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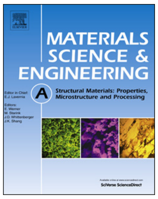

Short communication

Fracture initiation in multi-phase materials: A statistical characterization of microstructural damage sites

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ABSTRACT

Understanding the microstructural influence on the failure mechanisms in multi-phase materials calls for the identification of the worst-case scenario. This necessitates a statistical approach. By performing simulations directly based on micrographs, such an approach becomes feasible. This is applied here to extract the average microstructure around damage sites.

1. Introduction

Multi-phase materials present an attractive blend of ductility and strength by combining two or more phases in the microstructure. The distinct mechanical properties of the phases have a strong influence on the plastic response up to failure [1–3]. However, the phase *distribution* is one of the key drivers governing damage [4–6].

The role of the microstructure is not easily identified as it calls for the transparent and objective identification of the worst-case configuration. Micrographs of the material's cross-section or its fracture surface [7–9] are often restricted to snapshots prior to failure and require extensive expert interpretation. On the other hand, simulations are often limited to simplified microstructures with isolated observations [10,11], because their computational costs prohibit a statistically representative analysis. Idealized models [12,13] do allow a statistical treatment, but the approximation due to the idealization cannot easily be quantified.

This paper overcomes some of these obstacles by performing a statistical analysis using simulations that are directly based on a series of micrographs. The goal of this paper is two-fold. First, it is demonstrated that by employing an advanced FFT-based solver, computations on true microstructures become sufficiently efficient to render the proposed statistical approach feasible. Second, the average microstructure around damage initiation sites is characterized qualitatively and quantitatively.

We consider a two-phase microstructure, represented by an ensemble of 100 thresholded micrographs of a dual-phase steel microstructure in which martensite and ferrite are identified, considered simply as hard and soft as described in Section 2 together with the mechanical model. Sections 3 and 4 present the computed macroscopic and microscopic responses. Section 5 performs the statistical analysis by quantification of the average probability of hard phase around damage, followed with a discussion on how this insight can be used to screen microstructures for regions that may be suspected to develop damage, in Section 6. This paper ends with concluding remarks and an outlook in Section 7.

2. Microstructural model

The microstructure is modeled using an ensemble of 100 two-dimensional volume elements, each acquired from a micrograph of a commercial dual-phase steel. A protocol of grinding, polishing, and etching creates a small height difference between the hard and the soft phase. Two detectors of the scanning electron microscope are used simultaneously to image the spatial distribution of the phases. The secondary electron (SE) detector provides contrast due to the height difference (e.g. Fig. 1(a)) and the backscatter electron (BSE) detector due to the different crystal lattice of

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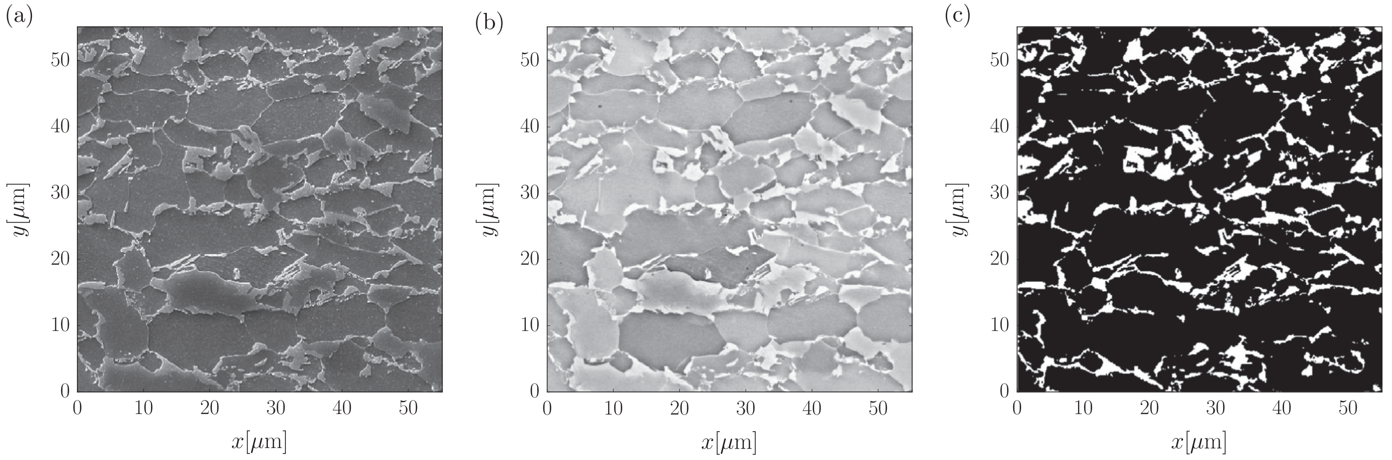

Fig. 1. Typical micrographs acquired with the (a) SE detector and (b) BSE detector; (c) segmented weighted average. In each image the martensite is brighter than the ferrite. The resolution is 451 × 451 pixels.

