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ASSESSMENT OF THE ROLLING SPEED OF A MULTI-CELL MILL FOR METAL SHEET HOT ROLLING

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Abstract

The study analyses the operation of a multi-cell mill for hot rolling of steel sheets, where the roll speed in each cell is previously known. A possible variation of metal speed during sheet pass through each cell is found keeping the requirement of metal continuous flow. An actual metal speed distribution throughout the mill is also found, solving the coupled thermo-mechanical problem of metal plastic forming by employing FEM.

Key words: rolling speed, coupled thermo-mechanical problem, plastic deformation, sheet cooling, FEM

1. Introduction. As it is known, rolling is one of the basic metal forming processes producing sheets, tubes, profiles with different shape of the cross section, etc. A major part of rolling-related studies tackle the mechano-mathematical modelling of plastic forming, usually accounting for a rigid-plastic material. Noteworthy, in this respect are the papers [1,2] and the results of [3] while [4] gives reference of metal and alloy mechanical characteristics under normal and high temperature. Modern approaches such as [5–8] attack the rolling problem using FEM technique while [9–11] and others treat the formation and evolution of metal microstructure during hot rolling. Yet, despite the numerous results in the field, it seems useful to perform a more detailed analysis of the problem of metal speed synchronization during sheet pass through a *multi-cell* mill since most studies analyze multipass sheet rolling within a *single* cell.

T a b l e 1

Roll diameter $R = 0.70$ m, h_1 is the sheet initial thickness, the distance between roll centres is 1.41 m

	Cell number					
	1	2	3	4	5	6
Sheet thickness h after each cell, 10^{-2}[m]						
h_1	h_2	h_3	h_4	h_5	h_6	h_7
1.8	1.50	1.05	0.75	0.60	0.44	0.40
Roll angular ω_R and peripheral V_R speed						
ω_R, [r/s]	4.8	6.9	8.8	11.9	16.2	17.1
V_R, [m/s]	1.6670	2.4171	3.0832	4.1671	5.6668	6.0005

2. Statement of the problem. Consider a typical 6-cell mill for final hot sheet rolling. Its parameters of operation are given in Table 1, as specified by [12]. There, h_1 is the sheet initial thickness, h_i, $i = 2, \ldots, 7$, is the sheet thickness after each cell and V_R and ω_R are roll peripheral and angular speeds, respectively.

Consider now a general scheme of the operation of a multi-cell mill for metal sheet hot rolling where the material is successively deformed to finally produce a sheet with a specific width and thickness. Figure 1 presents two neighbouring cells, where ω_{R_i} is the roll angular speed. A metal sheet with thickness h_{i-1} moving with speed V_{i-1} enters Cell "i". Due to friction, it is caught by the rolls, deforms and exits Cell "i" to enter Cell "$i+1$" with speed V_i and thickness h_i ($h_{i-1} < h_i$). Note that $ABCD$ is the deformation area, while α_{iB} is the bite angle, R is the roll radius, and θ_{i-1} is the sheet temperature at the entrance of Cell "i", θ_i is the sheet temperature at the exit of Cell "i" and θ_{i+1} is the sheet temperature at the entrance of Cell "$i+1$".

3. Task. The problem considered here is to find the distribution of the sheet speed within each cell of the mill, knowing the angular (peripheral) speed of the respective roll and obeying the condition of metal continuous flow. Note that knowing the specific distribution of metal speed within the mill is of essential importance for finding an optimal deformation regime with respect to minimum rolling time, minimum energy loss, maximum technological productivity, etc.

Assume now that a "neutral" point exists, where the sheet sticks to the roll and the metal speed is equal to the roll peripheral speed, as outlined in detail [3,5]. Then, the deformation area $ABCD$ in Fig. 1 can be divided into two sub-areas – sub-area $AEFD$, where the sheet falls behind the roll, and sub-area $EBCF$, where the sheet outruns the roll, and points E and F are the neutral points corresponding to a neutral angle $\alpha_{i,0}$. To find the entire distribution of metal speed within the whole rolling mill, we need to find the location of those points within each cell. Since the sheet is thin enough, assume uniform distribution of the speed horizontal projection along the sheet thickness and consider the condition

