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PRELIMINARY INVESTIGATION OF THE ROLE OF CRYSTAL PLASTICITY IN PREDICTIVE MODELLING OF IMPACT ON AEROSPACE STRUCTURES

Helen Sarsfield, Rachel Keenan, Li Wang, Nikica Petrinic and Fionn Dunne

Impact Engineering Team, Solid Mechanics and Materials Engineering Group
Department of Engineering Science, University of Oxford, UK
e-mail: Helen.Sarsfield@eng.ox.ac.uk, web page: www.eng.ox.ac.uk

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Summary. *This paper outlines the role of crystal plasticity within the adopted strategy for characterization of lightweight metallic alloys for aerospace applications subjected to impact loading. Microscopic observations have been used to determine textural properties of titanium alloys. The ability of crystal plasticity to assist in designing desired textures of aluminium alloys has been investigated with the aim to enable integrated material-structural design of aerospace components with improved resistance to impact loading.*

1 INTRODUCTION

Titanium, aluminium and their alloys have long been recognized as valuable engineering materials due to a rather unusual and desirable combination of properties; that is, their relatively low densities and high strengths, when compared to other metals[1].

A material's properties are dependent on its microstructure and in order to influence one, the other should be fully understood. It is crucial that a material's response to the loading conditions to which it might be subjected to in its lifetime can be accurately predicted. Materials for aerospace may undergo dynamic impact loading, for example in the sudden impact of foreign objects on aircraft turbine blades. The application of aerospace materials is becoming a holistic process combining materials and process routes with prediction of engineering and market performance, with developments predicted by modelling[2].

The tensors representing material properties are identical for a point with the same crystallographic orientation when expressed in crystal axes, but differ for grains of different orientations when referred to the same set of axes. This results in aggregates of crystalline grains exhibiting local variations of properties which arise from the distribution of orientations (texture) at the polycrystalline levels[3]. Crystallographic micro-textures, within grains, develop upon deformation and recrystallization annealing during the forming process. Thus they may be controlled by varying, for example, the deformation temperature and deformation mode, such that textures may offer an extra opportunity to design and optimise the performance of aerospace alloys.

This paper provides details of uniaxial tensile tests and numerical simulations of these using a phenomenological material model. A number of steps have been taken towards the development of a micromechanical approach to incorporate an understanding of the deformation mechanisms at the crystalline level of the material. The grain structure of the material will be modelled instead of purely considering the macroscopic response of a material to loading condition.

The specimens tested to fracture are mounted and then polished according to standard metallographic techniques to produce a good surface finish suitable for examination in a scanning electron microscope (SEM). Electron back scattered diffraction (EBSD) has also been employed; this is a method of characterizing crystallographic texture by determining the crystal orientations at discrete locations within a specimen.

Developments in the capability of crystal plasticity modelling are demonstrated with examples.

2 EXPERIMENTAL METHODOLOGY

2.1 Uniaxial tensile tests

Uniaxial tensile tests have been completed at four different rates of strain, from $1x10^{-6}s^{-1}$ to $1x10^{3}s^{-1}$. The stress required to produce plastic deformation, increases with strain rate. This phenomenon makes the alloy a good candidate for use in applications where it might be subjected to impact loading.

2.3 Microscopic observation

Examination of the fracture surfaces reveals the specimens undergo dimpled ductile fracture as a result of void nucleation, growth and coalescence. The microvoids nucleate at areas of localised deformation, such as inclusions and grain boundaries. The voids grow and coalesce into cracks.

The EBSD software calculates and outputs three Euler angles at each analysis point. These angles allow the formulation of an orientation matrix which can rotate a vector in the test specimen co-ordinate system to the crystal orientation. One type of EBSD output is an 'orientation map', as in *Figure 1* and *Figure 2*, a qualitative depiction of the microstructure of a region in terms of its orientation constituents. Further analysis shows that there is more crystal reorientation as a result of deformation near the fracture site.

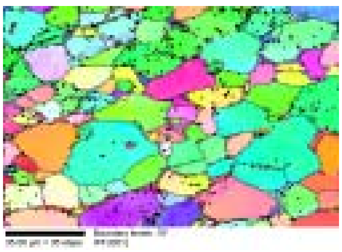

Figure 1: Orientation in the gauge length of a specimen

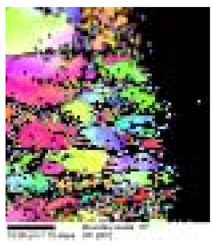

Figure 2: Orientation at the fracture site

4 CRYSTAL PLASTICITY AS A TEXTURE DESIGN TOOL

4.1 Phenomenological Modelling

Numerical simulations have been performed using a phenomenological constitutive model coupling temperature dependent isotropic elasto-viscoplasticity and scalar damage mechanics. It is possible to extract data from the simulation and plot the relative displacement and reaction forces at points either side of the parallel gauge length for direct comparison with experimental data. The material model is found to represent accurately the rate dependent deformation of Ti-6Al-4V.

