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Damage and fracture of dual-phase steels: Influence of martensite volume fraction

Q. Lai [a,*], O. Bouaziz [b], M. Gouné [c], L. Brassart [d], M. Verdier [a], G. Parry [a], A. Perlade [e], Y. Bréchet [a], T. Pardoen [d]

[a] SIMaP, CNRS UMR 5266, Université de Grenoble Alpes, F-38402 St Martin d'Hères Cedex, France
[b] Laboratoire d'Etude des Microstructures et de Mécanique des Matériaux (LEM3), CNRS UMR 7239, Université de Lorraine, F-57045 Metz, France
[c] ICMCB-CNRS-UPR 9048, F-33608 Pessac Cedex, France
[d] Institute of Mechanics, Materials and Civil Engineering, Université catholique de Louvain, 2 Pl. Sainte-Barbe, Bâtiment Réaumur, B-1348 Louvain-la-Neuve, Belgium
[e] R&D Automotive Products, ArcelorMittal, Voie Romaine, BP 30320, F-57283 Maiziéres-lés-Metz Cedex, France

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ABSTRACT

The influence of the martensite volume fraction (V_m) on the damage and fracture behavior of dual-phase steels was studied by combining experiments and micromechanical modeling. A transition in the dominating damage mechanism is observed when varying V_m. Martensite fracture dominates the void nucleation process at high V_m, while interface decohesion prevails at low V_m. Damage accumulation accelerates when V_m increases, resulting in a decrease of the fracture strain. Brittle fracture areas are observed in uniaxial tensile specimens for a sufficiently high V_m. The damage mechanisms and evolution are rationalized using a micromechanical analysis based on periodic finite element cell calculations. The results show that V_m is a key factor for controlling the balance between strength and fracture resistance.

1. Introduction

The reduction of weight in order to limit fuel consumption and gas emissions has become, for several decades, the main driving force for the development of advanced high strength steels (AHSS) [1,2]. In addition, AHSS exhibit superior performances regarding passenger safety and crashworthiness [2]. Among the grades of AHSS, ferrite-martensite (FM) dual-phase (DP) steels are the most widely used in the automotive industry owing to attractive mechanical properties, lean alloy content and robust processing. A DP steel is a composite essentially consisting of a hard martensite phase embedded in a soft ferrite matrix. The DP steels are characterized by a low yield/tensile strength ratio, high initial strain hardening capacity, and good bake-hardening properties [1]. However, the moderate fracture strain is one of the, if not the main, limitation for extending the range of applications for this steel grade, especially when the components undergo substantial deformation during forming. The trade-off between strength and fracture strain leads to microstructure engineering challenges depending on the specific requirements of application. A proper optimization adapted to each application requires the knowledge of the influence of microstructural features as well as quantitative micromechanical models.

Ductile fracture of DP steels results from a process of nucleation, growth and coalescence of internal voids [3–5]. Intense research activity has been devoted to understanding the damage behavior of DP steels [3–17]. Ghadbeigi et al. [7] studied the damage mechanisms in DP600 steel, and found that the failure of martensite islands mostly occurs as a result of micro-crack initiation at the boundaries with the surrounding ferrite followed by crack propagation to the center of the islands. An extreme case of martensite fracture is the failure of continuous martensite bands, which occurs very early during deformation and is detrimental to fracture resistance [14,15]. However, Kadkhodapour et al. [9] observed that the dominant void nucleation mechanism for the DP800 grade is ferrite grain-boundary decohesion in the neighborhood of martensite islands with no substantial contribution of martensite fracture. The variety of void nucleation mechanisms reveals the complexity related to the proper understanding and prediction of the damage behavior in DP steels. Additional efforts are needed to identify the respective influences of the various microstructural parameters.

The volume fraction of martensite (V_m) is considered as the most important parameter in the balance between strength and fracture strain [18], and a clear understanding of its effects is of

* Correspondence to: University of British Columbia, Canada.
E-mail addresses: qingquanlai@hotmail.com (Q. Lai), thomas.pardoen@uclouvain.be (T. Pardoen).

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primary importance. In the present work, the impact of V_m on the damage and fracture mechanisms and on the evolution of the damage accumulation is studied by detailed experimental investigations on specifically designed microstructures with well controlled morphology and phase properties. The results of damage characterization are rationalized by investigating the local response of martensite, which is provided by Finite Element (FE) unit cell calculations [19,20]. The FE unit cell calculations were performed in order to achieve a balance between computational cost and the capability to predict the deformation and damage characteristics of DP steels, compared to the microstructure-based FE models [9,21–24].

The paper is organized as follows. The experimental procedure is presented in Section 2. The experimental results, including microstructure processing, tensile data, damage and fracture characterization, are shown in Section 3. The micromechanical model and the results are presented in Section 4. The main points regarding the damage and fracture mechanisms are discussed in Section 5, before concluding.

