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J. N. Florando, M. M. LeBlanc, D. H. Lassila

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

J.N. Florando, M.M. LeBlanc, and D.H. Lassila
Lawrence Livermore National Laboratory, Livermore, CA 94550

Abstract

Uniaxial compression experiments on copper single crystals, oriented to maximize the shear for one slip system, show some unexpected results. In addition to the expected activity on the primary slip system, the results show appreciable activity perpendicular to the primary system. The magnitude of the activity orthogonal to the primary 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 1920's [1]. In the 1950's, 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.

Although there has been experimental evidence that suggests that this classical theory is not entirely valid [4-8], most of the work was done in tension with samples that rotate during deformation due to the boundary conditions. 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 3-D image correlation system was used to measure the full-field strains and displacements.

In this study, 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 6 degree of freedom '6DOF' apparatus [9], which allows nearly unconstraint deformation of the sample. This unconstraint motion is accomplished by loading the sample through a half sphere, and attaching the sample to a translation platen that sits on ball bearings. 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 [10, 11], 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 by 5.5mm by 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 correlation strain results over 2 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^o from the horizontal and 90^o 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^o bands on the A face corresponds to the primary slip system, (111) [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 {111} <110> 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. The primary slip plane is oriented at 45^o to the sample axis, which also corresponds to the plane of maximum shear. Under this configuration it is possible that 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 mm 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 long. 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 gradients occur in the center of the sample, and that the deformation near the ends is approaching zero, minimizing the effect from the platens. In addition, the magnitudes of both gradients are nearly the same in the center of the sample, signifying that the occurrence of secondary slip orthogonal to the primary still occurs even when the effect from the platen ends is eliminated.

The axial stress-strain data for samples #1 and # 2, figure 5, show that the yield stress is higher than typically seen in previous studies [2, 3]. The higher yield stress is probably due to the EDM processing. To see if the EDM process has an effect on the occurrence of slip orthogonal to the primary, a sample, sample #3, with dimensions 5.5 mm by 5.5 mm by 27.7 mm and round corners was EDM fabricated, then etched in a solution of 50% nitric acid and 50% water, and annealed in vacuum at 900C for 8 hrs. A summary of the sample geometries and processing steps for all three samples are shown in Table 1.

Figure 5 shows the axial stress-strain behavior for all the samples in this study, including for comparison a sample from Rosi's [2] work that had a similar orientation to our samples. For samples #1 and #3, the axial strain is measured by averaging the image correlation results over a large portion of the sample, but away from the ends, (as shown in figure 2). For sample #2, the axial strain is averaged over the gage section.

The annealed sample (sample #3) shows a much lower yield stress, signifying that the EDM process does affect the yield stress of the sample, mostly likely through the injection of dislocations near the surface of the sample that are removed during annealing. It is also interesting to note that although the yield stresses are different between the EDM and the EDM and annealed sample, the hardening rates are similar. The similarity in the hardening rates implies that after yield, the deformation mechanisms between the samples are also similar. In comparison, the sample from Rosi's study shows a lower initial yield stress, yet a higher hardening rate. It is unclear whether the differences in behavior can be attributed to the slight difference in orientation, differences in initial dislocation density through the different sample preparation steps, or the fact that Rosi's sample were testing in tension with gripped ends.

The rotated displacement maps for the annealed sample (sample #3), figure 6, show that while the primary is the most active, there is still an appreciable component orthogonal to the primary system. In addition, this orthogonal slip appears to occur during the onset of deformation, and in the very early stages is nearly equal to the primary system. While previous etch pit studies on Cu single crystals [8, 12, 13] have described bands that occur orthogonal to the primary slip system, this study quantifies the amounts using the image correlation data.

Given that there is no {111} <110> slip system directly orthogonal to the primary, it is still unknown the source of this slip phenomenon. On possible explanation, as mentioned in previous etch pit studies [12, 13] , is that 'glide polygonization' occurs on the primary system where edge dislocations align to form a band perpendicular to the primary. Another possibility is that the slip orthogonal to the primary is composed of a composite of other slip systems [5, 7, 10] that deform in such a way that the net slip is orthogonal to the primary. Regardless of the origins, our data suggests that this orthogonal slip begins to occur even in the early part of the deformation, traditionally known as stage I.