4.2 Crystal Plasticity model

The crystal plasticity model is based on that developed by Asaro[4], Anand and Kothari[5].

The deformation and rotation of a crystal can be described by the deformation gradient $\boldsymbol{F}$, which can be written in terms of its elastic and plastic parts

$$\boldsymbol{F} = \boldsymbol{F}^{e}\boldsymbol{F}^{p} \tag{1}$$

As the material is loaded it undergoes rigid body rotation together with elastic deformation and plastic slip, γ, through the crystal lattice described by $\boldsymbol{F}^{p}$. The velocity gradient of the total deformation is given by

$$\boldsymbol{L} = \dot{\boldsymbol{F}}\boldsymbol{F}^{-1} \tag{2}$$

The velocity gradient can be decomposed into the deformation rate $\boldsymbol{D}$ and the spin tensor $\boldsymbol{W}$ and these can in turn be described in terms of their elastic and plastic parts

$$\boldsymbol{L} = \boldsymbol{D} + \boldsymbol{W} \tag{3}$$

The plastic velocity gradient can be determined as the sum of the shearing rates, $\dot{\gamma}^{\alpha}$, occurring in the α independent slip systems. Slip is assumed to obey Schmid's law and occurs when τ, the resolved shear stress on any given slip system (α) exceeds a critical value, τ_c. A slip system is prescribed in terms of it plane normal $\boldsymbol{n}$ and slip direction $\boldsymbol{s}$.

$$\boldsymbol{L}^{p} = \sum \dot{\gamma}^{\alpha}\boldsymbol{s}^{\alpha} \otimes \boldsymbol{n}^{\alpha} \tag{4}$$

where

$$\dot{\gamma}^{\alpha} = K\left(\tau^{\alpha} - \tau_{c}\right)^{m} \tag{5}$$

Initially a simple power hardening law with just two material constants K and m has been implemented which will be improved upon.

3.2 Result of varying crystallographic orientation

An initial study into the effect of grain orientation on the mechanical properties of a material has been completed. It was found that strength and ductility are strongly related to grain orientation[6].

Contour plots of accumulated plastic strain show the development of shear bands which differ depending on the grain orientation. *Figure 4* shows grains with a single orientation, which means that the material is acting as a single crystal, whereas *Figure 3* has grains of prescribed orientation and those with Euler angles within ten percent of these.

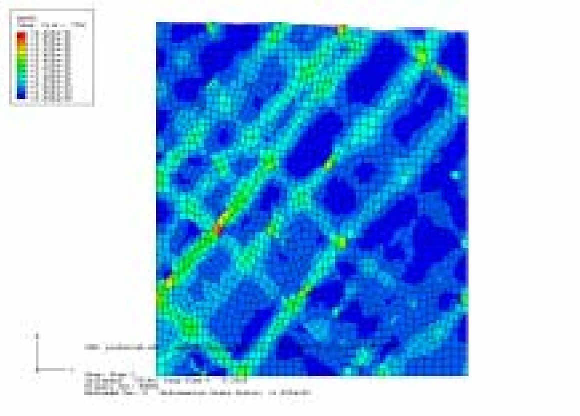

Figure 3: Single orientation

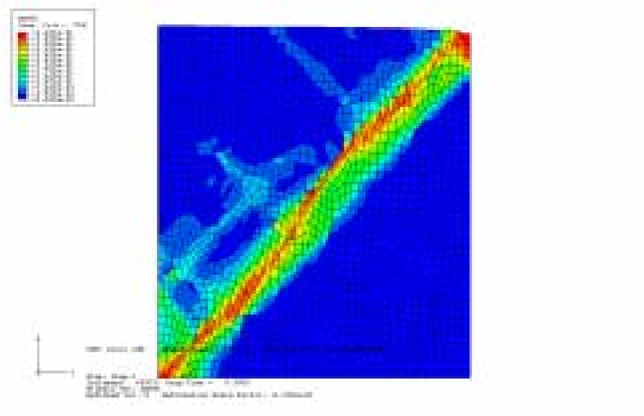

Figure 4: “Preferred” orientation

4 CONCLUSIONS

- It is possible to observe change in crystal orientation due to large deformation preceding fracture.
- It has been shown that crystal plasticity can be used as a predictive tool in designing the texture.
- The EBSD data will allow generation of unit cells that follow as closely as possible the phase arrangement of a given sample as obtained from metallographic sections. Velocity profiles extracted from points identified on the test specimen and matched to nodes in the numerical simulations can then be used to define boundary conditions for the unit cell modelled using a crystal plasticity code.

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