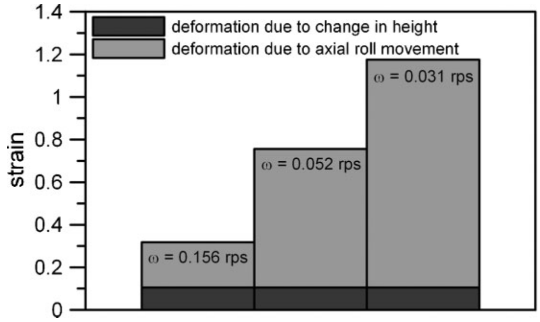

Figure 10. Contribution of the change in height and axial roll movement to the equivalent strain during the MEFASS process.

temperature is much smaller in comparison with the MEFASS process. The highest temperature values are obtained when high rolling velocities are used. Because an increase in strains in conventional rolling is mainly connected with the geometrical aspects of deformation, the results obtained for the three different velocities are similar (Figure 7b). These results can be compared with the theoretical prediction regarding the contribution of perpendicular shear to equivalent strain (**Figure 10**) [13].

As presented in Figure 7b and 9b, numerical simulation results are in good agreement with the results presented in Figure 10. In both cases the additional contribution of perpendicular shear to equivalent strain was significant.

Conclusions

A new numerical model of the MEFASS process was developed and provided the possibility to predict changes in the shape of the sample, deformation degree and temperature distribution.

Results obtained from the comparison between conventional and MEFASS rolling processes show that strain accumulated in the latter rolling case can be up to ten times higher compared to conventional rolling. These results were obtained by ensuring that the size of the roll gaps remained the same in both cases. The possibility of large strain accumulations in comparison to the conventional rolling process is the main advantage of the MEFASS process.

Interesting behaviour was observed in the case of additional deformation heating during the MEFASS rolling. Contrary to conventional rolling, it was observed that increases in temperature were higher when the rolling velocity decreased. This was mainly due to the number of oscillations induced to the material in the rolling gap.

Finally, it is important to highlight that the MEFASS process is not intended to substitute conventional rolling. The main goal is to create a highly deformed and refined microstructure with clearly visible micro and macro shear bands. The final shape and required surface quality is obtained in the next stage by using conventional rolling.

Acknowledgements

Financial assistance of MNiSW, project R07 026 01, is acknowledged. One of the authors LM is grateful for the financial support of the Foundation for Polish Science within the Start program.

References

[1] A. Korbel, W. Bochniak: Refinement and control of the metal structure elements by plastic deformation, Scripta Materialia, 51 (2004), 755–775.
[2] Z. Gronostajski, F. Grosman, K. Jeskiewicz, J. Pawlicki: Effect of variable deformation path on material's force-energy parameters and structure, in: Research in Polish Metallurgy at the Beginning of XXI Century, eds. K, Swiatkowski, M, Blicharski, K, Fitzner, W, Kapturkiewicz, M, Pietrzyk, J. Kazior, Akapit, Krakow, 2006, p. 347–368.
[3] A. Wrozyna, G. Niewielski, K. Rodak, D. Kuc, F. Grosman, J. Pawlicki: The impact of compression with oscillatory torsion on the structure change in copper, Archives of Civil and Mechanical Engineering, 7 (2007), 39–46.
[4] A. Korbel, W. Bochniak: The structure based design of metal forming operations, J. Material Processing Technology, 53 (1995), 229–237.
[5] W. Bochniak, A. Korbel: KOBO Type Forming forging of metals under complex conditions of the process, J. Material Processing Technology, 134 (2003), 120–134.
[6] L. Madej, S. Wegalrczyk, F. Grosman: Numerical modeling of bulk metal forming processes with induced strain path change, Computer Methods in Materials Science, 9 (2009), p. 234–240.
[7] F. Grosman, J. Pawicki, B. Lipska: Wykonanie badań doświadczalnych procesu walcowania z poosiowym ruchem walców. Wykonanie interpretacji wyników badan doświadczalnych procesów przeróbki plastycznej ze zmianą drogi odkształcenia, Politechnika Śląska, research report NB-50/RM-2/2005, p. 23 (in Polish).
[8] A. A. Milenin: Numerical properties of finite-element algorithms in the three-dimensional shaping of metals in Russian metallurgy, 5 Allerton Press, London, 1998, p. 38–43.
[9] A. Milenin: Mathematical modeling of the spread of metals with different rheological properties on rolling in Russian metallurgy, 4 Allerton Press, London, 1998, p. 65–68.
[10] A. Milenin, H. Dyja, S. Mroz: Simulation of metal forming during multi-pass rolling of shape bars, J. Material Processing Technology, 153–154 (2004), 108–114.
[11] S. Mroz, A. Milenin: Numerical modelling of the metal flow and stock bending during the rolling of unequal angle bar, J. Material Processing Technology, 177 (2006), 561–565.
[12] A. Markov: On variational principles in the theory of plasticity, Prikladnaja Matematika i Mechanika, 11 (1947), 333–350 (in Russian).
[13] F. Grosman, Z. Cyganek: The research of rolling process with cyclic change of the strain path, Proc. Metal Forming Conference 2008, Steel Research Int., 79 (2008), Special Edition, 453–458.

