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In-situ Elastic Strain Mapping via EBSD of Micro-Sized Specimens

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In-situ observation of a wide range of small-scale mechanical tests has become commonplace recently, in large part due to the insights that can be gained by observing the tests. However, direct strain measurement during the test is more valuable than simple observation. A variety of techniques have been developed to measure strains, but none offer the strain and spatial resolution of electron backscatter diffraction (EBSD) [1]. EBSD has been used in a variety of strain measurement applications, including strained epilayer films on substrates (typically $Si_{1-x}Ge_x/Si$) [2,3] and *ex-situ* measurements near micro-hardness indents in silicon [4,5]. Only a few have measured elastic strains *in-situ* while applying a mechanical load to the sample [3,6], and most of these studies have used larger-scale specimens and only measured the strain in a small area. In this work, *in-situ* strain mapping was performed using a micro-scale test specimen with a complex geometry in order to fully illustrate the richness of deformation information and spatial resolution of the technique.

The theta specimen geometry has previously been proven useful for measuring fracture strengths of small-scale silicon samples [7], where the relationship between the applied load and localized strains in the sample was determined solely from finite element analyses (FEA). In this work, theta samples were used not only to validate the FEA, but also to provide a more rigorous test of the technique than has been attempted before since loaded thetas have complex, spatially-varying strain states (including rigid-body crystal rotations). Testing was performed in a JEOL JSM7100 equipped with an Oxford NordlysNano EBSD detector[†]. Mechanical loading of the sample was performed with a Hysitron PI85xR indentation system using a conospherical tip with a 5 µm tip radius. All experiments were conducted with a nominal applied load of 150 mN. Figure 1 shows an SEM image of the indenter tip in contact with the specimen. An EBSD map was collected from a 400 µm × 385 µm region with a 1.5 µm step size, allowing for the entire theta sample to be mapped, as well as some of the strain-free material surrounding the sample. Maps were also collected at higher magnifications with smaller step sizes at various locations on the sample. Following collection, strains and rotations were calculated using the commercial software package CrossCourt3 [8].

Figure 2 shows a map of the (a) measured and (b) simulated principal strain, ε_{22}, which aligns with the uniaxial tensile strain in the central web of the sample. The average measured strain in the web is 2.38×10^{-3}, which compares extremely well with the expected value of 2.37×10^{-3} from FEA. For reference, this equates to a tensile stress of approximately 400 MPa. While this may be the most important strain value for this particular specimen, it is not the only information available. The entire deviatoric strain tensor as well as the rigid body rotation matrix are calculated, something that other strain measurement techniques cannot provide. One use of the crystal rotation measurements is as an indicator of misalignment between the indenter and the specimen. In this case, the maximum out of plane rotation, ω_{13}, was measured to be approximately 6 mrad, or 0.3°. With this value known, the FEA model can be adjusted to more accurately reflect the experimental loading conditions.

In order to test the spatial resolution further, an EBSD map was acquired from a 30 µm × 20 um area surrounding the filleted notch where the specimen attaches to the bulk material. A 200 nm step size was used in order to measure the strong localized strain gradients caused by the presence of the notch. Figure

3 shows the (a) measured and (b) simulated shear strain, ε_{12}, and clearly illustrates these gradients, as well as the agreement between the experimental and FEA results.

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[8] BLGVantage, CrossCourt3, www.blgvantage.com

[†] Any mention of commercial products is for informational purposes only and does not imply recommendation or endorsement by the National Institute of Standards and Technology.

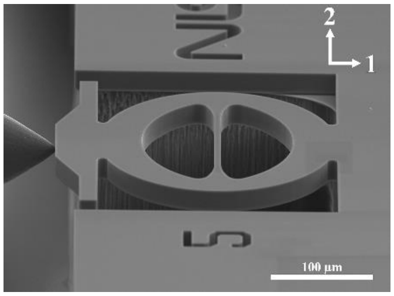

Figure 1. SEM image showing indenter tip in contact with theta specimen. Image is taken at 65° tilt. Directions 1 and 2 are in the specimen plane as labeled, and direction 3 is normal to the specimen surface.

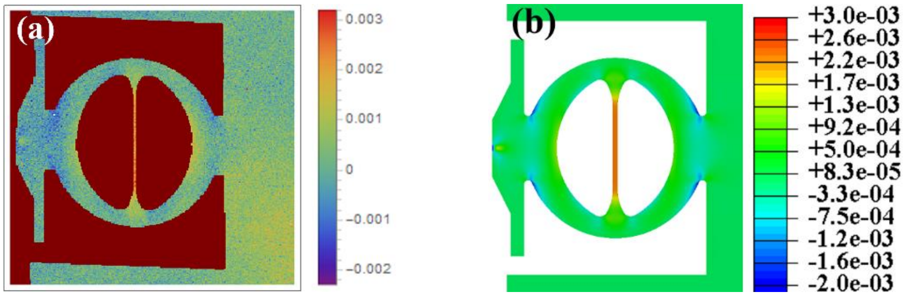

Figure 2. (a) Measured and (b) simulated maps of principal strain, ε_{22}, over entire theta specimen. Mapped region in (a) is 400 µm × 385 µm and is approximately the same in (b). Color scales are also similar, but not identical.

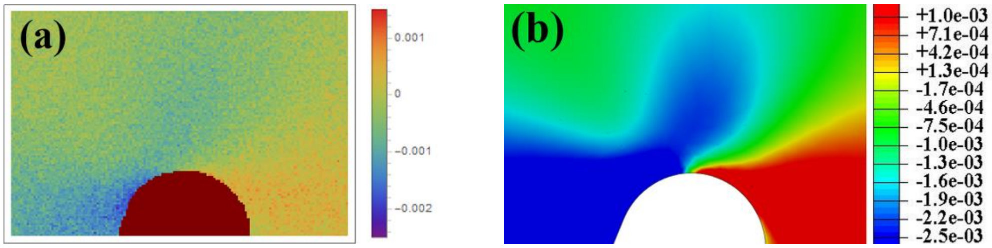

Figure 3. (a) Measured and (b) simulated maps of shear strain, ε_{12}, near the filleted notch where the theta specimen attaches to the bulk material. Mapped region in (a) is 30 µm × 20 µm and is approximately the same in (b). Color scales are also similar, but not identical.