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Multiple slip in copper single crystals deformed in compression under uniaxial stress

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Uniaxial compression experiments on copper single crystals, oriented to maximize the shear for one slip system, show activity on the primary slip system as well as appreciable activity orthogonal to the primary system. Utilizing three-dimensional digital image correlation, the amount of orthogonal slip has been quantified. The activity orthogonal to the primary occurs from the onset of deformation and varies from being equal to the primary for the as-fabricated samples to 1/5 of the primary in the samples annealed after fabrication.

Keywords: Copper; Compression test; Slip; Image correlation

Studies to understand the deformation of face-centered cubic crystals date back to the seminal work of Taylor and Elam in the 1920s [1]. In the 1950s, studies on Cu single crystals that focused on the initial stages of deformation (<2%) were conducted [2,3]. The conclusions drawn from these studies indicate that for orientations where a single slip system dominated, the initial deformation occurs only on the primary system, stage I, which corresponds to a plateau in the stress–strain curve. The initiation of secondary slip systems, stage II, corresponds to the upturn in the stress–strain curve.

There has been experimental evidence that suggests that this classical theory is not entirely valid [4–8], including numerous studies dating back to the 1950s [9–12] and a recent review by Wert et al. [13] that report "kink" or deformation bands orthogonal to the primary systems. The studies also suggest that the kink bands might be attributed to the constraints imposed on the ends of a sample during a traditional tensile test [2,13]. This conclusion could be drawn from Rosi's experiments [2], which did not report the existence of kink bands when deforming samples in tension using special gimbaled grips that greatly reduced the traditional constraints by allowing the ends to rotate.

In this study, single crystals samples were tested in compression using a unique testing apparatus, which was designed to minimize the constraints traditionally imposed during a tensile test. In addition, a commercial three-dimensional (3-D) image correlation system, which measures the full-field strains and displacements, was used to quantify the slip behavior.

Copper single crystals (99.99% pure), grown using the Bridgman technique, were obtained from Accumet Inc. Several sample geometries were fabricated using wire electrical discharge machining (EDM). The samples were tested in the six degrees of freedom "6DOF" apparatus [14], which allows nearly unconstrained deformation of the sample. This unconstrained motion is accomplished by loading the sample in compression through a half sphere, and attaching the sample to a translation platen that sits on ball bearings. This technique has two additional degrees of freedom over the gimbaled grips used by Rosi. The full-field strains and displacements are measured using the GOM Aramis 3-D image correlation system, purchased from Trilion Quality Systems. While details of the image correlation technique applied to single crystal experiments are contained in other publications [15,16], the basic premise is that a stochastic pattern of dots are applied to the surface of the sample, and photos of the pattern are compared before and after each deformation step.

A sample, sample #1, with dimensions 5.5 mm × 5.5 mm × 15 mm and rounded corners, was EDM fabricated with the $[\bar{2}\,9\,20]$ orientation along the z-axis, as shown in Figure 1a. The axial stress–strain response for this sample, calculated by averaging the image

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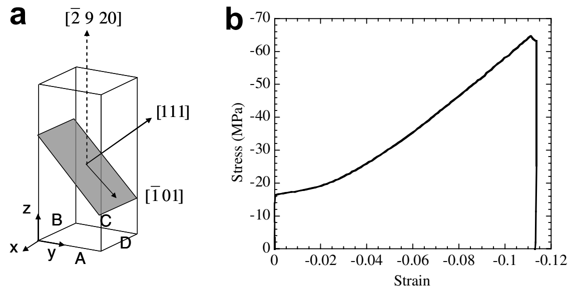

Figure 1. (a) Schematic of sample #1 showing the crystallographic orientations of the sample, including the primary slip plane. (b) Axial stress–strain curve for sample #1. The dip at the transition between load and unload is due to a slight amount of creep that occurs during the time it takes for the machine crosshead to change directions.

