Determination of Geometrically Necessary Dislocations in Large Shear Strain Localization in Metals

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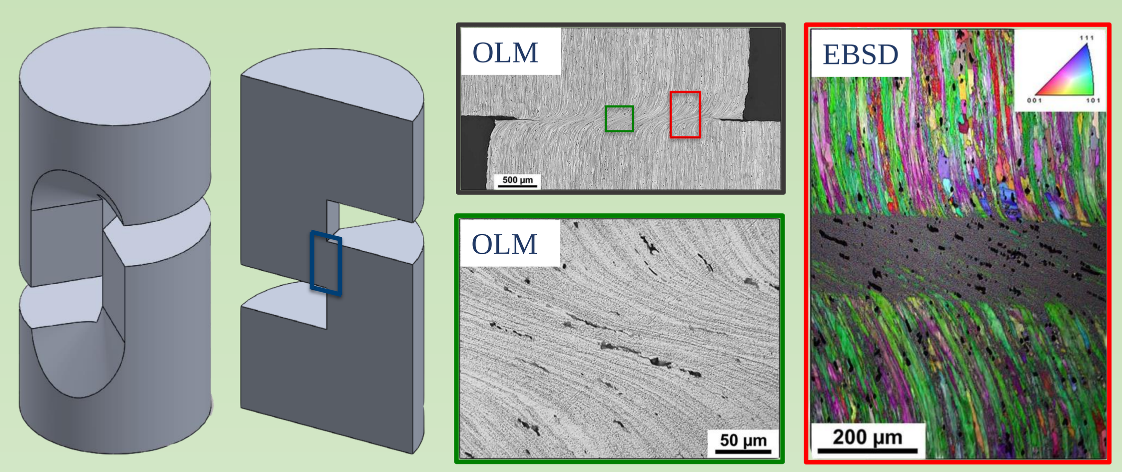
INTRODUCTION

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). In this study, we aim to quantify the role of anisotropy (either crystallographically or morphologically-based within a material) on the shear localization properties of quasi-statically deformed materials.

Specimen Design: Compact Forced Simple Shear Design (2016)

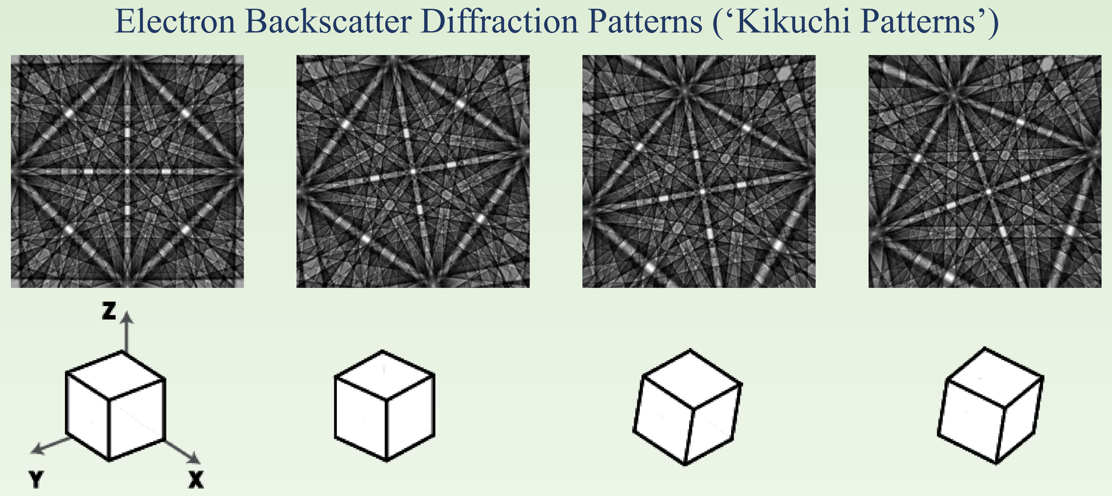


- ✓ Align a single plane to the shear direction.
- ✓ Simple pure shear-stress state in the shearing zone.
- ✓ Allow the alignment of shear plane to crystallographic texture
- ✓ Allow the alignment of shear plane to grain morphological features.