In conclusion, the deformation behavior of Cu single crystals has been studied utilizing a 6DOF apparatus and a 3-D image correlation system. The crystals, which were oriented for single slip, show that in addition to the primary system being active, there is appreciable activity orthogonal to the primary as well. A reduced-cross section sample, which was fabricated to eliminate the effects form the platen ends, also shows similar behavior. In addition, a sample that was heated to anneal out the effects from the EDM process shows a reduced but still appreciable amount of activity orthogonal to the primary slip system.

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Table 1: Summary of samples and processing steps.

	Sample #1	Sample #2	Sample #3
Shape of cross-section	Square	Round (reduced)	Square
Processing steps	EDM Etch	EDM Etch Anneal EDM Etch	EDM Etch Anneal

Figures

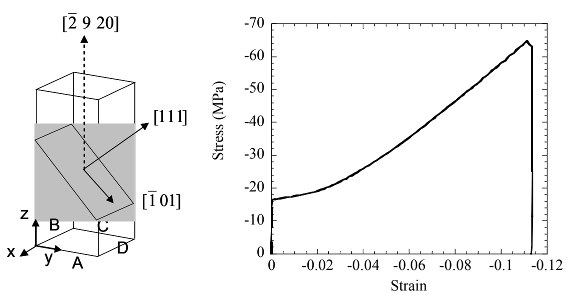

Figure 1-a) Schematic of sample #1 showing the crystallographic orientations of the sample including the primary slip plane. b) Axial stress-strain curve for sample #1. The dip at the transition between the load and unload is due to a slight amount of creep that occurs during the time it takes for the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

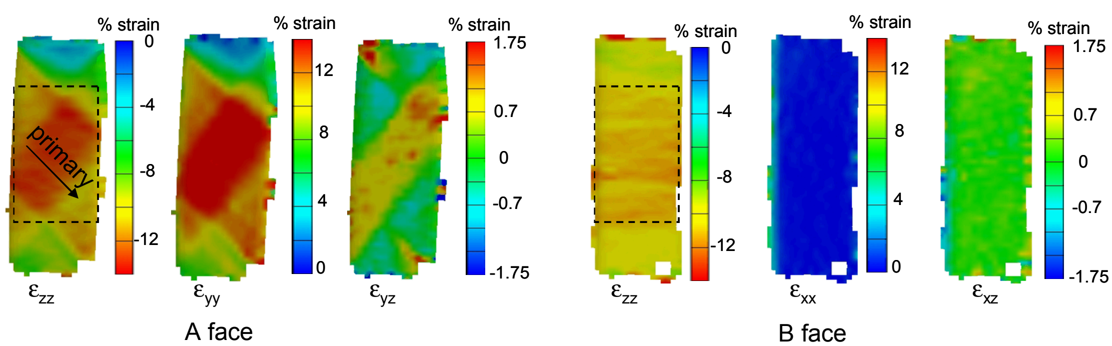

Figure 2-Image correlation strain maps at ~ 12 % axial strain of two faces showing the axial, transverse and shear components. The dash lines indicate the area on the sample where the axial strain is averaged. The fact that the transverse and shear components on the B face are essentially zero indicates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

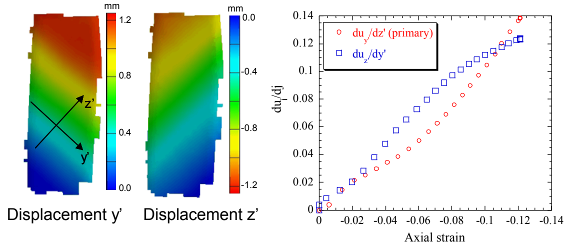

Figure 3-a) Image correlation displacement maps showing the local y' and z' displacements. The displacement gradient, indicated by the change in colors, can be calculated by taking the slope of the displacement in one direction with respect to the other coordinate. b) Activity (displacement gradient)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

