Effect of martensite volume fraction on cyclic plastic deformation behavior of dual phase steel: micromechanics simulation study

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A B S T R A C T

The cyclic plastic deformation of an archetypal microstructure dual phase steels has been examined via micromechanics modelling based on representative volume elements technique. The dual phase steel has soft ferrite–matrix with hard martensite–islands, which are distributed in a discrete manner. In the field of automobile industries, the suitable combination of strain hardening, strength and ductility, and their lean combination represent them as an economically desire option for huge multiple lightweight options. In this numerical approach, different microstructures for micromechanical modelling were constructed to detailed examination and analysis for the tensile and cyclic deformation response of dual phase steels. Due to the distinct difference in the stress–strain responses of ferrite and martensite phases, incompatibility of strain between matrix-softer ferrite and island-harder martensite phase arises during tensile straining. The effect of strain partitioning in cyclic plastic deformation response of dual phase steel has been studied in the present investigation. Apart from this, effect of martensite volume fraction on cyclic stress–strain response of dual phase steels, cyclic plastic deformation distribution in individual phases and cyclic deformation inhomogeneity at microstructural level have been systematically investigated.

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1. Introduction

Ferrite–martensite dual phase (DP) steel have good combination of mechanical properties and which make it suitable to use in engineering structural application such as automotive body section, wheels disc, reinforcement beams in inner bumper etc. Such engineering automobile components are inherently exposed to assorted cyclic loading conditions during the course of driving and that may cause cyclic plastic deformation of the material. Hence in such structural mechanisms of DP steel, it is significant to recognize the fatigue cracks places. Fatigue cracks can be generally found in places where stress/deformation concentration occurs. Normally deformation concentration takes place because of geometrical variation or alteration of material properties. Severe research has been concluded to comprehend the impact of the microstructural changes on the tensile and fatigue property of DP steels. Present authors Rana et al. [1] reported that the martensite volume fraction has direct important worthy attention effect on partitioning of strain apportioning between

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soft ferrite and hard martensite phases and hence tensile properties of DP steels. Yang and Chen [2] and Ramazani et al. [3] considered the impact of martensite volume part and martensite morphology on the mechanical collective possessions and failure behaviour of DP steels respectively. Paul et al. [4,5] revealed that the LCF life for apt plastic strain amplitude is fundamentally lessened by an expansion in the martensite volume division in the microstructure [4] and an increase in coarseness in martensite morphology [5]. As reported by Mediratta et al. [6], substantially LCF behaviour of DP steel is affected by the martensite morphology with a martensite volume fraction of 21%. Comparatively superior LCF life may be found in DP steel that has a fine grained matrix-soft ferrite and consistent emplacements of martensite, while considerably inferior LCF life can be seen in DP steel where the ferrite matrix has course martensite particles. All distributed literature on LCF conduct of DP steel reasoned that there is a slight variation in the specific behaviour of LCF life due to change in morphology of martensites. From the review of literature it has been observed that, although researchers unanimously mentioned that the martensite volume percentage of phases has an important effect on LCF life, but the systematic numerical detail investigation has not been done yet. Sherman and Davies [7] demonstrated that work hardening, which after-effects of flow-incited alter in the microstructure, has a considerable supremacy on behavior of fatigue of the dual phase steels. In addition to experimental findings, extensive computational modelling has been vigorously sought after to demonstrate the influence of microstructure on mechanical properties. Sun et al. [8,9] industrialized a microstructure-based modeling technique in which the failure mode and ultimate ductility of dual phase steels are anticipated under various quasi-static tensile loading settings utilizing the local plastic strain restriction hypothesis. For DP980 and DP780 steels Sun et al. [8], for DP 590 and DP 780 steels Paul et al. [10–12], and for DP steel Marvi-Mashhadi et al. [13] demonstrated that inhomogeneous microstructures in DP 980, DP 780 and DP 590 steels have been shown to act as imperfections that initiates the plastic instability causing plastic strain localization during deformation. Sodjit and Uthaisangsuk [14] found that a few short intruded on shear groups created with comparatively low fraction of martensite volume, they also observed that the volume part of martensite increments with expanding continuous pronounced long localize shear band, which is appeared in the DP microstructure prominently. Paul [15] showed that for DP steel ultimate tensile strength increases whereas percentage of elongation decreases with increase in martensite volume fraction. But all investigations are limited for tensile loading condition only. Therefore, computational modeling to study the mechanical behavior of DP steels for cyclic loading is justified.}

