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Microstructural modeling of dual phase steel using a higher-order gradient plasticity–damage model

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ABSTRACT

This paper focuses on the application of a higher-order gradient-dependent plasticity–damage model for microstructural modeling of dual-phase (DP) steels. Damage evolution is governed by the evolution of a nonlocal plasticity measure which is a function of the local equivalent plastic strain rate and its corresponding first-order gradient. Different two-dimensional representative volume elements of the DP microstructure are virtually generated by varying the martensite phase volume fraction, distribution, and size, and volume fraction and size of dispersed hard inclusions. It is shown that the employed modeling framework is capable of addressing three main issues that are not considered by the current studies on microstructural modeling of advanced high strength steels (AHSS); finite element mesh-dependency, size effects, and additional hardening due to plastic strain gradients. It is concluded that based on the employed mechanical properties of each phase in the DP steel, strength and ductility is governed by damage evolution and not necessarily by plastic strain localization alone. Therefore, it is shown that including nonlocal damage evolution is critical for accurate prediction of the strength and ductility of DP steels. It is also shown that dispersing 5% volume fraction of hard inclusions in the DP steel optimizes both strength and ductility such that a new generation of AHSS might be attained.

1. Introduction

Advanced high strength steels (AHSS), such as dual-phase (DP) steel, are very important materials for the automotive industry because of their exceptional strength and ductility as compared to other conventional grades of steel. Therefore, the automotive industry continuously explores different manufacturing routes for improving the mechanical performance of DP steel. The desired mechanical behavior of the relatively cheap DP steel, which is the focus of the current paper, can be achieved by a combination of a hard martensitic phase (10–80%) dispersed within a soft ferrite matrix. The composition of the steel, the volume fraction, size, morphology, and distribution of martensite phase in the ferrite matrix as well as the grain size and boundary in the ferrite phase and ferrite/martensite interface are some of the main controlling parameters on the mechanical behavior of DP steels (e.g., Calcagnotto et al., 2011, 2010; Kang et al., 2011; Pierman et al., 2014).

In order to speed up the process of designing DP steels with simultaneous enhancements in strength and ductility, it is highly desirable to develop an accurate computational framework that can be used effectively in exploring the main microstructural features and deformation mechanisms that control the overall stress–strain behavior of DP steels. Despite the many recent attempts in the literature of predicting the overall stress–strain response of DP steel in terms of its microstructure (e.g., Al-Abbasi and Nemes, 2003a, 2003b; Choi et al., 2009b; Katani et al., 2013; Kim et al., 2010; Marvi-Mashhadi et al., 2012; Paul and Kumar, 2012; Ramazani et al., 2012a; Sodjit and Uthaisangsuk, 2012; Stewart et al., 2012; Sun et al., 2009a,b; Uthaisangsuk et al., 2011; Vajragupta et al., 2012), reasonable predictions of its strength and ductility remains a challenge for the development of microstructure-informed constitutive model. Therefore, the focus of this paper is on the development of computational framework for predicting the mechanical performance (overall stress–strain response) of DP steel through modeling the DP's microstructure using the virtually generated representative volume element (RVE) approach. Unlike the many studies that have used classical (local) plasticity/damage models for microstructural modeling of DP steels and other types of AHSS, a

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higher-order gradient-dependent plasticity and damage constitutive model is used in this paper for predicting the macroscopic behavior of DP steels using virtually generated RVEs. As detailed later, the higher-order gradient-dependent plasticity and damage models (e.g., Abu Al-Rub, 2008; Abu Al-Rub et al., 2007; Anand et al., 2012, 2005; Bardella, 2010; Fleck and Hutchinson, 2001; Gudmundson, 2004; Gurtin, 2000, 2003; Hutchinson, 2012; Kuroda and Tvergaard, 2010; Luscher et al., 2010; Polizzotto, 2011; Shizawa and Zbib, 1999; Voyiadjis and Faghihi, 2012) can eliminate the mesh-dependency problem when simulating plastic strain and damage localization within the microstructure of the DP steel. Also, it can take into consideration size and interfacial effects in DP steels due to varying the size of the martensite phase, the grain size of the ferrite phase, the size of embedded inclusions, the ferrite grain boundary effect, the ferrite–martensite interface effect, and the inclusion's interface effect. These aspects are rarely considered in the literature in modeling DP steel.

In the last decade, there has been an increasing interest in using microstructural computational models based on the RVE approach for exploring the salient microstructural features and constituent properties that can increase the mechanical performance of AHSS. Here, we only review the work that has been done on using the RVE approach for modeling DP steels. In a series of papers, Khaleel and co-workers (Choi et al., 2009b,c; Sun et al., 2009a,b) have predicted the macroscopic stress–strain response of DP steels based on simulating actual two-dimensional (2D) RVEs obtained from scanning electron microscope (SEM). Those authors have used classical (local) von Mises plasticity without considering damage evolution to simulate the response of the actual microstructure of different types of DP steel. Based on these simulations, the main conclusion was that the softening and failure of DP steels is governed by plastic strain localization and not void nucleation, growth, and coalescence. It is noteworthy that these studies have been motivated by the preliminary work of Al-Abbasi and Nemes (2003a,b, 2007, 2008) who conducted micromechanical simulations based on a unit-cell idealization of the DP microstructure assuming the martensite as a spherical inclusion embedded in the ferrite matrix. Later and inspired by the aforementioned work of Khaleel, many other researchers have used real microstructures to simulate the plastic flow behavior of DP steels (e.g., Chen et al., 2014; Choi et al., 2013; Kadkhodapour et al., 2011a; Kadkhodapour et al., 2011b; Katani et al., 2013; Kim et al., 2010; Marvi-Mashhadi et al., 2012; Paul, 2013; Paul and Kumar, 2012; Ramazani et al., 2012a,b; Ramazani et al., 2013; Sodjit and Uthaisangsuk, 2012; Uthaisangsuk et al., 2011, 2009; Vajragupta et al., 2012). In these works, the dislocation-based strain hardening model of Rodriguez and Gutierrez (2003) has been used for determining the behavior of the individual phases in the DP steel, where the dislocation generation, recovery, and recrystallization rates have been used to correlate the flow stress to the dislocation density.

