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Microscale-calibrated modeling of the deformation response of dual-phase steels

Peng Chen [a], Hassan Ghassemi-Armaki [a], Sharvan Kumar [a], Allan Bower [a,*], Shrikant Bhat [b], Sriram Sadagopan [b]

[a] *School of Engineering, Brown University, Providence, RI 02912, USA*
[b] *ArcelorMittal, Global R&D – East Chicago, East Chicago, IN 46312, USA*

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Abstract

A combination of micropillar compression tests and microstructure-based numerical simulations were used to determine the flow strength and strain rate partitioning in uniaxial tension in two commercial low-carbon dual-phase sheet steels, DP980 (0.09% C–2.15% Mn–0.60% Si (wt.%)) and DF140T (0.15% C–1.45% Mn–0.30% Si (wt.%)). The two steels have different microstructures, with the martensite volume fraction in DP980 being ∼60%, compared to ∼40% in DF140T. Nevertheless, they exhibit similar uniaxial stress–strain behavior. To determine the microstructural origin of this behavior, micropillar compression specimens from ferrite and martensitic phases in both steels were deformed in uniaxial compression to obtain their individual response. A microstructure-based crystal plasticity model that accounts for non-Schmid behavior in the ferrite phase and contains a detailed description of the hierarchical microstructure of martensite was developed and material parameters were determined by fitting model predictions to the micropillar compression data. The crystal plasticity model was then used to predict the flow stress and strain rate partitioning during uniaxial tensile deformation of the two steels. The ferrite phase in the two steels was found to have similar flow strength. In contrast, the flow stress of martensite in DF140T was found to be approximately twice that in DP980. This strength difference is offset by the difference in martensite volume fraction in the two steels, resulting in nearly identical uniaxial tensile behavior. The strain rate partitioning and interfacial stress distributions in the two steels differ significantly, however, and have important implications on their tensile ductility.

Keywords: Martensite; Ferrite; Mechanical properties testing; Crystal plasticity; Finite element modeling

1. Introduction

Dual-phase sheet steels have a remarkable combination of strength and ductility. They are particularly widely used in automotive applications such as bumper reinforcement beams, door intrusion beams, seating components and structural cross members. The unusual properties of dual-phase steels can be attributed to their complex and highly heterogeneous microstructure, composed of a hard martensite phase dispersed within a soft ferrite matrix [1–3]. This complexity can be exploited to engineer steels with a wide range of properties, including high tensile-to-yield strength ratio, continuous yielding, high work hardening rate and good ductility. The overall mechanical properties of dual-phase steels depend not only on the individual properties of ferrite and martensite, but also on the microstructural characteristics such as the ferrite grain size, volume fraction and morphology of martensite [4,5]. The strength of ferrite in general is determined by its composition, grain size and initial dislocation density, while the strength of martensite depends primarily on its carbon content. The yield strength of martensite increases with its carbon content. Finer ferritic grain size, higher carbon content in martensite and higher volume fraction of martensite principally increase the strength of dual-phase steels.

* Corresponding author.
E-mail address: Allan_Bower@Brown.EDU (A. Bower).

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However, this increase in strength is usually achieved at the expense of lower ductility [5].

