Proceedings of the 9th International Conference on Aluminium Alloys (2004)
Edited by J.F. Nie, A.J. Morton and B.C. Muddle

Modelling the Microstructural Evolution During Hot Rolling and Subsequent Cold Rolling and Annealing of an AA3103 Alloy

K. Marthinsen, S. Abtahi, K. Sjølstad and E. Nes

Department of Materials Technology, Norwegian University of Science and Technology (NTNU) N-7491 Trondheim, Norway.

Keywords: Aluminium, hot and cold rolling, annealing, microstructure, modelling

Abstract

The paper reports on the use of physically based microstructure models to follow the microstructural evolution and mechanical properties during industrial processing of a commercial AlMn-alloy. The modelling approach involves models for the evolution in substructure and associated mechanical properties during deformation, and a softening model capable of handling the complexity of partial recrystallization between passes during multi-pass hot rolling and the combined effect of recovery and recrystallization during annealing. In combination with FE-models the microstructure models are able to account for the complex strain paths and through thickness variations experienced during industrial processing conditions.

1. Introduction

The overall objective of several recently finished EU-projects (i.e. the VIR[*]-projects) has been to develop so-called Through Process Models (TPM), i.e. an integrated modelling approach which is capable of predicting the combined influence of all major process parameters during processing on the microstructure and associated properties of the processed material. This may be realised by interfacing a set of microstructure models, which link the evolution in microstructure in each stage of the production chain to the preceding and subsequent production steps. Moreover, the microstructure models have to be combined with Finite Element (FE) models to account for the complex strain paths and their spatial variations encountered under industrial processing conditions

The present work reports on such a modelling approach carried out within one of these projects, i.e. the VIRFAB-project. It is based on physically based microstructural models developed within the Norwegian aluminium community over the last 10-15 years, including a recently developed work hardening model, *ALFLOW*, and a softening model nicknamed *ALSOFT*. Starting from an initial condition (e.g. the *as cast* and homogenized state), characterized in terms of solid solution levels of alloying elements, the volume fraction and mean size of constituent particles and dispersoids, and grain size, *ALFLOW* calculates the evolution in substructure and associated mechanical properties during plastic deformation. The softening behaviour between passes during multi-stand hot rolling, during coiling after hot rolling, and during final annealing after cold rolling is calculated with the *ALSOFT* model. The deformation conditions during hot rolling, in terms of accumulated strain, strain rate and temperature along certain material flow lines are provided by FE-calculations.

A brief presentation of the modelling approach is given, including a brief description the main elements of the work hardening model *ALFLOW* and the softening model *ALSOFT*. Their application and predictions will be demonstrated and discussed in relation to industrial processing of a commercial AlMn-alloy (AA3103). The model predictions are compared to experimental results from material characterization of sample material collected during the different stages of processing from the *as cast* condition, via hot rolling, coil cooling, cold rolling and final annealing until the fully soft condition [1].

2. Modelling

In the present work, the link between the microstructure models and the thermo-mechanical model (FEM) during hot rolling is based on post processing of calculated particle paths from FE-modelling. These FEM simulations involve 19 passes of breakdown rolling and 3 passes for the finishing mill. The strain rate, temperature, strain tensor, accumulated equivalent strain, and deformation gradients have been provided as a function of time for each pass [2]. During coil cooling and final annealing the microstructure predictions are based on a full implementation of *ALSOFT* in the FE-code *ABAQUS*.

The *as cast* and homogenized structure of AA3103, i.e. the initial microstructure at the start of the hot rolling process is partly taken from experiments and partly provided by the solidification and homogenization model A*LSTRUC* [3,4]. Based on the composition, the rate of cooling and the temperature schedule during homogenization, *ALSTRUC* provides the *as cast* and homogenized structure in terms of the solid solution level of solute elements as well as the volume fraction and mean size of the constituent particles and dispersoids. The microstructural evolution during subsequent processing, involving alternating steps of deformation and softening/annealing is calculated by the work hardening model *ALFLOW* and the softening model *ALSOFT*, briefly presented below.

