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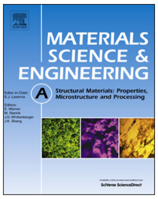

Realistic microstructural RVE-based simulations of stress–strain behavior of a dual-phase steel having high martensite volume fraction

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ABSTRACT

Micro-mechanical behavior of a low carbon, high-strength (980 MPa grade) dual-phase (DP) steel of current technological interest that contains high volume fraction of martensite is simulated and uniaxial stress–strain curve is computed. Polygon-based vectorized microstructural images obtained via a new image analysis procedure are used for simulations of the micro-mechanical behavior. Simulations are performed using physics-based constitutive relationships for martensite and ferrite constituents and generalized plane-strain mesh elements. It is shown that there are significant variations in the computed stress–strain curve from one microstructural field of view to another for microstructural windows of 110 μm × 110 μm size or less. A random statistical sample of 10 microstructural windows of 110 μm × 110 μm size or larger constitutes a RVE of this class of microstructures such that the simulated stress–strain curves of such RVEs are in close agreement with one another, and therefore, represent the global stress–strain response of the simulated material. For the constitutive equations, boundary conditions, and type of mesh elements used in the present work, such average simulated stress–strain curves are also in close agreement with the experimentally measured uniaxial stress–strain curve of the DP980 steel. It is also shown that in this dual-phase microstructure, martensite carries most of the stress whereas most of the strain is contained in ferrite. Consequently, the strain localization and failure is predicted to go preferentially through ferrite compared to martensite, which is in agreement with experimental quantitative fractographic observations reported elsewhere.

1. Introduction

In response to automotive industry push for cost effective material solutions for reducing weight, steel industry has developed many steel grades often termed Advanced High Strength Sheet Steels (AHSS) [1]. Low-alloy Dual-phase (DP) steels are a group of AHSS with excellent formability (absence of sharp yield point, high work hardening rate, and low yield ratio), as well as good weldability. Today, many varieties of DP steels with tailor made attributes and tensile strength levels from 600 MPa to 1200 MPa with or without sacrificial corrosion resistance coatings can be commercially obtained.

Notwithstanding the significant advances made in virtual design and computer simulation of sheet steel forming in recent years, predicting and controlling exact shapes, wrinkling, springback, sheared edge fracture, etc. are often challenges in complex automotive parts, especially when using AHSS. There have been numerous experimental investigations on the deformation and fracture behavior of DP steels [2–7] and analytical models have been proposed for predictions of some aspects of the microstructure-properties relationships in these DP steels [8–12], but they are not sufficiently advanced for accurate quantitative predictions of complex multivariate dependence of mechanical properties of commercial DP steels along many strain paths used in industrial applications. Therefore, realistic microstructure-based computational modeling of the mechanical behavior of DP steels is of particular interest.

Computational modeling and simulations of the stress–strain behavior of DP steels involve implementation of the binary digital vectorized images of microstructural fields of view (FOV) in the finite elements (FE)-based simulations. Many of the earlier investigations [13–19] typically used simulations of micro-mechanical response and stress–strain curves based on one or two microstructural FOVs of relatively small size (typically, 50 μm × 50 μm size) that do not necessarily constitute a sufficiently large statistical sample of the stochastic microstructure of a dual-phase steel that can be regarded as *statistical* representative volume element

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(RVE) of the global microstructure[1]. In addition, most of earlier investigations do not report the effects of type of mesh elements associated with different stress/strain constraints (for example, plane-stress vs. plane-strain conditions) on simulated stress–strain curves.

The focus of the present investigation is on the simulation of the uniaxial stress–strain behavior of a low carbon commercial DP steel of 1000 MPa tensile strength level. Digital vectorized microstructural images are implemented in the FE-based simulations using a new digital image processing route that eliminates "staircase" type geometry of interfaces in the standard digitized binary microstructural images. The constitutive equations of the ferrite and tempered martensite have been extracted from the available literature rather than using a numerical fitting process often used in the earlier FE-based simulations. The simulations of stress–strain behavior have been performed on 20 systematic random microstructural fields of view (FOV) of 110 μm × 110 μm size. It is shown that for the same boundary conditions and constitutive equations of the microstructural phases, there are substantial variations in the simulated stress–strain curves from one FOV to another indicating that a single random FOV of microstructure cannot be regarded as statistically representative segment of the DP steel microstructure. Nevertheless, it is shown that a collection of 10 such random FOVs does constitute a representative volume element (RVE) for this DP steel. It is also shown that the simulated stress–strain curves vary substantially with the type of mesh elements used in the FE simulations, and therefore, attention must be given to these details for simulating stress–strain behavior.

