Proceedings of the 12th International Conference on
Aluminium Alloys, September 5-9, 2010, Yokohama, Japan

pp. 566-571

Mathematical Modelling of the Extrusion of AA3xxx Aluminum Alloys

Yahya Mahmoodkhani[1], Mary A. Wells[1], Nick Parson[2], Yuanyuan Geng[3], Warren J. Poole[3]

[1]Department of Mechanical and Mechatronics Engineering, University of Waterloo, 200 University Avenue West, Waterloo, Ontario, N2L3G1, Canada

[2]Rio Tinto Alcan, 1955, boulevard Mellon, Jonquiere, Quebec, G7S4L2, Canada

[3]Department of Materials Engineering, University of British Columbia, Frank Forward Building, 309-6350 Stores Road, Vancouver, British Columbia, V6T1Z4, Canada

An integrated approach, involving laboratory experiments, extrusion plant trials, and finite element modeling (FEM) has been adopted for the study of the extrusion of aluminum alloy AA3xxx from a billet to an I-beam extrudate. Extrusion plant trials were conducted at the RioTinto Alcan Research and Development facility in Jonquiere, Quebec to measure load and temperature for model validation and to obtain samples for microstructure analysis. Microstructure evolution with respect to starting chemistry and industrial homogenization and extrusion conditions was examined by optical microscopy at different locations on the I-beam extrudate. A 3D FEM model based on the commercial code DEFORM was adopted for the simulation of the extrusion. Using an updated Lagrangian formulation, both the transient and steady-state regions of extrusion were modeled. Load and temperature predictions resulting from this model agree well with the measured values in the upsetting or break through stage and in the steady-state region. Temperature predictions are also very good and agree to within 3% of those measured. Thermomechanical histories at different locations were compared to the extruded microstructures in those areas.

Keywords: *Extrusion, aluminum alloys, microstructure, Finite Element Method, Recrystallization, AA3xxx, DEFORM-3D, Homogenization.*

1. Introduction

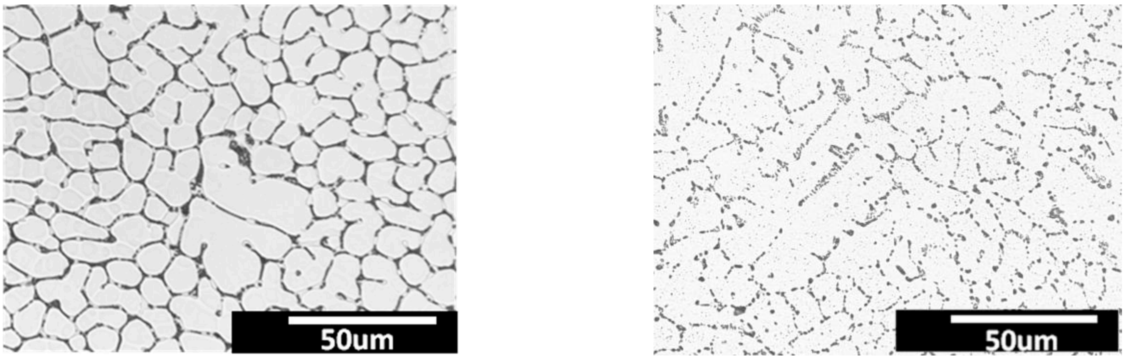
Hot extrusion is one of the most important forming technologies for aluminum alloys. During hot extrusion a preheated cylindrical billet is pressed through a die which determines the cross-sectional geometry of the extruded product. AA3003 is a widely used commercial aluminum alloy containing manganese (Mn), iron (Fe) and silicon (Si) as alloying elements. AA3003 alloys have relatively high thermal conductivity and the ability to be extruded into thin profiles and are used extensively in heat exchanges applications. During extrusion of AA3xxx alloys, inhomogeneity of deformation can result from redundant deformation and the effects of friction at the interfaces. This can lead to through profile effects such as different recrystallized grain structures at the surface as compared to the centre [1, 2]. In addition, the propensity for the material to recrystallize can vary through the profile and is dependent both on the starting microstructure as well as the thermomechanical history experienced by the material during extrusion. In order to understand the microstructure evolution both during and after extrusion it is necessary to develop mathematical models capable of accurately modelling the thermomechanical history experienced at different locations in the billet during extrusion and couple this to microstructure evolution equations.

