Title:

MODELING THE EFFECTS OF FRICTION AND
GEOMETRY ON DEFORMATION PATH DURING HOT
ROLLING OF ALUMINUM

Author(s):

DAVID A. KORZEKWA, MST-6
ARMAND J. BEAUDOIN, UNIVESITY OF ILLINOIS

Submitted to:

TMS FALL MEETING ON HOT DEFORMATION OF
ALUMINUM ALLOYS TO BE HELD AT ROSEMONT, IL
ON OCTOBER 11-15, 1998

Los Alamos
NATIONAL LABORATORY

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

MODELING THE EFFECTS OF FRICTION AND GEOMETRY ON DEFORMATION PATH DURING HOT ROLLING OF ALUMINUM

David A. Korzekwa[†] and Armand J. Beaudoin[‡]

[†] Los Alamos National Laboratory
Materials Science and Technology Division
Box 1663, Mail Stop G770
Los Alamos, NM 87545

[‡] University of Illinois at Urbana-Champaign
354 Mechanical Engineering Building, MC-244
1206 West Green Street
Urbana, IL 61801

Abstract

In this work, a parametric study of hot rolling is conducted. The effect of friction model, friction coefficient, roll gap geometry and temperature on the deformation rate field is demonstrated. This parameter space is restricted to a region which is tractable, yet provides considerable variety in the features of non-uniform deformation developed in rolling. The degree and nature of redundant work (shearing) is contrasted for different streamline locations within the bite. Recommendations for the application of material models in analysis of rolling is made with consideration of the simulation predictions.

Introduction

Rolling of aluminum alloys is used to produce a wide variety of products. A few examples are sheet for beverage containers, plate for use in structural airframe components, and sheet for stamping of autobody panels. This widespread application in commercial products encourages the continued enhancement of product quality. Correspondingly, research efforts into the mechanisms of deformation are prompted by the desire to improve performance in the target application. Recent efforts in the study of constitutive behavior, development of texture, ductile failure, and localization provide insight into the relationship between actions at the microstructural scale and material performance. Quite often, the feature of interest may be manipulated through the rolling process.

Processing conditions in the hot rolling of aluminum alloys lead to non-uniform deformation within the roll bite. The ratio of slab thickness to arc of contact in the roll gap can vary over a wide range because of the large initial slab thickness and the very large reductions that are possible for thinner slabs. The degree of non-uniform deformation also depends on friction conditions. In early slabbing operations, a sticking friction condition dominates; in later cold finishing, the coefficient of friction must be greatly reduced to effect rolling with a reasonable reduction. Likewise, the deformation zone geometry undergoes considerable change. The deformation zone may be characterized using the definition

$$\Delta = \frac{\bar{h}}{L} \quad (1)$$

where Δ characterizes the deformation zone, $\bar{h}$ is the average thickness in the roll bite, and L is the arc of contact. This parameter may vary from 3 to 0.2 over the course of breakdown to finishing passes.

From the perspective of the material behavior, changes are similarly dramatic. Early operations are characterized by hot deformation, in which rate dependence of the flow stress is evident. The final rolling passes are cold-working operations, in which rate-independent or negative rate-dependent behavior is present. It is necessary to know the regime of deformation rate and temperature space that is developed in the roll bite to make proper application of evolving material models.

The use of finite element analysis to study and optimize commercial deformation processes has become common. Improvements in constitutive models for plastic flow and friction at the tool-workpiece have improved the capabilities of the available analysis software. Hot rolling of aluminum alloys is a process that is sensitive to temperature, deformation rate, friction and roll pass geometry. An ideal model for this process should include heat transfer, accurate constitutive behavior for rate and temperature dependent plastic flow and a friction model that is based on appropriate mechanisms at the interface.

In this paper, a viscoplastic finite element code is used to study the effects of geometry, friction and temperature on the deformation history during hot rolling of aluminum alloy AA5182. A single state variable model is used to represent the rate and temperature dependent plastic flow, and friction models spanning a range of different friction traction distributions are investigated. The implementation of physically based friction models into finite element codes is currently at a primitive state.

