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Numerical analysis of the influence of rolling conditions on the microstructure evolution during hot rolling of aluminium alloy 5083 using a physical model

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Microstructure and hence the properties of aluminium respectively plates and sheets develop basically during hot rolling and depend strongly on the deformation conditions. The focus in this work is put on the numerical analysis of the influence of different friction coefficients between the billet and the lower as well as the upper roll on the evolution of the microstructure. A physical model based on internal state variables was implemented into the commercial FEM (Finite Element Method) program DEFORM to predict both the stored deformation energy, i.e. dislocation density, the subgrain structure during hot rolling as well as the statically recrystallized volume fraction after hot rolling of AA5083. To consider the retarding force of dispersed particles, the precipitation kinetics was investigated by means of the thermodynamic calculation software MatCalc. The critical value of the friction coefficient for the formation of inhomogeneous both microstructure and materials properties were determined by varying the friction boundary conditions in the simulations.

Keywords: *aluminium alloy 5083, microstructure modeling, asymmetrical hot rolling, friction.*

1. Introduction

The microstructure of hot rolled aluminium sheets depend on processing conditions [1-3], which can vary not only during hot rolling from pass to pass but also in the roll gap due to asymmetry. The asymmetry may be caused by variations in roll speed, roll diameter or roll surface conditions like different friction coefficients or different temperature between two work rolls [4-5]. It is an undesirable phenomenon in a rolled plate, and should be avoided. However at industrial conditions it is not possible to avoid the asymmetry completely. Hence the main objective of this work is the investigation of asymmetry conditions, which occur most frequently during industrial hot rolling: different friction coefficients because of a non-uniform wear of the work rolls as well as different temperatures of the rolls due to an irregular cooling.

The techniques of the microstructure modeling have been made great progress recently [6-9]. A physical based microstructure model implemented into the FEM program DEFORM was used to analyze the above named asymmetrical conditions. It is assumed that the parameters variability should not exceed 20%.

2. FEM model

The FEM was applied to simulate a single pass hot rolling of AA5083. The established model was validated by Sherstnev et. al. [10].

The material was rolled with initial temperature of 500°C in a mill with roll diameter of 100 mm. The roll temperature was varied between 80 and 100°C. The rotation speed of 1 rad/s was used. The initial slab thickness was reduced from 10 to 8 mm. After deformation the slab was held at temperature 15 s to investigate the static re-crystallization (SRX).

2.1 Friction behavior

The friction strongly influences the distribution of the shear strain and thus the recrystallization behavior near the surface [1].

The Tresca friction law was implemented in DEFORM to consider the sliding velocity between the work piece and the die:

$$\tau = -m\frac{\sigma_0}{\sqrt{3}}\frac{\Delta V}{|\Delta V|} \tag{1}$$

where σ_0 is the yield stress, m – the friction coefficient, ΔV – the velocity difference at the interface.

Duan reported that m=0.5 gives the best fit with the subsurface temperature whilst m=0.9 fits the centre temperature very well [1]. In the present work m=0.9 for the upper roll and m=0.75 for the lower roll were chosen.

2.2 Microstructural model

Physical based models, which consider dislocations, subgrain boundaries, precipitations and its interactions, are adequate for a realistic description of the microstructure evolution during and after hot rolling.

The approach to the modeling of dislocation density evolution during plastic deformation and dynamic recovery was investigated by Roters [11] including three dislocation classes. The physical model developed by Nes et al. [12] combined with the 3IVM from Roters, i.e. the following approximation for the total stored energy per unit volume was obtained to describe the subgrain structure evolution:

$$P_{\mathrm{D}} = \frac{G b^2}{4\pi(1-\nu)}\left(1-\ln\left(2b\sqrt{\rho_{\mathrm{in}}}\right)\right)\rho_{\mathrm{in}} + \frac{3\gamma_{\mathrm{SB}}}{\delta} \tag{2}$$

with G as the shear modulus, b as the Burgers vector, ν as the Poisson ration, ρ_{in} as the dislocation density in the cell interior and δ as the average subgrain size. The subgrain boundary energy γ is defined in present work as a function of the dislocation density in the cell walls:

$$\gamma_{\mathrm{SB}} = \left[\frac{G b^2}{4\pi(1-\nu)}\left(1-\ln\left(2b\sqrt{\rho_{\mathrm{w}}}\right)\right)\right]\sqrt{\rho_{\mathrm{w}}} \tag{3}$$

where ρ_{w} is the dislocation density in the cell walls.