However, all the aforementioned studies have adapted classical (local) plasticity theory or local plasticity–damage theory for conducting these micromechanical simulations. Also, unfortunately, none of the aforementioned studies that simulated the overall response of DP steels based on the microstructural RVE approach have solved the finite element method (FEM) mesh-dependency due to plastic strain localization and localized damage/failure. It is well-known by now that the application of local plasticity/damage constitutive relations for modeling localized plastic deformation and/or damage yields mesh-dependent results when using the FEM due to non-converged solution as the mesh is refined (e.g., Abu Al-Rub et al., 2010; Abu Al-Rub and Voyiadjis, 2005; Askes et al., 2000; de Borst, 1992; de Borst and Pamin, 1996; de Borst et al., 1993; Djoko et al., 2007). This is critical for the accurate prediction of ultimate strength and ductility of DP steels as by adapting the classical plasticity/damage continuum models the earliest onset of fracture is determined by the size of the finest FEM mesh such that the finer the discretization the lower the strength and ductility (Sanchez et al., 2008; Sun et al., 2009a). For example, in the study of Sun et al. (2009a) on microstructure-based modeling of DP steels, it was shown that adapting a coarse mesh at the ferrite grain boundaries, a strong stress–strain response is obtained as compared to the response from a finer mesh. The course mesh delays the onset of localization whereas the finer mesh accelerates the localization such that the failure occurs more rapidly with steeper post-critical slope in the stress–strain response. Similar mesh-dependency results have been reported by Vajragupta et al. (2012) in micromechanical modeling of DP steel's damage and fracture when using the extended finite element method.

Another issue with using the local plasticity/damage constitutive equations is their inability to capture size effects when size of microstructural features (e.g., ferrite grain size, inclusion/precipitate size, martensite phase size) is on the order of the material length scale. The local plasticity theory is also unable to describe the additional hardening due to presence of plastic strain gradients within the grain/phase interior and at the grain/phase boundaries, which is crucial in predicting the strength and ductility of AHSS. Strain gradient plasticity theory, specifically the higher-order gradient plasticity, has been successful in capturing various types of size effects and additional hardening due to plastic strain gradients (e.g., Abu Al-Rub, 2007, 2009; Aghababaei and Joshi, 2011; Aifantis and Willis, 2005; Anand et al., 2005; Bardella, 2010; Fredriksson and Gudmundson, 2005; Zhang and Aifantis, 2011). Although, those two main aspects are included in the constitutive model presented in the current paper, detailed simulations and investigations of the effects of these aspects on strength and ductility of DP steels will be the focus of future work.

The main novel objective of this paper is the use of the higher-order gradient-dependent plasticity–damage theory to overcome the aforementioned mesh-dependency and additional hardening in microstructural modeling of DP steel. To the authors' best knowledge, the use of higher gradient-dependent plasticity–damage theory for modeling DP steels has not been conducted before. A large and increasing number of gradient-dependent plasticity theories with various mathematical structures have been proposed until now (e.g., Abu Al-Rub and Voyiadjis, 2004, 2006; Aifantis, 1984, 1987; Anand et al., 2012; Bittencourt et al., 2003; Clayton et al., 2004; Fleck and Hutchinson, 2001; Fleck and Willis, 2009; Gao and Huang, 2001; Gudmundson, 2004; Gurtin, 2002, 2008; Kuroda and Tvergaard, 2010; Luscher et al., 2010; Niordson and Hutchinson, 2003; Voyiadjis and Deliktas, 2009). A critical overview of higher-order gradient plasticity theories as of 2004 was given by Gudmundson (2004). Recently, Hutchinson (2012) has provided a profound analysis of the basis of strain gradient plasticity. An elegant thermodynamic framework for formulating higher-order gradient plasticity theories, in which the principle of virtual power is the central theme, have been thoroughly discussed in the recent monograph of Gurtin et al. (2010) for small and large deformation problems and for polycrystalline and single crystal plasticity. In this paper, the higher-order gradient-dependent plasticity–damage model of Abu Al-Rub and Ettehad (2011), which is formulated using a thermodynamic framework, is used. This model, which also incorporates interfacial effects, is used for predicting the stress–strain response of DP (ferrite–martensite) steels based on virtually-generated two-dimensional microstructural-based RVEs. The effects of martensite volume fraction and the size and volume fraction of dispersed inclusions within the ferrite phase on the overall stress–strain response of DP steels have been investigated.

Notation: Hereafter, double vertical bars $\|\,\|$ denote the Euclidean norm of a tensor, the superimposed dot indicates the