

MULTISCALE MODELING OF CRYSTAL PLASTICITY IN AL 7075-T651

D.J. Littlewood and A.M. Maniatty

Rensselaer Polytechnic Institute
Department of Mechanical Engineering
Jonsson Engineering Center, 110 8th Street, Troy, NY 12180 USA
e-mail: littld@scorec.rpi.edu

Key words: Computational Plasticity, Multi-Scale Methods, Al 7075.

Summary. *An elasto-viscoplastic constitutive model and corresponding finite-element implementation are presented for Al 7075-T651. The material model is informed by micro-scale mechanisms and is suitable for providing heterogeneous stress and strain data at the grain scale to formulations for crack initiation and fatigue failure. A precipitation hardening model was selected to capture the Orowan looping mechanism observed experimentally in this material. The finite-element implementation utilizes an additional pressure variable for stability and a consistent tangent formulation for fast convergence. Model calibration was performed by comparing results from a 300-grain finite-element model to experimental data.*

1 INTRODUCTION

The accumulation of fatigue damage is a primary concern in the servicing of aircraft. To maintain flight safety, periodic inspections of aircraft components are carried out as dictated by probability-of-failure estimates. Current practice involves the combined use of stress-strain curves, fatigue-life curves, and crack-growth-rate curves for the estimation of fatigue life. Alternatively, full-scale tests on aircraft have been carried out using anticipated loading conditions. In the case of both analytical and experimental approaches, the resulting damage estimates are generally conservative, which may result in costly underestimation of life.

In the present study, a multi-scale model is under development for Al 7075-T651 with the goal of increasing the accuracy of life estimates by linking the heterogeneous material state at the grain scale to damage and fatigue failure mechanisms. The focus is on localized plastic strain and fatigue damage, in particular damage and crack initiation at second-phase particle inclusions. At the grain scale, crystallographic orientation has been observed to have a significant effect on crack initiation in 7XXX aluminum alloys.¹

We present the development and implementation of a crystal elasto-viscoplastic constitutive model for use in a multi-scale framework for life prediction. The constitutive model is informed by dislocation mechanisms at the microstructure level. Based on experimental observations of Al 7075-T651, Orowan looping is considered the primary mechanism for

hardening, and failure is assumed to initiate at inclusion sites.² The material model developed for Al 7075-T651 is well-suited for large-scale analysis of realistic grain structures containing particle inclusions using the finite-element method (FEM), where crack-growth and fatigue-life models may be incorporated to predict fatigue failure.

2 CONSTITUTIVE MODEL

A crystal elasto-viscoplastic model following that of Matouš and Maniatty³ is employed for AL 7075-T651. The model formulation is based on a multiplicative decomposition of the deformation gradient into elastic and plastic parts. Behavior in the elastic regime is treated as linear with cubic symmetry. Deformation in the plastic regime is a function of dislocation mobility, and is described in terms of slip rates using a power-law rule,

$$\dot{\gamma}^\alpha = \dot{\gamma}_o \left| \frac{\tau^\alpha}{g^\alpha} \right|^{\frac{1}{m}} \text{sign}(\tau^\alpha). \quad (1)$$

Here, $\dot{\gamma}_o$ is a reference rate, τ^α is the resolved shear stress on slip system α , g^α is the material's resistance to slip on slip system α , and m is a strain rate sensitivity parameter.

The evolution of g^α , which represents hardening, is based on the underlying dislocation Orowan looping strengthening mechanism observed in Al 7075-T651 (see, for example, Hart⁴ and Schmitt *et al.*⁵). An analysis of dislocation looping around non-shearable equiaxed precipitates results in the following evolution equation,

$$\dot{g}^\alpha = G_o \left(\frac{g_s - g^\alpha}{g_s - g_o} \right) \sum_{\beta=0}^{N_{ss}} 2 \left| \mathbf{S}_{ij}^\alpha \mathbf{S}_{ij}^\beta \right| |\dot{\gamma}^\beta|, \quad (2)$$

where G_o is a scaling constant, g_o is the initial hardness, g_s is the saturation hardness, g^α is the current hardness on slip system α , \mathbf{S}^α is the symmetric part of the Schmid tensor for slip system α , and N_{ss} is the number of slip systems (there are twelve primary systems in this case). The hardening model distinguishes between self and latent hardening, and bounds resistance to slip between initial and saturation values. Hardness evolution for each slip system is evaluated using the hardening rate and a backward Euler scheme.

The constitutive model is well suited to provide material state information to an accompanying failure prediction formulation. Accumulated plastic slip in the vicinity of an inclusion, for example, may be treated as a condition that promotes crack initiation. These data can be passed to a formulation for determination of probability of failure.