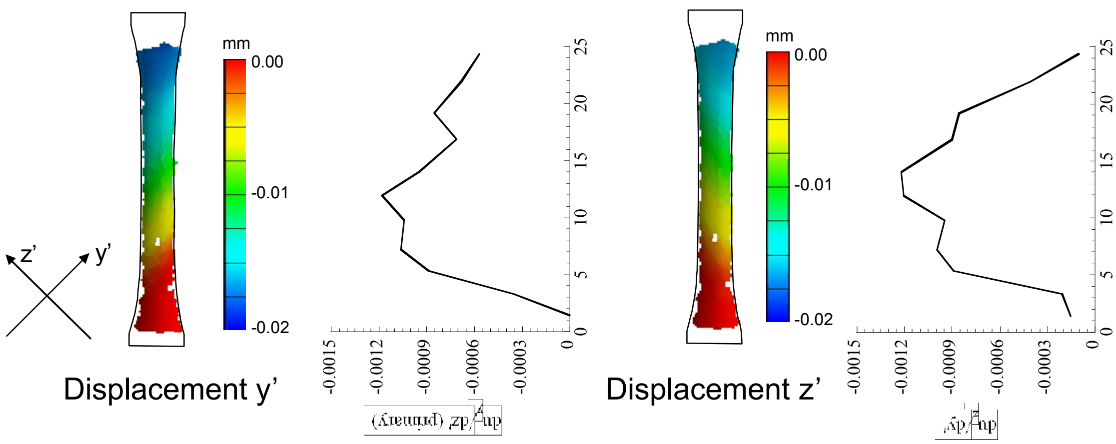

Figure 4- Image correlation maps showing the displacements along and orthogonal to the primary for ample #2. The plots next to the displacement maps show the displacement gradient as a function of position along the sample at an axial strain of 0.001. These plots show that most of the deformation is occurring in the center gage section of the sample, which eliminates the effect of the platen ends, and that appreciable activity is still occurring along and orthogonal to the primary system.

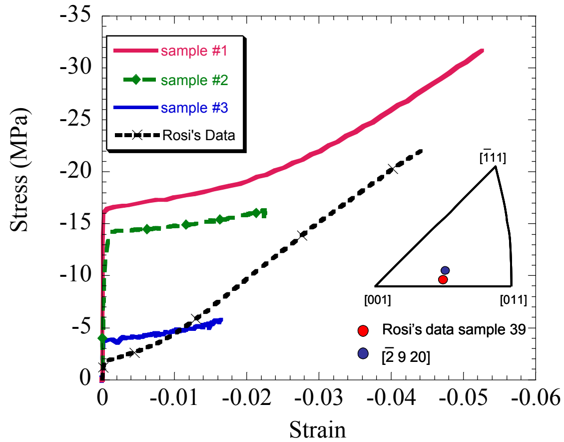

Figure 5- Summary of stress-strain curves for the Cu samples. Sample #1 is the standard compression sample, sample #2 is the reduced cross-section sample and sample #3 is the annealed sample. While the annealing reduced the initial yield stress, the overall behavior is consistent between the three samples. Rosi's data for a similar orientation is also shown.

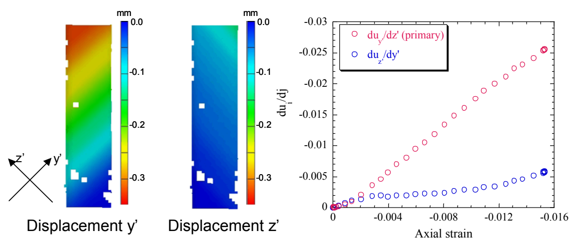

Figure 6- Image correlation displacement maps and plot of the activity along and orthogonal to the primary slip system for annealed sample (sample #3). Although the activity orthogonal to the primary is less, it is still an appreciable component, especially in the initial stages of deformation.