The recrystallization kinetics was calculated by applying the assumptions of three nucleation sites according to Vatne [13] and a random distribution of nucleation sites:

$$X(t) = 1 - \exp\left[-\frac{4}{3}\pi N_{\mathrm{TOT}}(\Psi t)^3\right] \tag{4}$$

where $X(t)$ is the fraction recrystallised after an annealing time t, and N_{TOT} is the total number of nuclei. In according to Vatne [13] N_{TOT} after the 1st deformation pass is given by:

$$N_{\mathrm{TOT}} = N_{\mathrm{PSN}} + N_{\mathrm{C}} + N_{\mathrm{GB}} \tag{5}$$

with N_{PSN} as the density of nuclei at coarse particles (PSN), N_{C} as the density of cube-oriented nuclei and N_{GB} as the density of grain boundary nuclei.

The growth rate of a recrystallized grain Ψ is given by:

$$\Psi = m\left(P_{\mathrm{D}} - P_{\mathrm{Z}}\right) \tag{6}$$

where m is the grain boundary mobility, P_{D} the effective driving pressure determined by the amount of stored energy and P_{Z} the retarding Zener drag [14]:

$$P_{\mathrm{Z}} = \frac{3F_{\mathrm{V}}\gamma_{\mathrm{GB}}}{2r} \tag{7}$$

with F_{V} as the volume fraction of random distributed spherical particles of radius r and γ_{GB} as the grain boundary energy. Static recrystallization will occur only if the stored energy (i.e. subgrain size and dislocation density) outweighs the restraining forces of disperse precipitations.

The precipitation kinetics during homogenization treatment (500°C/10h) was calculated by applying the computational thermodynamics program MatCalc [15].

3. Modeling results

The through-thickness distribution of internal variables is chosen to characterize the influence of the asymmetry conditions. The cross-section of the rolled slab after passing the roll gap, exemplarily for the stored energy P_D is depicted in Fig. 1.

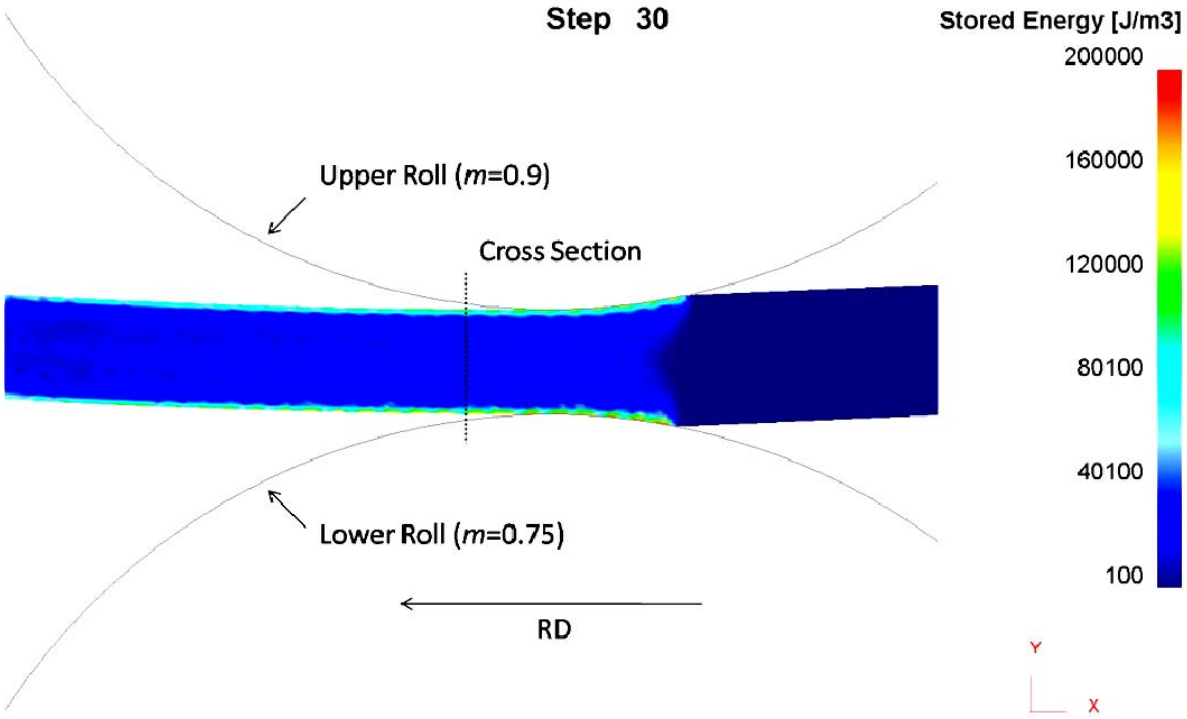

Fig. 1: Calculated distribution of stored energy during hot rolling of AA5083 with different friction coefficients. The dotted line shows the cross section for analyses of the through-thickness distribution of internal variables.

