The effect of the initial rolling temperature on the microstructure evolution during and after hot rolling of AA6082

P. Sherstnev[1], I. Flitta[2], C. Sommitsch[1, 3], M. Hacksteiner[4], T. Ebner[4]

[1]*Christian Doppler Laboratory for Materials Modelling and Simulation, University of Leoben, Franz-Josef-Strasse 18, 8700 Leoben, Austria*
www.cdl-mms.at pavel.sherstnev@cdl-mms.at; christof.sommitsch@mu-leoben.at

[2]*Unitec Te Whare Wananga o Wairaka, Mount Albert, Private Bag, 92025 Auckland New Zealand*

[3]*Chair of Metal Forming, University of Leoben, Franz-Josef-Strasse 18, 8700 Leoben, Austria*

[4] *AMAG rolling GmbH, P. O. Box 32, Ranshofen, Austria*

ABSTRACT: In this study, the importance of the initial rolling temperature on the microstructure evolution during and after hot rolling of AA6082 was investigated. A commercial Finite Element Analysis (FE) package FORGE3 was used to predict through thickness thermal and deformation history of AA6082 undergoing multi-pass hot rolling. A physical model based on dislocation density, subgrain size and misorientation was used to calculate the grain size evolution and the recrystallized volume fraction after hot working. To validate the simulation results, homogenization and hot rolling experiments were performed. Homogenization was carried out in an air circulating furnace at temperatures of 550 and 580°C. The homogenized samples were hot rolled in multipass process with different start temperature on a laboratory mill. The outputs from the simulation were compared with the experimental measurements.

KEYWORDS: AA6082, Hot Rolling, Microstructure Evolution, Simulation

1 INTRODUCTION

The homogenisation of AA6082 is necessary in order to spheroidize plate like particles and to precipitate dispersoids [1, 2]. Subsequent hot deformation activates dynamic recovery and static recrystallization, which have an important influence on the rolled product properties [3]. As well as the initial microstructure and the chemical composition, thermal changes and the deformation history i.e. strain, the strain rate and temperature experienced by the material during hot rolling, are key features that define the microstructure changes such as recovery, recrystallization and grain growth. These microstructure changes include both dynamic i.e. dynamic recovery and recrystallization during deformation and static changes i.e. static recovery and recrystallization that occur in the inter-pass region and after rolling is completed.

The FE modelling of aluminium hot rolling, coupled with microstructure models, has been proven to predict the grain size distribution and the recrystallized volume fraction in the hot rolled material after single pass rolling [4, 5]. In the present work a FE microstructure model is applied to simulate multi-pass laboratory rolling in order to investigate the influence of initial rolling temperature and inter-pass time on the microstructure evolution of AA6082. The numerical calculation helps to optimize the hot rolling process with regard to product properties.

2 EXPERIMENTAL PROGRAM

2.1 Homogenization and hot rolling experiments

The cast material, aluminium alloy 6082 (delivered from AMAG rolling GmbH, Table 1), was homogenized in an air circulated furnace at temperatures of 550 and 580°C for 10h in order to investigate the influence of different homogenization temperatures on the subsequent grain structure evolution.

Table 1: Chemical composition of AA6082 in weight per cent

Si	Mn	Zn	Fe	Mg
1.1-1.2	0.45-0.55	<0.1	<0.3	0.75-0.85
Ti	Cu	Cr	Al	
<0.05	0.05-0.1	<0.15	bal.	

The homogenized samples (19x150x150mm) were hot rolled in multipass process at two different initial temperatures (550 and 580°C) on a laboratory mill. The experimental pass schedule is shown in table 2. The rolling speed was set constant at 0.4m/s.

Table 2: Pass schedule

Pass	reduction per pass, %
1	10
2	15
3	20
4	30
5	40

The inter-pass time was fixed to 5 seconds. To preserve the achieved microstructure of the plate after hot rolling, it was quenched with water with a manipulation time of approximately 3 seconds.

The temperature was measured with a pyrometer in the plate centre after each pass. The result is given in table 3.