Finite Element Model

A viscoplastic finite element code was used for the hot rolling simulations [1]. The model was run in an Eulerian frame of reference, where the mesh was fixed and a steady state velocity field was calculated. The diameter of the rolls and the initial slab thickness were held constant at 812.8mm and 27.9mm respectively. The reduction in thickness was either 25%, 50% or 62.5%. Figure 1 shows the mesh for 50% reduction, where each element is a 9 node quadrilateral. Only the top half of the mesh was used in the calculation, with a symmetry boundary condition along the midplane of the slab. The coordinate system used in this paper is also defined in Figure 1.

Figure 1: Finite element mesh for 50% reduction

The constitutive model used is the mechanical threshold stress (MTS) model with a single scalar state variable [2, 3]. Only a very brief outline of the model will be provided here. The flow stress σ at constant structure is a function of temperature T , strain rate $\dot{\epsilon}$, and an internal variable which characterizes the structure, $\hat{\sigma}_\epsilon$. The flow stress is given by

$$\frac{\sigma}{\mu} = \frac{\sigma_a}{\mu} + S_i(\dot{\epsilon}, T) \frac{\hat{\sigma}_i}{\mu_0} + S_\epsilon(\dot{\epsilon}, T) \frac{\hat{\sigma}_\epsilon}{\mu_0} \quad (2)$$

where

$$S_i(\dot{\epsilon}, T) = \left\{ 1 - \left[\frac{kT}{\mu b^3 g_{0i}} \ln \left(\frac{\dot{\epsilon}_{0i}}{\dot{\epsilon}} \right) \right]^{\frac{1}{q_i}} \right\}^{\frac{1}{p_i}} \quad (3)$$

and

$$S_\epsilon(\dot{\epsilon}, T) = \left\{ 1 - \left[\frac{kT}{\mu b^3 g_{0\epsilon}} \ln \left(\frac{\dot{\epsilon}_{0\epsilon}}{\dot{\epsilon}} \right) \right]^{\frac{1}{q_\epsilon}} \right\}^{\frac{1}{p_\epsilon}} \quad (4)$$

In equation 2, σ_a represents an athermal contribution and the following two terms (S_i and S_ϵ) provide thermal components of the flow stress arising from dislocation interactions with obstacles. The evolution of the state $\theta = d\hat{\sigma}_\epsilon/d\epsilon$ takes the form

$$\frac{\theta}{\mu} = \frac{\theta_0}{\mu_0} \left[1 - \frac{\hat{\sigma}_\epsilon}{\hat{\sigma}_{\epsilon s}} \right]^\kappa \quad (5)$$

where $\hat{\sigma}_{\epsilon s}$ is a function of temperature and strain rate,

$$\frac{\hat{\sigma}_{\epsilon s}}{\hat{\sigma}_{\epsilon s 0}} = \left(\frac{\dot{\epsilon}}{\dot{\epsilon}_{0\epsilon s}} \right)^{\frac{kT}{\mu b^3 g_{0\epsilon s}}} \quad (6)$$

The evolution of $\hat{\sigma}_\epsilon$ is calculated using a streamline method [1]. The same streamlines can be generated from the solution to characterize the deformation and temperature histories

Table 1: Parameters for Mechanical Threshold Stress Model

μ	$\mu_0 - \frac{3440\text{MPa}}{\exp(\frac{215\text{K}}{T}) - 1}$	μ_0	$2.8815 \times 10^4 \text{ MPa}$	$\frac{k}{b^3}$	0.5899 MPa/K
σ_a	10 MPa	$\frac{\sigma_i}{\mu_0}$	0.010315	$\hat{\sigma}_{\epsilon s 0}$	1996 MPa
$\dot{\epsilon}_{0i}$	$1 \times 10^7 \text{ s}^{-1}$	$\dot{\epsilon}_{0\epsilon}$	$1 \times 10^7 \text{ s}^{-1}$	$\dot{\epsilon}_{0\epsilon s}$	$1 \times 10^7 \text{ s}^{-1}$
g_{0i}	1.196	$g_{0\epsilon}$	1.6	$g_{0\epsilon s}$	0.1058
p_i	1/2	p_ϵ	2/3	θ_0	6800 MPa
q_i	3/2	q_ϵ	1	κ	2