just rely on the stress–strain response of ferrite yet additionally volume portion and morphology of martensite [15–18]. Distributed works depicted that damage originated in DP steels amid tensile loading by the particle cracking of island (martensite) or decohesion of matrix — island interface, trailed by void nucleation and development in the matrix (ferrite) [19–25]. The technique in light of damage mechanics perception can’t be allied without considerable further advancement as the mechanisms of damage evolution are complex in nature of DP steel. Micromechanics representation using Representative Volume Element (RVE) was adopted by number of research groups [8,10–15,26,27] to model tensile deformation response of DP steels in microstructural level. The material input quantities supplied to the RVE are the individual flow response of ferrite and martensite. Detailed interaction between interfaces boundaries of the phases were neglected as it is insignificant (atomic sizes) compared to the RVE. Slight change in numerical value may be observed without noticeable change in trend. The results can be obtained from the micromechanics model without incorporating any separate damage law or failure criteria. Similar two dimensional RVE approach is adopted for the present work.

The cyclic deformation responses of DP steels were modelled by constructing four RVEs corresponding to martensite volume fractions of 13%, 23%, 33% and 43% (Fig. 1). The RVEs size for the present investigation is 1000 × 1000 μm and the average area of a martensite island is approximately 5 μm with aspect ratio of 2. A finite element code Abaqus is used in the present research. To mesh the RVEs, two dimensional plane strain elements are used. To simulate uniaxial tensile-compressive loading condition, all of the nodes along the bottom edge are compelled in the y bearing path and remain free in the x course. In RVEs loading, all of the nodes along the top length edge are given the similar relocations in the y course, whereas they stay free in the x bearing. The engineering strain in the y direction is attained by dividing the displacements of the top length edge by original length of the FE RVE. The engineering stress in the y direction is obtained from load divided by the primary area of cross section.

3. **LCF experimentation**

Using cognition from numerical (RVE) analysis and also for further experimentation, 75 mm × 150 mm sheet of 1 mm thickness was used for preparing LCF specimens for DP590 and DP780. The specimen length is considered in the rolling direction. For the fatigue test sample, a 2 mm width gauge and 7.9 mm parallel length was used, as done previously by Paul et al. [4,5]. As per ASTM E606-92 [28], total strain amplitude control LCF tests were conducted under fully reversed (R = −1.0) condition. Since large compressive strains tend to produce buckling, hence anti-buckling guides were used. As per the ASTM, E8 standard tensile test sample has been prepared considering gauge length and width 50 mm and 12.5 mm, respectively. Moreover, it was prepared by machining steel sheets along rolling direction. At room temperature, tests were conducted on the specimen. It was performed using an electro-mechanical testing machine at a crosshead speed of 1 mm min⁻¹ corresponding to a strain rate of 0.333 × 10⁻³ s⁻¹.

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2. **Micromechanical simulation of microstructure with a 2D RVE**

Dual Phase steels (DP590 and DP780) with their tensile strength and constitutive behavior are used for micromechanical RVE FE simulation in the present work. DP steels macroscopic perceptible mechanical properties are not only
Fig. 1 – Representative volume elements (RVEs) of the intended entire microstructures with various percentage of ferrite and martensite (a) 87% ferrite and 13% martensite (b) 77% ferrite and 23% martensite (c) 67% ferrite and 33% martensite (d) 57% ferrite and 43% martensite.

4. Numerical analysis of kinematic hardening parameter

Rana et al. [1] carried out RVE simulation of DP (ferrite-martensite) steels having major applied range of martensite volume fractions in used of 13%, 23%, 33% and 43% to determine stress-strain response under uniaxial tensile loading. These four grades of DP steel were supplied with individual stress-strain response of the two phases to determine the macroscopic stress-strain relationship of most commonly used range of automotive grade steel. The same
stress–strain relationships of the phases are employed in this study to understand the cyclic deformation characteristic of DP steels. The monotonically simulated stress–strain curve shown in Fig. 2 by 2D RVE model is matching well with the experimental (tensile test) result. By contriving different heat treatment processes and anneals, then it can be generated DP steels with different martensite fractions [4,5]. The tensile stress–strain relationships based on dislocation theory as per Paul and Kumar [10] of the each phases i.e. isle and matrix are employed in this study to understand the cyclic deformation characteristic of DP steels cognitive to Ohno and Wang [29], Abdel-Karim and Ohno [30], and Zhang and Jiang [31].

