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# The influence of a threshold stress for grain boundary sliding on constitutive response of polycrystalline Al during high temperature deformation

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**Abstract**

A continuum polycrystal plasticity model was used to estimate the influence of a threshold stress for grain boundary sliding on the relationship between macroscopic flow stress and strain rate for the aluminum alloy AA5083 when subjected to plane strain uniaxial tension at 450 °C. Under these conditions, AA5083 deforms by dislocation glide at strain rates exceeding 0.001 $s^{-1}$, and by grain boundary sliding at lower strain rates. The stress–strain rate response can be approximated by $\dot{\varepsilon} = A\sigma^n$, where $A$ and $n$ depend on grain size and strain rate. We find that a threshold stress less or equal to 4 MPa has only a small influence on flow stress and stress exponent $n$ in the dislocation creep regime (a threshold stress of 2 MPa increases $n$ from 4.2 to 4.5), but substantially increases both flow stress and stress exponent in the grain boundary sliding regime (a threshold stress of 2 MPa increases $n$ from 1.5 to 2.7). In addition, when the threshold stress is included, our model predicts stress versus strain rate behavior that is in good agreement with experimental measurements reported by Kulas et al. [M.A. Kulas, W.P. Green, E.M. Taleff, P.E. Krajewski, T.R. McNelley, Metall. Mater. Trans. A 36 (2005) 1249].


*Keywords:* Superplasticity; Finite element method; Aluminum alloy; Grain boundary sliding; Threshold stress; Strain rate sensitivity

## 1. Introduction

Complex parts for automobile and aerospace applications are often manufactured using hot blow forming processes such as superplastic forming (SPF) [1] and quick plastic forming (QPF) [2]. SPF involves deformation at low strain rates (<0.001 $s^{-1}$) and high temperatures (>500 °C), while QPF is performed at higher strain rates (>0.001 $s^{-1}$) and lower temperatures (450 °C) [3]. These processes are of particular interest in the automotive industry, where QPF has been found to be a particularly attractive technique for forming complex body parts [3]. The material used for both the SPF and QPF processes is usually aluminum alloy AA5083. The deformation behavior of AA5083 has been extensively studied: under QPF conditions, plastic flow occurs by a combination of grain boundary sliding and solute drag creep [4].

There is great interest in developing models that can predict the influence of alloy composition and microstructure on deformation behavior under SPF and QPF conditions, in the hope that such models can be used to develop new materials with improved formability. As part of this effort, Bower and Wininger [5] recently developed a microstructure-level model which accounts in detail for the various processes that contribute to plasticity at elevated temperatures. Their model idealizes a polycrystal as a set of grains (Fig. 1), whose constitutive behavior is characterized using a continuum crystal plasticity law. The grains are separated by sharp grain boundaries, which permit sliding and diffusion. Grain boundary sliding is modeled using a linear relation between resolved shear stress and slip rate, while grain boundary diffusion is modeled using a conventional linear diffusion equation.

Agarwal et al. [6] compared the predictions of this model with experimental measurements of plastic flow in AA5083 under QPF conditions. The experimental data consisted of (i) the flow stress under uniaxial tension as a function of strain rate, for materials with two different grain size, as illustrated in Fig. 2 (taken

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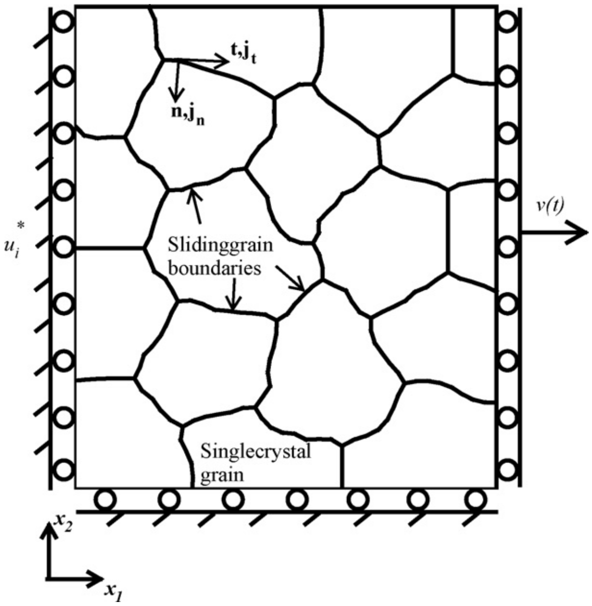


Fig. 1. A schematic illustrating the microstructure used in simulations.

from [6]) and (ii) measurements of texture evolution at various strain rates. The data showed a standard power-law relation between strain rate and stress of the form $\dot{\varepsilon} = A\sigma^n$ where $A$ and $n$ are functions of strain rate and grain size. For a fixed grain size of approximately 7 μm and temperature of 450 °C, it was observed that at slow strain rates ($\dot{\varepsilon} < 10^{-3}\,\mathrm{s}^{-1}$), the stress exponent has a value $n \approx 2.7$, while at fast strain rates ($\dot{\varepsilon} > 10^{-3}\,\mathrm{s}^{-1}$), $n \approx 4$. This suggests a transition in deformation mechanism at a strain rate around $10^{-3}\,\mathrm{s}^{-1}$. Texture measurements showed that at slow strain rates, the texture remains random while at fast strain rates a strong texture develops, providing additional indirect evidence for a mechanism transition, suggesting that grain-boundary sliding, is the dominant deformation mechanism at slow strain rates, while solute-drag creep dominates at fast strain rates.

