Micromechanics of elasto-plastic deformation of duplex stainless steel under biaxial loading

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Materials Science

A primary objective of mechanical engineering is to predict how materials behave when subjected to load. The mechanical response of a material is invariably linked to its microstructure and microstructural properties. To enhance our predictive ability, we must understand the link between material structure and properties for generalized loading conditions.

In this study we use *in situ* neutron diffraction experiments, coupled with polycrystalline finite element simulations, to understand the micromechanical response of a dual phase stainless steel alloy under biaxial loading. One objective is to understand where plasticity initiates locally and how it proceeds through a dual phase aggregate of crystals. Our ultimate goal is to develop an improved methodology that uses material microstructure and micromechanical properties to evaluate the local macroscopic yield surface. Improved yield surface evaluation, based on the relationship between microstructure and material properties, will greatly enhance the modeling of large deformations encountered in vehicular crashes and metal forming operations.

The material considered in this study is duplex stainless steel LDX-2101, a versatile structural alloy used in pressure vessels, heat exchanges, and piping, among other applications. It is comprised of 57% face-centered cubic (FCC) austenite and 43% body-centered cubic (BCC) ferrite. Packets of relatively equiaxed austenitic grains are embedded in a matrix of elongated ferrite grains. Two views of the material microstructure are presented in Figure 1.

The majority of mechanical testing and an even larger majority of in situ lattice strain measurements using diffraction are conducted under uniaxial loading. Engineering components, however, are frequently subjected to loads that are multiaxial. There is a genuine need for micromechanical data collected under multiaxial loading conditions. Biaxial loading, in which two of the principal stresses are nonzero, represents the next level of increased complexity from uniaxial loading.

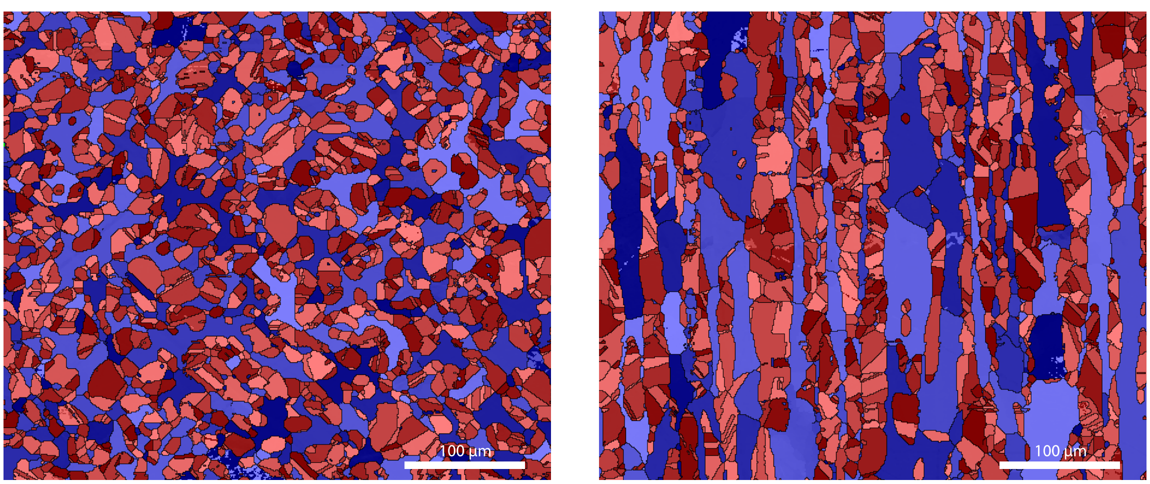

Fig. 1 Electron backscatter diffraction map of LDX-2101 viewed with the extrusion axis (left) out of the page and (right) vertical in the plane of the page. In these false colored images, austenite is red and ferrite is blue. Grains are shaded according to crystallographic orientation.

A system for conducting *in situ* lattice strain measurement of biaxially loaded specimens has been developed and implemented at the L3 beamline. Biaxial load is applied to hollow specimens using a combination of pressurization and axial loading. The experimental setup is presented in Figure 2. This technique has a major advantage over conventional tension-torsion biaxial loading in that the principal stress directions remain constant over the entire load history. It also avoids non-ideal conditions associated with the biaxial loading of cruciform specimens.

