Modeling of Microstructural Evolution During the Hot Rolling of Aluminum Alloy

H. R. Rezaei Ashtiani, H. Bisadi, M. Adabjou

Abstract – In this work, a numerical-based model has been proposed to calculate distributions of temperature, strain and inhomogeneity of effective strain through the strip thickness during hot rolling as well as the subsequent microstructural changes after hot rolling of an aluminum alloy. This study presents the application of the finite element method to simulation of microstructural mapping. To assess the hot rolling behavior of materials, finite element program DEFORM™ has been employed, here. These models include the effects of deformation temperature, applied strain (reduction), interface friction and cooling time on gradient of effective strain and inhomogeneity of static recrystallisation volume fraction. Results of simulation show that recrystallization will be increased by increasing of reduction (i.e. strain), temperature, and maintenance time duration after rolling. An important problem in modeling of microstructure is Microstructural gradient during thickness of rolled strip. Ingredient of this inhomogeneity has been investigated here, so that, simulation shows that strain and temperature inhomogeneity more effective rather than other impressive elements, on microstructural inhomogeneity. Copyright © 2010 Praise Worthy Prize S.r.l. - All rights reserved.

Keywords: Hot Rolling, Simulation, Microstructure, Effective Strain, Recrystalization, Temperature Distribution, Finite Element Method

Nomenclature

\( T \) \hspace{1cm} Temperature(°C or K)
\( k \) \hspace{1cm} Thermal conductivity (W m\(^{-1}\) °C\(^{-1}\))
\( \rho \) \hspace{1cm} Density (kg m\(^{-3}\))
\( c_p \) \hspace{1cm} Specific heat (J kg\(^{-1}\) °C\(^{-1}\))
\( \sigma \) \hspace{1cm} Effective flow stress (MPa)
\( \varepsilon \) \hspace{1cm} Effective strain rate (s\(^{-1}\))
\( \eta \) \hspace{1cm} Efficiency of conversion of deformation energy to heat
\( \tau_c \) \hspace{1cm} Critical shear stress (MPa)
\( \mu \) \hspace{1cm} Coefficient of friction
\( \dot{\varepsilon}_{ss} \) \hspace{1cm} Mean equivalent plastic strain rate of steady state (s\(^{-1}\))
\( \sigma_{ss} \) \hspace{1cm} Mean equivalent stress of steady state (MPa)
\( Q_{def} \) \hspace{1cm} Activation energy for deformation (kJ mole\(^{-1}\))
\( R \) \hspace{1cm} Universal gas constant (=8.314 J mol\(^{-1}\)K\(^{-1}\))
\( \rho_c \) \hspace{1cm} Critical value of dislocation density
\( \varepsilon_c \) \hspace{1cm} Critical strain corresponding to beginning of recrystallisation
\( \varepsilon_p \) \hspace{1cm} Strain corresponding to the flow stress maximum
\( \varepsilon_{ss} \) \hspace{1cm} Strain of steady state
\( d_0 \) \hspace{1cm} Initial grain size(m)
\( t \) \hspace{1cm} Time (s)
\( X_{drex} \) \hspace{1cm} Fraction of dynamic recrystallisation (%)
\( X_{srex} \) \hspace{1cm} Fraction of static recrystallisation (%)
\( t_{0.5} \) \hspace{1cm} Time for 50% recrystallisation (s)
\( \dot{\varepsilon} \) \hspace{1cm} Strain rate (s\(^{-1}\))
\( \varepsilon \) \hspace{1cm} Strain

I. Introduction

During hot deformation operations such as forging, rolling and extrusion, the workpiece undergoes continuous changes in the strain rate and temperature during straining. Such changes have a significant effect on the evolution of the microstructure and subsequent recrystallisation behaviour.

Several types of hot rolling models have been developed recently by lot of authors [1]-[4]. These generally predict the roll force and power, the microstructural changes taking place during hot rolling, and the final mechanical properties.

The FEM now provides sufficient flexibility to solve many ‘mechanical’ problems. They include load, temperature and structure prediction. Since the beginning of the 1990s, much progress has been made in computer modeling of microstructure evolution during the hot deformation process [5].

The FE modeling 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.

Modeling the microstructural evolution in aluminium alloys during hot deformation, in which static recrystallisation (SRX) plays a major role, has proved to be a difficult task. Different physically-based models have been developed in which recrystallisation is analysed in terms of nucleation and growth.

The internal state variables used in these phenomenological models are the main factors that control the flow stress and recrystallisation kinetics of the material, that finally are used to predicate roll load and torque and also mechanical and microstructural properties of finished rolled part.

As has been illustrated in Fig. 1, the interactions between stress/strain, temperature and microstructure during hot deformation are very complex.