As shown in Fig. 2 and Fig.3 the stored energy P_D and the total number of nuclei N_{TOT} decrease in general from the surface to the centre. However the value of P_D and N_{TOT} at the contact surface with the upper roll (m=0.9) is somewhat smaller than at the contact with the lower roll (m=0.75). This small difference (20%) influences the static recrystallized fraction (Fig.4). The same cross-section was analyzed after holding time of 15s.

The temperature difference between the work rolls according to these calculations does not result in a significant difference of the microstructure evolution in the two surfaces.

Because of the distribution of N_{TOT} and P_D the microstructure recrystallized predominantly near the surface (~ 1 mm).

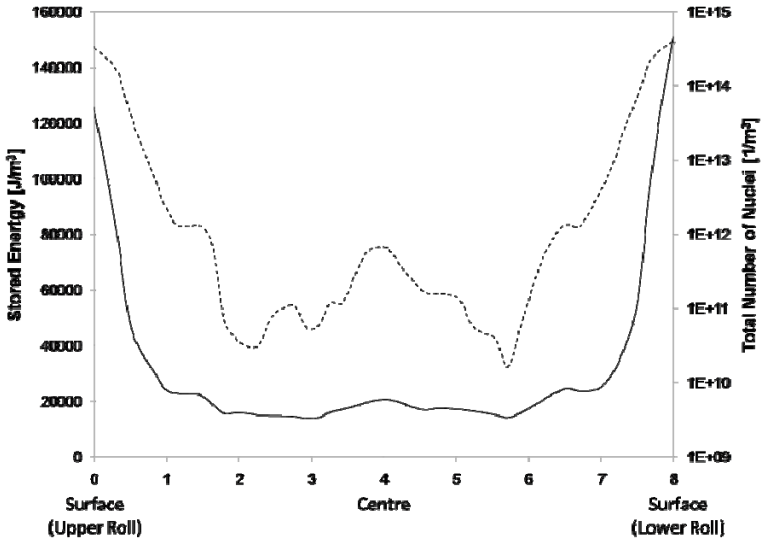

Fig. 2: Through-thickness distribution of the stored energy P_D (solid line) and the total number of nuclei N_{TOT} (dotted line) during hot rolling with different friction coefficients (Upper Roll *m=0.9* and Lower Roll *m=0.75*).

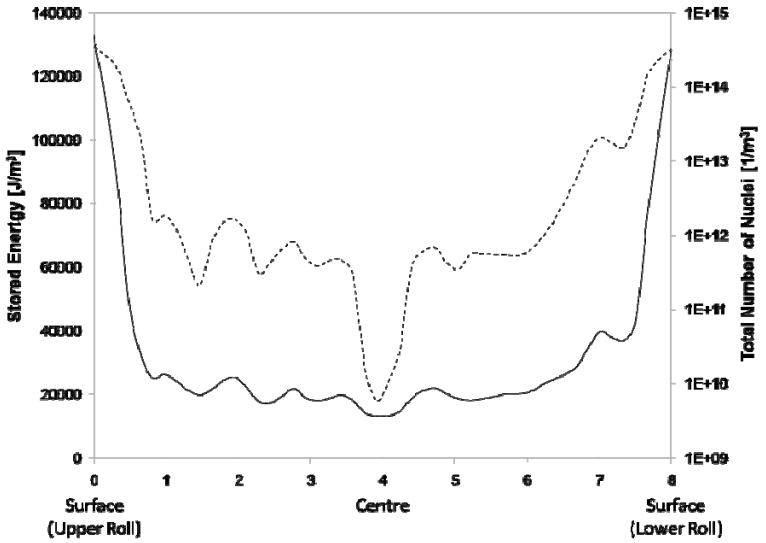

Fig. 3: Through-thickness distribution of the stored energy P_D (solid line) and the total number of nuclei N_{TOT} (dotted line) during hot rolling with different temperatures of the rolls (Upper Roll T=100°C and Lower Roll T=80°C).

The fluctuation of P_D in the centre causes different curves of N_{TOT} shown in Fig. 2 and Fig. 3. This can be explained by a cross-shear deformation zone between the backward-slip zone and the forward-slip zone [16]. The FEM calculation of the shear stress confirms this assumption (Fig. 5). The sample rolled with varying friction coefficients shows a higher value of the shear stress in the centre than the sample rolled with different roll temperatures.