EBSD-Based GND Density Calculation: Nye Tensor α (1953)

What is Electron Backscatter Diffraction?

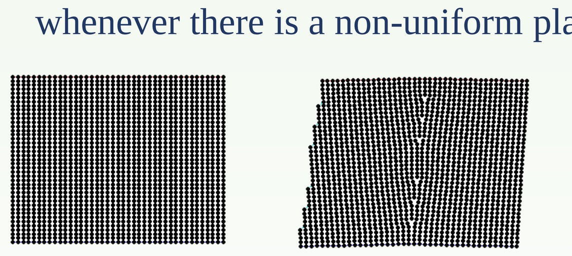
Electron Backscatter Diffraction Patterns ('Kikuchi Patterns')



$(\varphi_1,\Phi,\varphi_2) = (0,0,0)$	$(\varphi_1,\Phi,\varphi_2) = (10^\circ,0,0)$	$(\varphi_1,\Phi,\varphi_2) = (10^\circ,10^\circ,0)$	$(\varphi_1,\Phi,\varphi_2) = (10^\circ,10^\circ,10^\circ)$

What is Geometrically Necessary Dislocation?

- ➢ Dislocations required to accommodate the lattice curvature that arises whenever there is a non-uniform plastic deformation (Ashby, 1969).

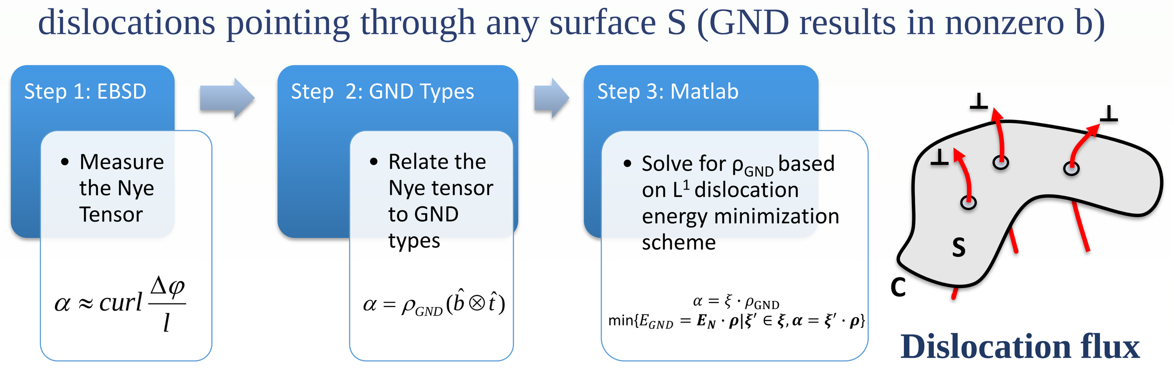


Undeformed **Bending (GND)**

- ✓ Residual dislocations
- ✓ Maintain geometric constraint
- ✓ Obstacles to dislocation motion
- ✓ Size effect on plastic deformation

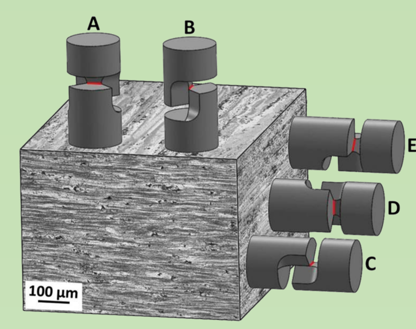
What is the Nye Tensor?