Fig. 1. schematic illustrating complex relationship between stress/strain, temperature and microstructure

Much previous modeling work by the use of FEM has over predicted microstructural properties and the fraction recrystallized at the surface and/or center region (with out investigation of inhomogeneity through thickness) [2]. In this paper, effects of processing parameters on inhomogeneity of thermo-mechanical (like effective strain and temperature) and microstructural through thickness of rolled strip by modeling and simulation are studied.

II. The Finite Element Model

To assess the hot rolling behavior of materials, finite element program DEFORM™ has been employed. The microstructure (recrystallization volume fraction, grain size, ..) distribution along the rolled strip is predicted. For this purpose, the effects of various process parameters such as amount of thickness reduction, initial temperature, interface friction of the strip and roll and cooling time after rolling, is considered, and their effects on inhomogeneity of effective strain and temperature through thickness and result of them on microstructure and inhomogeneity of static recrystallisation volume fraction for AA5083 was investigated by simulation.

II.1. Thermal Boundary Conditions

In order to find the temperature distribution in the strip, the governing heat conduction equations for both the strip and the work-rolls are solved iteratively. Because the thermo-physical characteristics and the flow stress are assumed to be functions of temperature, in each iteration, it is required the thermo-physical properties to be updated. The governing equation for the steady state conditions is assumed to be a convection/conduction equation.

During the rolling process, the temperature distribution in the strip and the work roll can be calculated using the governing partial differential equation (2D) shown in Eq. (1) [5].

\[
\frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k \frac{\partial T}{\partial y} \right) + \dot{q} = \rho c_p \frac{\partial T}{\partial t}
\]

where \( x \) is the distance along the length of the strip, \( y \) is the distance through the thickness of the strip and \( \dot{q} \) (in \( \text{W m}^{-3} \)) is a heat generation term representing the heat released due to plastic work. The heat generation term; \( \dot{q} \) is calculated using Eq. (2) [6].

\[
\dot{q} = \eta \sigma \varepsilon
\]

where \( \eta \) is the efficiency of conversion of deformation energy to heat; the latter is assumed to be 0.95 for aluminum alloys, which is considered reasonable.

II.2. Mechanical Boundary Conditions

A contact boundary condition describing the mechanical interaction of the strip and the roll was imposed along the strip/roll interface. Interfacial friction for the contact area is proportional to the normal force as shown in Eq. (3):

\[
\tau_c = \mu P
\]

Coefficient of friction comes from test conditions. For this study, static friction has been assumed without transition to or from dynamic friction conditions. Deformation symmetry in the strip is maintained through a zero displacement boundary condition in the through thickness direction along the strip centerline. This allows the reduction in geometric complexity and reduces computational time.

The roll gap and rolling speed are introduced in the model by applying a displacement and rotational velocity to a pilot node lying at the center of the roll.
II.3. Material Properties

The strip is assumed to behave as a thermo–elasto viscoplastic material with temperature dependent elastic modulus and Poisson’s ratio. The range of temperatures, strains and strain rates experienced by the material during the rolling process is large, hence it is necessary to define the plastic behavior of the strip as a function of temperature, strain and strain rate.

This was done using a hyperbolic sine equation, shown in Eq. (14), which relates the steady state flow stress of the material to the strain rate and temperature under which it is deformed [7]:

\[
\dot{\varepsilon}_{ss} = A \left( \sinh (\alpha \sigma_{ss}) \right)^m \left( \frac{Q_{def}}{RT_{def}} \right)
\]

(4)

where \(A\), \(\alpha\) and \(m\) are material constants and \(T_{def}\) is deformation temperature. The coefficients of the hyperbolic sine equation for AA5083 deformation are summarized in Table I [8].

<table>
<thead>
<tr>
<th>Table I</th>
<th>Summary of Hyperbolic Sine Constants for AA5083 [8]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>(2.87 \times 10^1)</td>
</tr>
<tr>
<td>(\alpha) (1/Mpa)</td>
<td>0.04</td>
</tr>
<tr>
<td>m</td>
<td>2.26</td>
</tr>
<tr>
<td>(Q_{def}) (kJ/mol)</td>
<td>162.5</td>
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</table>

II.4. Microstructure Model

In this Simulation, microstructural changes comprises of two more important parts dynamic and static recrystallisation, same has been illustrated for the microstructure changing during hot rolling in Figs. 2.

The dynamic recrystallization (DRX) is a function of strain, strain rate, temperature, and initial grain size, which change in time. It is very difficult to model dynamic recrystallization concurrently during forming. Instead, the dynamic recrystallization is computed in the step immediately after the deformation stops. Average temperatures, strain rate of the deformation period are used as inputs of the equations.