Table 3: History plot of the measured temperature during hot rolling after homogenizations at 550 and 580°C

Passes	550°C	580°C
1	491	520
2	439	461
3	384	421
4	340	358
5	318	338

2.2 Investigation of the substructure evolution

Samples were upset at varying Zener-Hollomon parameter *Z* to true strains of 0.8 and subsequently were quenched by water.

EBSD-analyses were applied in order to investigate the subgrain structure evolution as a function of *Z*. Figure 1 depicts the decreasing steady state subgrain size δ_{ss} with increasing *ln(Z)*. Hence follows the relationship between the subgrain size and the deformation parameters in the steady-state regime

$$\delta_{ss}^{-1} = -0.8274 + 0.0318 * LnZ \qquad (1).$$

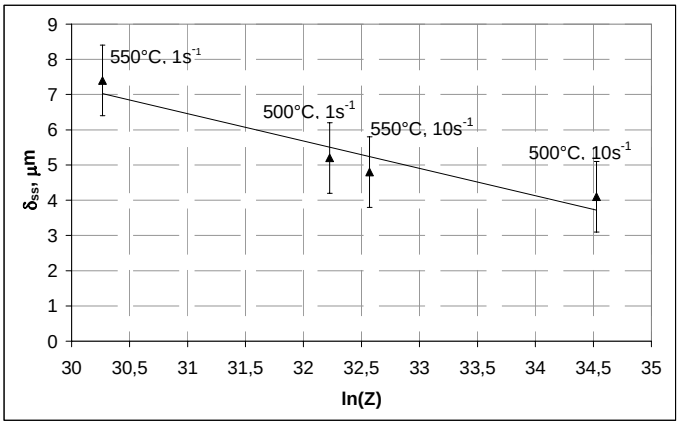

Figure 1: Subgrain size as a function of Zener-Hollomon parameter for AA6082

3 FE SIMULATION AND MICROSTRUCTURE MODEL

In this section a fully thermomechanical 3D FE model is adopted using FORGE3 according to the experimental procedure outlined in section 2.1. Due to the geometrical symmetry, a quarter of the plate is modelled. A very fine element size is applied to reduce any possible error caused by the mesh. Simulation has been carried out to study the substructure evolution in two dimensions.

Figure 2 presents the finite element analysis model. The workpiece is initially pushed into the roll gap by a punch. Once the net frictional force is large enough to draw the workpiece into the roll gap, the workpiece and the punch separate. A Tresca friction factor of 0.6 was used. A heat transfer coefficient between the roll and the plate of 18kWm^{-2}K^{-1} was chosen [4].

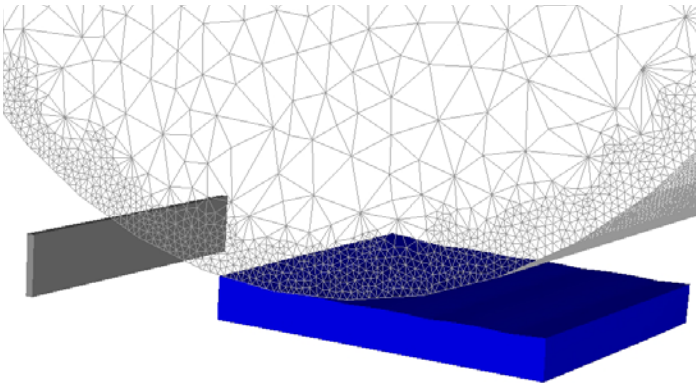

Figure 2: Finite element analysis model with the symmetrical quarter of the plate, the pushed and the roll

The material behavior is described by the following constitutive equation:

$$\sigma_p = \arcsin h\left(\frac{1}{A} Z^{1/n}\right)\frac{1}{\alpha} \quad (2),$$

and

$$Z = \dot{\varphi}\exp\left(\frac{Q}{RT}\right) \quad (3),$$

where σ_p is the peak stress and T, R as well as $\dot{\varphi}$ have their usually meanings.

The material constants α, n, Q and A (table 4) were found using regression analysis of flow curves of AA6082.

