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Deformation response of ferrite and martensite in a dual-phase steel

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Abstract

Deformation response of ferrite and martensite in a commercially produced dual-phase sheet steel with a nominal composition of 0.15% C–1.45% Mn–0.30% Si (wt.%) was characterized by nanoindentation and uniaxial compression of focused ion beam-milled cylindrical micropillars (1–2 μm diameter). These experiments were conducted on as-received and pre-strained specimens. The average nanoindentation hardness of ferrite was found to increase from ~2 GPa in the as-received condition to ~3.5 GPa in the specimen that had been pre-strained to 7% plastic tensile strain. Hardness of ferrite in the as-received condition was inhomogeneous: ferrite adjacent to ferrite/martensite interface was ~20% harder than that in the interior, a feature also captured by micropillar compression experiments. Hardness variation in ferrite was reversed in samples pre-strained to 7% strain. Martensite in the as-received condition and after 5% pre-strain exhibited large scatter in nanoindentation hardness; however, micropillar compression results on the as-received and previously deformed steel specimens demonstrated that the martensite phase in this steel was amenable to plastic deformation and rapid work hardening in the early stages of deformation. The observed microscopic deformation characteristics of the constituent phases are used to explain the macroscopic tensile deformation response of the dual-phase steel.

Keywords: Dual-phase steel; Mechanical behavior; Nanoindentation; Micropillar compression; Electron microscopy

1. Introduction

Dual-phase sheet steels find widespread use in the automotive sector for structural applications. Their high strength-to-weight ratio, low yield-to-ultimate strength ratio combined with a high initial work hardening rate and good formability make them particularly suited for these applications. These steels in the fully heat-treated condition are composed of ferrite and martensite, but sometimes can include ferrite and cementite with a bainitic morphology as well. In this paper, we limit the discussion to dual-phase steels composed of martensite and ferrite as they constitute the most relevant microstructure. The fraction of the hard martensite phase embedded in the softer ferrite phase ranges anywhere from 10 to >50 vol.% [1–5]. The specific steel grade investigated falls in the general category of 980DP steels, which are often used in automotive bumper applications.

The uniaxial tensile deformation response of these steels has been extensively studied over the past two or three decades; a general picture that emerges from these studies is that there exists an initial deviation from Hooke's law, signifying that the elastic limit is followed by continuous yielding and a high strain hardening rate, before a second change to a shallower work hardening rate occurs, which eventually leads to an ultimate tensile strength, neck formation and final fracture. The exact stress and strain levels at which these events occur are dependent on the composition of the steel, the volume fraction of the coexisting phases, their relative sizes, their distribution and their morphology [6–12]. Although the initial yielding is associated

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with the plastic deformation of ferrite, the stress and strain for the initial onset of plastic flow in martensite and the subsequent partitioning of plastic strain between the two phases as global deformation ensues have been points of discussion, debate and ongoing research [13–19].

The austenite–martensite transformation in these dual-phase steels is accompanied by a 2–4 vol.% change that is instrumental in generating residual stresses in the ferrite as well as producing geometrically necessary dislocations in the ferrite close to the ferrite/martensite interface [5,20,21]. Such geometrically necessary dislocations (GNDs) have been observed by transmission electron microscopy (TEM) and quantified by high-resolution electron backscattered diffraction (EBSD). The residual stresses are thought to be responsible for enhancing plastic flow in ferrite and for lowering the elastic limit, while the unpinned GNDs are thought to contribute to the continuous initial yielding as well as the observed initial strain hardening rate [5,22].

Recent advances in mechanical testing techniques at the microscale, including nanoindentation and micro- and nanopillar compression testing, have made it possible to ascertain properties of micron- and sub-micron-size single crystal regions/specimens of many metals and alloys. Numerous research articles and exhaustive reviews of advances in the field that also describe benefits and shortcomings of the testing techniques and their future potential are available, a few of which are cited here [23–34]. These techniques can also be applied to characterize the mechanical response of micron-scale individual phases in multiphase alloys.

Nanoindentation enables probing the mechanical response of individual phases in the size range between 1 and 10 μm in a multiphase alloy. The challenge lies in converting the obtained load–displacement data into a stress–strain curve (particularly in the plastic regime) that could form the input for computations or for making scientific connection with the global response of the alloy that is usually in the form of stress–strain curves. Several attempts have been made to extract portions of the plastic tensile stress–strain curve from nanoindentation data [24,26–28,35,36], but debate continues about the validity of such approaches. Choi et al. [26] attempted to predict the macroscopic plastic deformation response of a dual-phase steel from nanoindentation response of the constituent phases using two spherical indenter tips, while Delincé and coworkers [25] used different nanoindentation depths to isolate strengthening mechanisms in a dual-phase steel composed of ferrite and martensite. Recently, Kadkhodapour et al. [5] have used nanoindentation to probe the presence of GNDs in ferrite in the vicinity of the ferrite/martensite interface in a dual-phase steel. Nanoindentation has also been used to isolate the role of microstructure on lath martensite strength, and it was concluded from such studies that block boundaries are important in strengthening Fe–C martensite [37–39].

Uniaxial compression of micropillars machined using a focused ion beam (FIB) is another technique that can be used to assess mechanical properties in small volumes. Numerous studies have been performed on a wide range of materials using this technique; many metallic and ceramic materials, and especially those in which plastic deformation occurs by crystallographic slip, have been reported to exhibit a strong size effect in strength for sample sizes in the range between several microns and tens of nanometers [29–33,40–46]. In single crystalline face-centered cubic metals, this size effect has been attributed to dislocation source truncation, exhaustion hardening, source-driven plasticity and dislocation starvation [29–32]. Body-centered cubic (bcc) metals also exhibit size effects, which are unique to each individual material because of the more complex dislocation mobility in these metals [42–46].

The micropillar approach has been adopted for examining the mechanical response of a low-carbon martensite and has demonstrated that, while a single martensite block may exhibit elastic–perfectly plastic behavior, the presence of boundaries in the form of blocks and packets leads to significant hardening [47]. Stewart et al. [48] used similar micropillar compression tests to document the deformation behavior of constituent phases in a dual-phase stainless steel produced by powder metallurgy, and the results were utilized in a rule-of-mixture-type model after correcting for porosity to predict the ultimate tensile strength of the steel. The influence of crystallographic orientation on yield stress and subsequent hardening was not isolated, nor was post-deformation microstructure analyzed to ensure that the micropillars were single phase throughout their height.

In this work, we conducted nanoindentation and micropillar compression experiments to obtain the micromechanical response of the individual ferrite and martensite phases in a 0.15 wt.% C dual-phase sheet steel in the as-received condition. Macroscopic uniaxial tensile tests were performed using dog-bone geometry specimens excised from the sheet to obtain the overall stress–strain response. Tensile tests were performed to various strains along the stress–strain curve and unloaded. Micropillars were excised from the ferrite and martensite phases in these interrupted test specimens to understand how the global deformation influenced the properties of the individual phases. The microstructures of deformed micropillars were analyzed via TEM. The mechanical data and microstructural evolution obtained served to interpret the deformation response of the dual-phase steel. Plastic deformation and rapid hardening of martensite are recognized and their contribution to the deformation response of the dual-phase steel is considered.

2. Experimental procedure

The material examined in this study is a dual-phase sheet steel with a thickness of 2 mm and a nominal