Although a number of researchers have used Finite Element Method (FEM) models to analyze microstructure evolution during hot extrusion of aluminum alloys for AA6xxx and AA7xxx aluminum alloys there has been little work done on AA3xxx alloys in this field. In this work, the main objective is to develop and validate a 3D mathematical model of the extrusion process for AA3xxx aluminum alloys using the commercial FEM package DEFORM-3D[1]. The model predictions were then used to qualitatively understand the variation in extrudate microstructures observed when the material is processed under different extrusion conditions and starting microstructures.

2. Extrusion trials

Extrusion plant trials were conducted using an AA3003 (1.27% Mn, 0.54%Fe, 0.10%Si, 0.02%Ti) aluminum alloy which was cast into a 101.6mm diameter billets. To assess the effect of starting microstructure prior to extrusion, some billets were homogenized at 550°C for eight hours and extruded while others were extruded in the as-cast condition without any prior homogenization heat treatment. In both cases, samples were taken from the section of billets. Ground, polished and 0.5%HF etched samples are examined by optical microscope.

Figure 1 shows the starting microstructure of the as-homogenized billet prior to the extrusion process as well as the as-cast billet. The as cast microstructure shows a cellular dendritic structure with rod-like constituent particles, while the homogenized billet, shows the network of constituent particles is broken down with some precipitation of dispersoids.



(a) as-cast **(b) 550°C 8 hrs**

Fig. 1 - Homogenized microstructure for billets given: a) as-cast and b) 550°C for 8 hrs

Prior to extrusion, the billet was rapidly reheated in an induction furnace to the extrusion temperature and extruded into an I-beam extrudate (1.31mm thickness) with an extrusion ratio of 130 at a ram speed of 14 mm/s. The extrusion trials were carried out at two different temperatures namely: 400°C and 550°C. The extrudate was quenched in a water quench bath 1.5m away from the extrusion die hence some changes in the microstructure may have occurred after extrusion but prior to the quench.

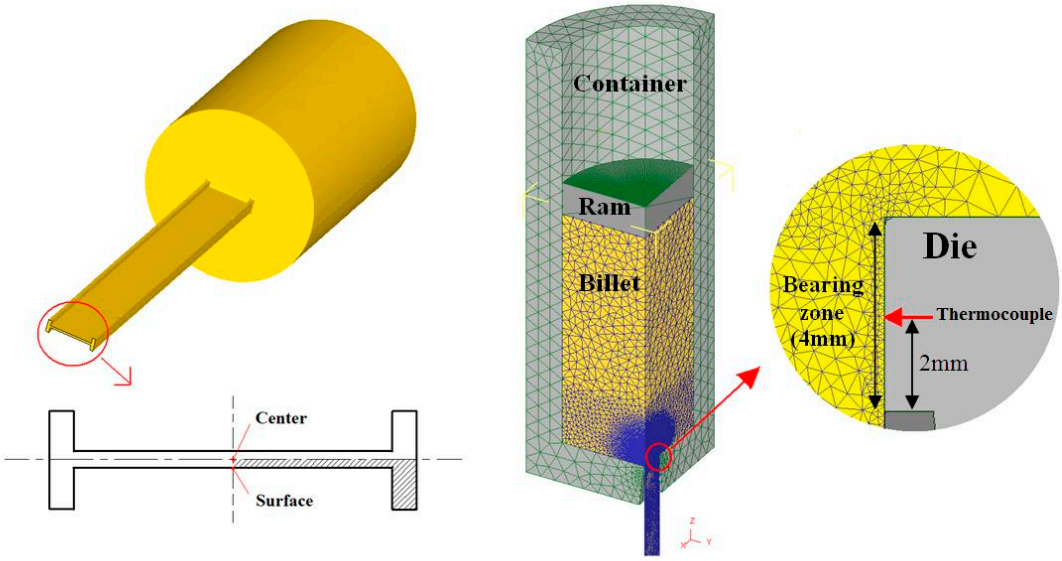
3. Mathematical model

The commercially available finite element package, DEFORM-3D was applied to the extrusion process. The code is based on the flow formulation approach using an updated Lagrangian procedure. The choice of model was dictated by two factors: the requirement that it should be capable of modeling large-scale deformation associated with extrusion (with the ability to remesh), and the need to predict loads over the whole range of deformation (i.e., under transient and steady-state conditions). In this study, the model consisted of three objects to be simulated: billet, ram and container which included the die, as schematically shown in Figure 2. Because of the large plastic deformation associated with the process, the billet material was assumed to behave as a rigid-viscoplastic material, whereas the other objects were defined as being rigid during computation, and only the billet was involved in deformation to which the flow formulation applies. In order to get

[1] DEFORM is a trademark of Scientific Forming Technology Corporation, Columbus, OH.

a reasonable combination of accuracy and speed, the mesh density was optimized spatially (finer near the die and coarser away from the die) and dynamically during the extrusion based on the magnitude of the strain rate and strain being experienced. Figure 2b also shows the location of the thermocouple in the die bearing which was used to measure the surface temperature of the extrudate during the extrusion process. The thermocouple is in contact with surface of extrudate.

