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A study of local deformation and damage of dual phase steel

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ABSTRACT

Deformation and fracture behavior of Dual Phase (DP) high strength steel were investigated by means of a microstructure based Finite Element (FE) modeling. Representative Volume Elements (RVEs) were applied to consider effects of various microstructure constituents and characteristics. Individual stress–strain curves were provided for ferrite, martensite as well as transformation induced Geometrically Necessary Dislocations (GNDs) taking into account in the RVEs. Principally, the GNDs occurred around phase boundaries during quenching process due to the austenite–martensite transformation. Flow behaviors of individual phases were defined on the basis of dislocation theory and partitioning of local chemical composition. Then, flow curves of the examined DP steel were predicted. Furthermore, the Gurson–Tvergaard–Needleman (GTN) model was used to represent ductile damage evolution in the microstructure. Occurrences of void initiation were characterized and damage parameters for RVE simulations were hence identified. Finally, influences of the GNDs, local stress and strain distributions and interactions between phases on predicted crack initiation in the DP microstructure were discussed and correlated with experimental results.

1. Introduction

On one hand, demand of more Advanced High Strength (AHS) steels applied in the automotive industries has been continuously increased with regard to lightweight and passive passenger safety design. On the other hand, competition between steels and low density metals has become stronger. Thus, steel industries are driven to develop various AHS steel grades for different applications. Dual Phase (DP) steel is one of the most important AHS steels, which exhibits outstanding combination of high strength and good deformability. Recently, AHS steels have been totally applied to the extent of around 65% weight of car body parts made of steel. Indeed, from all these used AHS steels, the DP steels are around 48% [1]. Examples are such dash cross member, A-pillar, B-pillar, front rail closeout, front-side members, floor-side reinforcement and roof structures [2]. Beneficial mechanical properties of the DP steels in forming processes are continuous yielding behavior, high work hardening rate and high ratio of yield and tensile strength when comparing with other conventional low-carbon steels. Usually, microstructure of DP steels consists of hard martensite islands or/and bainite phase dispersed in soft ferritic matrix, in which strength and ductility of both phases is appropriately combined. Effects of microstructure on mechanical behavior of the DP steels were studied in numerous investigations. An optimum combination of high strength and ductility with high impact toughness was found in finely dispersed ferrite and martensite phase by Bag et al. [3]. Al-Abbasi and Nemes [4] reported that overall mechanical properties of DP steel depended not only on individual properties of ferrite and martensite, but also on microstructure characteristics as volume fraction, morphology of martensite, phase distribution and ferrite grain size. Dependency between grain size and strain hardening of ferrite was examined by Delincé et al. [5]. The saturation of dislocations along grain boundaries was explained by net of back stresses. Thomser et al. [6] found that work hardening rate of finer dispersed DP microstructure was higher than that of coarse DP microstructure and strain ratio between martensite and ferrite in the fine microstructure was higher than that in the coarse microstructure. On one hand, strength of DP steels could be controlled by finer ferrite grain site, higher martensite volume fraction and high carbon content in martensite. On the other hand, elongation of DP steels could be enhanced by homogeneous distribution of microstructure constituents and finer martensite islands. Mazinani and Poole [7] examined influences of martensite plasticity on plastic deformation of DP steels. It was found that plastic deformation of martensite was favored by reduced carbon concentration and/or changed martensite morphology from equiaxed to banded structure.

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Phase transformation from austenite to martensite during quenching by production of DP steel was studied by Ramazani et al. [8]. Hereby Geometrically Necessary Dislocations (GNDs) due to the transformation occurred around interfaces between ferrite and martensite. The thermal austenite–martensite transformation led to a volume expansion of around 2–4% that was verified by electron backscatter diffraction (EBSD) technique. Thus, plastic deformation took place at the interfaces during quenching and caused strain hardening or strengthening of those areas, which showed higher hardness values than the center area of ferrite grains. This increase in hardness could be well correlated with observed dislocation density alterations. Calcagnotto et al. [9] investigated orientation gradients and GNDs in DP steels with different martensite island size and volume fraction. The orientation gradients originating from ferrite–martensite interphase were distinctly higher than those initiated at ferrite–ferrite interphase. The GNDs were increased by increasing martensite volume fraction, decreasing grain size and increasing martensite fraction in the vicinity of ferrite. Furthermore, GNDs induced residual stresses introduced in ferrite were examined by Asadi et al. [10]. Sinclair et al. [11] found that initial work hardening behavior of copper alloys was resulted from a combination of kinematic and isotropic hardening due to dislocations accumulated at grain boundaries. Representative Volume Elements (RVEs) simulations were carried out for DP steels, in which the transformation induced volume expansion during quenching was incorporated by Ramazani et al. [8]. It was noticed that the von Mises stresses in the GNDs zone were 1.3 times higher than those in the center of ferrite grain. The thickness of GNDs layer was smaller than size of martensite islands and dislocation densities in ferrite increased with martensite volume fraction. The thickness of GNDs layer was 0.25 times smaller than the average size of martensite islands. Additionally, effects of dimensionality of RVEs were studied with regards to different martensite phase fractions [12]. It was found that flow curves obtained by 2D RVE simulations more differed from experimental results when comparing with those from 3D simulations. This was due to that the 2D simulations were performed under plane strain or plane stress condition. However, generating 3D RVEs with real morphology and phase fraction was very complex and calculations of that 3D RVEs took much longer time. Sodjit and Uthaisangsuk [13] defined different stress–strain responses for ferrite, martensite as well as GNDs zone in their RVE modeling approach.