The level of macroscopic stress biaxiality is quantified by the biaxial ratio, *BR*, which is the ratio of hoop stress to axial stress. Biaxiality is controlled by adjusting the proportion of pressurization to axial loading. In previous experiments on austenitic stainless steel AL6XN [1] the specimen was first pressurized then loaded axially. Pressure remained constant throughout the axial loading episodes. As a result, the biaxial ratio decreased over the course of the experiment. A new hydraulic load frame and upgraded control software have enabled proportional load control, which allows both the pressure and axial load to be varied over the course of an experiment. As a result, it is possible to maintain a constant level of stress biaxiality. The LDX-2101 lattice strain measurements comprise the first complete data set measured at a constant biaxial ratio using this system.

Lattice strain data for LDX-2101 were collected at five biaxial ratios ranging from uniaxial tension (*BR* = 0) to balanced biaxial loading (*BR* = 1). A typical axial stress strain curve and macroscopic load path are presented in Figure 3. Specimens were loaded at constant biaxial ratio into the plastic regime. The maximum macroscopic axial stress was 700 MPa for each specimen, corresponding to macroscopic axial strains of about 10%. There are two elastic unloading episodes of the axial stress, which are used for experimental validation. In order to conduct diffraction measurements, the loading is stopped at select points along the load path. The load is then reduced by 5% to reduce creep deformation and then kept constant during data collection.

The macroscopic stress is biaxial, but the local stress at the crystal scale is non-uniform. The directions and magnitudes of the principal directions of the local stress vary spatially throughout the material. We cannot measure stress directly, but we can measure (elastic) lattice strains using neutron diffraction. Lattice strains are related to the crystal stress by the fourth-order crystal stiffness tensor. In this powder diffraction experiment, the measured lattice strains are fiber-averaged projections of the lattice strain tensor. Each measurement corresponds to an average along a crystallographic fiber, a subset of crystals that are related by a rotation about a common axis. Each measurement corresponds to a scalar projection of the full strain tensor along the scattering vector direction. Scattering vectors are chosen to align with the principal loading axes along the radial, hoop, and axial directions of the cylindrical specimens.

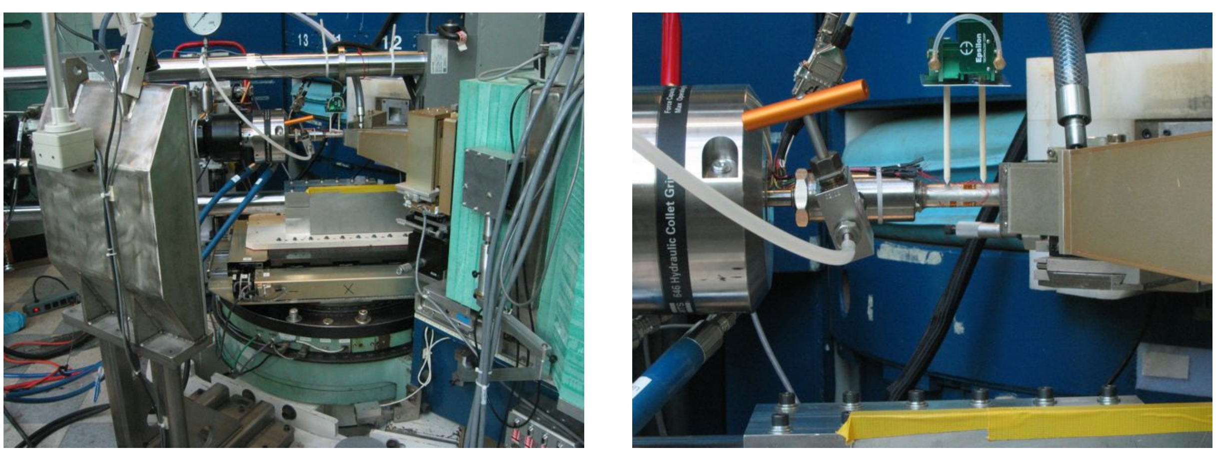

Fig. 2 In situ biaxial loading experiment at the L3 beamline. (left) Spectrometer, load frame and detector. (right) Close up of a hollow tubular specimen in the load frame grips and connected to the pressurization system.