- ➢ Dislocation tensor field (α) in a continuously dislocated state of the crystal lattice.
- ➢ Based on Stoke's theorem for Burger's circuit, the net Burgers vector (b) of all dislocations enclosed by the circuit C is equal to that of all dislocations pointing through any surface S (GND results in nonzero b)



Dislocation flux

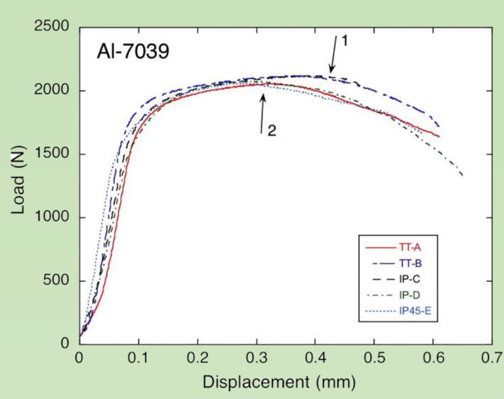
MORPHOLOGICAL ANISOTROPY



Specimen Orientations

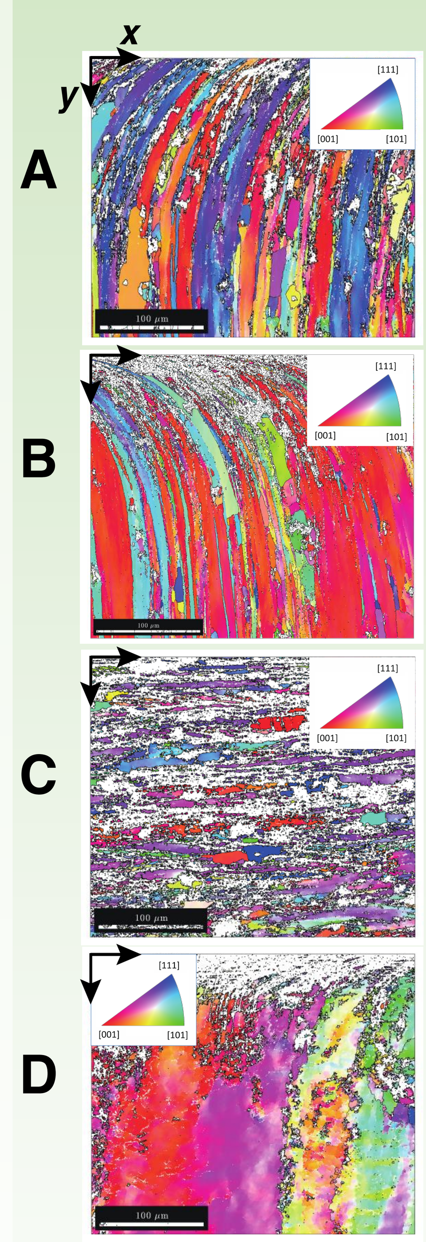
Aim: Combine the advantages of the CFSS sample for studying shear localization with respect to grain morphological anisotropy with EBSD analysis to extract quantitative differences in GND densities associated with shear localization in different microstructural orientation

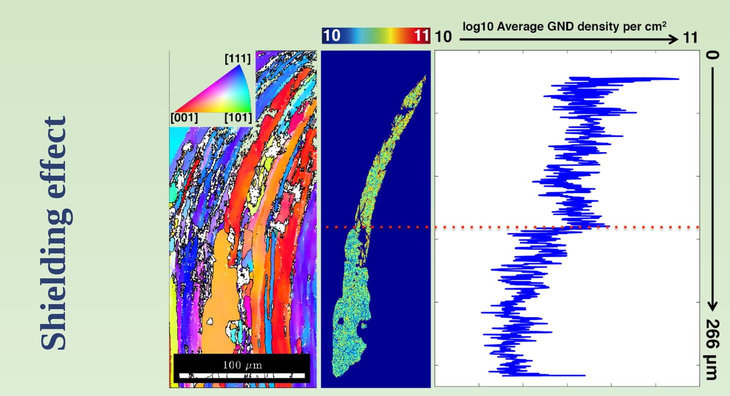
Materials: Hot-rolled plate of 7039-Al that has a weak crystallographic texture. It has pancake shaped grains highly elongated in the rolling direction (Gray *et al.*, 2016).They are quasi-statically compressed at a strain rate of 0.001/sec at 298K.



