International Journal of Plasticity 63 (2014) 198–210

Contents lists available at ScienceDirect

International Journal of Plasticity

journal homepage: www.elsevier.com/locate/ijplas

Strain localization and damage in dual phase steels investigated by coupled *in-situ* deformation experiments and crystal plasticity simulations

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ARTICLE INFO

Article history:
Received 8 February 2014
Received in final revised form 28 May 2014
Available online 21 June 2014

Keywords:
A. Microcracking
A. Voids and inclusions
B. Crystal plasticity
C. Electron microscopy
Digital image correlation

ABSTRACT

Ferritic–martensitic dual phase (DP) steels deform spatially in a highly heterogeneous manner, *i.e.* with strong strain and stress partitioning at the micro-scale. Such heterogeneity in local strain evolution leads in turn to a spatially heterogeneous damage distribution, and thus, plays an important role in the process of damage inheritance and fracture. To understand and improve DP steels, it is important to identify connections between the observed strain and damage heterogeneity and the underlying microstructural parameters, *e.g.* ferrite grain size, martensite distribution, martensite fraction, etc. In this work we pursue this aim by conducting *in-situ* deformation experiments on two different DP steel grades, employing two different microscopic-digital image correlation (μDIC) techniques to achieve microstructural strain maps of representative statistics and high-resolution. The resulting local strain maps are analyzed in connection to the observed damage incidents (identified by image post-processing) and to local stress maps (obtained from crystal plasticity (CP) simulations of the same microstructural area). The results reveal that plasticity is typically initiated within "hot zones" with larger ferritic grains and lower local martensite fraction. With increasing global deformation, damage incidents are most often observed in the boundary of such highly plastified zones. High-resolution μDIC and the corresponding CP simulations reveal the importance of martensite dispersion: zones with bulky martensite are more susceptible to macroscopic localization before the full strain hardening capacity of the material is consumed. Overall, the presented joint analysis establishes an integrated computational materials engineering (ICME) approach for designing advanced DP steels.

1. Introduction

Ferritic–martensitic dual phase (DP) steels are finding multiple applications in the automotive industry. There is, therefore, a permanent interest in further optimization of their microstructure aiming at lower energy consumption in sheet metal forming operations, higher energy absorption during crash loading conditions, etc. (Rashid, 1981; Llewellyn and Hillis, 1996; Calcagnotto et al., 2012; Bouaziz et al., 2013). Even when presence of other phases such as retained austenite or bainite are not taken into account, the micromechanical behavior of the composite-like dual phase microstructure of DP

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http://dx.doi.org/10.1016/j.ijplas.2014.06.004
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steels is rather complex (Tekoglu and Pardoen, 2010, Tekoglu et al., 2012, Kadkhodapour et al., 2011b,2011a, Sun et al., 2009a,2009b). Thus, following numerous reports on the mechanical performance of DP steel (which are typically based on conventional post-mortem microstructure characterization techniques), the microstructural strain and stress partitioning that governs the overall behavior of DP microstructures is still not fully understood.