To investigate the cyclic plastic deformation response of DP (ferrite–martensite) steel, kinematic hardening rule introduced by Chaboche is incorporated means of superposition of several kinematic hardening models to describe the cyclic stress–strain response of matrix and island phases singly in the finite element micromechanics RVE. The commonly accepted equation form of Chaboche kinematic hardening law [32] would be:

\[
\dot{\varepsilon} = \sum_{j=1}^{3} \dot{\varepsilon}_j \\
\dot{\varepsilon}_j = \frac{2}{3} C_j dP - z_j \dot{\varepsilon}_P \dot{v}_eq
\]  

(1)

(2)

Fig. 2 – Monotonic validation of stress–strain relationship of experimental and simulation.

The material constraints in the above equations are \( C_1, C_2, C_3, \gamma_1, \gamma_2 \) and \( \gamma_3 \), where \( C_1, C_2 \) and \( C_3 \) are the coefficients of kinematic hardening, and \( \gamma_1, \gamma_2 \) and \( \gamma_3 \) are the exponents of kinematic hardening. Whereas, \( \dot{\varepsilon}_j, \dot{v}_eq \text{ and } \dot{v}_eq \) are the increment of back stress vector, increment vector of plastic strain and equivalent plastic strain increment defined respectively in the Chaboche numerical model. In the above law, the result back stress \( \sigma \) is the addition of three \((3–1) \) decomposed back stresses \( \sigma = \sigma_1 + \sigma_2 + \sigma_3 \). The foremost one \( \sigma_1 \) is projected to forecast a high plasticity modulus at the onset of yielding point and it stabilizes very rapidly. The next one \( \sigma_2 \) is projected to simulate the transient nonlinear segment of the hysteresis loop. The last decomposed back stress \( \sigma_3 \) would simulate the linear hardening (i.e. constant plasticity modulus) in the higher strain range. The equation can be represented for the loading part of the flow curve as

\[
\sum_{j=1}^{3} \sigma_j + \sigma_0 = \sigma
\]

(3)

where \( \sigma_0 \) is the yield stress of cyclic flow.

Several earlier studies [32–34] have been made about the details material constant determination procedure. In Fig. 3, it has been shown that the Chaboche model was able to successfully predict monotonic stress–strain curve of ferrite and martensite phases. Stress vs. strain hysteresis loop of both ferrite and martensite for microstructure predicted by Chaboche model for result strain amplitude of 1.0% are shown in Fig. 4.

Fig. 3 – Prediction of tensile stress–strain curve of phases of DP590 steel by Chaboche model.

5. Results and discussions

The total strain in loading direction distributed in DP steel with 23% martensite fraction for both tensile and compressive peaks are illustrated in Fig. 5. During cyclic plastic deformation, there is inhomogeneous deformation of hard and soft phase. This occurs because the plastic deformation of the softer phase (ferrite matrix) is opposed by the harder phase (martensite particles). Fig. 6 examines the stress triaxiality build up when loading pattern is tension followed by compression for strain amplitude of 1.0% in same DP steel. Nature of stress triaxiality development in tensile and compressive peaks is same while the sign changes. Stress triaxiality builds up in microstructural level of DP steel occurs as the hard martensite particles restrict the plastic deformation of soft ferrite matrix locally and alters the local stress state. Fig. 7 shows plastic strain amplitude in loading direction during low cyclic fatigue for RVE with 13%, 23%, 33% and 43% of martensite volume fractions having strain amplitude of 1.0%. Fig. 7 shows inhomogeneous distribution of plastic strain amplitude in RVE of different grade DP steels with various martensite volume fractions. The plastic strain
amplitude in each integration points in ferrite phase of different DP steel RVEs having significant grades range martensite volume fractions are computed and plotted in Fig. 8. It can be made clear from Fig. 8 that the distribution become wider and the peak also become lower as the martensite volume fraction gradually ascends from 13 to 43%. The wider distribution indicates higher plastic strain amplitude in more integration points in ferrite phase i.e. higher plastic deformation in some areas of ferrite phase. During straining process, according to various research [11,15,35,36], DP steels show strain partitioning between the two phases. For a given applied strain level, the deformation in ferrite is far more than the other phase, obviously the extent of deformation in martensite phase depends upon the volume fraction and carbon content in martensite phase. As the martensite volume fraction ascends, it is logical that for a given applied strain level, the deformation in ferrite phase will increase. This explains the wider distribution of plastic strain amplitude
in ferrite phase with increasing volume fraction of martensite.