Recently, fracture modeling of high strength multiphase steels has been extensively developed. For example, cohesive zone model was applied in RVE simulations by Uthaisangsuk et al. [14]. The model was defined to represent debonding mechanism of interfaces in dual phase microstructures. Ramazani et al. [15] simulated martensite cracking on mesoscale by using RVEs modeling in combination with extended finite element method (XFEM) in order to study failure initiation in DP steels. Besides, ductile fracture models have been widely used to describe failure behavior of DP steels, by which damage occurred according to void initiation, void growth and void coalescence mechanism. The classical Gurson–Tvergaard–Needleman (GTN) model was applied by Uthaisangsuk et al. [16] to investigate local crack initiation in high strength steel sheets during forming processes. Sun et al. [17] indeed introduced plastic strain localization as fracture criterion for DP steels. The strain localization was resulted from incompatibility deformation between ferrite and martensite. It was clearly found that state of stress during plastic deformation strongly affected local fracture mode occurred such as shear, split and necking. Marvi-Mashhadi et al. [18] investigated failure mode of DP steels with different martensite volume fractions. Plastic strain localization was also used to predict ductile failure. A shear dominant failure model was proposed in all of the studied DP steels. Microstructure and failure mechanism of DP steels were studied by Kadkhodapour et al. [2]. It was reported that after necking of tensile samples, void initiations were found due to decohesion between martensite particles. Whereby, subsequently developed stress concentration or deformation mismatch led to more elongated voids at ferrite–ferrite grain boundaries. Nevertheless, more spherical voids were observed at interface areas between martensite islands. Voids around inclusion were stretched in the direction of tensile loading and ferrite grain boundaries before failure. Influences of void evolution in ferritic phase on ductility of DP steels were investigated by Sun et al. [19]. When volume fraction of martensite was more than 15%, the ductility of DP steels was not deteriorated by initial voids, but it was rather affected by incompatibility between mechanical behavior of ferrite and martensite. Maire et al. [20] examined density, size and aspect ratio of cavities in DP steels by means of tensile tests. It was stated that damage initiation in DP steels was caused by the nucleation, growth and coalescence of cavities. The cavities fraction was linearly increased under constant rate with homogeneous tensile strain. On the other hand, the cavities fraction was distinctly increased when necking first occurred, and thus cavities distribution became heterogeneous. In the center of tensile samples, the density of cavities was non-uniform and was at maximum as the induced stress triaxiality was strongly increased after necking occurrence. Effects of stress triaxiality on damage evolution were studied by Requena et al. [21]. It was observed that total void volume fraction considerably increased with the stress triaxiality. However, distribution of void nucleation size was independent of the triaxiality and strain. Moreover, void growth and void coalescence in porous ductile materials were studied by Siad et al. [22]. A unit cell was used to analyze void evolution, by which overall stress triaxiality of the unit cell was kept constant. It was found that void shapes with higher void aspect ratios, for example, an oblate and prolate shape, caused definitely slower increasing rates of void volume fraction. Increased overall triaxiality values led to decreased fracture strains.

The present work aimed to study and characterize crack initiation mechanism of a DP steel grade 1000, which contained about 50% martensite phase fraction. Tensile tests and fractography were carried out for determining local void initiation and void evolution in the investigated dual phase structure. 2D RVEs based on real micrographs were used to describe local deformation between phases. Flow curves for individual phases were given with regard to dislocation theory and alloying partitioning. Additionally, GNDs at interphases were taken into account by an additional strengthening. The GTN damage model was applied on the micro-scale to represent damage initiation driven by interface debonding in the DP structure. Model parameters were correlated with experimental results from Scanning Electron Microscope (SEM) and determined in combination with FE simulations. Distributions of local stress and strain were calculated and discussed with predicted damage initiations and damage evolutions under different states of stress. Additionally, relationship between critical plastic strain regarding crack initiation and stress triaxiality was proposed as a failure criterion for the examined DP steel.

2. Experimental procedure

A cold rolled DP steel sheet grade 1000 (DP1000) with a thickness of 1.4 mm from part making industries were used in this work. Chemical composition of the investigated DP steel was shown in Table 1. First, samples were prepared from the thickness plane for metallography examination, by which 2% Nital was used as etchant. The observed microstructure consisted of large amount martensite islands dispersed in ferritic phase matrix, as depicted in Fig. 1. In the micrograph the bright zones were ferrite and the dark distributed