3 FEM IMPLEMENTATION

The crystal elasto-viscoplastic constitutive model was implemented within a three-dimensional FEM code. The FEM program operates on a representative volume element (RVE) within a macro-scale component. The RVE contains a number of grains, providing an accurate model of the stress and strain interactions between grains. A higher-scale

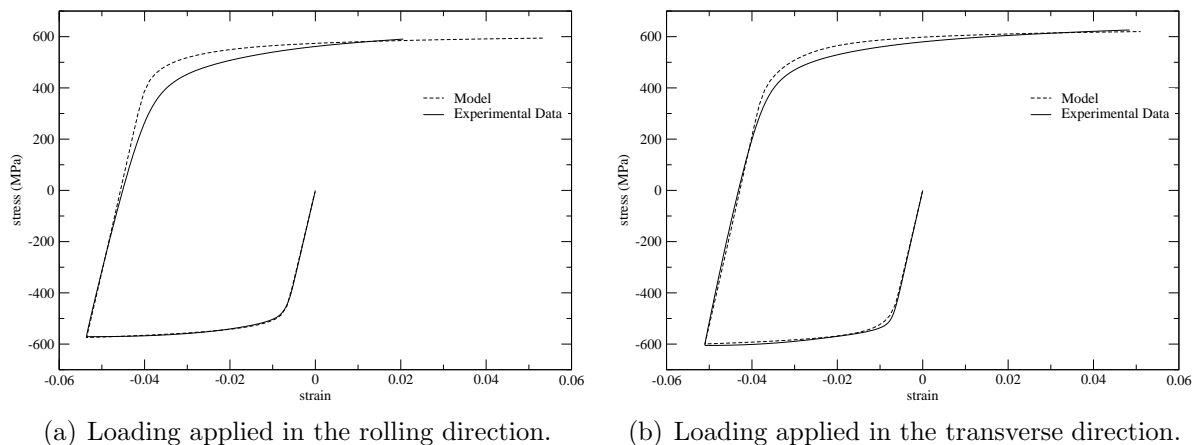


Figure 1: Calibration results.

FEM analysis at the macro-scale may be used to provide appropriate boundary conditions for the RVE.

The FEM routine contains features for increased stability and fast convergence. Specifically, a mixed displacement/pressure formulation allowing for a discontinuous pressure field is used for stability in the presence of nearly incompressible plastic flow. The linearized pressure equation is solved on the element level for computational efficiency. To ensure fast convergence, the FEM routine uses a consistent tangent formulation.

The state update routine utilized in the FEM formulation is based on a determination of the plastic velocity gradient using both the power-law slip rule and a backward Euler scheme. The state update routine is completed by minimizing the residual between these two calculations, which is accomplished when the proper decomposition of the deformation gradient into elastic and plastic parts is determined.

4 MODEL VALIDATION AND CALIBRATION

Model calibration was performed against experimental data from tension, compression, and cyclic loading tests. Model data were obtained by analyzing a 300-grain polycrystal model containing 42,503 elements. Based on experimental observations of Al 7075-T651, an aspect ratio for individual grains of 1:4:50 was used. Lattice orientations were assigned based on scanning electron microscope back scatter diffraction measurements.⁶ Results from a reversed-loading test are presented in Figure 1.

At present, the calibration results show good agreement with monotonic tension and compression test results. Upon reversal of the loading direction, however, the model fails to capture the full extent of the Baushinger effect observed experimentally.

5 DISCUSSION AND FUTURE WORK

The elasto-viscoplastic model and accompanying FEM implementation developed for Al 7075-T651 are suitable for identifying localized grain-scale phenomena for use in a crack-initiation formulation. Experimental observations have shown that crack initiation, stemming from particle inclusions, leads to fatigue failure of Al 7075-T651. The application of the material model to a RVE with a realistic grain structure and particle inclusions will yield improved life-prediction calculations.

Future work will involve model enhancements to better capture the Baushinger effect, a more detailed study of plastic slip and damage initiation near particles, and linking the model more directly to the macro scale. The calibration results show good agreement with test data for monotonic loading, but underestimate considerably the Baushinger effect. A potential remedy is the introduction of an additional kinematic hardening term at the slip system level.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the support of DARPA under contract number HR0011-04-C-0003. Discussions with H. Weiland, A.D. Rollett, J. Papazian and A. Ingraffea are gratefully acknowledged. The authors also thank A. Ingraffea and P. Wawrzynek of the Cornell Fracture Group for use of the FemLib software package, and M. Horstemeyer, Y. Xue, and B. Jordan of Mississippi State University for use of their experimental data for Al 7050-T651.

REFERENCES

- [1] G. Patton, C. Rinaldi, Y. Bréchet, G. Lormand, and R. Fougères. Study of fatigue damage in 7010 aluminum alloy. *Materials Science and Engineering A*, A254(1-2):207–218, 1998.
- [2] Weiland, H., Alcoa Technical Center. Private communication, 2005.
- [3] Karel Matouš and Antoinette M. Maniatty. Finite element formulation for modelling large deformations in elasto-viscoplastic polycrystals. *International Journal for Numerical Methods in Engineering*, 60(14):2313–2333, 2004.
- [4] E.W. Hart. Theory of dispersion hardening in metals. *Acta Metallurgica*, 20(2):275–289, 1972.
- [5] C. Schmitt, P. Lipinski, and M. Berveiller. Micromechanical modelling of the elasto-plastic behavior of polycrystals containing precipitates — application to hypo- and hyper-eutectoid steels. *International Journal of Plasticity*, 13(3):183–199, 1997.
- [6] Rollett, A.D., Carnegie Mellon University. Private communication, 2005.