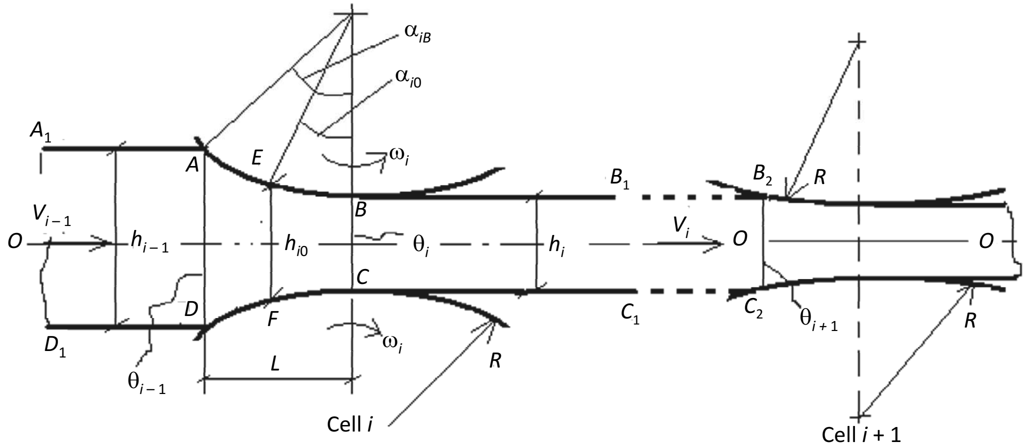


Fig. 1. General rolling scheme in Cells "i" and "$i + 1$"

of sheet smooth deformation in the cells, i.e. that of metal flow continuity:

$$V_{i-1,\mathrm{en}} \cos(\alpha_{iB}) h_{i-1} = V_{i,R} \cos \alpha_{i,0} h_{i,0} = V_{i,\mathrm{exit}} h_i, \tag{1}$$

where $V_{i-1,\mathrm{en}}$ is the speed with which the sheet enters the i-th cell, $V_{i,\mathrm{exit}}$ is the speed with which the sheet exits the i-th cell, $V_{i,R} \cos \alpha_{i,0}$ is the horizontal projection of the roll peripheral speed $V_{i,R}$ for $a = a_{i,0}$, h_{i-1}, h_i are the metal sheet thicknesses prior to and after deformation, respectively, and $h_{i,0}$ is the sheet neutral thickness corresponding to the neutral angle $\alpha_{i,0}$ as it is shown in Fig. 1. We know $V_{i,R}$, h_{i-1} and h_i only while the rest of the quantities are to be calculated. For that purpose we use the rolling geometry, as it is shown in Fig. 1 and find that

$$h_{i,0} + 2R \cos \alpha_{i,0} = h_{i+1} + 2R. \tag{2}$$

Hence assigning a value to $h_{1,0}$ (or $\alpha_{1,0}$) and coupling (1) and (2), we can calculate the values of $h_{i+1,0}$ for $i = 1, 2, \ldots, 5$. Moreover, varying $h_{1,0}$ (or $\alpha_{1,0}$) we find sets of values of $h_{i+1,0}$ ($\alpha_{i+1,0}$), $i = 1, \ldots, 5$. Note that we should check for a specified value of $h_{1,0}$ and for each respective value of $h_{i+1,0}$ whether condition (2) holds, i.e. whether $h_{i+1,0}$ falls within the deformation areas of Cell 2 – Cell 6.

Yet, for a specific rolling regime, as it is shown in Table 1, we need finding the specific values of $h_{i,0}$ or $\alpha_{i,0}$, $i = 1, \ldots, 6$, within the corresponding sets as outlined above. Note also that the contact pressure attains its peak at the neutral points E and F (Fig. 1) and friction changes its direction and sign. Solving the problem of sheet deformation within Cell 1, we find contact pressure distribution and hence, pressure peak (i.e. location of points E and F) and the values of $h_{1,0}$ and $\alpha_{1,0}$. Then, using relations (2)–(3), we can find $h_{i+1,0}$, $i = 2, \ldots, 5$, and $\alpha_{i+1,0}$ for the rest of the cells.

3.1. Treatment of the problem of metal plastic forming. Consider plastic forming of a rigid-plastic incompressible material in plain strain. Note that a thorough analysis of the problem is performed in [2] operating with equivalent stress $\overline{\sigma}$, equivalent plastic strain $\overline{\varepsilon}$ and equivalent plastic strain rate $\dot{\overline{\varepsilon}}$, while Von Mises yield criterion and associate flow rule are adopted. Note also that an application of that approach to multipass hot sheet rolling is given in detail in [6].

