

A Crystal Plasticity Finite Element Method (CPFEM) based study to investigate the effect of microvoids in single crystalline aluminium alloy

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ABSTRACT

Aluminium alloys are typically used in a variety of applications, which require high strength, ductility and formability. In order to understand the formability of such alloys along with underlying mechanisms, a CPFEM based study has been performed using crystal plasticity theory. Crystal plasticity finite element methods [1]–[4] have been used to perform the simulations on representative volume elements (RVE's) of single crystal metal with different configurations, sizes and shapes of voids (defects). A part of the rigorous study will be presented in this work by taking into account the effect of void geometry, void fraction, void orientation, loading type (level of triaxiality), and crystallographic orientations. Using these large sets of simulations, analyses will be presented to better understand the underlying physical mechanisms which include interrelation among void growth, applied strain, void fraction, void size/shape, and plastic anisotropy effects under different types of loading.

Keywords: Void Growth, Crystal Plasticity, Aluminium Alloys

1. Introduction

A variety of applications require materials being light weight, high strength, corrosion resistant and formable which makes aluminium alloy as being one of the many best candidates. The behaviour of different types of aluminium alloys has been studied for a long time. Fractography of these alloys generally show that void growth and coalescence is one of the dominant fracture mechanisms.

The research on void nucleation, growth and coalescence during ductile damage in metal and alloys dates back to late 1950's. Studies have been performed to understand the basic physical phenomenon of void growth and numerical issues in solving such problems [5]–[11]. Most of the investigations are based on simplified assumptions, such as isotropic material, 2D plane strain, axisymmetric models, cylindrical/spherical voids or limited number of loading states and slip systems.

The presented work is an effort to advance the research in the field by performing a rigorous fully-validated 3D CPFEM based RVE study to better understand the relationship among void growth, initial porosity, initial void size, and plastic anisotropy effects.

2. Crystal Plasticity based Modelling

2.1 Crystal Plasticity Theory

General crystal plasticity framework is based on the assumption that plastic deformation is due to the crystalline slip in different slip systems [2], [12].

Plastic slip in α -th slip system is given by the conventional crystal plasticity based power law

$$\dot{\gamma}^{\alpha} = \dot{\gamma}_0 \left[\frac{|\tau^{\alpha}|}{g^{\alpha}} \right]^{1/m} \text{sgn}(\tau^{\alpha}) \quad (1)$$

where τ^{α} is the resolved shear stress on slip system α , g^{α} is the strength of the slip system α , $\dot{\gamma}_0$ is a reference shear strain rate, and m is the rate sensitivity exponent.

The resolved shear stress τ^{α} in a specific slip system is computed through deviatoric stress tensor σ' and Schmidt factor based on slip system direction and normal, s^{α} and m^{α}

$$\tau^{\alpha} = \sigma' : (s^{\alpha} \otimes m^{\alpha}) \quad (2)$$

The evolution of the strength of the slip system is based on the saturation hardening rule and is given by

$$\dot{g}^\alpha = h_0 \left(\frac{g_s(\dot{\gamma}) - g^\alpha}{g_s(\dot{\gamma}) - g_0} \right) \dot{\gamma}, \quad (3)$$

where

$$g_s(\dot{\gamma}) = g_{s0} \left(\frac{\dot{\gamma}}{\dot{\gamma}_{s0}} \right)^{m'}$$

and $\dot{\gamma} = \sum_\alpha |\dot{\gamma}^\alpha|$

while h_0 , g_{s0} , g_0 , $\dot{\gamma}_{s0}$, and m' are material parameters to describe hardening behaviour for all slip systems.

2.2 Material Parameter Identification

Material parameters are identified through inverse modelling approach using uniaxial experimental stress strain data and are given in Table 1 while comparison between experimental and simulated response is given in Figure 1. Experimental data is from uniaxial test results obtained locally.