2.1 Substructure Evolution and Work Hardening.

To calculate the substructure evolution and work hardening during plastic deformation a recently developed work hardening model has been used [5-7]. This new approach is based on a statistical analysis of athermal storage of dislocations. By combining the solution for the dislocation storage problem with models for dynamic recovery of network dislocations and sub-boundary structures, a general internal state variable description is obtained. The result is a work hardening model, which *in principle* is capable of providing the stress-strain behaviour for a given metal or solid solution alloy under conditions ranging from deformation in the ambient temperature range to high temperature creep. A dedicated version of this model, designed for dealing with the problems of work hardening in aluminium alloys is referred to as *ALFLOW* [6]. The model relies on a three-parameter description for the microstructure, which at large strains are the subgrain size, δ, the cell interior density, ρ_i, and the sub-boundary misorientation, φ. The microstructure evolution is obtained by solving a set of differential equations describing the evolution of these parameters. The critical resolved shear stress at a given microstructure is given by the following expression.

$$\tau = \tau_t + \hat{\tau}_a = \tau_t + \tau_p + \alpha_1 Gb\sqrt{\rho_i} + \alpha_2 Gb(1/\delta + 1/D) \quad (1)$$

Here $\hat{\tau}_a$ characterises the rate and temperature *independent* interactions due to long-range elastic stresses, while the component τ_t characterises the rate and temperature *dependent* interactions with short-range obstacles, τ_p is the stress contribution due to non-

deformable particles, α_1 and α_2 are constants, *G* is the shear modulus, *b* is the Burgers vector, and *D* are the grain size. Extensive presentations of the model are found in [5-7].

2.2 Softening / Annealing

The core of the softening model is a recrystallization model that is described in detail in [8,9]. The model is an extension of the classical Johnson-Mehl-Kolmogorov-Avrami (*JMAK*) approach, treating recrystallization as a nucleation and growth process. The recrystallization reaction is a result of oriented nucleation, and three types of nucleation sites are considered, i.e. nucleation from deformation zones around large particles (PSN), nucleation from old grain boundaries and nucleation from retained cube bands. While the two former types of sites give a random texture the latter gives rise to recrystallized cube grains. The recrystallization kinetics is calculated by applying the standard assumptions of site saturation and a random distribution of nucleation sites, i.e. the following transformation kinetics law is obtained:

$$X(t) = 1 - \exp\left[\frac{4}{3} p N_{TOT} (nt)^3\right] \quad (2)$$

where *X(t)* is the fraction recrystallized after an annealing time *t* and *v* is the growth rate. When the fraction recrystallized is determined, the grain size in the recrystallized regions can be calculated as $D = (X / N_{TOT})^{1/3}$ where N_{TOT} is the total number of nuclei, while the fraction of the three recrystallization texture components are given as $f_i = N_i / N_{TOT}$. Input to the model is the deformation structure in terms of dislocation density, subgrain size, texture and particle size distributions (constituents and dispersoids). Model output is recrystallized grain size, texture (cube fraction) and recrystallization kinetics.

To model a complete industrial hot rolling schedule the recrystallization model has been extended to handle the complex situation of partly recrystallized sub-regions in between passes. For details it is referred [9].

The full version of the *ALSOFT* model combines the effect of static recovery and recrystallization during annealing of the deformed state. The model provides the yield stress, recrystallized grain size and fraction recrystallized as the main output. The flow stress at a given time (*t*) and temperature (*T*) is given as:

$$s_y = s_{y,0} + (1 - X_{rex}) \times M G b \left[\alpha_1 \sqrt{r_i} + \frac{\alpha_2}{d}\right] \quad (3)$$

where $\sigma_{y,0}$ is the flow stress of the undeformed material, and ρ_i and δ are the instantaneous values at a given time and temperature due to static recovery. Explicit expression for the rate of change of these quantities with time and temperature, as well as a more general discussion of the model may be found in [10].

