A multiscale experimental and numerical study of a martensitic steel at high shear strains

Pavan Sreenivasa Rao[1;2;a], Antony Youssef[1;2], Karthik Ramaswamy[2], Samaneh Isavand[1;2], Seán B Leen[3], Noel P O'Dowd[1;2]

[1]School of Engineering, University of Limerick, Limerick, V94 T9PX, Ireland

[2]Bernal Institute, University of Limerick, Limerick, V94 T9PX, Ireland

[3]Mechanical Engineering, School of Engineering, NUI Galway, Galway, H91 HX31, Ireland

[a] pavan.rao@ul.ie

Keywords: Notched Shear, Crystal Plasticity, EBSD

Abstract

The deformation behaviour of a martensitic steel (P91) under large shear strains is examined in this study. A notched shear specimen (based on ASTM B831–19) has been designed to achieve large uniform shear strains (> 30%), while minimising out of plane deformation to allow for ex-situ electron backscattering diffraction (EBSD). The deformation is captured experimentally over three length scales: an extensometer is used to measure the global elongation (cm scale), digital image correlation (DIC) is used to measure shear strains close to the notch (mm scale) and EBSD is used to measure the deformation induced crystal reorientation in the uniform strain region (µm scale).

Introduction

The power generation sector has seen a considerable change by moving towards renewable energy generation [1] and operating the conventional power plants on a flexible basis. The flexible operation of these powerplants which use 9Cr steels are prone type IV cracking in weldments leading to components failing within their design life [2]. In order to understand this behaviour, it is important to examine the deformation behaviour in as-received 9Cr steels at room temperature under large strains. This study defines a method of using shear geometry to achieve large strains and the ability to use EBSD without sectioning or polishing the surface post-deformation which could induce additional stress in the material.

Methodology

The geometry of the test specimen is shown in Figure 1 (a). The geometry was modified from ASTM B831 [3] to be accommodated within the sample chamber of a Helios G4 CX SEM. The SEM was used to obtain ex-situ EBSD scans. The shear specimens were machined using wire electric discharge machining. Two pin holes were drilled to accommodate the pins that were used to hold the sample. The two 45° notches were used to create a shear stress in the gauge region (3 mm between the notches) from a uniaxial load. DIC was used on one face of the sample to measure the macroscopic shear strains and EBSD scans were taken on the opposite face to measure the change in crystal orientation pre- and post-deformation.

Results

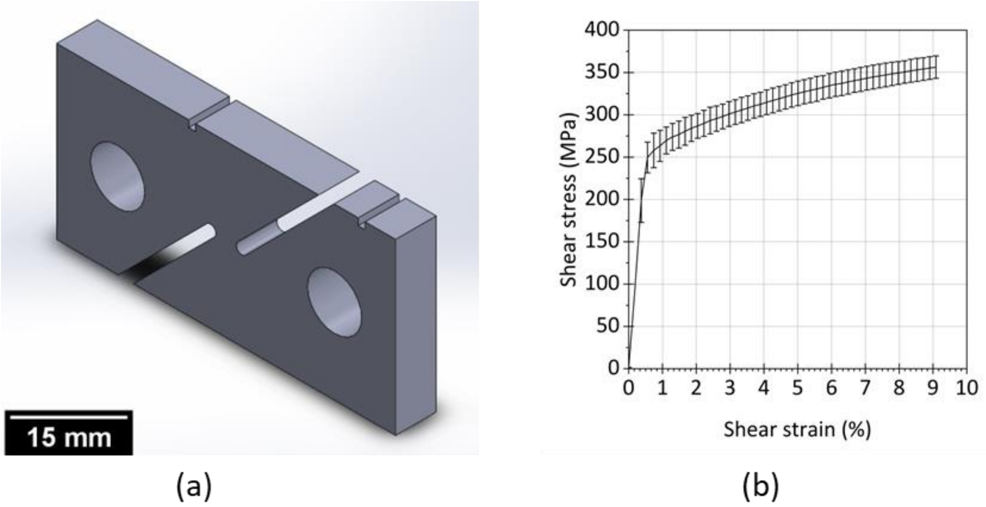
An average shear stress – shear strain curve from 4 repeat tests is shown in Figure 1 (b), standard deviation of 13 MPa is observed in the plastic region. Shear strains of 12%, 28% and 44% were achieved to evaluate the crystal reorientation post-deformation, at least two repeats were conducted for each strain value. The shear stress and shear strains were calculated using Equation 1 and Equation 2, where w is the distance between the notches, t is the thickness of the sample, u and v are the displacement measured using DIC.

