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Modeling of Microstructure Evolution during Multi-pass Rolling for AA5083 using a Physically Based Approach Integrating FE Model Predictions

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Abstract

A model has been developed to predict the thermomechanical and microstructural changes that occur during multi-pass hot rolling for an AA5083 aluminum alloy. Microstructure evolution during multi-pass rolling was modeled using a physically based approach to predict the evolution of the material stored energy and the resulting microstructure changes. Various approaches were employed to account for the change in the material stored energy, which acts as a driving force for recrystallization, in the inter-stand region. Model predictions of the time to achieve 50% recrystallization ($t_{0.5}$), were compared using different approaches to accumulate stored energy.

1. Introduction

The microstructure evolution in aluminum alloy strip during hot rolling is linked to complex interactions between the thermal and mechanical phenomena in the process and the metallurgical response of the material. In order to comprehend these interactions and to develop optimal processing strategies, it is desirable to develop knowledge-based process models which incorporate microstructure equations to provide a scientific understanding of the hot rolling operation**.** Although the rolling process is an intermediate process in the sheet processing, usually followed by cold rolling and coiling, control of the microstructure during hot rolling assumes critical importance as it can have a direct influence on the final sheet properties [1]. Towards this goal, the material behavior during deformation as well as after the deformation is completed should be understood quantitatively so that factors that affect the final aluminum sheet properties can be understood [2]. Physically based mathematical models have been developed to predict the microstructure evolution at each stage of the rolling process and hence achieve a greater understanding of the effect of the process variable on the final microstructure [3, 4].

In this paper, a mathematical model which was developed and validated to predict the microstructure evolution for single pass hot rolling operations is extended to multi-pass operations in which complete, partial, or no recrystallization may occur between the deformation steps. In this model, the deformed microstructure was described in terms of an average subgrain size, δ, an average misorientation angle between the subgrains, θ, and the average dislocation density inside the subgrains, ρ_i, which represent the stored energy in the material and acts as a driving force for recrystallization [5]. The recrystallization behaviour of the material in the inter-pass region can then be predicted based on knowledge of the deformation history during each pass and the thermal history experienced by the material after deformation is complete. A challenging aspect in modeling multi-pass deformation schedules for AA5083, is that recrystallization is often not complete between hot rolling passes and hence the correct accumulation of stored energy in situations where no, partial or complete recrystallization occurs between the passes is critical.

2. Mathematical Model

2.1 Finite Element (FE) Model

A 2D rolling model has been developed to simulate multi-pass hot rolling schedules for aluminum alloys based on the commercial Finite Element (FE) software package, ABAQUS^{TM}. As shown in Figure 1, the rolling model consists of a portion of the work roll and, due to symmetry along the centerline of the strip, only the top half of the strip. In both the strip and work roll, 4 node bilinear plane strain elements were used [6]. The first pass of the rolling process includes rolling the aluminum sheet in one direction and holding the sheet after the first deformation pass was complete for a certain periods of time. A second deformation pass was then applied in the reverse direction where the roll velocity was doubled in the second pass. In order to model the temperature change in the strip, a convection heat transfer coefficient of 4.5 W/m^2 °C and an emissivity of 0.09 were employed in the inter-stand region [7]. Details of the model development and its validation for single-stand rolling are discussed in previously published works[4, 6].

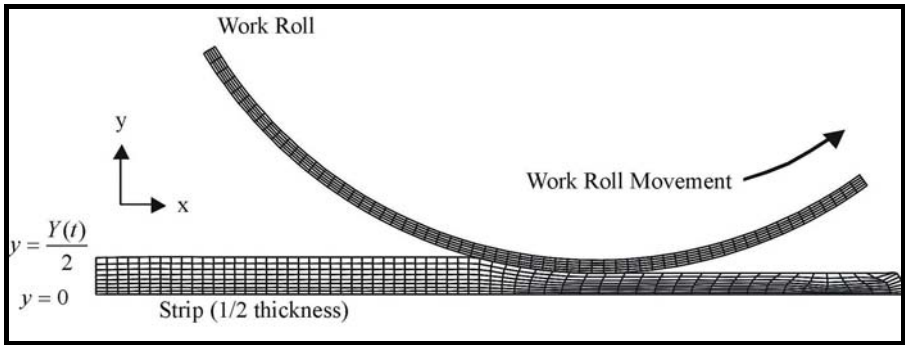

Figure 1: Geometry of the hot rolling model developed using ABAQUS^{TM}.