In automotive applications, to reduce cycle time, part-forming feasibility analyses are often carried out through finite element analysis-based virtual simulation techniques. While conventional constitutive models based on macroscopic standard stress–strain curves of steels often serve as inputs, much research effort is being spent on investigating the details of deformation behavior of multi-phase steels via experimental, analytical and simulation techniques to understand the influence of different microstructural length scales on deformation behavior. In this regard, a fundamental understanding of the properties and underlying deformation mechanisms in the individual phases of dual-phase steels, and the ability to predict quantitatively the macroscopic flow behavior and formability of a complex dual-phase microstructure, is expected to pave the way for better prediction of forming behavior under complex loading paths of practical interest. They may also serve as inputs for future development of steels with enhanced strength and ductility. The mechanical behavior of individual phases of dual-phase steels has been evaluated by using nanohardness or ultramicrohardness [6,7], in situ neutron diffraction [8] or in situ high-energy X-ray diffraction techniques [9–11]. Hardness measurements require a very small indentation contact area, and so are susceptible to indentation size effects. In addition, it is difficult to ensure that the material being indented is homogeneous below the indenter. In neutron diffraction, it is difficult to separate the ferrite and martensite diffraction peaks due to the similar body-centered cubic (bcc) and body-centered tetragonal crystal structures in ferrite and martensite. It has recently been shown that high-energy X-ray diffraction has the capability of separating (200) and (211) diffraction peaks for the ferrite and martensite phases, but diffraction measurements can only measure the average lattice strain in the ferrite and martensite as a function of macroscopic stress, so extracting the mechanical response of the individual phases is difficult. Recently, an alternative to these approaches has been developed in which microscale specimens are extracted directly from the microstructure and their load–displacement relation is subsequently determined using a nanoindenter. For example, Stewart et al. [12] have used this micropillar compression technique to measure the constituent behavior of dual-phase steels, while Ghassemi-Armaki et al. [13,14] have measured the mechanical response of individual martensite micropillars (composed of blocks and packets) extracted from a fully martensitic steel and, more recently, of ferrite and martensite microconstituents in a dual-phase steel.

Numerical simulations provide a more detailed picture of the partitioning of strain, strain rate and stress within a microstructure, and of the roles of microstructural features in controlling macroscopic material behavior. The simplest such models use a 2-D idealization of the microstructure, together with a phenomenological isotropic J_2 flow rule and isotropic Ludwik hardening law to investigate the flow and failure behaviors of dual-phase steels [5,15]. These models have predicted conditions to initiate shear localization in representative microstructures that are in good agreement with experiment. More sophisticated models use a crystal plasticity model based on Schmid's law to characterize the phases [6,16]. These generally model a ferritic microstructure using rate-dependent single crystal plasticity and model the martensitic phase using either crystal plasticity [11,16] or an isotropic hardening J_2 flow model [6]. Most recently, the effect of crystallographic orientation on the microscale flow behavior and plastic localization of dual-phase steel has been investigated using a 2-D crystal plasticity model [17]. Determining the properties of the individual phases in a complex microstructure is critical to obtaining accurate predictions of its macroscopic behavior. A common approach has been to fit parameters to match lattice strain measurements obtained using X-ray or neutron diffraction measurements [11,16,17], or to select a parameter so as to fit the macroscopic flow behavior [6]. The ability of micropillar experiments to determine the properties of the phases directly significantly improves the accuracy of microstructure-based simulations. Micropillar-calibrated constitutive models have been shown to predict the macroscopic tensile flow curves of fully martensitic steel correctly [13].

In this paper, our objective is to use a combination of micropillar compression tests and numerical simulations to study the flow and hardening behavior of two dual-phase steels, DF140T and DP980, with nominally similar tensile strength levels. The two steels have significantly different microstructures: for example, the martensite volume fraction in DP980 is approximately 50% greater than that in DF140T. Surprisingly, despite this difference, they have nearly identical uniaxial tensile stress–strain behavior. To explain these observations, the properties of the individual phases in both steels were measured by extracting microscale pillars from a bulk sample (using focused ion-beam milling), and then deforming the pillars using a flat-punch nanoindenter to determine their response to uniaxial compression. (Experimental details and validation of the approach for DF140T are presented elsewhere [14].) The experimental data were then used to determine material parameters in crystal-plasticity-based constitutive equations for the ferrite and martensite phases in the steels. Based on these measurements, a 3-D computational model was created of each dual-phase steel microstructure and subjected to loading representing uniaxial tension.

This combination of experiments and computations predicts the uniaxial behavior of both steels accurately. In addition, it provides a number of insights into the microstructural origin of their tensile behavior. In particular, the martensite phase in DF140T is found to have a compressive strength approximately twice that of martensite in DP980. This strength difference is offset by the different volume fractions of martensite in the two steels, explaining how they exhibit nearly identical tensile flow strength. In addition, our results show that the ferrite micropillars