Materials Science & Engineering A 670 (2016) 57–67

Contents lists available at ScienceDirect

Materials Science & Engineering A

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

Micromechanical analysis of martensite distribution on strain localization in dual phase steels by scanning electron microscopy and crystal plasticity simulation

M. Jafari [a], S. Ziaei-Rad [a,*], N. Saeidi [b], M. Jamshidian [a]

[a] Department of Mechanical Engineering, Isfahan University of Technology, Isfahan, Iran
[b] Department of Materials Engineering, Isfahan University of Technology, Isfahan, Iran

ARTICLE INFO

Article history:
Received 15 December 2015
Received in revised form
25 March 2016
Accepted 23 May 2016
Available online 24 May 2016

Keywords:
Micromechanisms
Dual phase steel
Void nucleation
Crystal plasticity
Finite element method

ABSTRACT

The morphology and distribution of the dispersed martensite islands in the ferrite matrix plays a key role in the formation of shear bands in dual phase steels. In this study, we investigate the relationship between the martensite dispersion and the strain localization regions due to the formation of shear bands in fine-grained DP 780 steel, employing experimental observations as well as numerical simulations. SEM studies of the deformed microstructure showed that voids nucleated at ferrite-martensite interface within larger ferrite grains and regions with low local martensite fraction. The experimental results were precisely analyzed by finite element simulations based on the theory of crystal plasticity. A parametric study was then performed to obtain a deeper insight in to the effect of martensite dispersion on the strain localization of the neighboring ferrite. Crystal plasticity simulation results revealed that in a more regular structure compared to a random structure, a greater region of the ferrite phase contributes to accommodate plasticity. In addition, these regions limit the formation of main shear bands by creating barriers against stress concentration regions, results in lower growth and interaction of stress concentration regions with each others.

1. Introduction

Dual phase (DP) steel consisting of hard martensite islands distributed in a ductile ferrite matrix can be considered as one of the most important steels employed in automotive industry due to its high tensile strength, low yield stress, continuous yielding behavior and high work hardening rate. During the last decade, numerous studies have been carried out to predict the mechanical behavior of DP steels and to further optimize their microstructure in order to achieve lower energy consumption in sheet metal forming operations and higher energy absorption during crash loading conditions [5,6,26]. These studies demonstrated that deformation of ferrite phase is closely related to the initial crystallographic orientation, grain size, volume fraction and morphology of the dispersed martensite islands in the ferrite matrix [8,12,17,23,26]. Sun et al. [23,24] utilized the finite element analysis of the actual steel microstructure to show that the microstructure-level inhomogeneities serve as the initial imperfection trigger for instability in the formation of plastic strain localization during the deformation process. Therefore, a prescribed failure criterion is not required for the individual constituent phases of DP steels. Kadkhodapour et al. [13] carried out experimental and numerical investigations on failure mechanisms of DP steels. They observed that crack initiation occurs in grain boundary regions and concluded that the main source of rupture is deformation localization. Ghadbeigi et al. [9,10] studied the evolution of damage in DP1000 steel using in-situ tensile testing in combination with digital image correlation (DIC) method. By analyzing local strain distribution within the ferrite-martensite microstructure, they observed a very heterogeneous strain distribution within the microstructure with the deformation localization in the bands orientated at 45 degree with respect to the loading direction. Ghassemi-Armaki et al. [11] characterized the deformation response of ferrite and martensite phases in DP steel by nano-indentation and micropillar compression tests. They observed that the ferrite far from the martensite gets work hardened during tensile deformation of the DP steel, but the ferrite near the ferrite-martensite interface gets softened. The inhomogeneous response persisted at least up to 7% global plastic strain of the DP steel. To investigate the effect of crystallographic orientation on the mechanical behavior of DP steels, Woo et al. [27] studied the

* Corresponding author.
E-mail address: szrad@cc.iut.ac.ir (S. Ziaei-Rad).

http://dx.doi.org/10.1016/j.msea.2016.05.094
0921-5093/

deformation behavior of ferrite and martensite phases in DP980 steel using in-situ neutron diffraction and the crystal plasticity method. They showed that crystallographic orientation of ferrite phase significantly affects shear strain localization and void initiation in the ferrite regions near the martensite phase during uniaxial tension. In another study, Chen et al. [7] combined the micropillar compression tests and numerical simulations to determine the flow strength and strain rate partitioning in DP steels. Using a crystal plasticity model accounting for the non-Schmid behavior in the ferrite phase, they could successfully predict the orientation dependence of the flow strength. Alaie et al. [1,2] conducted in-situ tensile tests and numerical simulations to investigate the key factors in the formation and coalescence of deformation bands in the ferrite phase of DP600 steels. Their results revealed that micro-cracks appear within the deformation bands in the final stages of deformation and in other words, the voids and defects outside the shear bands do not contribute to the final failure. Tasan et al. [25,26] produced microstructural strain maps by using in-situ deformation experiments on different DP steels and employing two different microscopic-digital image correlation techniques. Their analysis on local strain maps obtained from experimental and simulation results revealed that plasticity is typically initiated within larger ferrite grains and regions with lower local martensite fraction.