2.2 Internal State Variable Microstructure Model

The microstructure model adapts an internal state variable approach described by Sellars *et al.* [8], where microstructure evolution processes such as recrystallization are related to the

stored energy that develops in the material during deformation. In this model, the key feature to quantify this stored energy in the material after hot deformation is the dislocation substructure, which is described by three internal state variables, namely, the internal dislocation density (ρ_i), the average subgrain size (δ) and the average misorientation angle across the subgrain boundaries (θ) [9]. The microstructure model was linked to the FE model by using the FE model-predicted incremental strain and average Zener Holloman parameter (Z), where $\left(Z = \dot{\varepsilon} \exp\left(\frac{145101}{RT_{def}} \right) \right)$, at nodes through the strip thickness as inputs to the microstructure model. Details of the integration and validation of the thermo mechanical FE and microstructure for a single-pass rolling case can be found in [10]. The relationship between the fraction recrystallized (X_v) and the hold time (t) can be represented by the Johnson-Mehl-Avrami-Kolmogorov (JMAK) relation [5]. The principle of additivity is applied in the inter-pass region or after rolling is complete as the temperature of the strip decreases continuously as a function of time. Under these conditions, the application of a temperature compensated time parameter, W, is employed as shown in Equations 1 - 3. Using these equations, the fraction recrystallized, $X_{v,}$ can be predicted based on the thermal history experienced by the material after hot deformation.

$$X_V = 1 - \exp\left(-0.693 \cdot \left(\frac{W}{W_{0.5}} \right)^n \right) \tag{1}$$

$$W = \sum_i \partial t_i \cdot \exp\left(\frac{-Q_{rex}}{RT_i} \right) \tag{2}$$

$$W_{0.5} = t_{0.5} * \exp\left(\frac{-Q_{rex}}{RT_a} \right) \tag{3}$$

where W (in s) is the temperature compensated time parameter, T_a (in K) is the temperature the strip equilibrates to after exiting the roll pass, t_i is the time interval during which the slab has a temperature of T_i and Q_{rex} is the activation energy for recrystallization which was assumed to be 183 KJ mol^{-1}.

In this paper, a law of mixtures was used to determine the initial entry value to the second rolling pass of the strains, dislocation density, average subgrain size and average misorientation angle between the subgrains. These relations are illustrated in Equations 4-7.

$$\varepsilon_2^{eff} = X_1 \varepsilon_{rx} + (1 - X_1)\varepsilon_1 \tag{4}$$

$$\rho_2^{eff} = X_1 \rho_{rx} + (1 - X_1)\rho_1 \tag{5}$$

$$\delta_2^{eff} = X_1 \delta_{rx} + (1 - X_1)\delta_1 \tag{6}$$

$$\theta_2^{eff} = X_1 \theta_{rx} + (1 - X_1)\theta_1 \tag{7}$$

Where the numbers 1 and 2 represent the 1st and 2nd pass, respectively. Recrystallized grains were assumed to exhibit the following characteristics: ε_{rx} equal to 0, ρ_{rx} equal to 1x 10^{-11} m^{-2}, δ_{rx} equal to 1x10^{-6} m and θ_{rx} equal to 0°.

Several approaches were investigated in order to understand and predict the accumulation of stored energy in multi-pass rolling. In the first case, the stored energy was calculated by accumulating the aforementioned variables in the material during both the first and second passes where the fraction recrystallized before the entry to the 2nd roll bite X_1 is assumed to be equal to zero. In the second case, the stored energy was calculated based on the accumulation of the previous variables only during the second pass, hence X_1 is assumed to be equal to 1. For the third case, a law of mixtures was applied to predict the initial entry values of strains, dislocation density, average subgrain size and average misorientation angle between subgrains where X_1 is assumed to be equal to the predicted fraction recrystallized before 2nd pass rolling which varied from 11.44% at the center to 66.5% at the surface.

3. Plant Trial

An experimental program was undertaken using the Corus single-stand reversible rolling facility located in IJmuiden, Netherlands. The experimental work was carried out on a commercially significant aluminum alloy, AA5083 which was instrumented with a thermocouple at its centerline [4, 6]. As shown in Table 1, a two-pass rolling experiment was carried out such that the second pass had a higher *Z*-value as compared to the first one, typical of an industrial rolling schedule. After exiting the second pass the sample was quenched immediately.

Table 1: Conditions used for the multi-pass rolling trial using CORUS pilot rolling mill.

Pass number	ε	Average $\dot{\varepsilon}$ (s^{-1})	T_{entry} (°C)	*Z* value*	Inter-stand time (s)	Model-predicted fraction recrystallized entering 2nd pass (%)	
1	0.30	~6	466	1.08 x10^{11}	18.3	Center	Surface
2	0.34	~13.5	405	2.03x10^{12}	---	11.4	66.5

* Entry temperature (T_{entry}) and average strain rate value ($\dot{\varepsilon}$) are used to calculate *Z*.

4. Results and Discussion

4.1 Temperature Validation

Figure 2 shows the predicted centerline temperature compared to the measured data for sample No.1. during multi-pass rolling.

