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Towards the microstructure design of DP steels: A generic size-sensitive mean-field mechanical model

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ABSTRACT

An original mean field composite model able to explain and quantify the tensile behavior of as-quenched dual phase (DP) Ferrite-Martensite steels based on the relevant microstructural parameters (grain size, phase fractions and composition) is presented. The model is unique in that it is applicable to microstructures ranging from fully ferritic to fully martensitic. This generic nature makes it a powerful tool for both alloy and microstructure design and for sensitivity studies over the entire range of martensite fractions. The model is based on a detailed understanding of the hardening mechanisms of the individual constituent phases and their interactions. Special attention is paid to the complexities arising from the coupling between grain size, phase fractions and local compositions of the phases, most notably the local carbon content in martensite (dilution effect). The few fitting parameters that are required have been adjusted on a database of more than 60 tensile curves extracted from the literature.

1. Introduction

1.1. Industrial context and scope of the model

Dual-Phase (DP) steels were developed in the 1980's [1] and have been industrialized since the years 1990–1995. They are still very widely used in the automotive field [2,3] where they constitute the majority of the so-called first generation of advanced high strength steels (AHSS). These steels generally show high levels of Ultimate Tensile Strength (between 600 and 1200 MPa) and have excellent forming qualities (drawing or bending ability) which makes them suitable for the production of crash resistance parts [4,5].

The "Dual-Phase" epithet refers to the microstructure of these steels which is composed mainly of two phases, usually body centered cubic (BCC) ferrite with a polygonal morphology and metastable α' martensite showing a BCC or a body centered tetragonal (BCT) structure. The fraction of the latter carbon rich phase is variable (from 5% to almost 100%) depending on the targeted grades. In a simple approximation, the ferrite can be considered as a soft phase and the martensite as hard matrix reinforcement, although this representation obviously fails at high martensite contents. This composite nature confers excellent mechanical properties, i.e. a good balance between strength and formability.

The present approach is limited to the study of the mechanical behavior of as-quenched Ferrite-Martensite, although "tempered" DP steels are also of a great practical and industrial importance [6,7].

1.2. State of the art

Dual Phase microstructures were extensively studied in the 1970s and 1980s. This work was supported by steel producers and automotive and heavy plates industries [1]. After the industrialization of the first commercial DP products in the late 1990's the interest in this material decreased as ferritic TRIP steels appeared [8–11]. At the end of the 2000's, the interest in laboratories for DP structures has returned since the steel industry has faced low damage resistance roadblocks in the development of high strength DP concepts [7]. New tools have thus been proposed to manage these issues, in particular local field micromechanical models, which are particularly relevant to study fracture mechanics at phase scales.

1.2.1. Basic microstructure-property links

As shown in Fig. 1(a) and (b), DP steels tensile curves are characterized by low conventional yield strengths (YS) comparing to their Ultimate Tensile Strengths (UTS), absence of Lüders' plateau and high initial Work-Hardening (WH) rates. This combination of

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properties enables them to reach high Uniform Elongation (UEl) and as a consequence high UTS. The YS/UTS ratio is generally close to 0.5.

Some authors have attributed the low yield strength to second-order internal stresses generated during the final unrelaxed martensitic transformation at low temperature. In these approaches, ferrite is thought to experience high residual tensile stress states that promote early dislocation slip. However, the presence of these internal tensile stresses has never been confirmed by anisotropy in the tensile/compression behaviors of these steels (see for instance [12]). It seems more reasonable and sufficient to explain the yielding behavior by the low flow stress of the ferritic matrix.

The absence of a Lüders' plateau is rather surprising when compared to other multiphase steels such as High Strength Low Alloyed (HSLA) ferrite/pearlite steels, considering the high initial carbon contents and similar manufacturing conditions. The phenomenon is commonly explained by the presence of large densities of mobile dislocations generated at the interfaces between ferrite and martensite during the final martensitic transformation. These dislocation structures have been characterized for instance by [13,14]. It will be shown that the flow stress of the ferrite increases when the density of these "interface" dislocations increases. This effect cannot be captured when considering only second-order internal stresses generated by the phase transformation and even there are contradictions which arise (higher internal stresses should lead in fact to lower macroscopic yield strengths).