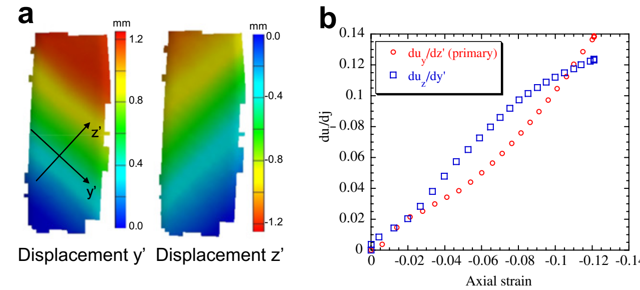

Figure 3. (a) Image correlation displacement maps showing the local y' and z' displacements. The displacement gradient, indicated by the change in colors, can be calculated by taking the slope of the displacement in one direction with respect to the other coordinate. (b) Activity (displacement gradient) along and orthogonal to the primary slip system versus axial strain.

correlation strain results over two adjacent faces, is shown in Figure 1b. After yield, there is a region of relatively low hardening, followed by an increase in the hardening slope, typical of the classic stage I and stage II hardening. The corresponding strain maps after the sample is unloaded for two adjacent sides of the sample are shown in Figure 2. Both the axial (ε_{zz}) and transverse (ε_{yy}) strain on the A face show two large bands of deformation, approximately 45° from the horizontal and 90° apart. While the map of the shear strains on the A face shows a band approximately orthogonal to the primary slip direction, the development of this band occurs at around 5% axial strain and may be associated with some non-uniform stresses due to the translation of the sample. The axial strain on the B face shows horizontal bands, while the transverse and shear strains are essentially zero. The lack of transverse and shear strain on the B face is consistent with a sample that is deforming under a plane strain condition.

One of the 45° bands on the A face corresponds to the primary slip system, (1 1 1) [1 0 1]. Using the image correlation software, the data can be analyzed by rotating the axes to line up with the primary slip system. The subsequent displacement gradient, du'_y/dz', is a measure of the slip activity along the primary slip direction. Conversely, the gradient du'_z/dy' is a measure of the activity orthogonal to the primary system. Figure 3a shows the displacement maps in the rotated coordinate system. Figure 3b shows a plot for both displacement gradients as a function of axial strain. Based on this plot, it appears that the slip activity orthogonal to the primary is nearly equal to or slightly larger than the primary throughout most of the test, even though there is no {1 1 1} ⟨1 1 0⟩ slip system orthogonal to the primary system.

One possible source for this unexpected behavior is the geometry of the sample in relation to the boundary conditions. While the 6DOF apparatus removes the constraints and end rotations typically imposed during a tensile test, with this sample orientation, where the primary slip plane and plane of maximum shear are oriented at a 45° to the sample axis, the stress concentrations at the bottom and top corners of the sample could initiate a shear band that propagates through the sample. In order to eliminate this effect, a round reduced cross-section sample, sample #2, was EDM fabricated from a sample that was previously EDM machined and annealed. This sample has a tapered gage section that varies from 3.56 to 3.4 mm in diameter. While the overall length of this sample is 27.7 mm, the length of the tapered gage section is 15 mm. The reduced cross-section allows for the deformation to be initiated in the middle of the sample away from the ends.

Figure 4 shows the corresponding rotated displacement gradients taken along and perpendicular to the primary system as a function of position in the sample. These gradients were measured at a nominal axial strain of 0.001, which is an example of the behavior during the early stages of slip. The plots show that the largest

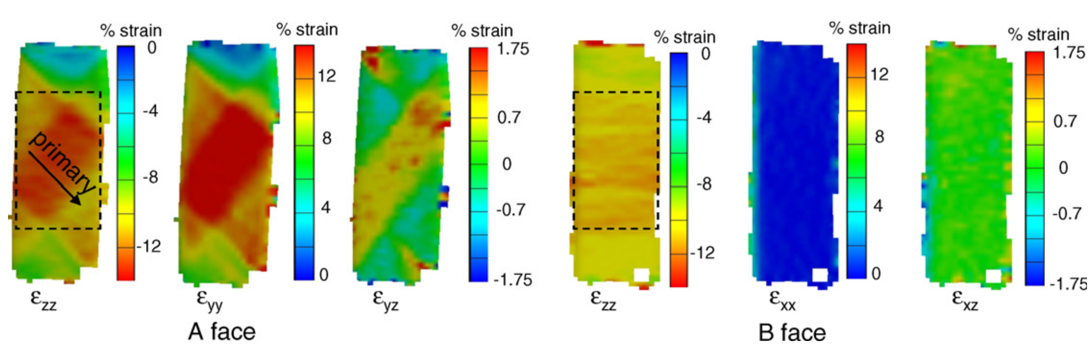

Figure 2. Image correlation strain maps at ~12% axial strain of two faces showing the axial, transverse and shear components. The dashed lines indicate the area on the sample where the axial strain is averaged. The fact that the transverse and shear components on the B face are essentially zero indicates that the sample deformed in a plane strain condition.