The centerline temperature shows 2 peaks during the rolling process corresponding to the first and second passes of the rolling schedule, which is attributed to the heat released during plastic deformation. As shown in Figure 2, the model predictions fit the measured data well at the centerline of the strip both during rolling and in the inter-stand region.

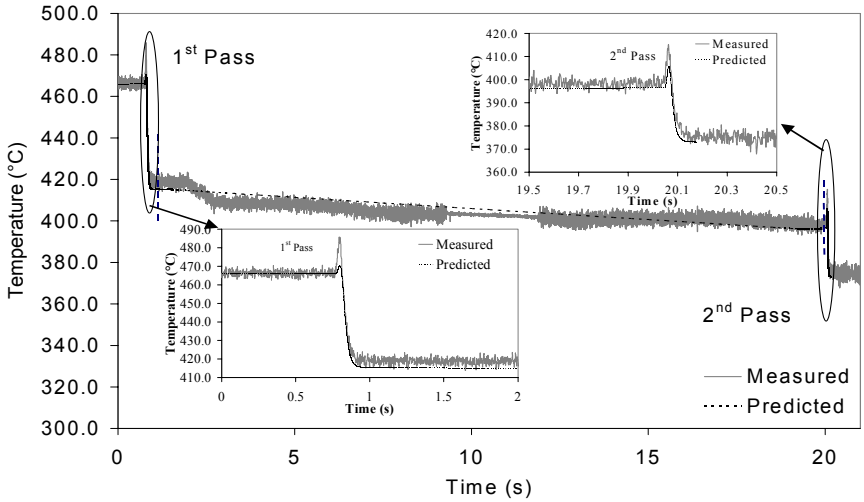

Figure 2: Comparison of ABAQUS predicted centerline temperature during 2-pass rolling to experimental measurements for sample No. 1.

4.2 Microstructure Evolution

The material stored energy was characterized in terms of the time required to achieve 50% recrystallization. A comparison between the model-predicted time to achieve 50% recrystallization for the aforementioned cases is shown in Figure 3.

Figure 3 shows that the first case represents an upper bound to the time required for 50% recrystallization as only the deformation in the second pass is considered. case 2 represents a lower bound for the time required for 50% recrystallization as the strains and dislocation density were accumulated in both the first and second pass and hence this case would have the highest driving force for recrystallization. For case 3, where a law of mixtures is used, the predicted time to achieve 50% recrystallization falls between case 1 and case 2 with the model-predictions being closer to case 2 since very little recrystallization occurred prior to the second pass.

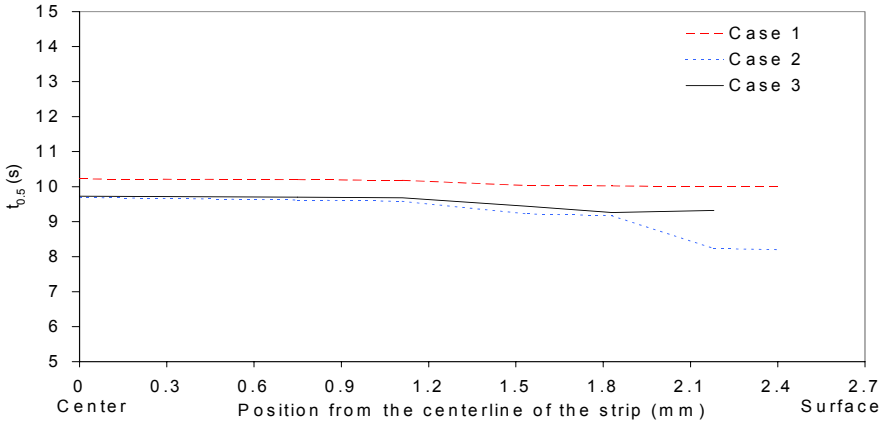

Figure 3: Comparison of predicted time to achieve 50% recrystallization using different approaches.

Both case 1 and case 2 predict a decrease in the $t_{0.5}$ from the centre to the surface of the strip consistent with the higher strain rates, higher strains and lower deformation temperatures occurring at the surface. For case 3, the model-predicted $t_{0.5}$ deviates from the behaviour exhibited by cases 1 and 2 by showing an increase within 1mm of the strip surface. This behaviour is consistent with a higher level of recrystallization in this region prior to the second pass as compared to the centre of the strip and hence lower driving force after pass 2.

5. Summary and Conclusions

This paper outlined the development of a model that integrates the predictions of an FE rolling model with an internal state variable microstructure model to simulate industrial multi-pass hot rolling of an AA5083 aluminum alloy. Various approaches were compared to investigate different methods to accumulate stored energy in the strip during a two step deformation operation. These included: 1) summing the stored energy from the first and second deformation steps, 2) using the stored energy from the second or last deformation step and 3) using a law of mixtures between the first and second deformation steps based on the amount of recrystallization prior to the second deformation step.

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