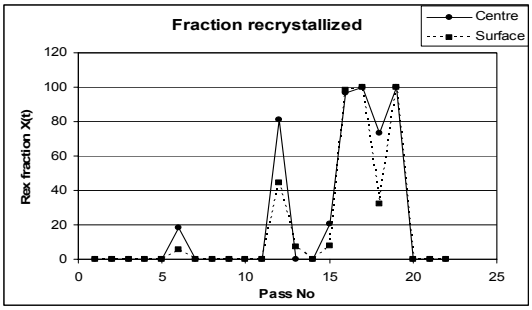
3. Microstructure Predictions

3.1 Multi-Pass Hot Rolling

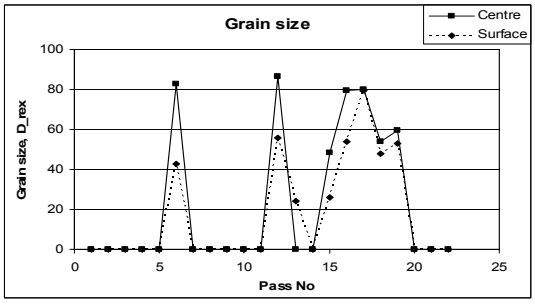
The temperature, the effective strain rate and the accumulated equivalent strain in each rolling pass are provided by FEM calculations. Together with the inter-pass times and estimated inter-pass temperatures, these parameters define the processing conditions

used for the hot rolling calculations. Necessary material parameters used as input to the *ALSOFT/ALFLOW* models is further; the initial grain size, initial volume fraction of cube texture, the size distribution of large particles, mean size and volume fraction of dispersoids and the solid solution level of solute atoms. Data for the dispersoids and the solute levels have been provided by *ALSTRUC*, the other material parameters in this work are taken from experiments [11]. For the initial texture, a random texture is assumed with a cube fraction ~ 4 %. As all models of this kind, both the *ALSOFT* model and the *ALFLOW* model involves several tuning parameters. The tuning parameters used in the present work are based on independent laboratory experiments on the AA3103 alloy.

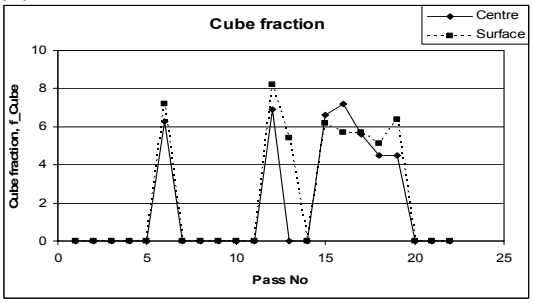
Model predictions for the recrystallized fraction, $X(t)$, grain size D, and texture (f_C, fraction of cube) during hot rolling (all 22 passes) are shown in Figure 1, both for the centre-line (z = 0) and at z = 0.8, i.e. close to the surface. We note that the model predicts 100% recrystallization first after the 17th pass (65 mm gauge). The fact that the material recrystallizes here is partly due to the long inter-pass time after this pass (due to cropping). 100% recrystallization is also obtained at the transfer gauge (22 mm), i.e. after the 19th pass. According to the model the material does not recrystallize during the final hot rolling in the finishing mill and is not recrystallized even after 1000 s at the exit temperature after exiting the hot rolling mill (4.2 mm gauge). The fraction of cube in the recrystallized regions is fairly low, i.e. 5-6%.



(a)



(b)



(c)

Figure 1: ALSOFT predictions for the multi-pass hot rolling of AA3103, corresponding to a centre streamline (z = 0) and a streamline close to the surface (z = 0.8). (a) Recrystallized fraction. (b) Recrystallized grain size, and (c) Fraction of cube in the recrystallized volumes.