2. Experimental procedure

2.1. Microstructure processing and characterization

The steel grade used in this work (0.1 wt% C, 3.5 wt% Mn) was processed in a research center of the company ArcelorMittal. After casting, the ingot was held at 1200 °C and then hot-rolled above 900 °C. A martensitic microstructure was produced by quenching, followed by cold-rolling to 1 mm thickness involving 70% reduction. Tempering of the as-received material was performed in order to produce a spheroidized microstructure. The spheroidized microstructure was than intercritically annealed at 700 °C for durations varying from 20 min to 6 h.

Samples for Scanning Electron Microscope (SEM) observations were prepared by standard mechanical grinding and polishing procedures, finishing with 8 min colloidal silica polishing. The samples were etched with 2% Nital to reveal the microstructure. The microstructures were analyzed by quantitative image analysis. The SEM images were binarized into black–white in order to distinguish the ferrite and martensite phases. The area fraction of martensite, which corresponds to the volume fraction in 3-dimension [25], was measured with ImageJ [26]. The method of intercepts was used to quantify the average size of martensite [25].

2.2. Mechanical tests

Nanoindentation was used to locally probe the hardness of martensite. A matrix of indents was performed on the specimens after colloidal silica polishing to eliminate the plastically deformed surface layer. The location of each indent was identified under Back Scatter Electron (BSE) mode in SEM and only the indents exactly located within the martensite islands were analyzed. The hardness of the phases was continuously measured during the loading thanks to the Continuous Stiffness Measurement (CSM) mode which imposes small load oscillations during the indentation [27]. The hardness was extracted as a mean value between 60 and 90 nm penetration depths. The nanohardness of martensite in each sample is an average of five to ten indents.

The mechanical properties were measured by uniaxial tensile testing using dog-bone specimens with 25 mm gauge length and 5 mm width. The tests were performed at room temperature and 1.5 mm/min displacement rate which corresponds to an engineering strain rate of 0.001/s. The yield strength is defined as the stress corresponding to 0.2% plastic strain. The uniform elongation is quantified through the true strain at the onset of necking determined by Considère criterion [28], and the corresponding stress is the true tensile strength. Three specimens of each grade were tested.

2.3. Fracture and damage characterization

The fracture surfaces were observed in a SEM. For ductile fracture surfaces, the dimple density was characterized by the mean distance between all neighboring dimple centers, which was done manually on the SEM micrographs.

The fracture strain is defined as the cross-sectional area reduction measured on the fracture surface and expressed by

$$\varepsilon_f = \ln\frac{A_0}{A_f} \tag{1}$$

where A_0 and A_f are the initial and final cross-sectional area measured on SEM images.

Damage accumulation was characterized through the evolution of the density and area fraction of voids as a function of strain. One specimen per condition was selected for damage analysis. Post-mortem 2D analysis of the voids was performed on broken tensile specimens. A half fractured specimen was sectioned through the thickness approximately along the midwidth, in the longitudinal direction. These samples were then polished and cleaned with ethanol. The specimens were observed in a SEM using BSE mode, which is more sensitive to porosity at the surface [29]. The SEM micrographs have a grid of 1022×680 pixels. The images with $1000\times$ magnification were adjusted with the adequate brightness and contrast, and binarization was applied in order to properly differentiate voids from the non-porous surrounding material. The density and area fraction of voids were analyzed with ImageJ. A threshold void size was fixed to the value of 0.11 μm^2, which corresponds to 9 pixels, and this is used for the comparison of damage accumulation between different microstructures. In addition, the evolution of void size distribution with deformation is also evaluated. After quantifying the damage accumulation, the samples were etched with 2% Nital and observed in a SEM.

The local strain is taken as the true thickness strain $\varepsilon_{thickness}$ given by

$$\varepsilon_{thickness} = \ln\frac{h_0}{h} \tag{2}$$

where h_0 and h are the initial and current thickness in the corresponding zone [16]. The measurements of the damage parameters are averaged over five micrographs for each level of deformation, and the evolution of damage accumulation with thickness strain is compared among the samples with different V_m.

3. Experimental results

3.1. Microstructure and nanohardness

The as-received spheroidized microstructure (QT) is shown in Fig. 1a. After an intercritical annealing at 700 °C, DP microstructures were produced with V_m equal to 15%, 19%, 28% and 37%, as shown in Fig. 1b–e. The martensite islands form mainly at ferrite grain boundaries. The dual-phase microstructure is relatively uniform and equiaxed when V_m is low (Fig. 1b), but the martensite islands tend to organize in clusters elongated along the rolling direction at V_m above 19%, see Fig. 1c. Continuous martensite bands develop for V_m equal to 28% (Fig. 1d) and the banded structure is significant when V_m reaches 37%, see Fig. 1e. The mean linear size of martensite increases with increasing V_m, as shown in Fig. 1f.