Referring to Figure 2, the billet, container and ram were discretized into a three-dimensional quarter section of the extrusion setup with a series of four-node, tetrahedral, isoparametric elements (Figure 2b).



a) Solid model of the billet and extruded I-beam **b) Mesh used in the container, billet and I-beam**

Fig. 2 - Schematic showing the billet being extruded into an I-beam section showing: a) Solid model of the billet and I-beam and b) mesh used in the container, billet and I-beam.

3.1 Material properties

In this work the physically-based constitutive model developed by Kocks and Chen [3] shown in Eq. 1 was used to capture the temperature and rate dependence of the material as it is being deformed as well as the influence the chemistry and homogenization treatment had on the flow stress of the material:

$$\dot{\varepsilon} = A\left(\frac{\sigma}{\mu}\right)^{n} \frac{\mu b^{3}}{kT} \, exp\left(-\frac{Q_d}{RT}\right) \tag{1}$$

Where, σ is the stress, μ is the temperature dependent shear modulus, n is the stress exponent, $\dot{\varepsilon}$ is the strain rate, k is the Boltzman constant, T is the deformation temperature, b is the temperature dependent magnitude of the Burgers vector, Q_d is the activation energy for diffusion of the diffusing species, R is the gas constant, A and n are material constants that were calculated based on the starting chemistry and homogenization treatment [4].

Thermophysical properties used for the billet (AA3003) and container, die and ram (H13 tool steel) in the model are listed in Table 1.

Table 1 – Thermophysical properties used in the model.

Material	Thermal conductivity ($W.m^{-1}.K^{-1}$)	Volumetric heat capacity ($kJ.m^{-3}.K^{-1}$)
AA3003	180.2	2433
H13	24.5	4000

3.2 Boundary conditions

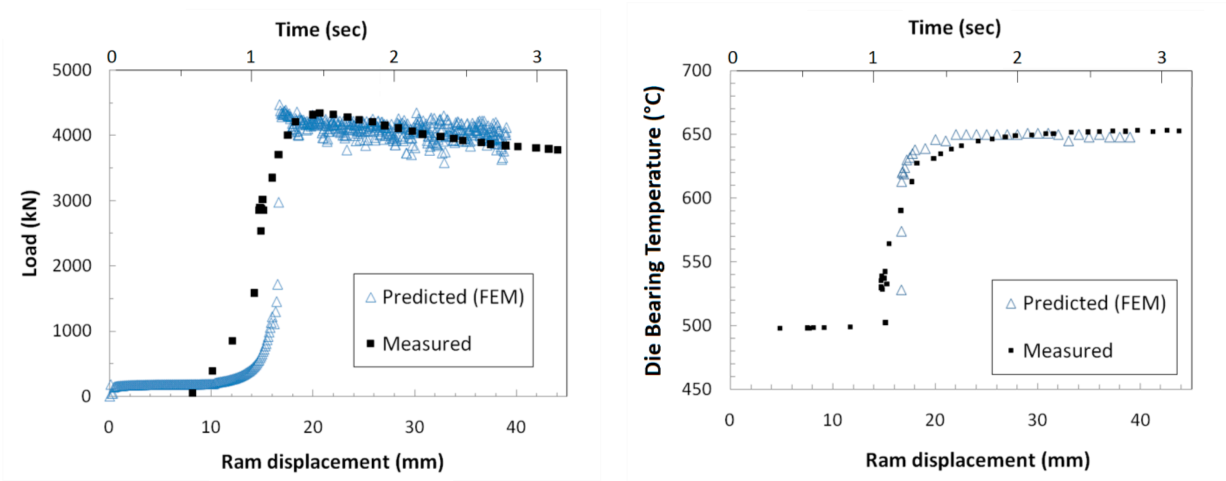
To model the friction between the ram and the end of the billet and container and the billet, an interface shear factor approach was used as shown in Eq. 2:

$$f_s = m\,k \tag{2}$$

Where f_s is the frictional stress, k is the shear yield stress of the material and m is the interface shear factor. In this simulation the interface shear factor between the billet and ram was considered to be 0.7. Between the billet and container and billet and die sticking friction was considered to exist with an interface shear factor of 1.0. Finally the interface shear factor between the extrudate and bearing zone in die it is 0.4. The heat transfer coefficient between the billet and tooling (ram, container and die) was assumed to be 25 $kW.m^{-1}.K^{-1}$. The initial temperature of the container was set to 450°C and that of ram to 250°C. It was assumed that 90% of the work done during deformation was converted to heat.

