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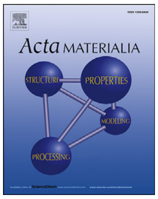

Full length article

Determination of geometrically necessary dislocations in large shear strain localization in aluminum

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ABSTRACT

In this paper, a systematic approach is presented to quantifying shear band evolution by quantifying geometrically necessary dislocations (GND) associated with morphological anisotropy in 7039-aluminum alloy using the compact forced-simple shear (CFSS) design. A statistically motivated approach, i.e. the line averaged GND density profile, has been developed to investigate the GND density near heavily deformed, shear band regions. Our study shows that: i) line average GND density profiles for the Al samples machined in the A-direction (transverse to pancake-shaped grains), B-direction (parallel to longitudinal pancake-shaped grains, shearing in through-thickness direction), C-direction (parallel to pancake-shaped grains, shearing in the in-plane direction) and D-direction (parallel and through the pancake-shaped grains) are nominally similar; ii) apart from 7039-aluminum alloy C-direction that has a uniform GND distribution in the direction normal to shear due to a grain-sliding mechanism, GND profiles for other samples decrease steadily away from the shear band as plastic strain diminishes, in agreement with Ashby's theory of work hardening, iii) anisotropy in damage evolution and shear-stress shear-strain response of 7039-aluminum alloy is associated with the grain structure of the material, i.e. morphological anisotropy creating variations in grain boundary interactions; iv) microbands formation in D-direction is associated with local GND peaks; v) stress-relief crack propagating along grain boundaries due to the presence of voids or inclusions generates a 'shielding effect' on neighboring grains; and vi) the line average GND density profile within a single grain usually varies inversely with the width of the grain for A-, B- and D-directions, leading to generally pronounced higher GND density near triple junctions.

1. Introduction

Localized unstable deformation of ductile metals and alloys when subjected to complex loading stress states and/or high-strain-rate-loading paths is most often associated with shear rupture (shear localization or shear bands). Shear localization and shear banding propensity has been extensively studied for more than half a century and several very detailed reviews of this work exist in the literature [1–36]. These studies have shown that shear localization depends on a number of aspects of the material microstructure and loading environment including: 1) physical properties of the material (heat capacity, thermal conductivity, thermal softening), 2) details of the mechanical loading to which the material is subjected (stress state, temperature, strain rate), and 3) details of the material microstructure including crystallographic texture, grain morphology and shape, dislocation density and distribution, and microstructural and phase stability [3,4,6,15,18,36]. Mechanics modelling, as well as numerous experimental studies of shear localization, has shown that a metal or alloy is prone to localized shearing during deformation if the material possesses a low strain/work-hardening rate and high degree of thermal softening under the loading conditions applied, a negative strain-rate sensitivity globally or locally within a material, and a low specific heat [4,6,36]. In addition, metals and alloys that undergo dynamic strain aging, strain-induced martensitic transformations, and crystalline to amorphous transitions under the loading rates and temperatures of interest are also more susceptible to shear localization [4,6,36]. The role of anisotropy (either crystallographically or morphologically-based within a material), in addition to

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Nomenclature

$\mathbf{u}$	Displacement
β^{el}	Elastic distortion
β^{pl}	Plastic distortion
ε_{ij}^{el}	Element of the elastic strain tensor
ω_{ij}	Element of the lattice rotation tensor
θ_k	Element of the lattice rotation vector
k_{ij}	Element of the lattice curvature tensor
$\boldsymbol{\alpha}$	Nye dislocation tensor
δ_{ij}	Element of the small deviation tensor
g_{ij}	Element of the lattice orientation tensor
$\hat{\boldsymbol{l}}$	Normalized dislocation line direction
$\boldsymbol{r}$	Normal vector of an selected area
ρ_{GND}	GND density
$\Delta\phi_{dis}$	Disorientation angle
$\boldsymbol{O}^{cry}$	Crystal symmetry operators
Λ	Lattice rotation gradient vector
ξ	Active slip systems matrix
$\boldsymbol{\rho}$	Dislocation density vector

directionality of loading relative to a materials microstructure, represent a current area of active shear-localization research aimed at the development of physically-based predictive modelling linking material processing to structure to properties to performance.

