1-to-1 comparison of SEM-DIC to CP strain fields of ultrathin steel films to unravel plasticity to damage initiation

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Abstract

In Dual-Phase steels, crack propagation and fracture is preceded by damage initiation and propagation, yet, the nature of the plasticity mechanisms leading to damage are debated. To fully unravel the plasticity-to-damage mechanisms, we present a novel integrated experimental-numerical nanomechanical framework for testing ultra-thin specimens, yielding (i) full 3D reconstruction of grain/phase shapes and orientations, (ii) front&rear-sided, high-resolution, microstructure-correlated SEM-DIC strain fields, and (iii) one-to-one comparison to numerical strain fields computed with (advanced) crytal plasticity. Results on martensite 'bridges' show that limited plasticity results in martensite damage whereas significant plasticity prevents damage; analysis reveals the key role of 'substructure boundary sliding' in martensite on damage initiation.

1. Introduction

Recent years saw advancement in simulations of plasticity, localizations and damage of various alloys and steels, using crystal plasticity or more advanced models. However, experimental validation of these simulation frameworks, particularly at the micro- and nanoscale, remains challenging due to (i) the unknown 3D subsurface microstructure, (ii) proper matching of boundary conditions and stress states, and (iii) the intricacy of damage mechanisms.

2. Results

A novel integrated experimental-numerical nanomechanical framework for testing ultra-thin specimens is introduced. '2D' tensile specimens, a few micron thick with a central hole, are extracted by Twin-Jet ElectroPolishing from the bulk microstructure, in this case Dual-Phase (DP) steel, see Fig. 1. Rich data is obtained: (i) the full-field thickness profile by two-sided optical profilometry, (ii) two-sided microstructure maps by BSE and EBSD, including habit plane orientation through prior austenite grain (PAG) reconstruction, (iii) high-resolution strain maps from SEM-DIC [1,2], and (iv) careful 3D alignment of all data [3]. The full 3D crystal structure and geometry is meshed and its DP material behavior is modelled using SEM-DIC displacement data as local boundary conditions to best replicate the experimental loading conditions. Figure 1 shows that standard crystal plasticity cannot capture the complex martensite behavior, i.e. the CP model needs to be extended with 'substructure boundary sliding' in martensite [4] as well as a discrete slip activity model for martensite and ferrite [5] to find a reasonably good match.

Several 'martensite bridges' have been characterized in detail using EBSD and subsequently tracked during deformation under high-resolution in-situ SEM-DIC, see Fig. 2, yielding the full evolution of the strain fields at/around the damaging site at a ~40nm spatial resolution [2]. Unexpected, interesting observations of martensite plasticity before martensite "cracking" occurs, in contrast to the usual assumption that martensite fails in a brittle manner. Moreover, some martensite notches show strong plastic deformation without any damage. This is currently studied to great depth, by applying a novel slip system identification framework, named Slip Systems-based Local Identification of Plasticity (SSLIP), which automatically identifies crystallographic slip activity fields from DIC data, even for 48 concurring BCC slip systems, and even for even for intersecting, diffuse and cross slip [6]. It appears that activation of the 'substructure boundary sliding' mechanism plays a decicive role in damage initiation in the 'martensite bridges', which will be further investigated in the upcoming months and included in the presentation at the ICF 2023.

3. Conclusions

Our novel nanomechanical testing framework enables deep analysis of damage and fracture mechanics. Experiments on martensite bridges reveal new insight in how plasticity controls damage initiation.

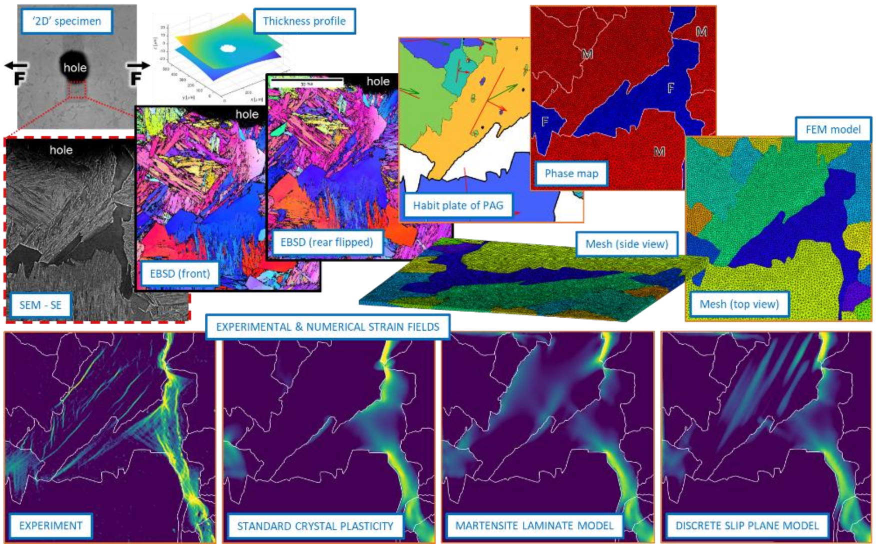

Fig.1 – Integrated experimental-numerical nanomechanical testing framework that enables in-depth, quantitative characterization of damage and fracture mechanisms, with (top left) an ultra-thin '2D' specimen characterized by two-sided EBSD characterization yielding the '3D' grain shapes, orientations, phases (martensite and ferrite) and prior austenite grain reconstruction, providing all input for (top right) the micromechanical model with 3D mesh of the grain shapes and orientations. (bottom row) High-resolution SEM-DIC strain fields of an in-situ SEM tested '2D' specimen is one-to-one compared to the simulated strain fields of (advanced) crystal plasticity models.

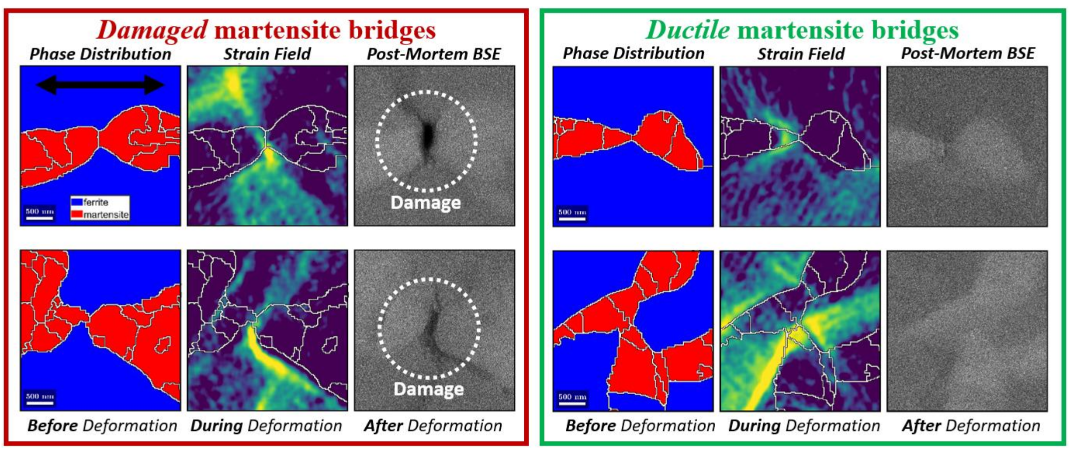

Fig.2 – Examples of martensite "bridges" showing (left) damage after minor plasticity versus (right) strong plasticity without damage. A few maps are shown of the rich data obtained before, during, and after deformation.

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