Figs. 2(a) and (b) show the schematic diagrams of the microstructure development during hot rolling: the original grains are deformed and elongated as the slab is reduced between the two rolls. During this period, continuous deformation causes dislocation accumulation. If the dislocation density increases above the critical value required for DRX, \(\rho_c\) (corresponding to \(\varepsilon_c\)), which is dependent on the deformation conditions, new DRX nuclei will be generated on the elongated boundaries of the original grains and begin to grow as shown in Fig. 2(a). Otherwise, SRX is expected to occur in the strip while dwelling in the inter-pass zone as demonstrated in Fig. 2(b).

Corresponding to Eq. 7, the Avrami equation is used to describe the relation between the dynamically recrystallized fraction \(X_{drex}\) and the effective strain. Where \(\varepsilon_{0.5}\) denotes the strain for 50% recrystallization (Eq. 8):

\[
X_{drex} = 1 - \exp \left[ -t \left( \frac{\varepsilon - \varepsilon_{0.5}}{\varepsilon_{0.5}} \right)^k \right]
\]

(7)

\[
\varepsilon_{0.5} = a_5 \dot{\varepsilon}_{0.5} \exp \left( \frac{Q_s}{RT} \right)
\]

(8)

When deformation stops, the strain rate and critical strain are used to determine whether static or meta-
dynamic recrystallization should be activated. The static and metal-dynamic recrystallization is terminated when this element starts to deform again. When strain rate is less than \( \dot{\varepsilon}_{ss} \) (Eq. (9)), static recrystallization occurs after deformation:

\[
\dot{\varepsilon}_{ss} = A \exp \left( b_1 - b_2 d_0 - \frac{Q_s}{T} \right)
\]  
(9)

The model for recrystallization kinetics is based on the modified Avrami (JMAK) equation (Eq. (10)). Where \( t_{0.5} \), similar to Eq. (11), is an empirical time constant for 50% recrystallization:

\[
X_{\text{rec}} = 1 - \exp \left[ -\beta \left( \frac{t}{t_{0.5}} \right)^{\beta} \right]
\]  
(10)

\[
t_{0.5} = a_3 d_0^{b_3} \dot{\varepsilon}^{b_4} \varepsilon^{m_3} \exp \left( \frac{Q_3}{RT} \right)
\]  
(11)

As shown by Eq. (12) the recrystallized grain size is expressed as a function of initial grain size, strain, strain rate, and temperature:

\[
d_{\text{rec}} = a_6 d_0^{b_6} \dot{\varepsilon}^{b_7} \varepsilon^{m_6} \exp \left( \frac{Q_6}{RT} \right) + c_6
\]  
(12)

In this equation, if \( d_{\text{rec}} \geq d_0 \) then \( d_{\text{rec}} = d_0 \).

The coefficients of the above equations for AA5083 deformation are summarized in Table II.

<table>
<thead>
<tr>
<th>( a_i )</th>
<th>( n_i )</th>
<th>( b_i )</th>
<th>( \beta_i )</th>
<th>( Q_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.16</td>
<td>-0.75</td>
<td>0.693</td>
<td>0.11</td>
<td>74.79</td>
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</table>

Finally, the general components employed in the rolling model incorporating the combined thermo-mechanical (i.e. deformation) and microstructure models are shown in Fig. 4.

### III. Simulation Results

Fig. 5 shows strip and roll on FEM simulation of hot rolling that has been used for this analyzes, schematically.

Fig. 6 Shows different position of strip model that investigation of effective strain has been done.

The effective strain has a non uniform distribution through the thickness direction of the workpiece, at different positions in the deformation zone as depicted in Fig. 7.

As can be seen from Fig. 7, effective strain inhomogeneity decreases for the position near the natural point in rolling, for example X=65 (in Fig. 6).
III.1. Reduction Effects

The amount of reduction is an important factor affecting the strain inhomogeneity during hot strip rolling. Fig. 8 presents the effect of reduction on the through thickness strain distribution at the exit of the deformation zone and in constant thermal (initial temperature: 400°C) and interfaces conditions (friction: 0.3).

It is obvious from this figure that the amount of reduction can strongly control the manner of strain distribution and strain inhomogeneity. For small value of reduction, the strain inhomogeneity is reduced, whereas the strain inhomogeneity will be increased by increases of amount of reduction. However, if amount of the reduction is very small, less than 10%, effective strain inhomogeneity through the thickness of hot rolled strip will decrease in very low value as can discover that effective strain inhomogeneity is condonable for this value for reduction.

Because of high stacking fault energy of aluminum alloys, these materials have very low dynamic recrystallisation whereas static recrystallisation is extensive.

So in this investigation, the effects of DRX on microstructural changes have been condoned and SRX has been considered only.