Table 1: Material Parameters for Aluminium Alloy AA-5xxx

m	$\dot{\gamma}_0$	h_0	g_0	g_{s0}	m'	$\dot{\gamma}_{s0}$
0.03	1.0 /sec	200.40 MPa	105 MPa	110 MPa	0.0	5e10 /sec

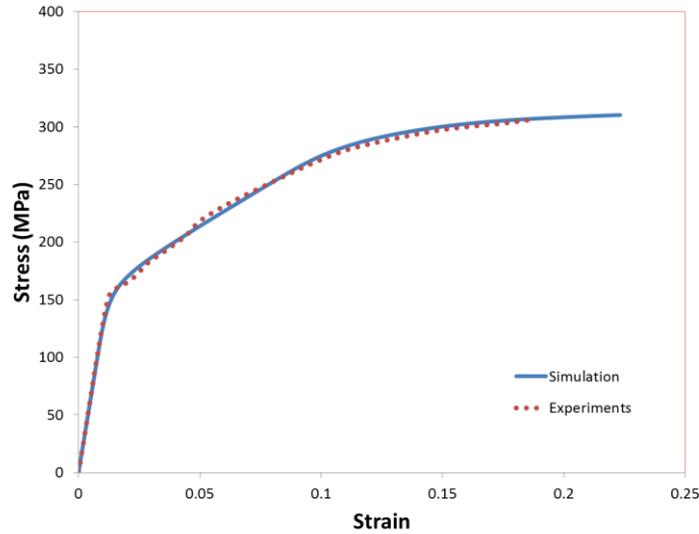


Figure 1: Comparison of Stress-Strain Curves after Material Parameter Identification

2.3 RVE Model

Finite element based 3D RVE model have been constructed for various void diameters (ranging from 310nm to 1.44mm); void fractions (0.001, 0.005, 0.01, 0.03, 0.05); loading types (triaxialities 1/3, 1, 2, 3) and crystal orientations (5 different orientations). A representative half sectioned model of two different porosities has been shown in Figure 2.

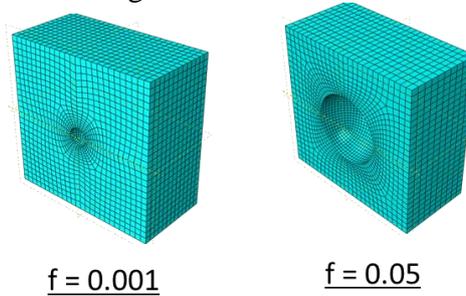


Figure 2: Half sectioned model of spherical void RVE

3. Results and Discussion

Four different loading types by varying the triaxiality were simulated for different porosities. Figure 3 shows the plot of void growth as a function of applied strain, and triaxiality for two different porosities with same crystal orientation. It can be inferred from the Figure 3 that as the applied strain is increased the void grows exponentially. It can also be inferred that the amount of void growth increases with the level of triaxiality. It is also found that larger voids (higher porosity) grow more, i.e. reaching to higher porosity value, than smaller voids at higher triaxialities. Lattice orientation evolution has been plotted in Figure 4 as {111} pole figures for initial porosity of 0.01. It can be inferred from figure that as the triaxiality increases the lattice rotation in the individual elements also increase. Uniaxial case shows very small amount of rotation due to the small amount of void growth. It can also be inferred from Figure 4 that larger the void growth higher is the lattice rotation. It was also found during the investigation that lattice rotation is higher for larger void growth and triaxiality. Also, most of the lattice rotation was found to occur in the vicinity of the defect.

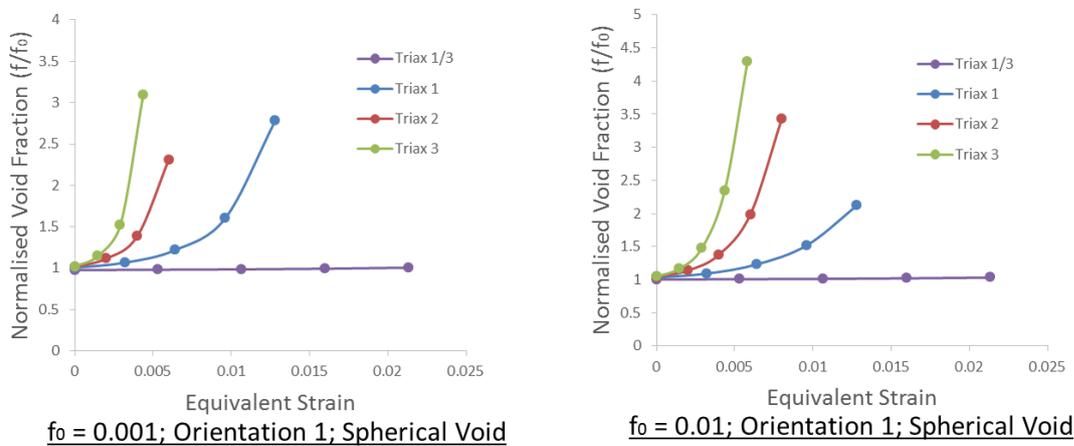


Figure 3: Void growth as a function of triaxiality and applied strain for two different porosities