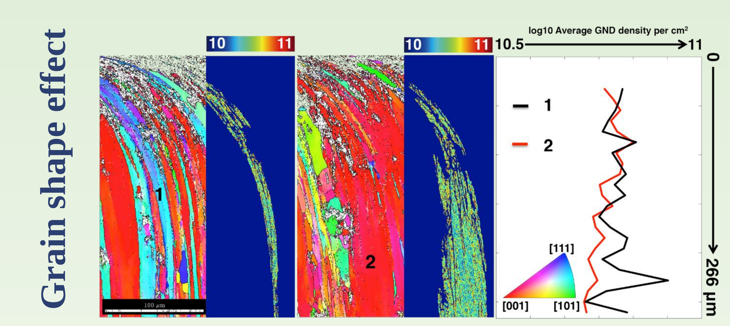
Load-displacement curves

Mechanical Response: Distinct damage evolution near shear bands but nominally similar load-displacement curves except B and C direction specimens which retain higher peak loads to a greater displacement.

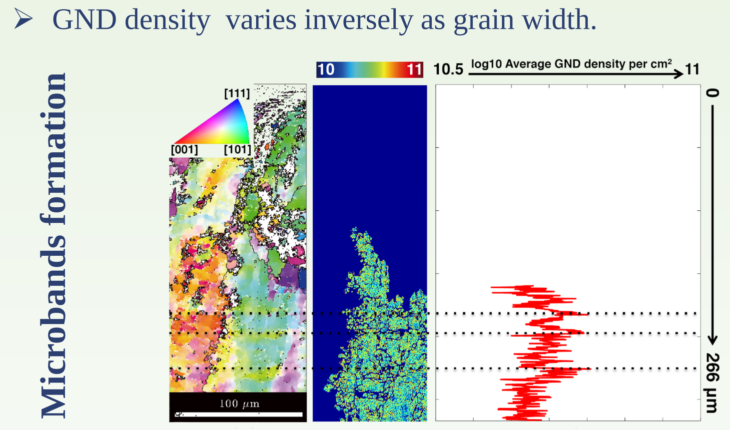




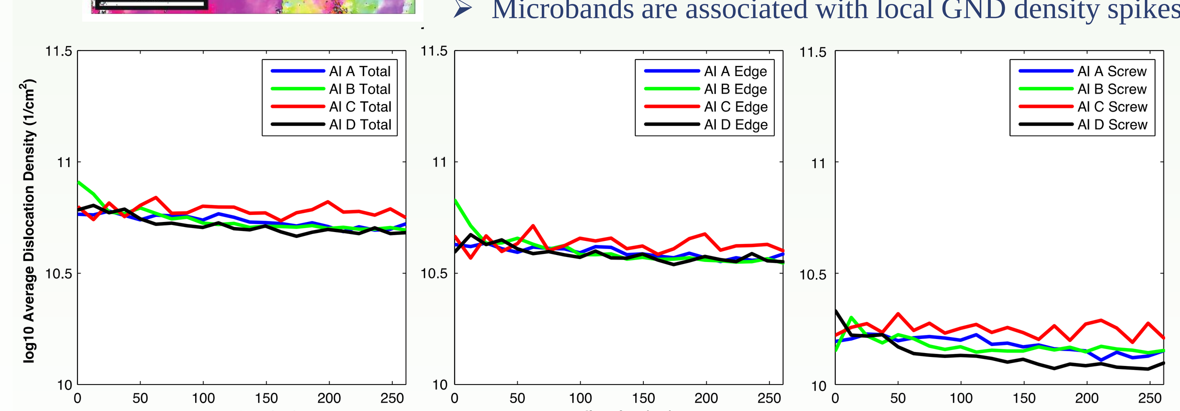
- ➢ Stress-relief crack formation along grain boundary which 'shields' the lower grain from shear deformation.