of a material point in the slab. The parameters for the model were fitted for AA5182 over an appropriate range of strain rates and temperatures, as described elsewhere in this volume [4, 5]. These parameters are listed in Table 1.

Boundary conditions were specified as friction at the roll-slab interface and 11 MPa tension at the exit side of the mesh. The roll velocity was specified as 1.0 m/s. Heat transfer was specified at the roll-slab interface and on the free surfaces, using a simple model where the flux is a linear function of the temperature difference across the interface.

Although friction models based on state variables at the surface are being developed[6, 7, 8], a suitable model for hot rolling was not available for this study. Three different friction models that span a range of expected behavior for this process were chosen for this investigation. For the Coulomb model the friction traction (τ_f) is proportional to the normal traction (τ_n) at each point.

$$\tau_f = \mu \tau_n \quad (7)$$

A strain-based model was also used that assumes a simple linear increase in friction traction with increasing strain in the workpiece up to a saturation value (τ_s). The accumulated strain in the workpiece at the surface, ϵ_f , is treated as a state variable and the friction traction is given by

$$\begin{aligned} \tau_f &= \tau_{f0} + b\epsilon_f \\ \tau_f &\leq \tau_s \end{aligned} \quad (8)$$

The strain model parameters are chosen to saturate at a strain smaller than the equivalent rolling reduction. This gives behavior similar to a constant friction stress model with a gradual increase in friction stress as the slab enters the roll gap. Note that this model does not depend on the normal traction at the interface, and is intended to be appropriate for mixed lubrication conditions.

The third model is a velocity-difference model that is appropriate for hydrodynamic lubrication, where the friction traction is proportional to the difference in velocity (u) between the roll and slab.

$$\tau_f = \beta(u_{\text{roll}} - u_{\text{slab}}) \quad (9)$$

It is difficult to determine the friction model which most accurately describes the actual friction mechanisms developed in rolling. However, the three models selected provide quite different friction traction distributions along the interface - providing for study of the effect of this boundary condition. In each case, the friction parameters were adjusted to give a reasonable value for the forward slip (or location of the neutral point). The range of temperatures, reductions and friction parameters that was investigated is listed in Table 2.

Table 2: Hot Rolling Parameters

Temperature	Percent Reduction/ <i>Delta</i>	Friction Level, μ	Friction Model
300C	25 / 0.46	0.15	Coulomb
400C	50 / 0.28	0.20*	Strain
500C	62.5 / 0.23	0.30*	Velocity

* Approximate Coulomb coefficient for strain and velocity models

Results

The first part of this section will show results for a typical solution and discuss the general characteristics of the model for a baseline set of parameters. The second part will show the effects of changing the various parameters, and the relative sensitivities will be discussed. The streamline results are plotted as a function of the x coordinate, where the slab is moving in the positive x direction and 0 is the position where the slab exits the roll gap.

Typical Rolling Solution

Results for a simulation at 400C, 50% reduction and Coulomb friction with $\mu = 0.20$ are shown in Figures 2-4. An interesting result is the degree of localization of the strain rate in Figure 2. Even though the material is quite rate sensitive at this temperature, the deformation tends to be concentrated in bands that appear to be diffuse slip lines. This effect is delineated more quantitatively in the streamline plots.

The temperature field plot shows a maximum temperature rise of 50C in the center of the slab, and the minimum temperature along the streamline nearest the roll-slab interface was ≈ 380 C. The state variable plot shows a very rapid hardening as the slab enters the roll gap, but the model predicts that the material does not continue to harden, but essentially saturates at a fairly low strain.

