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A method to quantitatively upscale the damage initiation of dual-phase steels under various stress states from microscale to macroscale

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ABSTRACT

The aim of this paper is to develop a micromechanical model to quantitatively upscale the damage initiation of dual-phase steels under various stress states from micro to macro and reveal the underlying mechanisms of the damage initiation dependency on stress states from a microstructural level. Finite element (FE) model based on the real microstructure of a DP600 steel sheet is employed by representative volume element (RVE) method. Several numerical aspects are also discussed, such as mesh size and discretisation feature of the phase boundary. The plastic strain localisation theory is applied to the RVE modelling without any other damage models or imperfections. Three typical stress states, uniaxial tension, plane-strain tension and equibiaxial tension, are considered to investigate the influence of the stress state on damage initiation. The quantitative evaluation of the damage initiation for three stress states obtained from the RVE simulation shows the dependency on both stress triaxiality and Lode angle. The results are further compared to the experimentally calibrated damage initiation locus (DIL) and a fairly good agreement is achieved. From this study, the general physical understanding of the effect of stress states on damage initiation is explored and the method for quantitative analysis of the damage initiation in a microstructural level is also established. The microstructure heterogeneity is considered as the key factor that contributes to the damage initiation behaviour of the dual-phase steel.

1. Introduction

The dual-phase steel, recognized as the first generation of the advanced high strength steels (AHSS), can be defined as low carbon steel that is thermo-mechanically processed to have a better formability than ferrite–pearlite steels of similar strength. They are widely used in industry, in particular automotive industry for light weight design due to their mechanical advantages, such as attractive combination of strength and formability. Dual-phase steels contain two phases, normally soft ferritic matrix and hard martensite islands dispersed in the matrix. Due to the strong distinctions in yielding of the two phases, the plastic deformation of dual phase steels is mainly dominated by ferrite. Tasan et al. [1] compared the deformation of a dual-phase steel at different strain stages of a uniaxial tension test by scanning electron microscopy (SEM) micrographs, and it was observed that the hard martensite islands only constrain the plastic flow of the soft ferrite, while they remain primarily elastic deformation. Shen et al. [2] also studied the strain distribution pattern between ferrite and martensite of dual-phase steels with different volume fraction ratios by SEM micrographs at different stages under uniaxial tension loading. It was reported that for steels with low martensite volume fraction, the martensite phase remains elastic deformation while the ferrite deforms plastically, but for steels with high martensite volume fraction, the martensite phase can undergo plastic deformation due to the shearing of the ferrite–martensite phase boundary. Recent studies of the deformation mechanism of dual-phase steels often incorporate the digital image correlation (DIC) with the in situ test to quantitatively describe the strain partitioning in the ferrite and martensite phase at grain level [3–5]. The plastic deformation of martensite was detected and calculated. Different local strain partition ratios between the ferrite and martensite phase were found depending on the martensite phase fraction, carbon partition and the method used to characterise the strain partitioning [4,5]. Despite the different behaviour of the martensite phase in different dual-phase steels, a common finding from these studies is that the localisation of the plastic deformation in the ferrite phase or at the ferrite–martensite interface due to the constrain of the adjacent martensite is the main source to trigger the subsequent damage, which can be in the ferrite phase, the martensite phase or at the interface.

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Attributed to the deformation mechanism of the dual-phase steels, the damage or failure mechanism is often concluded to be three modes of void nucleation: martensite cracking, ferrite–martensite interface decohesion and ferrite–ferrite grain boundary decohesion. All of these void nucleation modes were observed in different types of dual-phase steels [5–10]. The factors that control the dominant damage mechanism or the inhomogeneity of the plastic deformation could be the chemical composition, the volume fraction of the martensite phase, the yield stress ratio of the ferrite over martensite phase, the morphology of the martensite phase, i.e. the size, shape and distribution of the martensite phase [11]. Maire et al. [7] carried out in situ tensile tests on a DP600 steel sheet with 11% martensite phase and concluded that damage is never observed in the ferrite phase, but both the martensite cracking and ferrite–martensite decohesion were observed. Recently, Kadkhodapour et al. [8,9] carried out a set of interrupted uniaxial tensile tests and subsequent SEM analysis of a DP800 steel sheet with about 23% martensite, and revealed that the main void initiation pattern should be the ferrite–ferrite grain boundary decohesion. The different behaviour of the damage mechanism shown above is approximately in line with the observation by Ahmad et al. [6], that for dual-phase steels with low or intermediate martensite volume fraction, the void initiation mode is mainly ferrite–martensite interface decohesion, while with high volume fraction of the martensite phase, the ferrite–ferrite interface decohesion and martensite cracking are more dominant. Other researchers have also confirmed that the ferrite–martensite decohesion is the main damage mechanism of dual-phase steels [12–14]. However, the volume fraction of martensite is not the only factor that decides the preferred damage mechanism of dual-phase steels. Erdogan [15] concluded that the morphology of the coarse and interconnected martensite along the ferrite grain boundaries can facilitate the martensite cracking. Avramovic-Cingara et al. [10] compared the damage mechanisms of two types of DP600 steels, and concluded that the void nucleation for the DP600 with the martensite bands at the centre line of the sheet thickness is caused by martensite cracking, ferrite–martensite interface decohesion and separation of the adjacent martensite grains, while the major void nucleation of the DP600 with uniformly distributed martensite phase is ferrite–martensite interface decohesion. Calcagnotto et al. [16] showed that in dual-phase steels with coarse grains, the main damage mechanism is martensite cracking and the ferrite–martensite interface decohesion is the primary damage mechanism with ultra-fine grains.