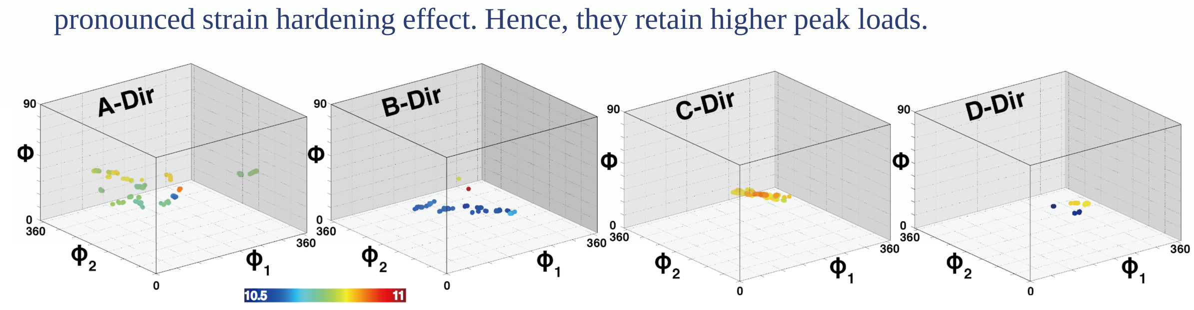
- ➢ GND density varies inversely as grain width.



- ➢ Microbands are associated with local GND density spikes.



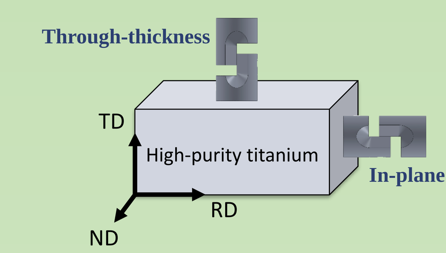
- ➢ Higher GND density close to center of shear band for B-Dir and across the C-Dir lead to pronounced strain hardening effect. Hence, they retain higher peak loads.



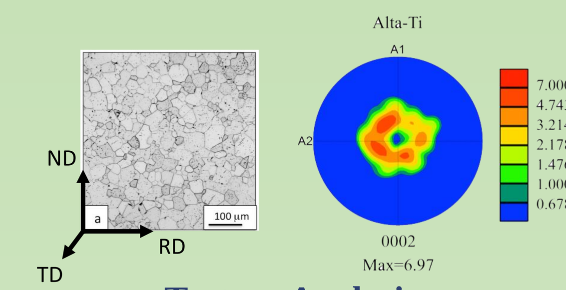
- ➢ Orientation dependence of the grain average GND density is negligible.

CRYSTALLOGRAPHIC ANISOTROPY

Aim: Employ the use of the CFSS sample to examine the effect of texture in high purity-Ti and then utilize measurements of geometrically necessary dislocations (GNDs) derived from analysis of electron backscattered diffraction (EBSD) patterns to provide quantitative assessment of the shear banding behavior difference as they relate to the differences in texture.



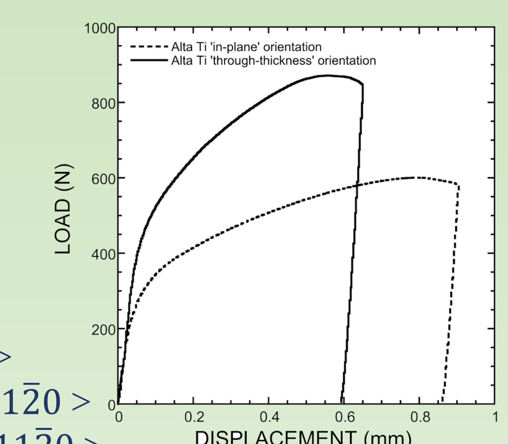
Specimen Orientations



Texture Analysis

Materials: High-purity titanium with strong in-plane basal texture (Gray *et al.*, 2016). The in-plane specimen's shear plane is aligned to the basal texture whereas the through-thickness specimen retains a non-basal texture. They are both quasi-statically compressed at a strain rate of 0.001/sec at 298K.