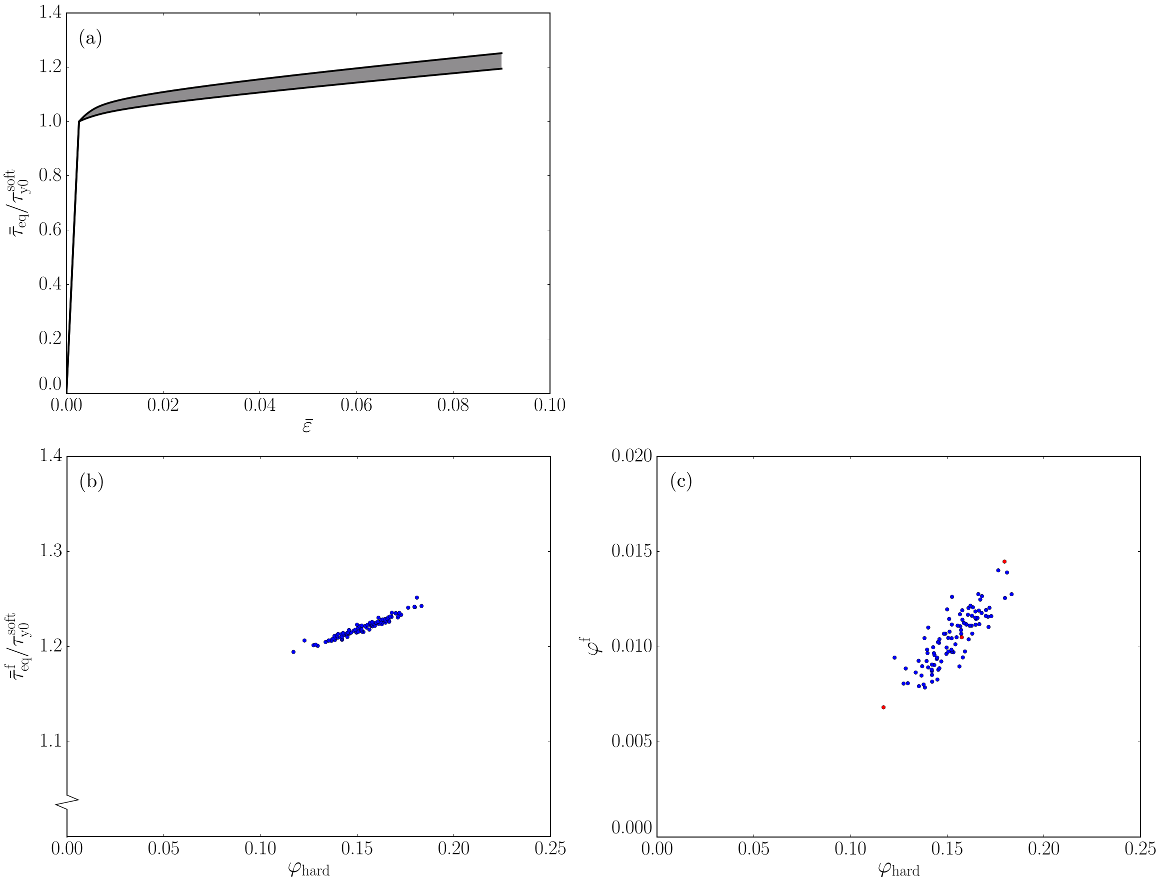

Fig. 2. (a) Statistical range of macroscopic equivalent stress responses, $\bar{\tau}_{eq}$, as a function of the applied equivalent strain $\bar{\varepsilon}$. Correlation between the hard phase volume fraction φ_{hard} and (b) the equivalent stress at the final increment, $\bar{\tau}_{eq}^{f}$ and (c) the "void" volume fraction φ^{f} both for $\bar{\varepsilon} = 0.09$.

the phases (e.g. Fig. 1(b)). The phases are identified from a weighted average of the two images. The weight is optimized to obtain a maximally separable image according to Otsu's method [14]. A typical result is shown in Fig. 1(c), wherein the hard phase is white and the soft phase is black.

Both phases are modeled isotropic elasto-plastic using the finite strain model as proposed by Simo [15]. This model involves a linear relation between the logarithmic elastic strain and the Kirchhoff stress $\boldsymbol{\tau}$ which is parametrized using Young's modulus E and Poisson's ratio ν. The elastic domain is bounded by a yield criterion, wherein the yield stress hardens linearly with the accumulated plastic strain ε_p beyond an initial value τ_{y0}. The two phases are assumed elastically homogeneous and differ only in terms of their plastic response. The parameters are taken in a regime that is relevant for the dual-phase steel that has been imaged [11,16]:

$$\tau_{y0}^{hard} = 2\tau_{y0}^{soft} = 0.006\,E \quad H^{hard} = 2H^{soft} = 0.008\,E \quad \nu = 0.3 \tag{1}$$

The soft phase fails in a ductile manner, while the hard phase is assumed not to fail. A damage descriptor D is used to track the material degradation, but it does not weaken the material. It is