Consequently, inhomogeneity of static recrystallisation volume fraction for different reduction value that conditions of immediately after deformation, initial temperature 400°C and friction 0.3 govern, has been shown in Fig. 9 (measurements have been obtained in exist of roll).

It is clear from this figure that inhomogeneity and amount of static recrystallisation volume fraction will be increased by increase of reduction.

It should be noticed that static recrystallisation volume fraction shows in Fig. 9, is corresponding to immediately after rolling with out cooling time or holding time.

III.2. Temperature Effects

Another important factor affecting the strain inhomogeneity during hot strip rolling is temperature. Fig. 10 presents the effect of temperature on the through thickness effective strain distribution at the exit of the deformation zone. It is obvious from this figure that the amount of temperature can also control the manner of strain distribution and strain inhomogeneity. For small value of temperature (350°C), the strain inhomogeneity is very large, whereas the effective strain inhomogeneity will be decreased by increasing of amount of temperature. Also, this figure shows that total effective strain is increased with increase of temperature.
III.3. Friction Interface Effects

As can be seen in Fig. 12 the coefficient of friction in Eq. 3 has a large effect on the strain at the surface. This can be explained by the resulting shear forces between the work roll and the strip, which results in large changes in surface strain.

The effect of friction on the through thickness of SRX volume fraction can be found from the curves presented in Fig. 13.

Obviously, friction coefficient has a very important influence on static recrystallisation volume fraction within the surface region.

It can be seen that when friction coefficients increase, inhomogeneity of static recrystallisation volume fraction through thickness of the rolled strip will be increased very fast, namely friction coefficient has a very important influence on microstructural inhomogeneity.

III.4. Cooling Time Effects

According to the FE simulation results, it has been revealed that recrystallization begins shortly after plastic deformation in hot rolling, and continues to progress after the material passes the rollers until the dislocation density reduces to a certain level. When the dislocation density drops to a certain level, recrystallization stops.

The predicted data of SRX volume fraction and inhomogeneity of its through thickness at the exit position of deformation region that have been plotted in Fig. 14 represents the kinetics behavior of recrystallization during interpass time. It is evident that in hot rolling of AA5083 cooling time is strongly influential (however cooling time is not very long in this investigation). So, in industrial processes in order to achieve expected properties, cooling time must be adjusted strictly.

The effect of cooling time on SRX volume friction for different reduction has been shown in Fig. 15. As it is clear from this figure, if the amount of cooling time is increased, the value of SRX volume friction will increase. Also it is obvious from simulation results and Eq. 11 that increasing in the reduction (corresponding to applied strain) leads to increasing the rate of recrystallization.

Fig. 16 shows the effect of cooling time on SRX volume friction for different temperature. It is obvious from this figure, if the amount of cooling time is increased, the value of SRX volume friction will increase. Also it is obvious from simulation results and Eq. 11 that increasing in the temperature (and other
parameter such as reduction, friction are constant) leads to increasing the rate of recrystallization.

The results show that rolling temperature has the greatest influence on the kinetics of static recrystallization as displayed in Figs. 11 and 16. It can be seen that in spite of difference in rolling speed and reduction for all specimens, the higher rolling temperature, the more rapid kinetics of static recrystallization. It is consistent with other researches [10], [11].

![Reduction influence on static Rex Friction during cooling time](image1)

**Fig. 15.** The modeling evolution of SRX during cooling time for different reduction

![Temperature influence on static Rex Friction during cooling time](image2)

**Fig. 16.** The effect of temperature on SRX during cooling time

**IV. Conclusion**

An integrated mathematical model has been developed which can predict the deformation field and the temperature profiles in the deforming metal, the temperature distribution within the work-rolls and static recrystallization kinetics during hot strip rolling. Only coupled thermo-mechanical/microstructural models that can predict the influence of these factors can be helpful in the design of industrial rolling processes of AA5083 aluminum alloy, as has been done in this paper.

Results of this simulation show although rolling temperature has the greatest influence on the kinetics of static recrystallization. Rolling speed, inter-pass time, and reduction in area are three other factors that may affect microstructural changes as well. The amount of these parameters always lies in a wide range.

Investigations show that effective strain inhomogeneity through thickness increased by increasing of the amount of reduction and friction and decreasing of temperature. Also, inhomogeneity of SRX through thickness will be increased by increasing of the amount of reduction and friction and decreasing of temperature. As friction coefficient have strong effect on inhomogeneity of effective strain and SRX.

Also results show that if the amount of cooling time is increased, the value of SRX volume fraction will increase. It has been revealed that recrystallization begins shortly after plastic deformation in hot rolling, and continues to progress after the material passes the rollers until the dislocation density reduces to a certain level. When the dislocation density drops to a certain level, recrystallization stops. If the amount of reduction, temperature and cooling time is increased, the value of SRX volume friction will increase.

**References**

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