3.3 Comparison of Model Predictions with Measured Data

Load/temperature predictions are compared with measured data during the extrusion trials in Figure 3 for both the transient break through phase (peak pressure) and towards the steady state regime. As can be seen the agreement is good for both the load and temperature predictions (within 5% for load and 3% for temperature).



(a) Extrusion load (b) Temperature

Fig. 3 - Validation of simulation results for: a) Extrusion load and b) Temperature (Homogenization treatment prior to extrusion: 550°C for 8h, Extrusion temperature = 550°C).

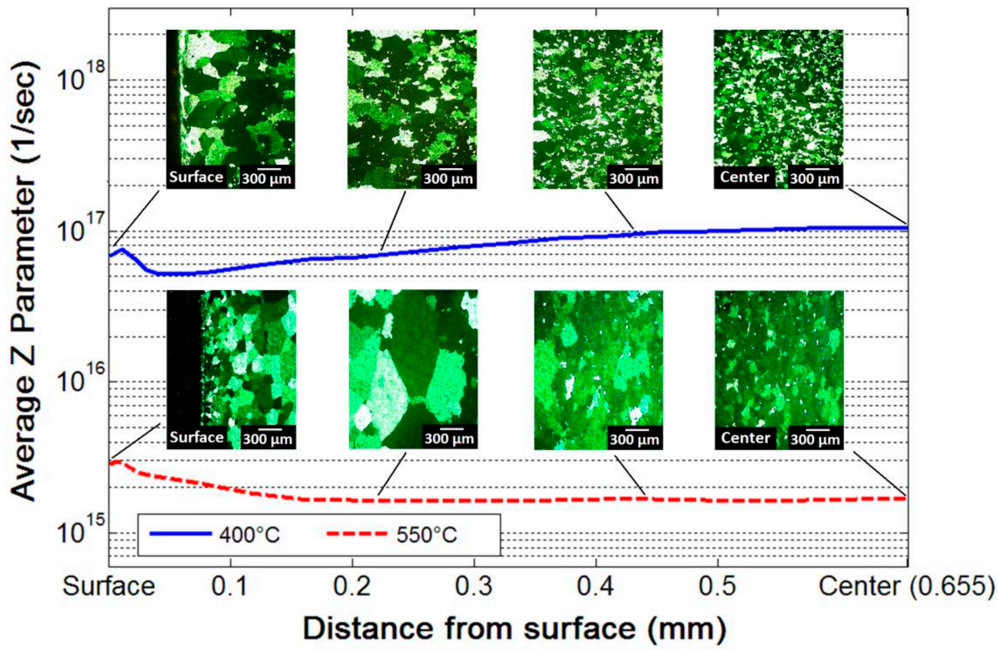
4. Results and discussion

Tapered samples from the as-extruded I-beam were examined using an optical microscope as shown in Figure 4. The samples were electropolished using Barker's solution at room temperature for 1~4 minutes at 40 volts to produce an anodic film. It is found that the as-extruded microstructure through the I-beam profile was significantly influenced not only by the temperature at which it was extruded but also the starting microstructure (as cast versus homogenized). Surface to centre locations shown are reflective of the surface and centre location in the I-beam shown in Figure 2a. As shown in Figure 4, at the surface the grains are quite fine but at a subsurface location there is evidence of coarse grains. This occurs in billets extruded at both 400 and 550°C. Referring to Figure 4, moving from the surface of the I-beam towards the centre, the microstructure changes such that the recrystallized grains become smaller.

