Materials and Design 68 (2015) 167–176

Contents lists available at ScienceDirect

Materials and Design

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

Micromechanics stress–strain behavior prediction of dual phase steel considering plasticity and grain boundaries debonding

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ARTICLE INFO

Article history:
Received 24 September 2014
Accepted 10 December 2014
Available online 18 December 2014

Keywords:
Dual phase steel
Cohesive zone
Stress–strain
Interface debonding
Ferrite and martensite interfaces

ABSTRACT

Stress–strain response of multiphase materials similar to dual phase (DP) steel depends on the elastic–plastic and damage behavior of all ingredient phases. DP steels typically contains of ferrite and martensite phases, but the grain boundaries of martensite phase may act as important location with possible occurrence of damage or debonding under static loading. The focus of this paper is consideration of ferrite and martensite interface debonding in addition to the elastic–plastic behavior of ferrite and martensite to predict the stress–strain behavior of DP steel using a finite element (FE) micromechanical approach. For this purpose the micromechanics representative geometry is selected from scanning electron microscopy (SEM) images and the finite element mesh is generated based on the real shape of grains. Interface elements based on the cohesive zone modeling are also used for consideration of damage or debonding on the ferrite and martensite interfaces. Therefore, the developed micro mechanic finite element model is based on the real microstructure, uses cohesive elements between martensite islands and ferrite matrix and also considers the elastic–plastic behavior of ferrite and martensite phases. Handling of such simulation procedure with two source of material nonlinearity (plasticity and cohesive zone damage) is not an easy task. It is shown that the obtained stress–strain behaviors are in well agreement with the experimental results.

1. Introduction

Recently, automotive industries explore a material solution for lightweight and crash-safe designs. Dual phase steels are among the most important advanced high strength steel (AHSS) products recently developed for the automotive industry. This group of steels is very interesting for light weight constructions because it combines a high ultimate strength with a high fracture strain [1]. Dual phase steels consisting of hard martensite islands within a ferrite matrix have received considerable attention due to their continuous yielding behavior, high work hardening rate and ductility [2]. The key microstructural characteristics for DP steel are the amount, strength and distribution of the martensite islands [3]. One approach for the commercial production of dual phase steel is the continuous annealing approach, where hot or cold rolled steel strip is uncoiled and annealed intercritically to produce the desired microstructure [4]. Irrespective of the chemical composition of the alloy, the simplest way to obtain a ferritic–martensitic steel is intercritical annealing of the ferritic–pearlitic microstructure, followed by a sufficiently rapid cooling to enable the austenite to martensite transformation. The microstructure and the final amount of ferrite and martensite in DP steel can be controlled by the holding time, intercritical temperature, and the cooling rate [5,6].

Microstructural components of DP steels are under three distinct deformation processes in the mechanical response up to the failure point. In the first stage both the ferrite matrix and martensite particles deform elastically. In the second stage the ferrite phase deforms plastically while the martensite phase continues to deform elastically. In the third stage both the ferrite and martensite phases deform plastically [7,8]. Then, the voids nucleation in the microstructure may leads to the failure of component. In the failure procedure of dual phase steel during the necking and localization, large deformation, rotation and displacement occur in the ferrite matrix and subsequently rotation and displacement transmit to the martensite grains [9]. SEM microstructure analysis of dual phase steel reveals three distinctive mechanisms of voids nucleation: cracking of the martensite, de cohesion at ferrite and martensite interface, and separation of adjacent martensite regions [10,11].

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http://dx.doi.org/10.1016/j.matdes.2014.12.013
0261-3069/

In recent years, computational modeling has been successfully established to study the material behavior at microstructure level. Al-Abbasi and Nemez [12] reported microstructure modeling using a representative volume element (RVE) with consideration of axisymmetric condition and two different particle sizes. In another investigation for micromechanical simulation, a plane strain idealization was used to represent the periodic array of a two-phase material based on a simple square array, staggered square array and stacked hexagonal array [13]. These modeling procedures were not based on the real microstructures of the DP steels. Sun et al. [14] performed elastic–plastic finite element analyses for a RVE of microstructure that is selected from SEM. It is worth to note that generations of unstructured finite element mesh on a selected SEM–RVE make the researchers capable to consider the real geometries of ferrite and martensite interfaces and their effects on the mechanical behavior and damage progress of multi-phase materials [15].

Shear failure pattern could describe the failure scenario. Also, relative deformation of martensite grains caused strain localization in the ferrite matrix and led to initial void formation and coalescence [16,17]. According to the previously performed investigations, the voids nucleation could occur at the interfaces between ferrite and martensite phases [18]. Kadkhodapour et al. [19,20] create a microstructure model based on real micrographs to achieve stress–strain curve using finite element method. In these analyses, damage and debonding of ferrite and martensite interfaces have not been considered. On the other hands the presented microstructure models and meshing were not compatible with the interfaces of real grain boundaries in SEM images.

Cohesive zone modeling can be used to predict the initiation and propagation of debonding at ferrite and martensite interfaces in dual phase steels. In cohesive zone modeling, interface elements are set up between the two phases and lose the stiffness when damage occurs. Degradation of material property and damage progress at the boundaries of the martensite grains can be effective on the prediction of overall mechanical behavior. Therefore, consideration of both elastic–plastic material constitutive law and cohesive elements can approximately model more realistic conditions which may improve the predicted mechanical responses.