$$\tau_{xy} = \frac{P}{wt} \qquad \text{Equation 1}$$

$$\gamma_{xy} = \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \qquad \text{Equation 2}$$

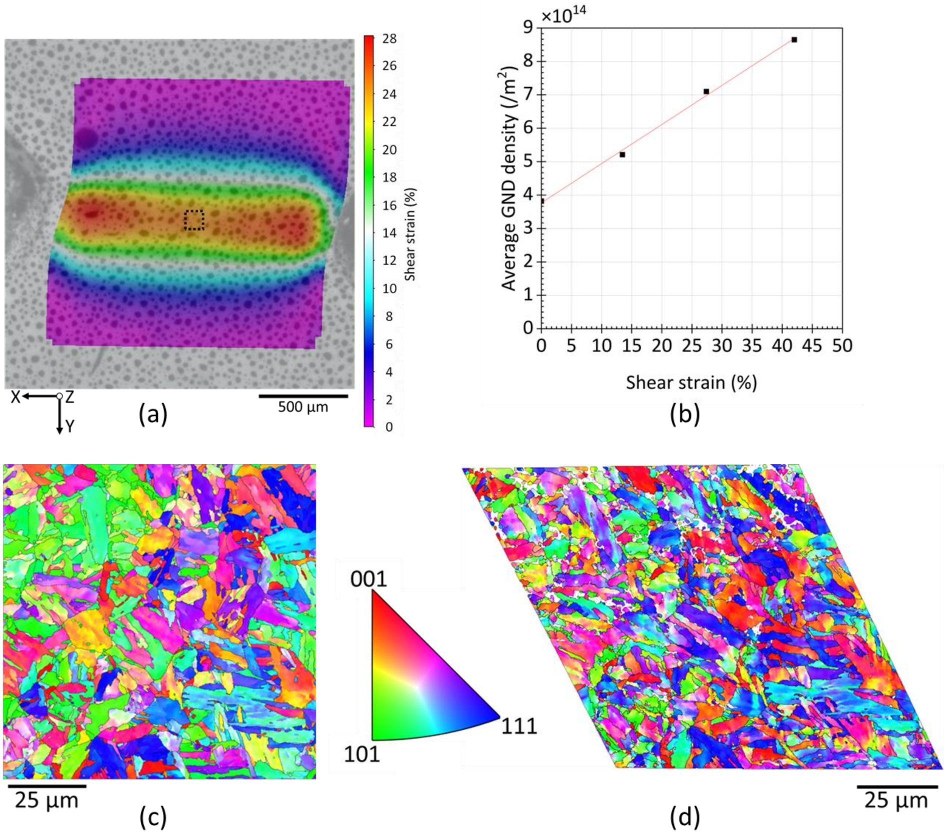
The shear strain contour with the area of acquisition of EBSD scan is shown in Figure 2 (a). The average geometrically necessary dislocation (GND) density is measured using the orientation data from EBSD, a linear relationship between the GND density and shear strain is shown in Figure 2 (b) and Equation 3. Large changes in the grain orientation can be observed in Figure 2 (c) and Figure 2 (d).

$$\rho_{GND} = 1.17\ \times 10^{15}(\gamma_{xy}) + 3.77\ \times 10^{14} \qquad \text{Equation 3}$$



(a) (b)

Figure 1 (a) Schematic of the shear specimen, (b) Average shear stress – shear strain curve measured using the DIC



(a) (b)

(c) (d)

Figure 2 (a) Shear strain contour with a max strain of 28% measured using DIC (area in the broken is the location of the EBSD scan), (b) Distribution of average GND density with shear strain in the sample, (c) IPF map in the Y direction of the undeformed sample, (d) IPF map in the Y direction of the deformed sample

Conclusion

A multiscale approach has been developed for measuring crystal reorientation post large mechanical deformation and geometrically necessary dislocations appear to linearly increase with measured shear strain by 1.17×10^{15} /m^2.

References

[1] I. Sustainable Energy Authority of, "ENERGY IN IRELAND 2022 Report," 2022. [Online]. Available: https://www.seai.ie/data-and-insights/seai-statistics/key-publications/energy-in-ireland/

[2] A. Shibli and F. Starr, "Some aspects of plant and research experience in the use of new high strength martensitic steel P91," *International Journal of Pressure Vessels and Piping,* vol. 84, no. 1-2, pp. 114-122, 2007/1// 2007, doi: 10.1016/J.IJPVP.2006.11.002.

[3] ASTM, "Standard Test Method for Shear Testing of Thin Aluminum Alloy Products," vol. 02.02, 2019.