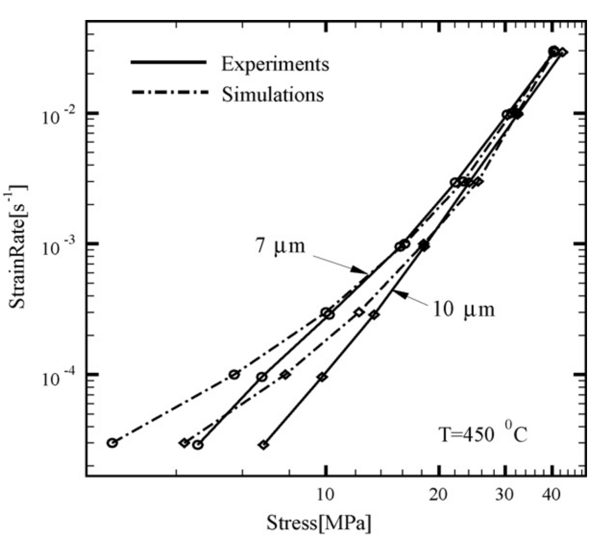


Fig. 2. Comparison of simulations without threshold stress and experiments of flow stress as a function of strain rate (from Agarwal et al. [6]; experimental data from Kulas et al. [12]).

The Bower–Wininger model was found to predict behavior that was in good qualitative and quantitative agreement with experimental data. In particular, (i) the simulations predicted a transition in deformation mechanism from grain-boundary-diffusion-mediated sliding at slow strain rates, to solute drag dislocation creep, assisted by grain-boundary sliding, at fast strain rates; (ii) the model correctly predicted the influence of grain size on both the mechanism transition and the strain rate sensitivity of the solid; and (iii) the model predicted a transition in rate sensitivity with strain rate that qualitatively matched the experimental measurements. However, simulations were found to substantially over estimate the strain rate sensitivity of the solid at low strain rates, giving a strain rate exponent that was higher than the experimental value.

The most likely explanation for this discrepancy between theory and experiment is that the simulations over-simplified the sliding response of grain boundaries. The model used a simple linear viscous relation between the sliding velocity and resolved shear stress. However, both experiments [7–10] and atomic-level simulations [11] suggest that the behavior of actual grain boundaries is significantly more complex. In particular, there is strong (indirect) experimental evidence to suggest that there is a threshold stress for grain boundary sliding in AA5083 [7–10]. Similarly, molecular dynamics simulations of grain boundaries show that sliding occurs only if the resolved shear stresses exceed a critical magnitude [11]. Estimates of the threshold stress for grain boundary sliding vary, and suggest it is a function of temperature, grain size and grain boundary misorientation.

In this paper, our objective is to extend the finite element model of Bower and Wininger [5] to include a threshold stress for grain boundary sliding, and to compare the predictions of the extended model with experimental data. We find that even a small threshold stress (1 MPa) substantially increases the flow stress at low strain rates, and also reduces the strain rate sensitivity. As a result, the model predictions are in agreement with experimental data over the full range of strain rate.

## 2. Finite element model

Our finite element model is described in detail in Bower and Wininger [5] and will be only briefly outlined here. The model idealizes a polycrystal as a two-dimensional assembly of grains, separated by sharp grain boundaries, as illustrated in Fig. 1. The grain structure was taken from a section through a representative sample of AA5083 with 7 μm grain size—the microstructure is identical to that used in the simulations reported by Agarwal et al. [6]. Each grain is modeled as a face centered cubic single crystal. The grain boundaries permit sliding, and also provide a path for stress driven mass transport. The material is subjected to boundary loading that is intended to approximate plane-strain uniaxial tension. Symmetry conditions are applied on boundaries at $x_2 = 0$ and $x_1 = 0$; the top surface of the microstructure, $x_2 = h$, is taken to be free of traction; and the solid is subjected to a constant strain rate of $\dot{\varepsilon}_{11} = \dot{\varepsilon}^{\infty}$ by displacing the boundary at $x_1 = L$. A standard finite element method, suitably extended to account for grain boundary sliding and diffusion, is used to calculate the displacement, strain and stress fields $[u_i, \varepsilon_{ij}, \sigma_{ij}]$ in the