Consider now steady rolling of a metal sheet. The equilibrium condition in area $ABCD$ in Fig. 1 reads

$$\sigma_{ij,j} = 0, \quad \forall x_i \in ABA_1B_1. \tag{3}$$

Initial condition. Assume initial distribution of the equivalent strain at $t = 0$, i.e.

$$\overline{\varepsilon}(x_i, 0) = \overline{\varepsilon}^0. \tag{4}$$

Boundary conditions. Assume symmetry condition along the symmetry axis $O - O$. Prescribe friction along arc AB in Fig. 1 and account for the speed of the respective cell roll.

3.2. Treatment of the thermal problem within a cell. Since we consider hot plastic forming, material yield limit σ_p should generally depend on the equivalent strain $\overline{\varepsilon}$, equivalent strain rate $\dot{\overline{\varepsilon}}$ and temperature θ, i.e.

$$\sigma_p = \sigma_p(\overline{\varepsilon}, \dot{\overline{\varepsilon}}, \theta). \tag{5}$$

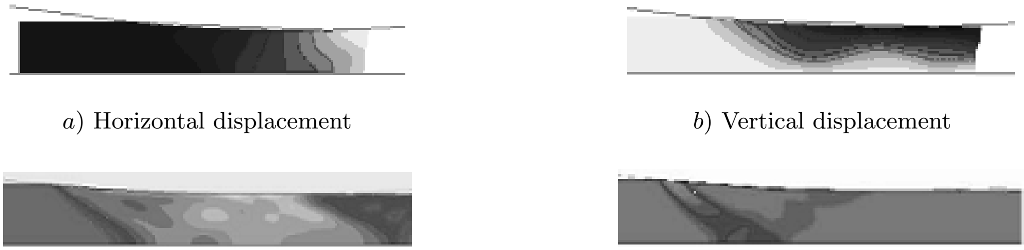
Note that the sheet enters the mill with initial temperature θ_0 and cools down to temperature θ_n at the end of the process. Account also for the opposite process of sheet heating due to heat generation as a result of the deformation. Then, the equation of thermal balance within a cell will read

$$\dot{\theta} = \lambda_\theta \theta_{ii} / \rho C_\theta + \dot{Q} / \rho C_\theta. \tag{6}$$

Notations in the above equation are as follows: λ_θ is the coefficient of metal heat conductivity, C_θ and ρ are the metal specific heat and the density, $\dot{Q}$ is the rate of energy dissipation, $(\dot{\ })$ is the derivative with respect to time t and $t \in [0, t_{\text{pass},1}]$, where $t_{\text{pass},1}$ is the time of metal pass through a cell. Note also that

$$\dot{Q} = k_\theta \sigma_p \dot{\overline{\varepsilon}}, \tag{7}$$

where k_θ is the Taylor–Quinny coefficient, accounting for heat generation within the deformed sheet, and σ_p is material yield limit. Relations (5)–(7) pose the coupled thermo-mechanical problem of hot sheet rolling. It should be solved specifying thermal initial and boundary conditions regarding the deformation area $ABCD$ in Fig. 1 (see [5, 13, 14] for more details).



a) Horizontal displacement

b) Vertical displacement

c) Equivalent strain distribution

d) Equivalent strain rate distribution

Fig. 2. Change of the basic quantities in Cell 1

Initial conditions.

$$\theta(x, y, t)_{t=0} = \theta_0(x, y), \tag{8}$$

where θ_0 is the metal initial temperature $\forall(x, y) \in ABCD$.

Boundary conditions. Heat flux is specified along the normal to the metal-roll interface – arc AB in Fig. 1, reading:

$$q_{c,n} = a_c(\theta_m - \theta_r). \tag{9}$$

Here a_c is the heat transfer coefficient, and θ_m and θ_r are metal and roll temperatures, respectively; zero heat fluxes are specified along boundaries AD and BC in Fig. 1; symmetry condition is specified along axis $O - O$.

