COMPETITION BETWEEN INTERGRANULAR AND TRANSGRANULAR FAILURE IN ALUMINUM ALLOY: EXPERIMENTS AND CRYSTAL PLASTICITY MODELLING

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Abstract

Aluminum alloys commonly used in airframe structures have been observed to show orthotropy in fracture when processed through hot rolling or extrusion, while other properties such as yield are more isotropic. Fracture orthotropy is likely due to a competition between damage accumulation within the grains by void growth and cleavage along the grain boundaries. Analysis of the fracture surface indicates varying degrees of dimpled regions (indicating damage by void growth) and quasi-brittle flat regions coinciding with the grain boundary (indicating grain boundary failure). To help determine structure-property relations in such materials, this paper describes a computational model for fracture in ductile polycrystals accounting for both the damage mechanisms. The model is validated by comparing with experiments on a high strength aluminum alloy, AA2139.

1. Introduction

Transgranular failure by void growth and intergranular failure by grain boundary (GB) decohesion are key modes of failure in polycrystalline microstructures under tensile stress states. Voids nucleate from second phase particles and grow due to plastic deformation within the grains. On the other hand, GB decohesion can occur due to the low strength of the GBs, presence of GB precipitates, or due to the presence of precipitate free zones near the GBs. The extent of each failure mode depends on many factors: composition, size and distribution of second phase particles, grain size, grain shape, texture, and stress state. Using only experiments to establish structure-property relations is prohibitively difficult. Therefore, we build a computational model which incorporates relevant microstructural effects. Deformation within the grain is described by a phenomenological *crystal plasticity* (CP) constitutive model to account for texture. The CP model is extended to handle grain-size and grain-shape effects, as well as to account for the loss of flow strength due to the growth of voids within the grains. GB decohesion at the grain boundaries is represented as a cohesive surface interaction using suitable traction-separation laws. Experiments are performed on rolled sheets of AA2139. Tensile specimens are drawn at different angles to the rolling direction. Orientation-dependence of fracture strain and fracture surface characteristics is measured and is used for model parameters identification and validation.

2. Finite element model and constitutive equations

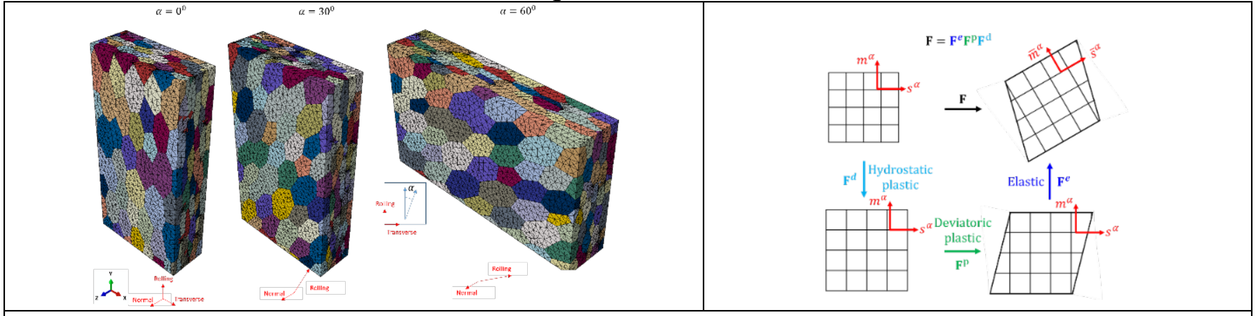

Fig. 1 (a) FE models of tensile specimens drawn at different angles relative to the rolling direction in the plane of the sheet. (b) Multiplicative decomposition of deformation gradient to elastic, deviatoric plastic and hydrostatic plastic (damage) parts.

Fig.1(a) shows finite element (FE) models used in this work; the specimens shown represent tensile specimens drawn at different angles relative to rolling direction. A CP constitutive model is assigned to the grain interiors. Fig. 1(b) shows the multiplicative decomposition of the deformation gradient at each material point; unlike conventional CP models, in which the plastic strain is only deviatoric, the current model accounts for both the deviatoric (representing dislocation slip) and hydrostatic (representing void growth) parts of plastic strain. Table 1 lists the key constitutive equations used in the model. The interaction between adjoining grain boundaries is modelled as a surface-based cohesive behavior.