Recently, it has been demonstrated that direct information on strain partitioning can be obtained using *in-situ* mechanical testing setups, which enable microstructural imaging during deformation and follow-up microscopic-digital image correlation (μDIC) analysis (Kang et al., 2007; Tasan et al., 2010; Ghadbeigi et al., 2010, 2013; Kapp et al., 2011; Joo et al., 2013; Marteau et al., 2013; Han et al., 2013). Kang et al. (2007) have shown that strain partitioning between ferrite and martensite can be significantly decreased by a tempering treatment, leading to an increase in the critical damage nucleation strain. Tasan et al. (2010) demonstrated that the detrimental influence of microstructural banding strongly depends on the continuity of the band, as well as its morphology and the mechanical character of the phase that composes the band. Ghadbeigi et al. (2010) have presented a quantitative analysis of critical strain levels for different damage nucleation mechanisms in a DP1000 microstructure (Ghadbeigi et al., 2010). Local strains well above 100% are reported for damage incidents within ferrite and at martensite–ferrite phase boundaries. Kapp et al. (2011), also focusing on a DP1000 steel, reported the severe heterogeneity of the strain distribution, which rises with increasing global deformation level. "Hot spots" of deformation are revealed to develop in ferrite channels between bulky martensite regions, and grain boundaries normal to the loading direction. More recently, Joo et al. (2013) have pointed out – using an advanced technique for higher strain resolution – that the strain heterogeneity in DP steels is more complex than suggested by earlier work. Marteau et al. (2013), employing a microlithography based pattern and electron backscatter diffraction (EBSD) based microstructure characterization, presented a detailed report on the role of different microstructural factors in strain heterogeneity. Their results suggest that the most critical factor causing the strain heterogeneity is the local microstructural neighborhood rather than the specific grain orientation, shape or size. These observations are also supported by a recent report by Han et al. (2013). Ghadbeigi et al. (2013) have demonstrated in a more recent work that martensite morphology is critical in early damage nucleation. Carrying out nanoindentation and micro-pillar compression experiments on martensite and ferrite regions in a DP steel, Ghassemi-Armaki et al. (2014) have shown that ferrite hardness and strength is significantly heterogeneous even within a given grain.

The results presented in the recent works clearly demonstrate the strength of the μDIC approach in capturing the complex strain patterns evolving in DP steels. However, the nature of such *in-situ* analyses enforces a trade-off between representative statistics and high-resolution (*e.g.* lower magnification imaging allows more grains to be assessed, but with less pixels per grain), while reliable characterization of DP steel micro-mechanics requires both. The former is especially critical because the *in-situ* analyses at the surface of the bulk material are distracted by the behavior of the microstructure underneath, and thus may be subjected to a significant inaccuracy. Given the above-mentioned reports with the rather unexpected absence of correlation of strain localization with local microstructure properties (*e.g.* grain size, shape, orientation, etc.), the issue of statistical representativeness becomes even more critical. The motivation for maximal spatial resolution, on the other hand, is motivated by (i) the scale of the microstructure reaching well below the sub-micron regime within martensitic regions; and also by (ii) the locality of the plastic response in martensite and in ferrite regions.

The main goal of this report is to deepen the understanding of the role of the underlying microstructural parameters on (i) the heterogeneous plastic behavior, and (ii) the damage micro-mechanisms in DP steels. More specifically, the influences of ferrite grain size, ferrite orientation and martensite dispersion are investigated. To this end, to fulfill both the statistical and resolution requirements, we employ two different μDIC methodologies: the first method enables the mapping of large field-of-view microstructure patches, but at lower spatial resolution strain mapping; while the second one allows high spatial resolution strain mapping at smaller field-of-view. Both analyses are coupled to high resolution *microstructure mapping* based on EBSD measurements. The former is additionally coupled to the results obtained from an image post-processing based damage detection algorithm, and the latter to full-field crystal plasticity (CP) simulations. The simulations play a key role, as they provide an (indirect) analysis of the local stress partitioning process, which is otherwise challenging to access through experimentation only.

In what follows, first the employed experimental and theoretical methodologies are explained. Then, results of the aforementioned two types of *in-situ* deformation experiments are presented in connection to the results of the accompanying microstructure analysis and CP simulation results. Finally the results are discussed and conclusions are presented.

2. Methodology

2.1. Materials

The DP steels investigated in this report have a tensile strength of approximately 600 MPa (DP600) and 800 MPa (DP800), respectively. Both steels are non-commercial grades provided by Tata Steel, IJmuiden, the Netherlands. The microstructure of both materials consists of a soft ferrite matrix surrounded by martensite islands. Details on the composition and overall properties of these two steels are provided in Table 1. Within this study both of these steels are deformed in multiple strain paths using two different deformation setups described below. We present here the results of biaxial tension for the DP600 steel and uniaxial tension for the DP800 steel. The motivation of investigating the two microstructures in these two strain paths is as follows. As seen in Fig. 1 and Table 1, the microstructures possess differences in ferrite grain size (larger in DP600),