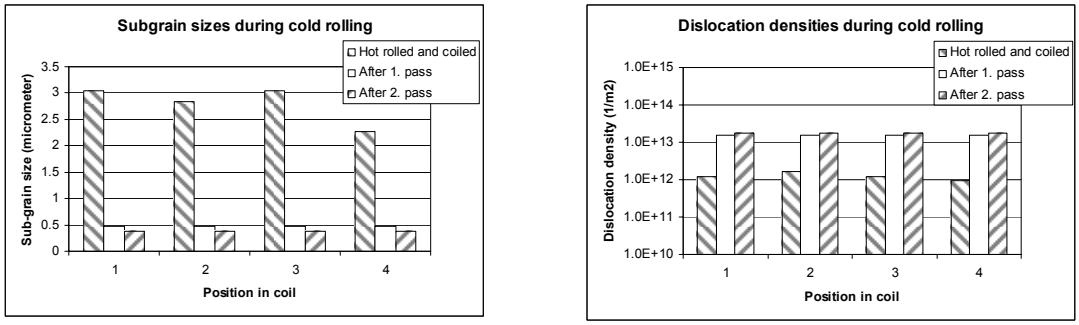
We note small differences between the centre and the surface regions. In accordance with a slightly more severe deformation in the surface regions (higher strain rate and lower temperature) compared to the centre line, the model predicts slightly lower subgrain sizes after each pass (not shown), which again is reflected in a slightly faster softening kinetics (Figure 1a) and smaller recrystallized grain size (Figure 1b). Small differences between centre and surface with respect texture (fractions of cube) are also observed.

3.2 Coil Cooling and Cold Rolling

Calculation of the microstructure evolution during coil cooling is based on a full implementation of *ALSOFT* in the FEM-code *ABAQUS*, to account for the variation in

thermal history in the different parts of the coil. The calculations show, however, that the actual variations are quite small. The *ALSOFT* calculations take as input the output deformation microstructure of the as hot rolled condition. The total time before the material enters the cold rolling mill is 10 hours. During this period of time the temperature drops from 310-320 ^{o}C to about 180 ^{o}C. The yield strength decreases from about 100 MPa to about 55 MPa without recrystallizing during the time of the coil cooling.

Cold rolling is then calculated using the *ALFLOW* model, with the as-coiled microstructure as starting structure. Cold rolling is carried out in two passes with a total reduction in sheet thickness from 4.2 mm to 2.1 mm. The coil temperature is 179 ^{o}C and 124 ^{o}C, respectively, in the two consecutive passes. An estimated average strain rate of 50 s^{-1} has been used in the calculations.



(a) (b)

Figure 2: Evolution in (a) subgrain size (b) and dislocation density during cold rolling, corresponding to the four extreme different positions in the coil.

Model predictions for the substructure evolution, corresponding to four extreme positions in the coil are shown in Figure 2. The results for the subgrain sizes compare well with corresponding experimental observations [11]. From Figure 2 it is interesting to notice that although the initial substructure varies from position to position, the final deformed microstructure after cold rolling is the same irrespective of position, i.e. we can consider the material as homogeneously deformed.

3.3 Final Annealing

After cold rolling the cold rolled sheet has been batch-annealed to soft temper according to the following temperature schedule: 30 ^{o}C/h to 370 ^{o}C and held at 370 ^{o}C and then air-cooled. Based on the full version of the *ALSOFT* model, the evolution in microstructure and associated mechanical properties has been calculated. The grain size of the fully soft condition is calculated to be 17 μm.