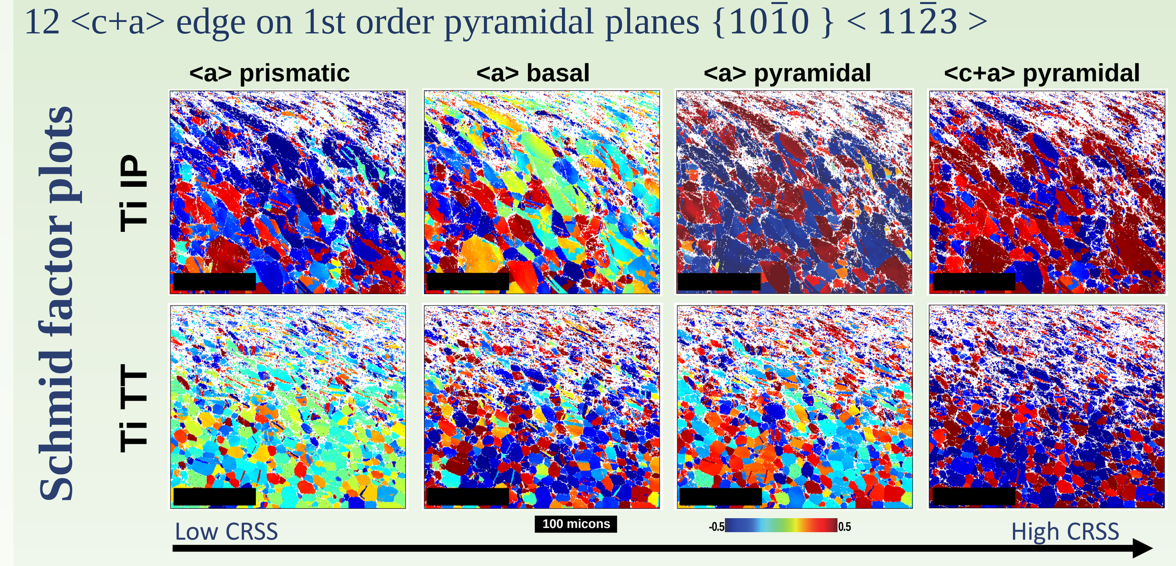
Mechanical Response: Through-thickness specimen display significant strain-hardening and retain a much greater flow stress. However, the ductility of through-thickness specimen is compromised.



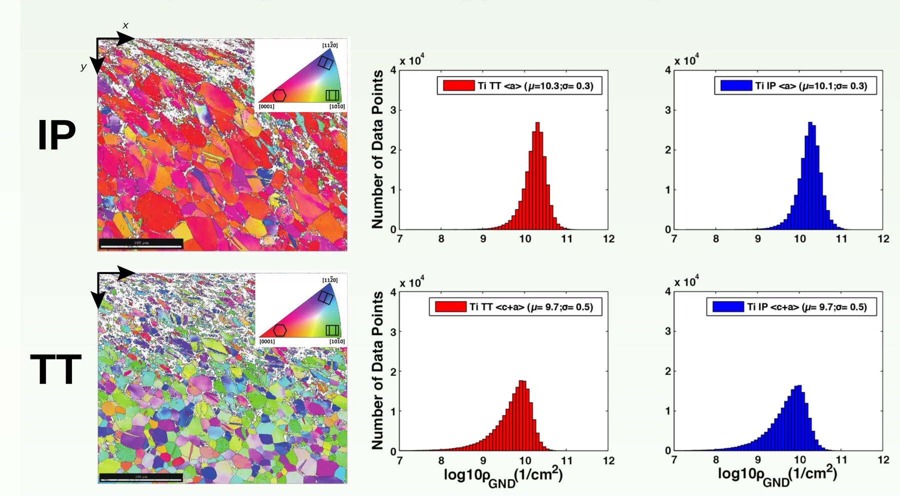
Load-displacement curves

Dislocations (Jones and Hutchinson):