Figure 2: Effective deformation rate plot for $\mu = 0.20$, 400C and 50% reduction

Figure 4 shows the location of three streamlines within the slab for material points near the surface, at 1/4 of the final thickness, and near the midplane. The temperature histories of the three points are plotted in Figure 5. The material closest to the surface is cooled by the rolls while in the roll bite, but eventually reaches a temperature higher than the initial temperature.

The strain rate components for shear and extension along the rolling direction are plotted in Figure 6. Both components show a large peak in strain rate at the entrance of the rolls.

Figure 3: Temperature and state variable plot for $\mu = 0.20$, 400C and 50% reduction

Figure 4: Three selected streamlines for $\mu = 0.20$, 400C and 50% reduction

The shearing rate is highest near the surface, and goes to zero at the symmetry boundary at the midplane. The strain rate in the rolling direction oscillates as the material passes through the bands of high deformation rate, producing four peaks in strain rate along the surface and three along the midplane.

The tractions on the surface of the slab are shown in Figure 7. The normal traction or pressure on the slab is relatively constant at approximately 200MPa, and the magnitude of the friction traction is, as expected, 0.20 times the normal traction, except in the vicinity of the neutral point. The friction algorithm uses a smoothing function when the velocity difference between the roll and slab changes sign. The origin of the abscissa is an arbitrary point along the surface prior to entering the roll gap.

Geometry, Friction and Temperature Effects

The rolling gap geometry was varied by changing the reduction in thickness. The shear strain rates near the surface and the x strain rates near the midplane are shown for three reductions in Figure 8. The magnitude of the strain rates is similar for all three cases, as is the difference between the maximum and minimum rates. The number of diffuse slip lines present in the work zone (Figure 9) depends on Δ , and is approximately equal to $2/\Delta$. At the surface and midplane, these bands intersect, resulting in the number of peaks along these streamlines approximately equal to $1/\Delta$.

The tractions at the roll-slab interface are shown in Figure 10 for the three different friction models with parameters chosen to give roughly equivalent tractions and neutral point locations. In contrast to the Coulomb model, the strain based model is designed to give a more gradual application of friction as the slab come into contact with the roll, but in general the results for the strain model are very similar to those of Coulomb friction for the range of parameters in this study. The velocity difference model results in significantly less localization. It is a characteristic of the velocity difference model to develop maximum tangential traction at the entry of the bite, where the velocity difference is greatest. This is in contrast to the Coulomb and strain models, where the traction magnitude generally

Figure 5: Temperature along three streamlines.

Figure 6: Strain rate in the rolling (x) direction and shear strain rate along three streamlines.

Figure 7: Surface tractions on the slab at the roll interface.

Figure 8: Shear strain rate and X strain rate for three different reductions.

Figure 9: Effective strain rate field plots for three different reductions.

Figure 10: Normal and friction tractions for three different models at approximately the same average friction level.

follows the friction hill. Localization evident in the deformation rate fields reflect the trends indicated by the surface tractions (Figure 11). The velocity model exhibits well-developed slip lines at the bite entry - where tangential tractions are highest for this model. The Coulomb and strain models show distinct slip lines at both the entry and exit regions of the bite. Corresponding plots for a streamline near the surface are shown in Figure 12.

Figure 11: Effective strain rate field plots for three different friction models.

Figure 12: Shear strain rate and X strain rate for three different friction models.

Increasing the friction level tends to move the neutral point away from the exit of the roll gap and increase the forward slip. This is to be expected since the total tangential force that drives the slab through the roll gap is the sum of the forces acting in opposing directions on either side of the neutral point. This is illustrated in Figure 13 for three friction levels using the strain based friction model. The resulting deformation rate and strain rate components are shown in Figures 14 and 15. The level of friction has the strongest effect on the degree of localization of strain rate in the slab.