In this paper, stress–strain response of the dual phase steel is predicted using the finite element analyses of the microstructure using a selected RVE from the SEM images. In these analyses elastic–plastic behavior of the phases are taken into account and damage nucleation and possible debonding of ferrite–martensite boundaries are modeled using cohesive elements.

On the other hand using the cohesive elements in the finite element analysis provides the capability to predict the voids and micro-cracks locations along the ferrite and martensite interfaces in a 2D finite element model with respect to the separation and stress values in the cohesive elements. Therefore, the finite elements meshes should be compatible with the real microstructure because of the ferrite and martensite interfaces importance. The predicted stress–strain behavior from various RVEs will be compared with the experimental and numerical results.

2. Cohesive elements

Cohesive or interface elements follow a constitutive cohesive law. A cohesive law describes the non-linear interfacial softening behavior during the damage or debonding process by forming of damage accumulation or an extended crack tip. A cohesive zone model can be incorporated in a finite element code by implementing so-called interface elements. Usually, interface elements relate the interfacial tractions to the relative displacements [21]. Cohesive zone model is a general model which can deal with the nonlinear zone ahead of the crack tip due to the plasticity or micro-cracking presented in the material. Furthermore, the cohesive zone modeling is able to adequately predict the mechanical behavior and degradation of un-cracked structures [22].

Interface debonding can be modeled by traditional fracture mechanics method such as node release or crack closure techniques. Alternatively, one can use techniques that directly introduce the damage and fracture mechanism by adopting softening relationships between the tractions and separations, which in turn introduce a critical fracture energy that is also the energy required to break apart the interface surfaces. This technique called the cohesive zone modeling (CZM) is capable to predict both damage initiation and crack propagations in mixed mode conditions. In this method, the interface between two phases or materials can be represented by a special set of interface elements, and a CZM constitutive model can be used to characterize the mechanical behavior of interface [23].

Interface element constitutive model contain two softening model: Bilinear and exponential softening law. Both models can be used in commercial finite element code such as ANSYS to define the constitutive law for interface elements. The interface element constitutive model which is used in present work is the exponential softening law proposed by Xu and Needleman [24]. The exponential softening law model is represented in Eq. (1) which uses a surface potential as follows:

$$\phi(\delta) = e\sigma_{\max}\bar{\delta}_{\mathrm{n}}\left[1 - (1 + \Delta_{\mathrm{n}})e^{-\Delta_{\mathrm{n}}}e^{-\Delta_{\mathrm{t}}^2}\right] \tag{1}$$

where $\varphi(\delta)$ is a surface potential, $e = 2.7182818$, $\sigma_{\max}$ is the maximum normal traction at the interface, $\bar{\delta}_{\mathrm{n}}$ is the normal separation across the interface where the maximum normal traction is attained with $\delta t = 0$, $\bar{\delta}_{\mathrm{t}}$ is the shear separation where the maximum shear traction is attained at $\delta t = \frac{\sqrt{2}}{2}\bar{\delta}_{\mathrm{t}}$, $\Delta_{\mathrm{n}} = \frac{\delta_{\mathrm{n}}}{\bar{\delta}_{\mathrm{n}}}$, and $\Delta_{\mathrm{t}} = \frac{\delta_{\mathrm{t}}}{\bar{\delta}_{\mathrm{t}}}$. ($\delta_{\mathrm{n}}$ and δt are respectively normal and shear separation.)

The traction is defined as:

$$T = \frac{\partial\phi(\delta)}{\partial(\delta)} \tag{2}$$

or

$$T_{\mathrm{n}} = \frac{\partial\phi(\delta)}{\partial(\delta_{\mathrm{n}})} \tag{3}$$

and

$$T_{\mathrm{t}} = \frac{\partial\phi(\delta)}{\partial(\delta_{\mathrm{t}})} \tag{4}$$

Combining Eqs. (3) and (4) with (1), the interface normal and shear tractions are obtained as:

$$T_{\mathrm{n}} = e\sigma_{\max}\Delta_{\mathrm{n}}e^{-\Delta_{\mathrm{n}}}e^{-\Delta_{\mathrm{t}}^2} \tag{5}$$

$$T_{\mathrm{t}} = 2e\sigma_{\max}\frac{\bar{\delta}_{\mathrm{n}}}{\bar{\delta}_{\mathrm{t}}}\Delta_{\mathrm{t}}(1 + \Delta_{\mathrm{n}})e^{-\Delta_{\mathrm{n}}}e^{-\Delta_{\mathrm{t}}^2} \tag{6}$$

Then the normal traction work of separation is:

$$\phi_{\mathrm{n}} = e\sigma_{\max}\bar{\delta}_{\mathrm{n}} \tag{7}$$

and similarly the shear traction work of separation is defined as:

$$\phi_{\mathrm{t}} = \sqrt{2e}\tau_{\max}\bar{\delta}_{\mathrm{t}} \tag{8}$$

According to the mentioned formulation and obtained experimental data the interface element's material properties are elicited later in the next sections of the present work.