Stress–strain hysteresis loop during LCF with total strain amplitude of 1.0% for RVE with 13–43% volume fraction of island phase is plotted in Fig. 9. The strain hardening rate in the plastic region of the stress–strain hysteresis loop shows an upward trend as the martensite volume fraction ascends. This can be explained in two combine phenomena: stress partitioning and deformation constrain in ferrite by martensite island. Stress partitioning between the dual phases

Fig. 8 – Distribution of plastic strain amplitude in loading direction during LCF with strain amplitude of 1.0% for RVEs with considered ascending martensite volume of 13–43%.

Fig. 9 – Stress–strain hysteresis loop during LCF with total strain amplitude of 1.0% for RVE with significant range of volume fraction of martensite.
Fig. 10 – Prediction of flow hysteresis loops during LCF at the total strain amplitude for 1.0%: (a) DP 590 steel, (b) DP 780 steel.

during plastic deformation consequences higher stress level in martensite phase in comparison to ferrite phase. Higher martensite volume fraction contributes higher microstructural volume fraction of DP steel carries high stress level and hence high strain hardening behaviour. Apart from this, it is well established that martensite island restrict deformation in ferrite phase of DP steel and which results higher strain hardening behaviour. As the volume percentage of martensite ascends, the restriction of deformation in ferrite phase also increases and as a consequence strain hardening behaviour also increases in DP steel. The stress–strain hysteresis loop during LCF with total strain amplitude of 1.0% for distinct DP590 and DP780 steels are plotted in Fig. 10(a) and (b), respectively. It follows a prediction trend obtained from simulation. Variation of stress/plastic strain amplitude of two phase steel with volume fraction of martensite having total strain amplitude of 1.0% during LCF is shown in Fig. 11. Stress amplitude shows enhancement where as the plastic strain amplitude shows an opposite behavior as the volume fraction of martensite ascends in DP steels. Stress partitioning between dual phases and deformation constrain in soft matrix by martensite island are the cause of increase in stress amplitude with ascending martensite. The strain amplitude as a whole is maintained constant and as stress amplitude increases with increasing volume fraction of harder phase (martensite), therefore plastic strain amplitude decreases when the volume fraction of harder phase (martensite) increases.

6. Conclusions

Cyclic plastic deformation responses of dual phase steels with different martensite volume fraction were investigated in the present work with microstructure based micromechanical modelling technique. In this research, the main investigated conclusions are summarized as follows:

- All DP steels without reference to ascending martensite volume fraction, the cyclic plastic deformation in microstructural level is inhomogeneous. Extent of inhomogeneous cyclic plastic deformation increases gradually from 13 to 43% of martensite volume fraction in the microstructure. Distributions of plastic strain amplitude in ferrite phase widen and peak becomes lower with increasing martensite volume fraction.
- Due to local deformation restriction in the ferrite phase, the local stress triaxiality builds up. Similar type non uniform local stress triaxiality build up is noticed in ferrite phase during tensile and compressive peak.
- Shape of the stress vs. strain hysteresis loop of ferrite–martensite dual phase steel alters with ascending martensite volume. The hardening rate becomes higher in the plastic region, stress amplitude enhances and plastic strain amplitude lessens with increasing martensite volume fraction.
- The RVE simulated and experimental hysteresis flow loop shows close concurrence. Hence, micromechanics investigation with trivialized experiment is justified and can be considered as a method to predict the cyclic deformation behavior of dual phase steel with volume fractions. However more rigorous investigation is required before engineering application.