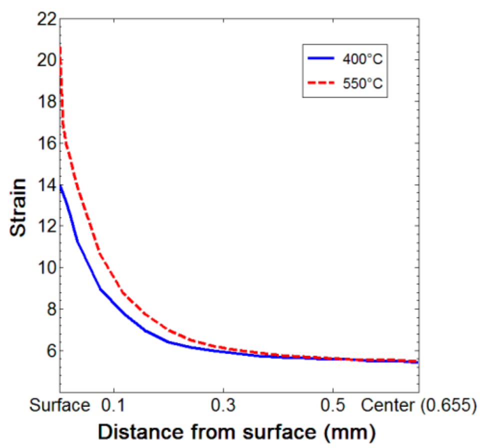
Figure 4 also shows the model predicted distribution of the average Zener-Hollomon parameter (Z) and effective strain in the extruded I-beam from surface to centre predicted for both extrusion temperatures. The Zener-Hollomon parameter was calculated using $Z=\dot{\varepsilon}\exp(Q_d/RT)$ in which Q_d, activation energy for deformation, is 211.4 $KJ.mol^{-1}.K^{-1}$ [4] and T is the deformation temperature. The average Z parameter was determined based on a weighted average with respect to the strain experienced as shown in Equation (3).

$$Z_{avg} = \frac{\int_{\varepsilon_1}^{\varepsilon_2} Z\, d\varepsilon}{\varepsilon_2 - \varepsilon_1} \qquad (3)$$

As shown in Figure 4, there is evidence of a subsurface peak in the average Z parameter and this appears to correspond with the larger grains sizes observed in this region. Both the Z parameter and strain vary significantly from surface to centre and will play a role in the microstructure uniformity. At 400°C, recrystallized grain size is smaller and the variation of the grain size through the thickness appears smaller.



(a)



(b)

Fig. 4 - (a) Average Zener-Hollomon parameter and micrographs of different areas of extrudate and (b) strain distribution in extrudate (Center and surface refer to center and surface points mid-width across the I-beam as shown in Figure 2a, homogenization treatment before extrusion: 550°C for 8h)

Figure 5 shows the calculated flow field for material extruded at 400°C and 550°C. As shown, the flow behavior of the material through the die is quite different based on the material temperature. Based on the results presented, it is evident that the processing route, specifically the application of a homogenization step as well as the way the material is extruded has a significant influence on the final microstructure.

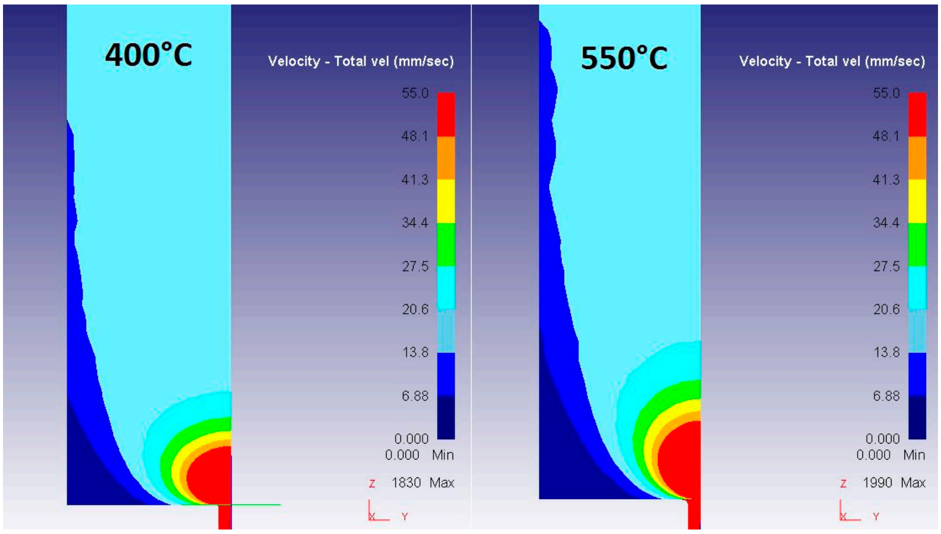


Fig. 5 - Calculated flow velocity for material extruded at 400°C (left) and 550°C (right).

5. Summary and Conclusions

From an integrated approach, a model has been developed for the simulation of the extrusion of the AA3xxx aluminum alloy from a billet into an I-beam profile. Load predictions resulting from this model agree to within 5 pct of the measured values and temperature predictions agree to within less than 3 pct. Using the model a qualitative understanding on the effect of extrusion temperature on the stored energy and homogeneity of the microstructure through the thickness of the I-bean was developed as well as the role homogenization can have on the microstructure evolution.

Acknowledgment

The authors would like to gratefully acknowledge the financial support of NSERC (Canada) and Rio Tinto Alcan (RTA).

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