In understanding the relation of the microstructural features and the mechanical properties of materials, in particular the relation between the plastic deformation and damage mechanisms in microstructural level and the macroscopic behaviour of plasticity and ductility, micromechanics-based finite element (FE) model using the representative volume element (RVE) technique is typically employed. Based on the early studies by McClintock [17] and Rice and Tracey [18] on the analytical derivation of the growth of cylindrical and spherical voids in a rigid plastic matrix, a unit cell model incorporating a regular array of circular, cylindrical, spherical or elliptical inclusions representing voids or hard phase particles was developed [19–24]. In addition to the unit cell modelling, another approach of the RVE modelling is based on the explicit description of material microstructure, generated either by real microstructure [25–37] or statistically characterised synthetic microstructure [38–40]. According to the damage mechanisms addressed above, a straightforward implementation in the RVE is that different damage mechanisms, such as brittle fractures of the martensite phase as described by cleavage fracture stress criterion, brittle or ductile fractures due to the debonding of interfaces as described by the cohesive zone model or ductile fracture as described by the empirical or porous plasticity ductile damage models, are assigned and interacted with each other [25–30]. Alternatively, Sun et al. [33,34] developed a plastic deformation localisation theory for the prediction of failure modes and ultimate ductility of dual-phase steels. The theory emphasized that the microstructural-level inhomogeneity of deformation serves the sole source of the initial imperfection and triggers the instability of dual phase steels. In the RVE, no prescribed failure or damage models and imperfections are assigned, and the ductile failure and failure models are the nature outcome of the plastic strain localisation. Different from the previous one, this theory neglects the specific damage mechanisms possibly visible in the dual-phase steels and addresses the significance of the plastic strain localisation due to the deformation incompatibility which is the ultimate source of different damage mechanisms. This approach has been applied in many different grades of dual-phase steels [35–37,41], and also extended to transformation induced plasticity (TRIP) steels [42,43].

The initiation of crack or damage has been addressed by many aforementioned researchers in their RVE simulations. The focus varies from demonstrating different damage mechanisms or revealing the dominant damage mechanism to the study of failure strain under uniaxial tensile condition and the modes or patterns of failure under different loading conditions. These studies are so far mainly qualitative. However, the initiation of crack or damage in reality is more complicated and it is strongly dependent on stress states. In addition to the early theoretical work by McClintock [17] and Rice and Tracey [18] that concluded that the failure strain is dependent on stress triaxiality, recent numerical studies on the cubic unit cell containing a void under various triaxial loading conditions showed that both stress triaxiality and Lode angle have effect on the failure strain [44–46]. With the different design of specimens and advanced testing machines developed, these findings are proved by many researchers in experiments [47–52]. These experimental and numerical investigations focus on the macroscopic crack initiation observed by naked eyes or DIC. However, for the application of dual-phase steels, damage has become such a pronounced phenomenon that large amount of damage in terms of voids for example are accumulated in the material before crack and fracture [1]. Therefore, to address the importance of the damage initiation and evolution rather than fracture, Lian et al. [52] proposed a hybrid approach to describe the plasticity and damage behaviour of a DP600 steel sheet, and in the study a microstructural level based damage initiation locus (DIL) with the dependency on both stress triaxiality and Lode angle is also observed and calibrated from experiments. Despite the good precision of predictive capability, the model brings a large number of material parameters. The effort to calibrate these parameters is severely hindering the application of it to a general or industrial scale. Another main disadvantage is that the model has a phenomenological character, as there is no material information involved. This also limits the application of the model to consider material microstructure in order to optimize the material for improved mechanical behaviour.

The key purpose of this study, therefore, is to quantitatively upscale the damage initiation under various stress states from microscale to macroscale and reveal the underlying mechanism of the damage initiation dependency on stress states from a microstructural level. In this paper, we use 2D real microstructure of a DP600 steel to generate the RVE. The plastic strain localisation theory by Sun et al. [33] is applied to the simulation without any other damage models or imperfections and the damage initiation under different stress states is considered as the nature outcome of the localisation of the plastic strain due to the microstructural-level deformation incompatibility. Three typical stress state scenarios for sheet metal forming are considered in this study, uniaxial tension, plane-strain tension and equibiaxial tension. The quantitative