The aforementioned review of the present literature clearly demonstrates that the morphology and distribution of the dispersed martensite islands in the ferrite matrix highly affect the formation of shear bands and subsequently the deformation behavior of DP steels. However, it seems that there is a question about how the shear bands can be affected by the distribution of martensite islands. How does the dispersion of martensite islands influence on the distribution of created shear bands or their probable localization? Therefore, in the present study we investigate the relationship between deformation bands and martensite dispersion for DP 780 steel specimens by utilizing experimental observation and numerical simulation. Void creation mechanism and its correlation with the ferrite grain size and martensite dispersion is primarily examined for a tensile specimen using SEM analysis. Subsequently, measured results are precisely analyzed with crystal plasticity simulations to identify the correlation between shear bands and microstructure-level inhomogeneity.

2. Material, experimental procedure and observations

The material investigated in this study is commercial DP780 steel sheet with a thickness of 1 mm. The average volume fraction of martensite is 17%. The chemical composition of the material is shown in Table 1. Tensile specimens were machined by electrical discharge machining (EDM) method in the rolling direction according to ASTM A370 standard. The sheet thickness and the gage length were 1 mm and 50 mm, respectively. The tensile tests were performed at a constant cross-head speed of 1 mm/min with a servo-hydraulic MTS machine. Fig. 1 shows the geometries of the specimen and the engineering stress–strain diagram of the investigated DP steel. The yield strength of the steel, the ultimate tensile stress and failure strain were obtained to be 550 MPa, 893 MPa and 0.24, respectively.

Table 1
Chemical composition of the DP 780 steel.

Alloying element	C	Si	Mn	Cr	S	p
%Weight	0.15	0.4	1.1	1.	0.025	0.035

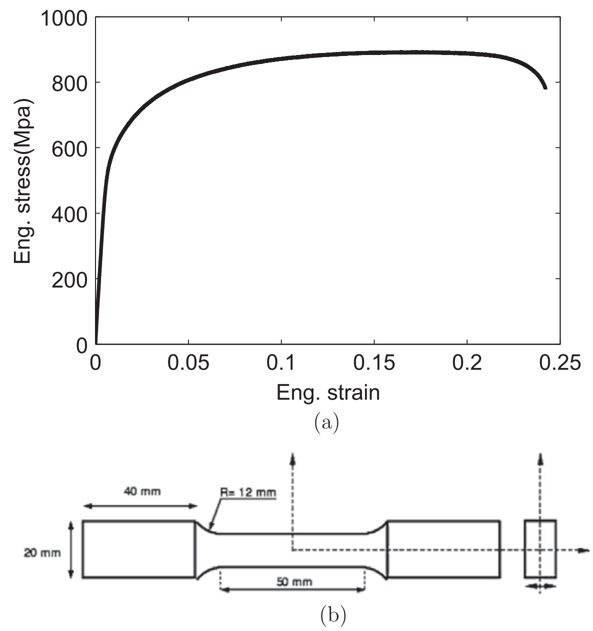

Fig. 1. (a) Material stress–strain diagram, and (b) the geometry of the specimen.

Scanning electron microscopy (SEM) equipped with an EBSD detector was employed for examination of the deformed microstructures of the specimens. The initial microstructure and EBSD image quality map with inverse pole figure of the investigated DP steel are shown in Fig. 2. As shown in this figure, the distribution of martensite particles are nearly uniform within the microstructure of the steel and no noticeable banding can be observed.

Saeidi et al. [20,21] have shown that voids nucleation mostly happens between closely spaced martensite grains which are themselves situated between rather two large ferrite grains. In this study, we will analyze such a statement more precisely and interpret it with numerical simulations. Fig. 3 shows the deformed microstructure of the specimens obtained from detailed SEM observations, at true strain value of 0.1. A straightforward criterion for finding void nucleation strain was supposed to be the strain at which the void volume percent is equal to 0.1 [15,16,22]. Considering this criterion, the void nucleation strain was found to be 0.1, in the current examination as shown in Fig. 4. Although, at this strain there would be some amount of void growth, it would be negligible. Fig. 3 shows that the region with the lower ratio of ρ_m/ρ_f, where ρ_f is the local density of voids and ρ_m is the local density of martensite particles, is more prone to void nucleation. The reason is that the volume expansion during austenite to martensite transformation causes a compressive stress in the boundaries between ferrite-martensite phases. Therefore at the low applied strain, the applied tensile stress frustrates the compressive stress in the boundaries between ferrite-martensite phases and it creates more deformation within ferrite grains. Therefore a deformation gradient is created from inside ferrite grains (that are under more tension) toward ferrite-martensite boundaries (where there is lower tensile stress). The deformation gradient is more intense between closely spaced martensite particles which are located between large ferrite grains. In other words, the regions with the lower ratio of ρ_m/ρ_f are expected to bear a higher deformation gradient. As a result, such regions can be considered to be the first candidate for the formation of the localized strain areas.

On the other hand, considering the fact that plastic strain within martensite grains is less than ferrite grains, most of the deformation is imposed on the softer ferrite phase surrounded by