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Mechanisms of void formation during tensile testing in a commercial, dual-phase steel

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Abstract

A detailed analysis of the microstructure and failure mechanism of a dual-phase steel material as a function of strain was conducted. Accordingly, three tensile tests were performed and interrupted at different strain levels in order to investigate void nucleation, void growth and void coalescence. Scanning electron microscopy analysis revealed that void nucleation occurs by ferrite grain-boundary decohesion in the neighborhood of martensite grains. Further, void initiation could be observed between closely situated martensite grains. Martensite morphology and distribution has a significant impact on the accumulation of damage. The mechanism of failure was found to be influenced by deformation localization due to microstructural inhomogeneity. Based on the experimental observations and simulation results, a model describing the failure mechanism is proposed for dual-phase steel material.

Keywords: Dual-phase (DP) steel; Failure mechanism; Tensile test; Void initiation; Martensite shape effect

1. Introduction

1.1. Motivation for using dual-phase steel

In modern transportation engineering, the application of lightweight components is a central challenge. For economic and ecological reasons, as well as improving product properties, a reduction in mass is desired. This involves input from different engineering disciplines. Thus, lightweight construction can be considered as an integrative technique using all available means from the fields of design, materials science and manufacturing so as to reduce the mass of a whole structure and its individual elements while at the same time enhancing its functional quality [1].

Enhancing the strength of a material without decreasing the fracture strain is a design goal in modifying the microstructure of material. In terms of steel materials, the class of dual-phase steels is very interesting for lightweight constructions because it combines a high ultimate strength with a high fracture strain. DP800 steels with an ultimate strength of 800 MPa and a nominal fracture strain of approximately 20% are currently available. Other advantages of this material are its low yield strength, high hardening ratio and the absence of discontinuous yielding. Therefore, dual-phase steel sheets are well suited for forming and deep-drawing processes.

The above-mentioned useful material properties of dual-phase steels are derived from their microstructure, which consists of a ferritic matrix with a second phase of martensite arranged in between the ferrite grains. A small amount of bainite and retained austenite may also exist in the microstructure [2]. Depending on the production process, the volume fraction, size and shape of the martensite phase can vary, but the basic principle that a hard and more brittle martensite phase is arranged within a soft and more ductile ferrite phase is typical for dual-phase steels.

In the literature two main approaches can be identified to account for the damage behavior of dual-phase steels. The first one [3–8] considers the classical ductile damage

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mechanism of failure (void initiation, void growth and void coalescence), while the second one discusses local shear banding and localization on the microscale as the dominant failure mechanism [9–17].

1.2. Void nucleation due to ductile damage

In many studies the ductile failure model is used to explain the experimentally observed damage behavior of dual-phase steels. The void initiation mechanism is a matter of particular interest in this model. Depending on the particular dual-phase steel material being analyzed, different mechanisms for void initiation have been observed.

Some researchers consider the martensite grains to be the site of the void initiation. The brittleness of the martensite phase in the microstructure of dual-phase steels is likely to promote damage. Many investigators [18–26] have observed that void formation arises from both martensite particle fracture and interface decohesion. Kang and Kwon [27] studied the fracture behavior of intercritically treated structures in medium-carbon steels and observed that the ferrite–martensite interface decohesion was the predominant mode of void nucleation and growth, where martensite structure was the lath type. Others [28–32] have reported that void formation occurs only due to martensite–ferrite interface decohesion. Szewczyk and Gurland [31] did not observe any particle cracking for V_m in the range 15–20%.

Ahmed et al. [33] reported three modes of void nucleation, namely martensite cracking, ferrite–martensite interface decohesion, and decohesion at the ferrite–ferrite interfaces with minimum plastic deformation, which has been uniquely identified by them. They reported that at low to intermediate V_m, void formation was due to ferrite–martensite interface decohesion, while the other two mechanisms also occurred at high V_m (above 32%).

1.3. Void formation due to localized deformation

The local deformation field and its effect on the failure pattern has also been studied by various researchers [9–17,34,35]. Even though dual-phase steels exhibit a macroscopic, uniform and homogeneous deformation mode, from a micromechanical perspective, their plastic deformation is inherently inhomogeneous due to the nature of its grain level inhomogeneity. Shen et al. [17] used a scanning electron microscope (SEM) equipped with a tensile straining stage to illustrate the inhomogeneous strain distributions between the ferrite and martensite grains in dual-phase steels. They observed that, in general, the ferrite phase was deformed immediately and at a much higher rate than the delayed deformation of the martensite phase. For dual-phase steels with low martensite volume fraction, only the ferrite deforms and no measurable strain occurs in the martensite particles. For dual-phase steels with high martensite volume fraction, shearing of the ferrite–martensite interface occurs, extending the deformation into the martensite islands. In situ SEM testing was also carried out recently to observe the deformation field in dual-phase steels and the same result was obtained [15,16].

Tomota and Tamura [36] provide pictures of deformation fields in different dual-phase steels. They report that the degree of plastic deformation inhomogeneity is highly influenced by three factors: the volume fraction of the martensite phase, the yield stress ratio of the ferrite–martensite phases and the shape of the martensite phase.

1.4. Present work

The present work aims to look closely at the process of failure in this specific dual-phase steel and to observe the process of failure in different loading stages considering in particular the mechanisms for void nucleation, void growth and void coalescence. Therefore tensile testing of specimens was interrupted at specific strains: (i) when diffuse necking happens; (ii) after diffuse necking and before failure in a region which is predicted to be localized necking; and (iii) after failure. The main area of focus is the necking region: the process of void nucleation and growth away from this region does not provide precise information about the failure mechanism. This part of the specimen was observed by SEM and light microscopy and the results are reported. It is emphasized that for materials as complex as dual-phase steels the interpretation of observations and discussion about the underlying mechanisms may suffer from a lack of information about the local properties which may vary with production process and/or chemical composition. Given these limitations, this work attempts to observe the failure behavior in the currently available commercial DP800 steel. It is noteworthy that most previous observations have been carried out on laboratory-produced dual-phase steels, and the present work is novel in terms of its use of a commercial material. Our discussions are based on the present observations but might be applicable to interpretation of failure mechanisms for a larger range of multiphase materials.

The issue of statistical representativity was considered in more detail in this study. Most studies on microstructural behavior suffer from a lack of good statistical representation. This is due to the fact that they usually extract their results from a small aggregate, e.g. in situ SEM test, and then extend their findings to the whole structure [15,16].

In this research, in situ SEM testing was not carried out because the area of observation would be very small and thus could not be considered as the representative of the whole aggregate.

Statistical representativity at the microstructural level was considered in the following way. The specimens were tested and then investigated thoroughly in different locations after each interruption. Around 80 SEM pictures were taken from different locations, and the reported results can thus be expected to reveal the general manner of the whole microstructure.