Changing the initial temperature of the slab affects the results primarily through the rate dependence of the flow strength. For the range of parameters investigated here the effect

Figure 13: Friction tractions for three different friction levels using the strain based model.

Figure 14: X strain rate and shear strain rate for three different friction levels.

Figure 15: Effective strain rate field plots for three different friction levels.

is quite small, as shown in the plots in Figure 16. As the temperature decreases, the rate dependence of the flow stress decreases, and the peaks in the shear strain rate at the surface increase.

Figure 16: X strain rate and shear strain rate for three different initial slab temperatures.

Conclusions

It is generally known that the deformation and temperature histories of the material in a hot rolling operation vary significantly as a function of location through the thickness of the slab. The magnitudes of the variation of the deformation rate and temperature both through thickness and along the path of a material point are illustrated in this article. Application of accurate material models and systematic variation of friction behavior in high resolution finite element simulations illustrates the relative effects of geometry, friction and temperature on the uniformity of the deformation and the resulting material properties.

The velocity field has the character of a diffuse slip line field in many cases, and the deformation rate can vary by more than an order of magnitude for a material point on the centerline of the slab. Near the surface, the shear strain rates depend strongly on the friction conditions, and the all of the strain rate components vary substantially as the material travels through the roll gap. The degree of shearing and rotation changes with friction conditions, reduction and temperature, which can explain the variation in texture through the thickness for these products.

The strongest effect on the degree of localization of the deformation is that due to friction. In addition to increasing the shearing rates at the surface, the slip line pattern is sharper and the variation in deformation rate is greater as the friction is increased. The combination of high shearing rates and the intersection of high deformation rate bands with the roll-slab interface could be responsible for surface defects or other slab quality problems.

The slip line pattern is also affected by the geometry of the roll gap. For low friction the slip bands intersect the surface at approximately 45° , and the number of bands increases as necessary to fill the work zone as the aspect ratio of the work zone changes. The weakest effect is that of temperature. It would be expected that the slip bands would become sharper as the rate dependence of the flow stress decreases, but the effect seems to be quite weak for AA5182 between 300C and 500C.

These steady state simulations allow very fine meshes to be used without requiring long computation times. These results indicate that the application of improved material and

friction models will allow simulations to resolve relatively subtle differences in material response and process parameters.

Acknowledgments

This work was supported by the Department of Energy under contract W-7405-ENG-36.

References

- [1] P. R. Dawson, "On Modeling of Mechanical Property Changes During Flat Rolling of Aluminum," International Journal of Solids and Structures, 23 (1987) 947-968.
- [2] P. S. Follansbee and U. F. Kocks, Acta Metallurgica, 36 (1988) 81-93.
- [3] S. R. Chen and G. T. Gray III, "Constitutive Behavior of Tantalum and Tantalum-Tungsten Alloys," Met. Trans. A 27A (1996) 2994-3006.
- [4] S.R. Chen, U.F. Kocks, S.R. MacEwen, A.J. Beaudoin, and M.G. Stout, "Constitutive Modeling of a 5182 Aluminum as a Function of Strain Rate and Temperature," elsewhere in this volume.
- [5] M.G. Stout, S.R. Chen, U.F. Kocks, C. Tome, S.R. MacEwen and A.J. Beaudoin, "Mechanisms Responsible for Texture Development in a 5182 Aluminum Alloy Deformed at Elevated Temperature," elsewhere in this volume.
- [6] S. Sheu and W.R.D. Wilson, "Mixed lubrication of strip rolling," STLE Tribology Transactions, 37 (1990) 483-493.
- [7] M.P.F. Sutcliffe and K.L. Johnson, "Lubrication in cold strip rolling in the mixed regime," Proc. Inst. Mech. Eng., 204 (1990) 249-262.
- [8] Wing Kam Liu, Yu-Kan Hu, and Ted Belytschko, "ALE finite elements with hydrodynamic lubrication for metal forming," Nuclear Engineering and Design, 138 (1992) 1-10.