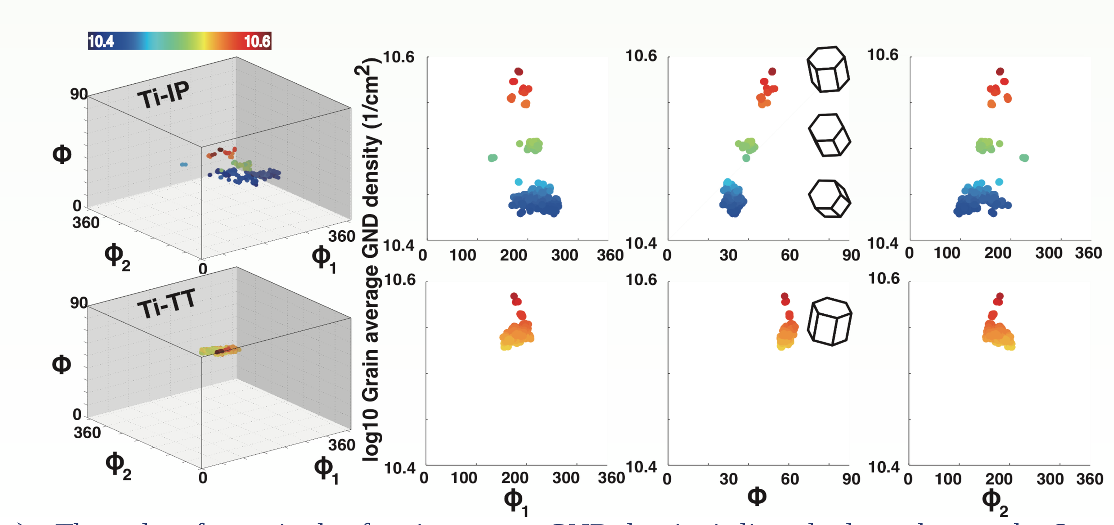
3 <a> screw $\langle 11\bar{2}0\rangle$
3 <a> edge on basal planes {0001} $\langle 11\bar{2}0 \rangle$
3 <a> edge on prismatic planes $\{10\bar{1}0\}$ $\langle 11\bar{2}0 \rangle$
6 <a> edge on pyramidal planes $\{10\bar{1}0\}$ $\langle 11\bar{2}0 \rangle$
6 <c+a> screw $\langle 11\bar{2}3 \rangle$
12 <c+a> edge on 1st order pyramidal planes $\{10\bar{1}0\}$ $\langle 11\bar{2}3 \rangle$



- ➢ IP: easy <a> prismatic and pyramidal slips; TT: unfavorable <a> type slips.



- ➢ The number of <a> type GND >> the <c+a> type in both samples.
- ➢ The <a> type in TT sample is slightly higher than the IP sample.



- ➢ The order of magnitude of grain average GND density is linearly dependent on the Φ angle.

CONCLUSIONS

- ❑ While the deformation response and extent of lattice rotation was found to be similar for the A- and D-direction 7039-Al samples, the damage evolution differed including microband/ shear band formation, void nucleation, crack propagation between inclusions along grain boundary each consistent with the differences in the grain structure orientation relative to the shear direction, i.e. morphological anisotropy.
- ❑ Additionally, near all the shear bands, the nominal magnitudes of the GND total/edge dislocation densities were roughly the same for all the samples for the different grain structure/shear testing directions, whereas geometrically necessary screw dislocation densities generally differ from sample to sample.
- ❑ The increased shear resistance displayed by the B- and C-direction samples at large shear strains is thought to be due to a higher GND density near the shear band for the B-direction and an overall higher GND density across the C-direction sample.
- ❑ When slip is restricted in titanium due to texture, the material displays an inhomogeneous deformation response, even at low to moderate plastic strains, leading to strain localization upon forced shear loading. The strong basal texture in the high-purity Ti is reflected in approximately 50% higher yield strength and reduced displacement prior to localization for quasi-static shear loading in the TT direction compared to the IP direction.
- ❑ In the high-purity titanium samples, the damage evolution for the in-plane and through thickness samples was seen to be generally similar, whereas the lattice rotation associated with shear was found to be different near the shear band, with the through thickness sample having a higher overall GND density near the center of shear band for <a> type but the density of <c+a> type GNDs are less responsive to the initial texture.
- ❑ Order of magnitude of grain average GND density was determined to vary linearly with the Euler angle Φ, which is clearly demonstrated in the case of IP sample.

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