3.3. Treatment of the thermal problem during metal pass from one cell to another one. The heat conductivity equation in this case reads as follows:

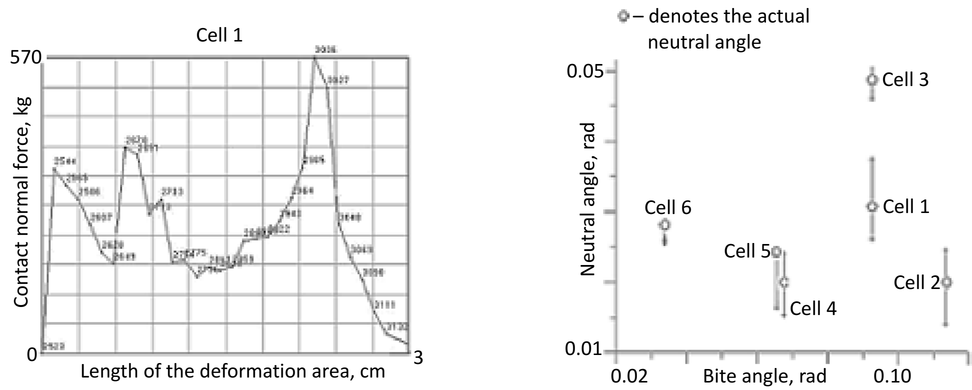
$$\dot{\theta} = (1/\rho C_\theta)\lambda_\theta\theta_{ii}, \tag{10}$$

where $t \in [0, t_{\text{pass},2}]$ and $t_{\text{pass},2}$ is the time needed by the sheet to cover the distance between two neighbouring cells.

Initial condition. It has the form (8) where the metal initial temperature $\theta_{i,0}$ for the interval between Cell "i" and Cell "$i+1$" is taken to be θ_i – the sheet temperature at the exit of Cell "i" (see Fig. 1).

Boundary conditions. Since symmetry conditions hold along axis $O - O$, we consider metal cooling that takes place along line BB_2 in Fig. 1. For the case considered here, we specify a combined heat flux on that line owing to radiation and convection as it is shown in detail in [5].

4. Results and discussion. Consider hot rolling of a rigid-plastic isotropic material (mild steel) in the range 900–1100 °C. Neglect roll flattening and bending, as well as sheet width spread and assume a constant friction factor. The process parameters are as follows: metal initial temperature $\theta = 1050$ °C; mate-



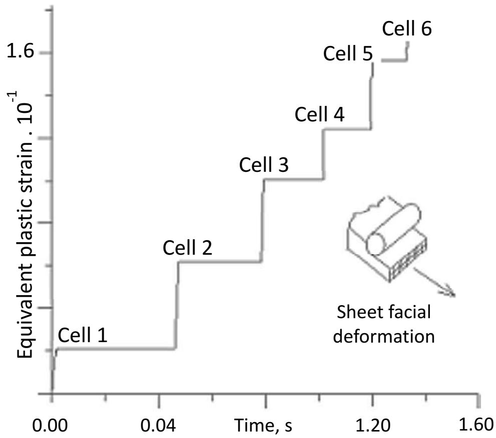
a) Contact stress distribution in Cell 1 *b*) Range of variation of the neutral angle

Fig. 3. Contact stress distribution and range of variation of the neutral angle throughout the aggregate

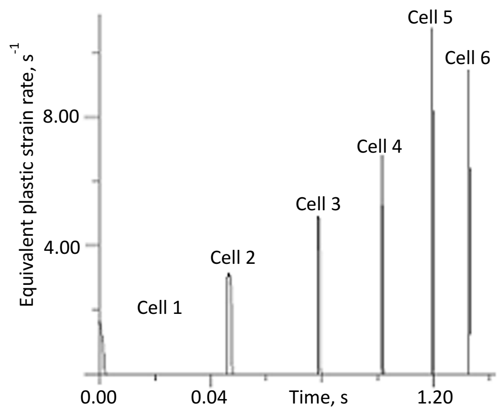
rial density $\rho = 7873$ kg/m^3; specific heat $C_\theta = 2811$ J/kg.K; heat conductivity coefficient $\lambda_\theta = 30$ J/s.m.K; coefficient of heat transfer at the sheet-roll interface $a_c = 20$ kJ/s.m^2.K; effective coefficient of heat exchange between air and metal $a = 20$ kJ/s.m^2.K; Coulomb metal-roll friction factor $\mu = 0.4$; Taylor–Quinny coefficient $k_\theta = 0.9$; a rule of metal nonlinear hardening $\sigma_p = \sigma_0 + K.\bar{\varepsilon}^n$, where parameter values are found using data of [4] – $\sigma_0 = 10^8$ N/m^2, $K = 1958$ and $n = 0.171$.