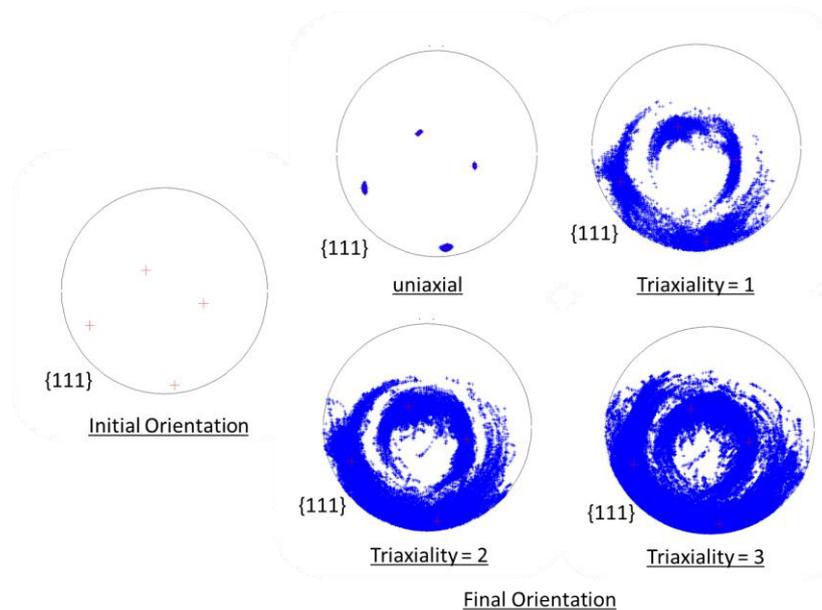


Figure 4: {111} pole figures showing initial (left) and final orientations for different loading types ($f=0.01$; Or1)

Figure 5 shows the plot of void evolution as a function of equivalent strain for five different orientations and three different triaxialities (1/3, 1, 2). It is found that void growth strongly depends on crystal orientation for uniaxial cases (Figure 5 (left)). The effect reduces as the triaxiality is increased and for higher triaxialities the effect of crystal orientation diminishes.

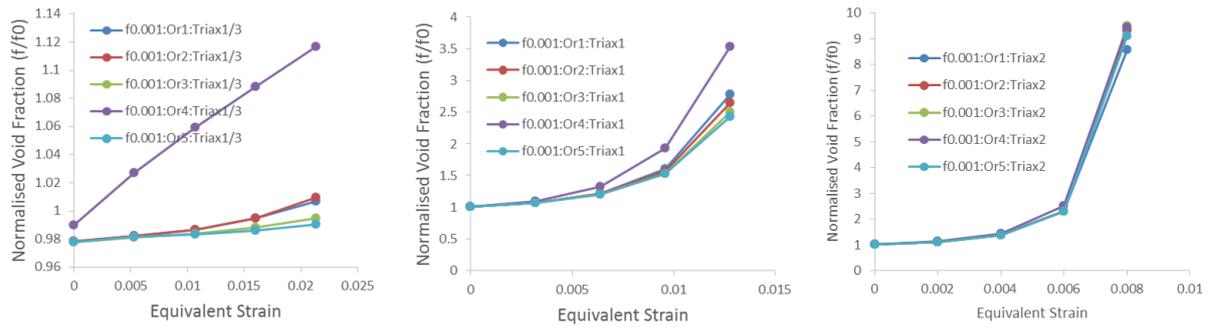


Figure 5: Void growth as a function of applied strain for different orientations and triaxialities

4. Conclusions

A three dimensional CPFEM based study has been presented to understand the formability of aluminium alloy single crystals. Material parameters were identified through inverse modelling approach using experimental data. The effect of applied strain, initial porosity, void size, initial crystal orientation, and triaxiality on void growth is presented. An effort was put to explain the void evolution behaviour by correlating with the lattice rotation. It is found that defects show exponential increase with respect to the applied strain. Larger voids grow more than smaller voids. Higher triaxiality cause higher amount of lattice rotation due to higher void growth. Plastic anisotropy has significant effect on the void growth and this effect diminishes as the triaxiality increases.

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