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Influence of martensite volume fraction and hardness on the plastic behavior of dual-phase steels: Experiments and micromechanical modeling

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ABSTRACT

Model dual-phase microstructures were developed to decouple the effect of martensite volume fraction and martensite hardness on the plastic behavior of dual-phase steels. The martensite volume fraction ranges from 11% to 37%, involving two levels of martensite hardness. The yield strength and tensile strength increase with increasing martensite volume fraction, while the uniform elongation decreases. The martensite hardness has a weak impact on the initial yield strength, but it significantly affects the flow behavior for sufficiently large martensite volume fraction. Increasing the hardness of the martensite leads to higher tensile strength combined with only a limited impact on uniform elongation, resulting in an improved strength/ductility balance. The experimental results are successfully captured using finite element based micromechanical analysis. Among others, periodic cell calculations show very good predictive capabilities of the overall plastic response when the stage-IV hardening of the ferrite is taken into account. Our numerical analysis reveals that an accurate description of the elasto-plastic behavior of the martensite is a key element to rationalize the mechanical behavior of DP steels. This modeling approach provides a framework for designing dual-phase steels with optimized plastic flow properties.

1. Introduction

Weight reduction and crashworthiness improvement have been among the main targets of car manufacturers over the past decades (Bleck, 1996; Bouaziz et al., 2013), motivating the development of advanced high strength steels (AHSS) with

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improved performances. Among the grades of AHSS, ferrite–martensite dual-phase (DP) steels are increasingly used due to their attractive mechanical properties, such as a low yield/tensile strength ratio, continuous yielding and moderate strain hardening capacity (Bleck, 1996). The lean alloy content and the robust processing route add to the competitiveness of DP steels in automotive applications. Current research focuses on microstructure optimization for a better combination of strength and formability in order to extend their application range. As formability, which is characterized by the uniform strain and/or fracture strain, usually decreases with increasing strength, a proper trade-off between the two properties must be found depending on the requirements of each specific component.

Physics-based models that explicitly account for microstructure parameters are needed to guide the optimization of DP steels. However, the large number of microstructural parameters and the lack of knowledge on the precise role of each of them make a quantitative description of the structure–property relationship in DP steels challenging. In this context, it is also the role of a model to deliver fundamental understanding of the root causes of the different observations. For example, the role of martensite hardness on the mechanical behavior of DP steels has only received limited attention and remains unclear. In an early work based on measurements on a series of alloys, it was concluded (Davies, 1978) that the mechanical properties of DP steels depend on the volume fraction of martensite (V_m) but not on its composition or strength. In contrast, a recent study (Pierman et al., 2014) demonstrates the impact of the martensite carbon content (C_m) in fibrous DP steels involving various V_m. These contradictory results could be related to different levels of plastic deformation within the martensite (Pierman et al., 2014), see also Mazinani and Poole (2007). Hence the study of the specific response of martensite remains a key, not fully resolved issue. Detailed local strain measurements confirmed that the martensite may undergo plastic deformation, although its amplitude is significantly smaller than in the ferrite (Marteau et al., 2013), see also Han et al. (2013) and Tasan et al. (2014). The plastic responses of the phases were also investigated by in-situ synchrotron-based high-energy X-ray diffraction (HEXRD) (Sun et al., 2009) and in-situ neutron diffraction (Choi et al., 2013b; Woo et al., 2012). The constitutive response of the martensite was probed by nanoindentation (Delince et al., 2006; Ghassemi-Armaki et al., 2013) and compression tests on nanopillars (Ghassemi-Armaki et al., 2013).

Despite these recent advances in the characterization of the intrinsic phase behavior, a quantitative description of the effects of the microstructure parameters on the mechanical properties of DP steels remains elusive. A key experimental difficulty stems from the fact that several microstructural parameters are interrelated. The first original element of the present work is to develop model steel microstructures in order to experimentally decouple the effects of martensite volume fraction and martensite hardness, based on the evolution of microstructure and austenite composition during intercritical annealing. A stable spheroidized microstructure is used as initial material state for subsequent heat treatment. For certain temperature, annealing the spheroidized microstructure for different durations is found to lead to different V_m with similar martensite hardness. Annealing performed at two different temperatures leads to dual-phase microstructures with the same morphology and identical martensite volume fraction but with different levels of martensite hardness.

A micromechanical model explicitly accounting for the volume fraction and properties of the phases is needed to rationalize the experimental findings, as well as to guide microstructure optimization. Several micromechanical approaches have been proposed in the context of DP steels, with various degrees of accuracy and complexity. Nonlinear mean-field homogenization models, see general references by Doghri and Ouaar (2003), Tekoglu and Pardoen (2009), Brassart et al. (2012) and Lahellec and Suquet (2013), and application to DP steels by Delince et al. (2007), Mazinani and Poole (2007), Perdahcioglu and Geijselaers (2011) and Pierman et al. (2014), have the advantage of low computational cost. Nevertheless, they remain partly deficient to accurately deal with materials involving large contrast in strength and large volume fractions of particles and to capture complex effects related to microstructure heterogeneity. On the other hand, finite element (FE) analysis on representative microstructure volume elements can provide a detailed description of the microfields within the phases (Choi et al., 2013b; Marvi-Mashhadi et al., 2012; Paul and Kumar, 2012; Sun et al., 2009; Uthaisangsuk et al., 2010). For instance, Sun et al. (2009) performed FE analysis on 2D realistic microstructures extracted from SEM images in order to reproduce the tensile response of DP steels as well as the local damage and failure modes. Ramazani et al. (2013) adopted a similar approach to investigate the effect of transformation-induced geometrically necessary dislocations (GNDs) on the stress-strain response. Compared to the approaches on realistic microstructures, FE solutions on simple microstructures (unit cells) are computationally much cheaper, allowing comprehensive optimization analysis but at the expense of a simplified description of the heterogeneities of the flow field. Simple axisymmetric or 2D unit cell models with periodic conditions can capture to first order the effect of reinforcement volume fraction, shape and distribution (Al-Abbasi and Nemes, 2003, 2007; Bao et al., 1991; Christman et al., 1989; Huper et al., 1999), and, if needed, additional effects like phase transformation (Kadkhodapour et al., 2011b) and/or strain gradient plasticity contributions (Mazzoni-Leduc et al., 2008).

The second key element of this work is to show that the use of a basic FE micromechanical model relying on an axisymmetric unit cell is sufficient to capture the elastoplastic response of model DP steels up to moderately large strain, when playing with the martensite volume fraction and hardness. An essential ingredient to get accurate results is the use of a Voce law involving stage-IV hardening for modeling the response of the ferrite. The influence of C content is considered in the constitutive response of the martensite, with direct impact on martensite hardness. A parametric study is conducted to investigate the effects of the microstructure parameters on the strength and ductility of the DP steels, revealing that an accurate description of the elasto-plastic behavior of the martensite is a key element to rationalize the mechanical behavior of DP steels.