Table 1 Constitutive equations used in the model: here, τ^{α} is the resolved shear stress on the slip plane, g^{α}_{eff} is the critical resolved stress of the slip system, g^{α} is the slip system strength due to forest hardening, τ^{α}_0 is the lattice friction, f is the porosity, ϕ is the ductile damage, m is the rate sensitivity exponent, and T is the triaxiality. c_1, and c_2 are fitting parameters.

$\dot{\gamma}^{\alpha} = \dot{\gamma}_0 \left(\frac{\tau^{\alpha}}{g^{\alpha}_{eff}}\right)^m sgn(\tau^{\alpha})$	(1)	$g^{\alpha} = \tau^{\alpha}_0 + \mu b^{\alpha} \left(\sum A_{\alpha\beta}\rho^{\beta}\right)^{0.5}$	(3)
$g^{\alpha}_{eff} = g^{\alpha}(1-\phi)$	(2)	$\phi = c_2 f$	(4)
		$\Delta f = c_1 \sinh\left\{\frac{m-0.5}{m+0.5}T\right\}\left[\frac{1}{(1-f)^m} - (1-f)\right]\sum\lvert\Delta\gamma^{\alpha}\rvert$	(5)

3. Results

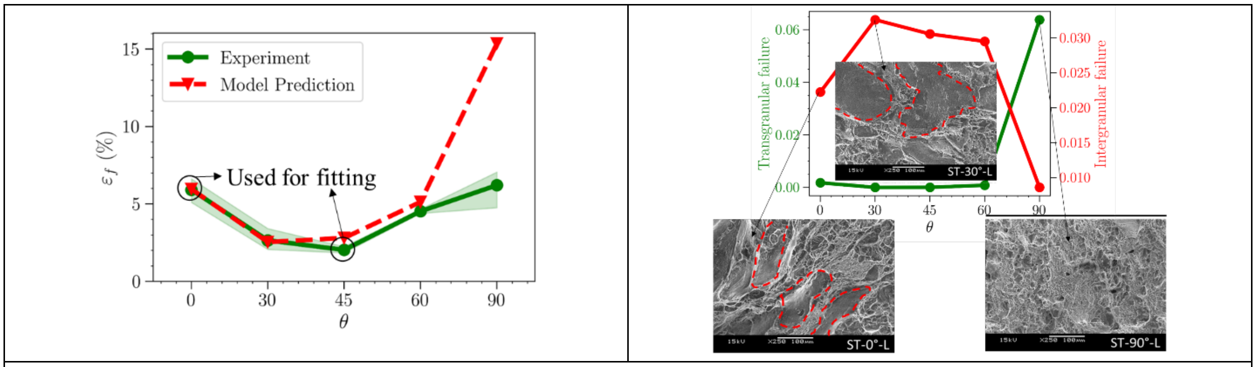

Fig. 2 (a) Comparison of experiment vs model predictions of ε_f. (b) Extent of intergranular and transgranular damage for different orientations.

Fig. 2(a) compares the model predictions for the strain at incipient failure (ε_f) to the experimental values. ε_f is maximum when the loading is at $\theta = 90°$ and is minimum when the loading is at $\theta = 45°$. The model qualitatively captures the fracture orthotropy as observed in the experiments. Fig.2(b) compares the extent of intergranular and transgranular damage for different specimens. The model predicts that failure is dominated by transgranular failure when $\theta = 90°$, consistent with experimental observations of dimples on the fracture surface. On the other hand, for $\theta = 30°$, the model predicts that the failure is dominated by intergranular failure, consistent with experimental observations of flat facets on the fracture surface.

Conclusions

The current modeling approach integrates damage mechanisms at two scales in polycrystalline materials: void nucleation, growth, and coalescence in the grain interiors and decohesion at the grain boundaries along with a classical crystal plasticity model enhanced to account for grainsize effects. This approach allows for computational investigation of the coupling between the microstructure and the damage mechanisms in determining the microstructure-property relations in polycrystalline materials. The model was utilized to analyze fracture orthotropy in rolled high strength Al alloys.

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