Table 4: Constants for the constitutive equation

Alloy	α	n	Q[J/mol]	A
AA6082	0.002	9.209	148587	$1.684*10^{19}$

The relationship between the volume fraction statically recrystallised X_v and the holding time t is generally represented by the Avrami equation

$$X_v = 1 - \exp\left(-0.693\left(\frac{t}{t_{50}}\right)^k\right) \quad (4),$$

where k is the Avrami exponent with a commonly reported value of 2 and t_{50} is the time to 50% recrystallization. For the calculation of t_{50}, a physical model is regarded as revealing the mechanics driving the transformation. For the physical model [4], t_{50} is calculated based on the stored energy P_D and the density of recrystallization nuclei N_V

$$t_{50} = \frac{C}{M\,P_D}\left(\frac{1}{N_V}\right)^{1/3} \quad (5),$$

where M is a grain boundary mobility and C is a material constant. The stored energy is approximated by

$$P_D = \frac{Gb^2}{10}\left[\begin{array}{l}\rho_i\left(1-\ln(10b\rho_i^{\frac{1}{2}})\right)+\\ \frac{2\theta}{b\delta}\left(1+\ln\left(\frac{\theta_c}{\theta}\right)\right)\end{array}\right] \quad (6),$$

G is the shear modulus, b is the Burger's vector, ρ_i is the internal dislocation density, θ is the misorientation and θ_c is the critical misorientation for a high angle boundary (15°). The evolution of δ, ρ_i and θ is given by

$$d\delta = \frac{\delta}{\varepsilon_\delta \delta_{ss}}(\delta_{ss} - \delta)d\varepsilon \quad (7),$$

$$d\theta = \frac{\theta}{\varepsilon_\theta}(\theta_{ss} - \theta)d\varepsilon \quad (8),$$

and

$$d\rho_r = d\rho_r^+ + d\rho_r^- = (C_1\rho_r^{1/2} - C2\frac{\overline{\sigma}}{Z}\rho_r)d\varepsilon \quad (9),$$

where δ_{ss} and θ_{ss} are respectively the subgrain size and misorientation at steady-state deformation, ε_δ and ε_θ are characteristic strains, ρ_r is the random dislocation density, σ_f is the flow stress, C_1 as well as C_2 are constants.

The initial dislocation density consists of two parts – ρ_r and ρ_g, which is the geometrical necessary dislocation density [4]

$$\rho_i = \rho_r + \rho_g \quad (10)$$

For site saturated nucleation, the recrystallized grain size is simply approximated by

$$d_{rex} = D(N_V)^{-1/3} \quad (11),$$

where D is constant.

4 GRAIN STRUCTURE COMPARISON BETWEEN EXPERIMENT AND SIMULATION

The Figure 3 shows the resulting subgrain structure in the plate center by EBSD-nalysis after the last pass. The elongated grains are located in the rolling direction. At the grain boundaries the nucleation of recrystallized grains is observable.

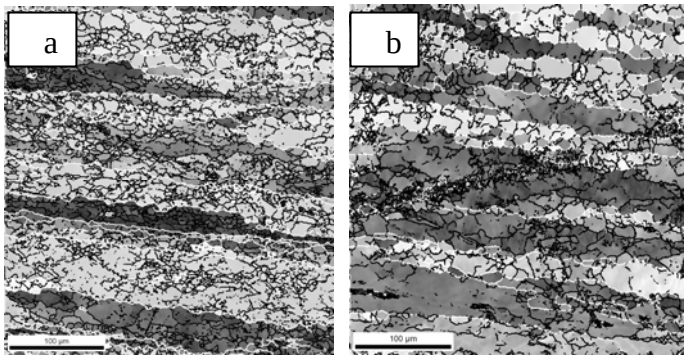

Figure 3: Subgrain structure analysis by EBSD. Low angle boundaries in black, high angle boundaries in white. Initial rolling temperature of a) 550°C and b) 580°C

From EBSD-analysis the measured average subgrain sizes after the last pass were determined (table 5).

Table 5: Measured subgrain size after the last pass, δ_{ss} [μm]

Initial rolling temperature [°C]	δ_{ss}
550°C	2.6
580°C	3.2

In Figure 4 the calculated subgrain size evolution during the last pass is depicted experimentally for an initial temperature of 550°C. Due to the contact between the roll and the plate the latter cools down, hence the subgrain size decreases. When the plate temperature increases and stabilizes because of dissipation of deformation energy, the subgrain size reaches a steady state.