2. Experimental

The primary focus of the present study is on numerical simulation; the experimental data were extracted from an earlier study [20]. Briefly, the experiments were performed on a DP980 steel produced commercially on a water quenched continuous anneal line with a nominal composition of 0.1 wt% C, 2.0 wt% Mn, and 0.5 wt% Si. The tensile test specimens (JIS5 geometry) were cut along the transverse direction of the coil. Tensile tests were performed at room temperature in a displacement control mode at the strain rate of 10^{-4} per second.

For microstructure characterization, a metallographic section of planar orientation (i.e., a plane containing rolling direction and transverse direction of the coil) was mounted and polished using standard metallographic techniques. Two step etching procedure was used to clearly reveal martensite and ferrite phases: the specimens were first etched with 3% nital solution for 5 s followed by etching with 10% aqueous sodium metabisulphite solution for 28 s. Fig. 1 depicts the microstructure of a planar metallographic section revealed in this manner.

Volume fraction of martensite estimated using standard stereological techniques [21] is 62.5 ± 2.5%, and therefore, martensite may be considered the topologically continuous phase. Binary raster microstructural images were converted to vectorized images using a new image processing technique described in the next section.

3. Digital image processing

Two-dimensional [22,23] as well as reconstructed three-dimensional [24] microstructural images are being used as microstructure models for FE-based simulations of micromechanical behavior for more than a decade. The image processing algorithms used for such applications have evolved considerably in the past decade and they vary with the image modality, geometry of the microstructure, and the size of FE mesh elements compared to the binary image pixel/voxel size. Although FE mesh can be automatically generated from a binary digital microstructural image using software like OOF [25], such a mesh may not closely conform to the real microstructural interfaces due to the inherent "stair-case" nature of the binary pixel images, which can be particularly problematic if the pixel size is on the order of or larger than the mesh size. Numerous boundary smoothing algorithms have been proposed to address the issue of jagged digital boundaries in the binary microstructural images. These algorithms require explicit description of microstructural interfaces [26–29], which can be difficult. Recently, Kim and coworkers [16] have proposed a technique for generation of smooth continuous interface boundaries from a binary pixel image via the application of a continuous phase function comprising of a combination of interpolation functions of specific functional forms. However, as FE mesh elements are discrete and polygonal (polyhedral in 3D), advantage of using mathematically smooth interfaces in the vectorized microstructural images is not clear.

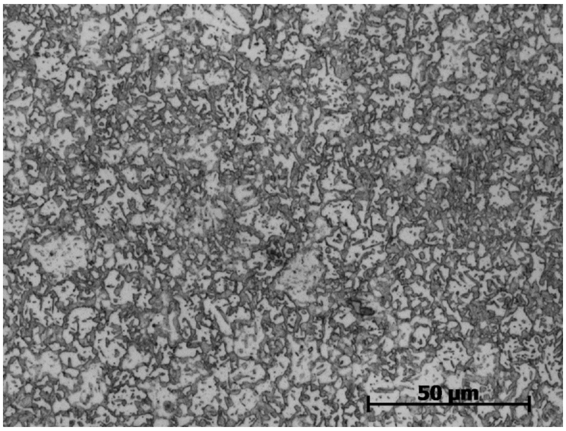

Fig. 1. Microstructure of DP980 steel observed in a planar metallographic section. Dark phase is tempered martensite, whereas the bright regions are ferrite.

In the present contribution, a different approach is used where the interface boundary contours are represented by a set of straight line segments that form polygons. The algorithm is illustrated in Fig. 2. The polygonizing algorithm treats each pixel of the ferrite (bright phase in the digital images) perimeter as a square region and starts out at the "first" pixel (topmost, and leftmost among them if there is more than one topmost) and proceeds counterclockwise including within the group all pixels found until it finds a "non-collinear" pixel[2]. The group ends with the pixel just before the first "non-collinear" pixel, and the search is reset, now considering the "non-collinear" pixel as the first. When all perimeter pixels have been visited, the search ends and line segments drawn from the coordinates describing the last pixel of a group to those describing the last pixel of the next group comprise the polygon. The polygons generated in this manner are not necessarily convex. Fig. 3(b) illustrates the polygon-based vectorized image obtained from a binary raster image of microstructure shown in Fig. 3(a). Observe that the polygons in Fig. 3(b) contain straight line segments of a wide range of orientations as opposed to traditional vector images where

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[1] In the present context, RVE size is the smallest random statistical sample of microstructure such that all samples of that size (or larger size) drawn from the bulk microstructure yield identical simulated stress-strain curves for the same boundary conditions and constitutive equations.

[2] In the present context, a non-collinear pixel is a pixel such that no line segment drawn from a point within the first pixel to a point within the one just found would pass through all of pixels found so far in the order they were found in.