By analogy with metal matrix composites, the high WH of DP steels is explained by the presence of hard phases in a soft matrix (the so-called "DP effect"). It will be shown that the plastic behavior of martensite plays a major role in the macroscopic behavior of DP steels and in particular the importance of the martensite elastic–plastic transition. The latter is often neglected and the martensite behavior is simplified and considered as elastic-perfectly plastic [15]. From this composite behavior point of view, it naturally appears that the WH of DPs is controlled to first order by the fraction of martensite F_m. Fig. 1(a) shows the tensile curves of three DP steels with the same composition but different fractions of martensite (after [16]). Fig. 1(b) shows similar results taken from [17].

As in all composite structures, the difference of flow stresses between the constituent phases (see for instance [9,18–20]) leads to a kinematical contribution to the WH. In DP steels, this effect is essential. From a mechanical point of view, it explains the strong Bauschinger effects measured on these steels. At the microstructural scale, the difference in the mechanical behavior between ferrite and martensite is at the origin of strain incompatibilities [20–23]. The resulting strain gradients are often localized in the ferrite, i.e. the soft matrix, and are revealed by the presence of high densities of Geometrically Necessary Dislocations (GND) around martensite islands. These structures have been characterized by [11,13,14,24–26].

The existence of these localized gradients makes the behavior of DP steels very sensitive to size effects, especially to the grain size of the recrystallized ferrite and to the martensitic island size, as highlighted recently by [12]. In practice, it is difficult to decouple these size effects experimentally as the sizes are correlated for metallurgical reasons. Fig. 1(b) shows the tensile curves of DP steels with constant fractions of martensite (33% or 40%) but variable ferrite and martensite grain sizes, after [17]. The large ferritic grain sizes explain why the YS of the steels appears roughly constant but the work hardening rates increase significantly when decreasing the sizes of the features. The two complementary hardening mechanisms related to second-order internal stresses at the scale of the DP microstructure (ferrite grain boundaries, ferrite/martensite interfaces) will be discussed and modeled in the following.

Unexpectedly, the tensile behavior of DP steels is not sensitive to the phases morphology (shape of martensitic structures) or to the topology (spatial distribution, connectivity) [18,27,28]. This experimental finding is the key that permits the development of micromechanical models of DP steels based on simple mean field assumptions. Some recent results of Pierman et al. are puzzling from this point of view [29] as they show a high sensitivity of DP steels to the local morphologies (polygonal or elongated structures). They in fact compare the tensile behaviors of different steels not only with varying morphologies but also with varying structure sizes, which leaves no possibility to capture the sole effect of the morphology. Moreover, when compared to the steels of the database discussed below, it seems that their flow stress values are rather low which could imply that their DP steels are partially tempered or self-tempered. This is why these recent experimental results have not been considered in the following analysis.

In the literature, one can identify three main families of micromechanical modeling of the behavior of DP steels that will be compared below

- "Monophase" mean field approaches
- "Composite" mean field approaches
- Local field approaches

1.2.2. "Monophase" mean field approaches

The expression "monophase" can sound rather surprising when applied to DP structures but it represents well the main assumption of this family of models. The behavior of the composite is reduced to the behavior of the ferritic matrix which is hardened by the presence of martensite [8,9,17,21,30,31]. Modeling the behavior of DP steels consists in adding two contributions to the behavior of fully ferritic steels

- The first one is purely kinematical and is explained by the unrelaxed strain gradient [32,33] close to martensite islands due to localized GNDs. These GNDs induce a long range back stress in the microstructure, which is proportional to the fraction of martensite and could depend on the martensite islands size (martensite fraction is low).
- The second one is isotropic and corresponds to the effect of GNDs distributed far from the particles in the ferrite grains (not more than about 1 μm however). These dislocations contribute to the WH according to a forest model (third-order stresses interactions). The associated hardening contribution is often taken proportional to the square root of the fraction of martensite and is not null at the beginning of the deformation due to the unrelaxed martensitic transformation.

These two contributions will naturally saturate along with the deformation thanks to relaxation mechanisms (emission of secondary loops for instance [26] or martensite plasticization). In fact, these models implicitly assume that martensite remains mostly elastic during loading and account simultaneously for size and fraction effects. Nevertheless, they only apply in the case of a "dilute" composite, i.e. low fraction of martensite, no percolation of the martensite network, high local carbon concentration in martensite.

1.2.3. "Composite" mean field approaches

In this family of mechanical models, the behavior of the DP steel is a function of the respective behaviors of the two constituent phases, i.e. the ferrite and the martensite weighted by their average fractions. In the literature, they are often based on specific homogenization schemes: single parameter approach [34], self-consistent with local elastic-viscoplastic behaviors [35], Mori-Tanaka approach with local elasto-plastic behaviors [11,15,29,36],