4. Discussion and Conclusions

Qualitatively there is good agreement between the model predictions and the experimental observations during hot rolling. The material is fully recrystallized both at the 65 mm gauge and the transfer gauge (22 mm gauge) while the 4.2 mm gauge is not recrystallized at all, in full agreement with model predictions. Also quantitatively most of the model predictions are reasonably good, although with some exceptions. The results with respect to grain size are summarized in Table 1. At the 65 mm gauge and in the centre a recrystallized grain size of 81 μm is observed, while the model prediction of 80 μm is only slightly smaller. However, a much larger grain size, i.e. 132 μm, is observed experimentally at the surface (z = 0.8), while the model here predicts a slightly smaller grain size (79 μm). The model

predicts a small decrease in recrystallized grain size from the 65 mm gauge to the transfer gauge, however, not as much as observed experimentally where the grain size is reduced by nearly a factor of 2, to 43 μm. Also here the actual grain size is slightly larger at the surface while the model predicts a somewhat smaller grain size at the surface than in the centre. Thus the model in the present stage does not account for the somewhat unexpected through thickness variations in grain size at the 65 mm gauge nor the considerable drop from the 65 mm to 22 mm gauge, which points to the need to better understand strain path effects. However, the predicted grain size of the fully soft condition after final annealing of the cold roll material (17 μm) compares well with an experimental value of 23 μm.

Table 1: Comparison of experimentally measured grain sizes and corresponding model predictions throughout the production chain

. Grain size	As homohenized	65 mm	22 mm	O-temper
Exp. – centre	110 μm	81 μm	43 μm	23 μm
Exp. – surface	110 μm	132 μm	45 μm	
Model – centre	100 μm*	80 μm	59 μm	17 μm
Model – surface	110 μm*	79 μm	53 μm	

* Model input

Also as far as it concerns the mechanical properties, the model predictions compares reasonably well with the experimental observations. In the hot rolled and cold rolled condition respectively the yield strength is predicted to be ~110 MPa and ~200 MPa, respectively, while the corresponding experimental values are 107 MPa and 195 MPa.

With respect to texture the ALSOFT model only predicts the volume fraction of cube in the recrystallized condition. However, where experimental results are available the model predictions compare well with the experimental observations, a very weak cube-texture at the transfer gauge of approximately 5 %.

Acknowledgements

This research was carried out as part of VIR[FAB] which is a Fifth Framework project (Contract N° G5RD-CT-1999-00132). The authors would like to thank the VIR[FAB] consortium for their collaboration and support, and in particular Drs. C. Allen and C. Liu, Corus RTD, for providing the experimental results serving as reference for the model predictions and Dr. J. Talamantes-Silva, Univ. of Sheffield for the FEM results for hot rolling. Financial support from the European Community is gratefully acknowledged.

References

[1] C. Allen and C. Liu, (2003), Internal VIRFAB-report.
[2] J. Talmantes-Silva, (2003), Internal VIRFAB-report.
[3] A.L. Dons, E.K. Jensen, Y.Langsrud, E. Trømborg, and S. Brusethaug, Metall. Trans. A, Vol. 30A, 2135-2146, 1999.
[4] A.L. Dons, Journal of Light Metals, Vol. 1, 133-1, 2001.
[5] E. Nes, Prog. Materials Sci, Vol. 41, 129-193, 1998.
[6] K. Marthinsen and E. Nes, Materials Science and Technology, Vol. 17, 376-388, 2001.
[7] E. Nes and K. Marthinsen, Materials Science and Engineering, Vol. A322, 176-193, 2002.
[8] H.E. Vatne, T. Furu, R. Ørsund, R. and E. Nes, Acta Materialia, Vol. 44, 4463-4473, 1996.
[9] H.E. Vatne, K. Marthinsen R. Ørsund and E. Nes, Metall. Trans. A, 27A, 4133-4144, 1996.
[10] J.A. Sæter, B. Forbord, HE. Vatne and E. Nes, Proceedings of The 6th International Conference on Aluminum Alloys, ICAA6 eds. T. Sato *et al*., JILM, Japan, pp.113-126, 1998.
[11] K. Sjølstad. Ph-D-thesis, Norwegian University of Science and Technology (NTNU), 2003.