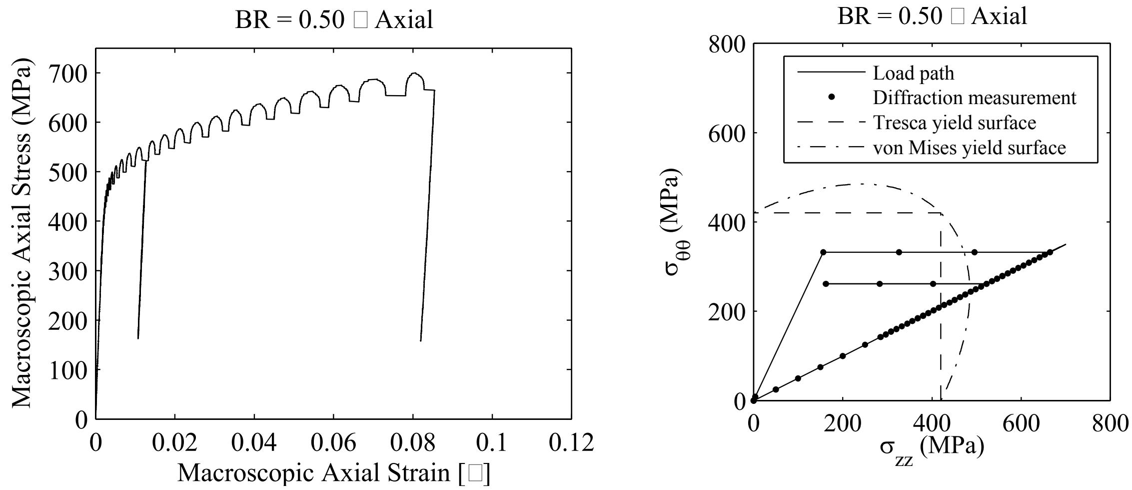

Fig. 3 (left) Representative macroscopic axial stress-strain curve and (right) load path in stress space.

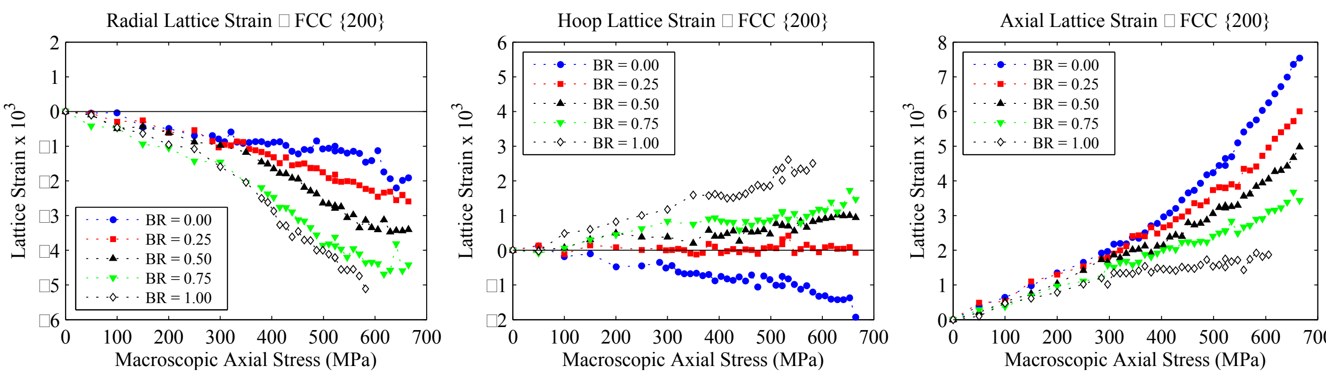

Fig. 4 Lattice strain data for the FCC {200} radial, hoop, and axial fibers at five levels of stress biaxiality.

