FINITE ELEMENT SIMULATION OF ALUMINUM SHEET WARM FORMING USING ALFLOW HARDENING MODEL

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Summary. In order to accurately model the plastic deformation of Aluminum sheet at elevated temperatures, a model is required that incorporate the temperature and strain rate dependency of the material. In this article, two physically based models are compared: Bergström and Alflow model. Although both models can be fit quite well to monotonic tensile tests of 5754-O alloy, large differences appear if strain rate jumps are applied. The Alflow model also represents the negative strain rate sensitivity behavior of Al-Mg alloys at temperatures below 125°C.

1 INTRODUCTION

Mass reduction has long been identified as a key priority for improving automotive fuel economy. However, replacing steel in the structure and body with lighter materials such as aluminum can be costly and is not simple or straightforward, because it has much lower formability at room temperature than typical sheet steel. The formability of automotive aluminum sheet alloys (such as 5754-O) can be greatly improved by warm forming. Since elevated temperature produces decreased flow stress and increased ductility in the sheet, which can allow deeper drawing and more stretching to form panels without design modifications. An extra benefit of warm forming is that the stretcher lines due to PLC effect occur when 5xxx alloys are deformed at room temperature do not appear at elevated temperatures. However, experience with temperature controlled forming process is lacking and numerical models would be beneficial in optimizing the process simulations. A large number of constitutive models of the plastic behavior of aluminum sheet are available for finite element modeling. However, their applicability is usually limited in terms of varying strain, strain rate, temperature and changing microstructure, particularly in warm forming we cannot ignore the strain rate and temperature influence. Material models based on consideration of the underlying physical processes are expected to have a larger range of usability in this respect. This report focuses on the implementation of one such physically based hardening model developed by Nes, Marthinsen and co-workers. It is referred to as Alflow and it uses the dislocation density as a way to model plastic deformation. The Alflow model is
based upon a model for sub-structure evolution and consequent work hardening during plastic deformation proposed by Nes\textsuperscript{2} and dedicated to aluminum alloys. The model can directly take into account the chemical composition and the fabrication process influence on the stress-strain curve by changes of solute level, particle fraction and grain size.

\section{Constitutive Model}

In the present study, the anisotropic yield function of Vegter is used. The Vegter yield criterion\textsuperscript{3} is defined in principle stress space for plane stress situations meant for planar anisotropic material, i.e., the yield function depends on the angle between the principal axes and the rolling direction. For a particular angle $\theta$, four experiments are necessary to determine the model parameters: a simple shear test, a uniaxial tensile test, a plane strain tensile test and an equibiaxial tensile test. Between the measured stress points a Bezier curve is used to describe the yield locus. Extensive information is given in\textsuperscript{3}.

\section{Microstructure Evolution and Dislocation Mechanics Based Work Hardening Model}

The model approach relies on multi parameter description for the microstructure evolution. At small strains the stored dislocations are arranged in a cell structure characterized by the cell size, $\delta$ and the dislocation density within the cells, $\rho_i$. At large strains the dynamic recovery of dislocation becomes important and the cell walls collapse into sub-boundaries of well defined misorientations, $\varphi$. Extensive presentations of the model are given in\textsuperscript{1,2}. The microstructure evolution is covered by the following three differential equations:

\begin{align}
\frac{d\rho_i}{d\gamma} &= \frac{d\rho_i^+}{d\gamma} + \frac{d\rho_i^-}{d\gamma}, \quad \frac{d\delta}{d\gamma} = \frac{d\delta^-}{d\gamma} + \frac{d\delta^+}{d\gamma} \quad \text{and} \quad \frac{d\varphi}{d\gamma} = \frac{d\varphi^+}{d\gamma} + \frac{d\varphi^-}{d\gamma}.
\end{align}

Here, $\gamma$ is the resolved shear strain, which is defined as the algebraic sum of resolved shears of each slip system in the Taylor theory and interpreted as an average of the grains in this context. $\frac{d\rho_i^+}{d\gamma}$, $\frac{d\delta^-}{d\gamma}$ and $\frac{d\varphi^+}{d\gamma}$ are storage terms, describing different ways of athermal storage of dislocations, whereas $\frac{d\rho_i^-}{d\gamma}$ describes the dynamic recovery of cell interior dislocations by dipole annihilation and $\frac{d\delta^+}{d\gamma}$ is subgrain growth at elevated temperatures. Explicit expressions for these terms can be found in\textsuperscript{1}. The Alflow model expresses the critical resolved shear stress of the slip systems within each grain as a function of its microstructure:

\begin{align}
\tau = \tau_t + \tau_p + \tau_{cl} + \alpha_1 Gb \left[ \Gamma_1 \left( \frac{q_c}{\delta \sqrt{\rho_i}} \right) \sqrt{\rho_i} + \Gamma_2 \left( \frac{q_c}{\delta \sqrt{\rho_i}} \right) \frac{q_c}{\delta} \right] + \alpha_2 Gb \left[ \Gamma_2 (0) \frac{1}{\delta} + \frac{1}{D} \right]
\end{align}

Here $\tau_t$ is the thermal component of stress due to rate and temperature dependent interactions with short range obstacles, Orowan stress, $\tau_p$ due to non-deformable particles, $\tau_{cl}$ clustering stress respectively. Details may be found in\textsuperscript{1,2}. In applications of the model the stress tensor at a macroscopic continuum scale is required representing contributions from many grains of various crystallographic orientation and microstructure. The equivalent stress and strain can be
calculated as: $\sigma_{eq} = M\tau$ and $\varepsilon_{eq} = \gamma/M$, here $M$ is the Taylor factor and $\tau (\gamma)$ follows from the microstructure evolution predicted by the Alflow model.

4 RESULTS

Figure 1 shows the simulated engineering stress-strain curves plotted for the Alflow model, together with experimental data for various temperatures and strain rates. It can be seen that the model is more or less capable of describing the experiments. A large difference between the Alflow and Bergström models is observed if a jump in the strain rate is applied. In Figure 2, stress-strain curves are plotted for deformation at 250°C. If a strain rate change from 0.002 to 0.02 or from 0.02 to 0.002 is applied, with the Bergström model the constant strain curve is only slowly approached after continuous straining, whereas the Alflow model better represents the experiments. In Figure 3, even though the difference is small, it is clearly observed that the Alflow model can represent the negative strain rate sensitivity of Al-Mg alloys at low temperatures that is attributed to dynamic strain ageing caused by solutes, whereas hardly can find this behavior with the Bergström model.
5 CONCLUSIONS

In order to accurately model the plastic deformation of Aluminum sheet at elevated temperatures, a model is required that incorporate the temperature and strain rate dependency of the material. In this article, two physically based models are compared: Bergström and Alflow model. Although both models can be fit quite well to monotonic tensile tests of 5754-O alloy, large differences appear if strain rate jumps are applied. Alflow model also represents the negative strain sensitivity behavior of Al-Mg alloys at temperatures below 125°C. Deep drawing simulations need to be carried out yet for further validation of the Alflow model with experiments.

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REFERENCES


