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Investigation of the shear response and geometrically necessary dislocation densities in shear localization in high-purity titanium

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The influence of microstructural anisotropy on shear response of high-purity titanium was studied using the compact forced-simple-shear specimen (CFSS) loaded under quasi-static loading conditions. Post-mortem characterization reveals significant difference in shear response of different directions in the same material due to material crystallographic texture anisotropy. Shear bands are narrower in specimens in which the shear zone is aligned along the direction with a strong {0001} basal texture. Twinning was identified as an active mechanism to accommodate strains in the shear region in both orientations. This study confirms the applicability of the CFSS design for the investigation of differences in the shear response of materials as a function of process-induced crystallographic texture. A detailed, systematic approach to quantifying shear band evolution by evaluating geometrically necessary dislocations (GND) associated with crystallographic anisotropy is presented. The results show that: i) line average GND density profiles, for Ti samples that possess a uniform equiaxed-grain structure, but with strong crystallographic anisotropy, exhibit significant differences in GND density close to the shear band center; ii) GND profiles decrease steadily away from the shear band as the plastic strain diminishes, in agreement with Ashby's theory of work hardening, where the higher GND density in the through-thickness (TT) orientation is a result of restricted <a> type slip in the shear band compared with in-plane (IP) samples; iii) the anisotropy in deformation response is derived from initial crystallographic texture of the materials, where GND density of <a> GNDs are higher adjacent to the shear band in the through-thickness sample oriented away from easy slip, but the density of <c+a> type GNDs are very similar in these two samples; and iv) the increase in grain average GND density was determined to have strong correlation to an increase in the Euler Φ angle of the grain average orientation, indicating an increased misorientation angle evolution.

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Nomenclature

β^{el}_{ij}	Element of the elastic distortion tensor
ε^{el}_{ij}	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
$\Delta\varnothing_{,l}$	Lattice orientation gradient
ρ_{GND}	GND density

1. Introduction

The stability of plastic deformation in a given metal or alloy, which is determined by physical, mechanical, and material/microstructural factors, has been the subject of numerous research studies (Meyer et al., 2012; Rinehart and Pearson, 1954; Klepaczko et al., 1999; Anand and Kalidindi, 1994; Chung et al., 1977; Argon and Reed-Hill, 1973; Xu et al., 2008; Xue et al., 2005a; Meyers et al., 2001; Meyer et al., 1994; Xue et al., 2007, 2008; Xue and Gray, 2006a; Xue and Gray, 2006b; Xue et al., 2002, 2005b; Zhang et al., 2004). Shear bands have been reported to occur in a variety of metals and alloys such as aluminum alloys, brass, steels, and titanium alloys. Moreover, shear bands have been considered failure indicators since experiments indicate that large plastic deformation involves shear localization, void nucleation, void growth, and coalescence leading to ultimate failure. It has been known for many years that shear localization is a dominant mechanism for plastic deformation in structural materials at high strains and high-strain-rate conditions and has always been considered as a precursor of catastrophic failure (Rittel and Osovski, 2010; Rittel and Wang, 2008; Rittel et al., 2006); however their origin, evolution, and role during plastic deformation are still not well understood nor predictably modeled.

While the shear behavior of titanium and its alloys continues to receive considerable attention owing to the significant influence shear localization has on the response of these materials in applications ranging from aerospace applications associated with crash-worthiness and foreign object damage (FOD), to military platforms required for ballistic protection, to rapid manufacturing processes such as forming and machining, the majority of the material characterization studies remain largely qualitative in nature. To overcome the limitations due to shear localization, more quantitative data on shear banding and shear location is required to develop and validate physically based constitutive models for titanium alloys that incorporate concurrent influences of temperature, strain rate, strain, and microstructural features such as texture, both crystallographic and morphological. One specific feature of interest toward understanding the plastic strain evolution in shear bands is to document the evolution of dislocation structures and their densities and relate them to variations in local work-hardening behavior.

Previous studies into shear localization in titanium alloys (Xue et al., 2002; Schoenfeld and Kad, 2002a; Klepaczko, 2000; Kad et al., 2002; da Silva and Ramesh, 1997; Kailas et al., 1994a; Bai et al., 1994; Khan et al., 2004, 2007, 2012; Khan and Yu, 2012; Ye et al., 2013; Li et al., 2014) have examined the propensity for shear localization at the continuum level. A subset of these studies have focused on probing the influence of crystallographic texture and how texture may play a role in promoting or mitigating the susceptibility of titanium alloys to localization (Schoenfeld and Kad, 2002a; Kad et al., 2002; Salem and Semiatin, 2009; Woodward, 1979; Zhang et al., 2016a, 2016b). Texture can influence the relative orientation of grains for slip versus twinning, as well as the work-hardening capacity of individual grains relative to one another, as well as their propensity for thermal softening (Salem and Semiatin, 2009). For example in the work of Salem and Semiatin (2009), annealed CP-titanium exhibited a higher susceptibility for shear banding in the rolled plate direction compared to the transverse direction, attributed to easy slip along prismatic planes, but quantitative validation of these effects is still lacking.

One problem that has hindered the fundamental understanding of the shear banding phenomenon is the difficulty of comparing results obtained from various different types of shear loading experiments that have been developed, because shear bands have been observed to most often nucleate from geometrical defects rather than microstructural defects.

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. (2009), Field et al. (2012), Ruggles et al. (2016)., and Calcagnotto et al. (2010). 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.

One of the major challenges of shear banding studies, as it related to examining texture influences, is the control of the shear localization relative to the crystallographic texture that may exist in the material. The recent development of the

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