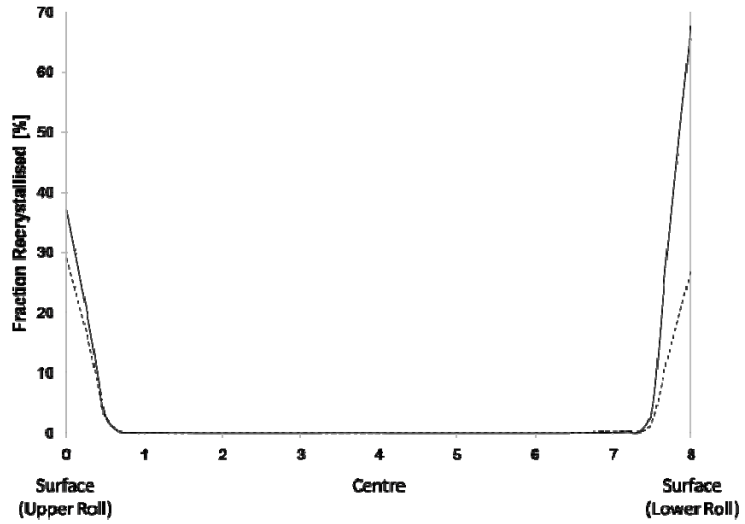

Fig. 4: Through-thickness distribution of the static recrystallized fraction $X(t)$ after holding time t=15s. Calculation with different friction coefficients (solid line) and with different roll temperatures (dotted line).

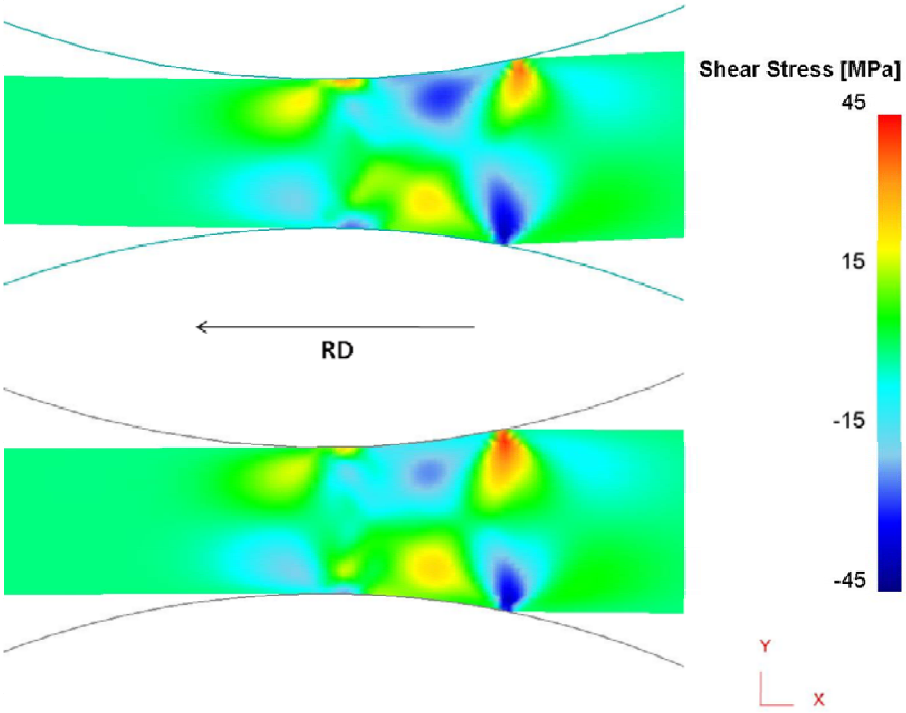

Fig 5: Distribution of the shear stress in the roll gap during hot rolling with different asymmetrical conditions: different friction coefficients (top) and different temperature (bottom).

4. Summary

The present work focused on the analysis of asymmetric conditions such as different friction coefficients as well as temperature difference between the work rolls during industrial hot rolling of aluminium alloys using a complex physical based model implemented into the FEM program DEFORM.

According to numerical analysis different friction conditions have more influence on the asymmetry of the microstructure evolution during hot rolling than the different roll temperatures.

The optimum shear deformation required to achieve a tailored recrystallized microstructure can be determined by varying friction coefficients.

Further systematical study of the asymmetrical effect caused by different friction conditions between the work rolls using physical approaches to describe the microstructure evolution during hot rolling of aluminium alloys, is necessary.

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