As it is said, we assign values to $\alpha_{1,0}$ (or $h_{1,0}$) and using relations (1) and (2) we find sets of values of $\alpha_{i+1,0}(h_{i+1,0})$ for $i = 1, \dots, 5$, checking for each specified value of $h_{1,0}$ whether the respective values of $h_{i+1,0}$ fall within the deformation area of the respective cell. Our next step is to find the actual neutral angles $a_{i,0}$ for each cell. For that purpose we solve the coupled thermo-mechanical problem of hot sheet rolling in Cell 1, as specified above. We employ the licensed FEM software MARC, using 4-node isoparametric finite elements with three degrees of freedom which account for displacements along axes x and y and temperature [1,14]. Then, we find from Fig. 3*a* the actual value of the neutral angle $\alpha_{1,0}$ for Cell 1, corresponding to the contact pressure maximum, and calculate via relations (1) the actual neutral angles for the rest of the cells. Figure 2 shows the distribution of the horizontal and vertical displacements, and the distribution of the equivalent plastic strain and strain rate in Cell 1. Figure 3 shows also the range of variation of $\alpha_{i,0}$ for each cell ($i = 1, 2, \dots, 6$).

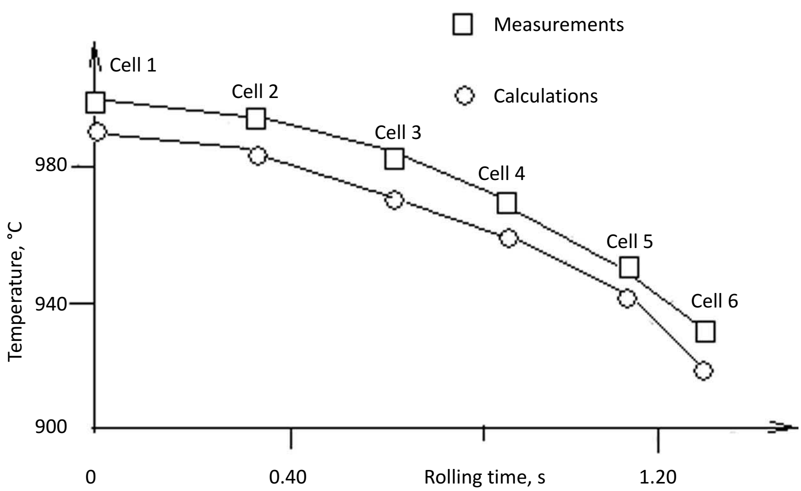
Having found $\alpha_{i,0}$ ($i = 1, \dots, 6$) we calculate metal speed distribution throughout the aggregate. Then, using that data we solve in general plain strain (GPS) the coupled thermo-mechanical problem of metal rolling [15] employing FEM software MARC (see also [16] for more details on the FEM computational efficiency in solving contact problems). The results are shown in Fig. 4.



a) Change of the equivalent plastic strain



b) Change of the equivalent plastic strain rate



c) Change of the sheet surface temperature throughout the mill

Fig. 4. Change of the basic quantities in time throughout the aggregate – MARC solution

Note Figure 4*c* which shows the calculated change of the metal surface temperature throughout the aggregate. As it is seen, the calculation results are commensurable with the experimental data submitted in [5]. Moreover, the comparison between patterns in Fig. 2 and those found in [1,5,6], for instance, shows acceptable agreement. Thus, the numerical solution of the coupled thermo-mechanical problem of hot rolling of a metal sheet in a multi-cell rolling mill is completed and verified.

5. Conclusions. The approach developed proves to be effective in finding the actual distribution of metal sheet speed within the whole mill when knowing the respective roll speed, only. As a result, the coupled thermo-mechanical problem of sheet rolling within a multi-cell mill can be successively solved, establishing satisfactory agreement between calculation results and experimental evidence. Last but not least, rolling kinetics analysis thus performed may be helpful in real time control of metal damage, cooling, speed, etc.

Note. Some of the results presented here have been reported at the Scientific Conference "65 Years Faculty of Machine Technology", 2010, Sozopol, Bulgaria, and the National Conference on Machine Design, Varna, 2010.

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