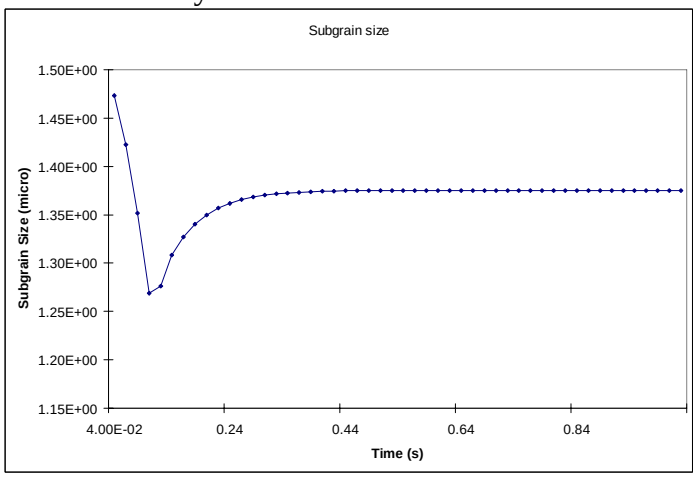

Figure 4: Subgrain size evolution in the plate center during pass 5 for an initial rolling temperature of 550°C

The statically recrystallized volume has been analysed by light microscopy (Figure 5), therefore samples were cut from the plate center, grinded, polished and etched according to Weck (1. *90ml H_2O, 10ml H_3PO_4*; 2. *100ml H_2O, 4g $KMnO_4$, 1g NaON*)

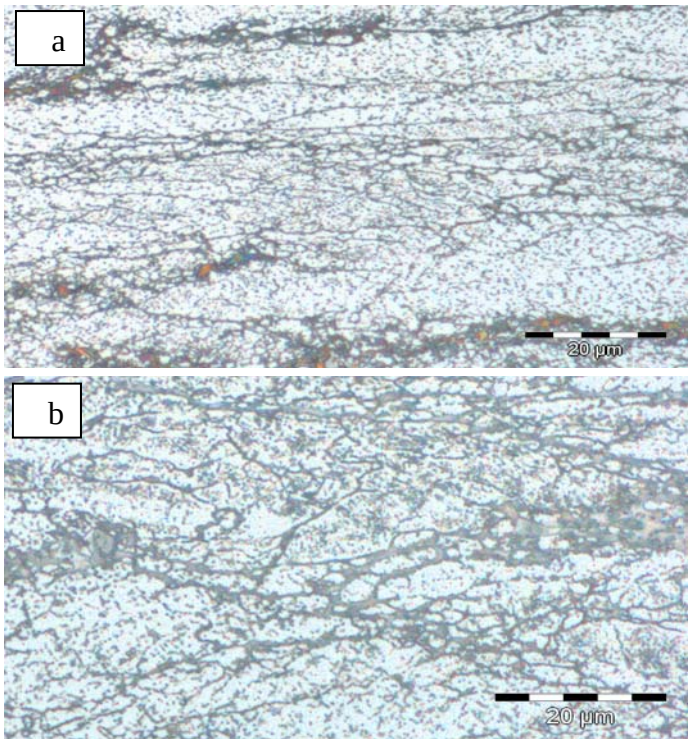

Figure 5: Microstructure in the rolled plate center after the last pass at an initial rolling temperature of a) 550°C and b) 580°C. Statically recrystallized grains are located at elongated deformed grains

The microstructure after the last pass indicates the beginning of statically recrystallization (<10%), whereas at 580°C the recrystallization apparently is more advanced. The calculations from the physical model also show the onset of static recrystallization, however with even smaller volume fractions (<1%).

5 SUMMARY

In this work, the effect of the initial rolling temperature on the microstructure evolution during and after hot rolling of AA6082 was described. A commercial FEM package FORGE3 was used to predict the subgrain structure evolution during rolling as well as the grain structure development after multi-pass hot rolling.

It was shown that the homogenization temperature, i.e. the initial rolling temperature has a reasonable influence on the final grain structure, because the subgrain structure strongly influences the subsequent statically recrystallization. Both calculations and experimental analysis indicate a rather smaller amount of statically recrystallization.

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