In spite of all this research, the study of shear localization still has significant limitations in terms of quantitative assessments of shear localized microstructure evolution. Nearly all studies to date have been unable to provide any numerical assessment of microstructures in shear bands, and initial microstructures that undergo shear localization have largely been treated as isotropic continuums. Recently, the introduction of the compact forced simple shear (CFSS) sample [37] enabled, for the first time, detailed quantitative examination of the influence of microstructural anisotropy on the evolution of shear localization and shear banding phenomena. Due to the simple design of the sample, the shear region can be oriented very accurately with respect to the microstructure, to probe grain anisotropy in either crystallographic texture or grain morphology texture.

With the advent of electron backscattered diffraction (EBSD), it is now possible to probe the evolution of deformation in terms of: initial grain textures, grain crystal rotations, and quantification of deformation in terms of geometrically necessary dislocations (GNDs) that are associated with lattice curvature. This latter aspect has been discussed in more general terms by Brewer et al. [38], Field et al. [39], and Calcagnotto et al., [40]. These studies demonstrate the ability and methodology to extract quantitative geometrically necessary dislocation (GND) densities from the lattice curvature as determined by EBSD within deformed samples. However, in each of these studies, the plastic deformation was limited to axial deformation and the extent of the deformation limited to less than 20% plastic strain.

The purpose of the present study is to combine the advantages of the CFSS sample for studying shear localization with respect to grain morphological anisotropy with EBSD analysis to extract quantitative differences in GND densities associated with shear localization in different microstructural orientations. Within the shear localization regions, the plastic shear strain can easily exceed 1, and because of the shear deformation mode, grain lattice curvatures approaching the shear band center can be very large. However, as will be demonstrated herein, with well-prepared samples for EBSD analysis, it is possible to obtain EBSD patterns from very close to the shear band centerlines, determine the lattice curvatures involved as a function of the microstructure orientation, and thus relate the extracted GND densities to differences in grain morphology. Lastly, by determining differences in the GND densities, it is possible to glean details related to local strengthening differences, clarify the operative defect generation and storage mechanisms, and provide quantitative metrics for modelling of shear localization in ductile materials.

2. Experimental

2.1. Materials

In the present study, hot-rolled plate of 7039-Al that has a weak crystallographic through-thickness ⟨101⟩ texture and a weak ⟨001⟩ rolling direction texture is analysed. ‘Pancake-shaped’ grains, highly elongated in the rolling direction, characterize the microstructure of the 7039-Al plate. The 7039-Al samples examined here are the same samples used in the previous study by Gray et al., [37]. Details of the materials, sample fabrication and orientation designations, sample testing procedures, and initial sample preparation for metallography can be found in this paper [37]. Additional polishing and etching methods were employed in this study to improve the quality of the EBSD data obtained from the shear band regions.

2.2. Design of CFSS samples from Al-7039 plate

For analysis of the anisotropic dependence of simple shear mechanisms, the compact forced-simple-shear (CFSS) sample design depicted in Gray et al. [37], is employed. The sample is designed in order to create a simple shear region parallel to the loading direction of the sample [37] in order to determine the effect of morphological anisotropy in Al-7039. Fig. 1 contains three images depicting the CFSS sample design from three viewing angles: perspective view, side vide and cross-section view. This CFSS sample design facilitates the alignment of specific microstructure features to the shear direction, which is essential to the development of GND profiles with respect to the microstructure anisotropy. Machining of the specimen was done parallel or perpendicular to the 7039-Al plate's ‘pancake-shaped’ grains.

2.3. Metallographic analysis

For cross sectional analysis of the shear region, the samples were cut in half down the long axis perpendicular to the shear region. The cross sections were mounted in Struers Condufast™ mounting resin and polished to 0.05 μm alumina. Prior to EBSD analysis, a final attack polish was performed on each sample to remove the mechanically deformed surface layer imparted during previous grinding and polishing. The attack polish solution for Al was 0.05 μm alumina in a water suspension with 3% NaOH.

EBSD was conducted using a Bruker e-Flash EBSD detector on a FEI Quanta 600 SEM at 20 kV and working distance around 15 mm. To determine the angular resolution of the detector, a scan of a single crystal germanium sample was run using a step size of 200 nm, and the misorientation distribution was plotted from 0 to 2°. The maximum number of occurrences of misorientation in this region was taken as the angular resolution of the system. In addition, step size analysis was carried out as detailed in the following section to ascertain the ideal number of pixels to be utilized for the GND calculation. To ensure that the center of the shear band was aligned to the top edge of the EBSD scan, the shear-band crack was first aligned to the edge at the specified magnification of 500× and moved horizontally to the region of interest.