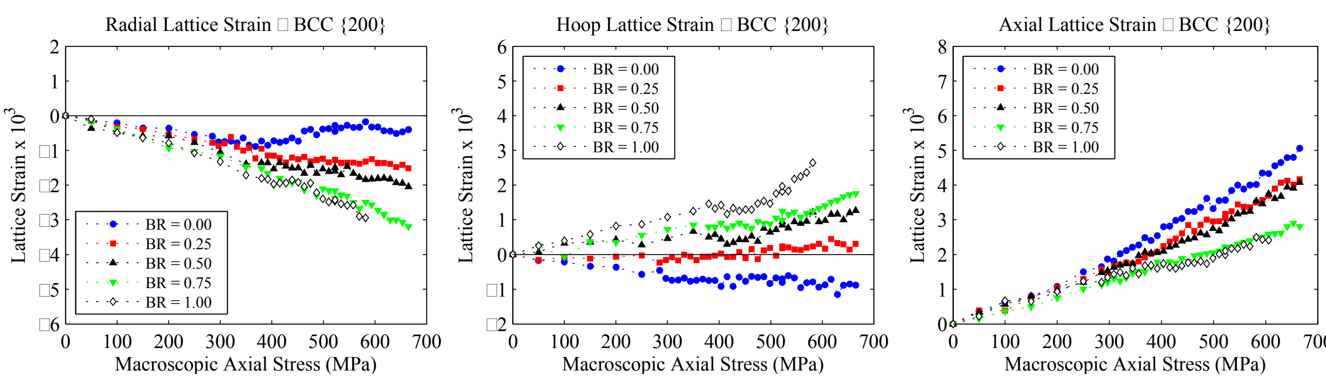

Fig. 5 Lattice strain data for the BCC {200} radial, hoop, and axial fibers at five levels of stress biaxiality.

Lattice strain measurements were taken for the FCC {200}, {111}, and {220} lattice planes and the BCC {200}, {110}, and {211} lattice planes. A subset of the lattice strain data is presented in Figures 4 and 5 for FCC and BCC crystals with {200} lattice plane normals aligned with the principle axes of the sample for five levels of stress biaxiality. For these fibers, hoop lattice strains increase with increasing stress biaxiality, whereas radial and axial lattice strains decrease with increasing stress biaxiality. Lattice strain sensitivity to biaxial ratio varies for each fiber. For example, the change in lattice strain with biaxial ratio is greater for FCC {200} fibers than BCC {200} fibers. Additionally, inflections in the lattice strain plots provide important information pertaining to the relative order in which crystals yield and relative crystal hardening rates.

To interpret the results of the experiment finite element simulations will be performed on virtual polycrystalline specimens. Virtual polycrystals comprise representative sample volumes and typically contain 3,000 to 10,000 grains. Each grain is resolved by multiple 10-node tetrahedral elements, with typically 50 to 200 elements per grain. Traction boundary conditions, corresponding to the experimental load history, are specified on the surfaces of the virtual polycrystal. The model incorporates equations for crystallographic slip, elastic anisotropy, and the evolution of material state [2-3]. The time domain is discretized into a series of time steps. At each time step, the velocity field is obtained and the displacement field and material state is updated.

Virtual diffraction experiments will be performed on the deformed virtual polycrystals to obtain simulated fiber-averaged lattice strains. The simulated lattice strains will then be compared to experimental lattice strains to validate the model. The model provides access to additional quantities of interest including stress, plastic deformation rate, and slip system hardness. Furthermore, the simulation results are not restricted to fiber-average quantities, and can be used to examine neighborhood effects and distributions over orientation space. Thus, the simulation provides complimentary data to the experiment that can be used to explain the observed experimental lattice strain trends.

In conclusion, a full suite of lattice strain measurements was conducted on LDX-2101 duplex stainless steel under *in situ* biaxial loading using neutron diffraction. Coupled with finite element simulations, these data will provide insight into how deformation initiates and proceeds at the microscale for a dual phase alloy. These data will also be used to better understand the link between material microstructure and macroscopic properties and lead to improved modeling capabilities for elasto-plastic deformation of crystalline structural alloys.

References

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