Finite element analysis of AHS steel under dynamic loading using a micromechanical modelling

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Abstract. Currently, advanced high strength (AHS) steel sheets have been increasingly used in the automotive structural parts, where improved crashworthiness and lightweight design are required at the same time. Such steel sheets provide an excellent combination between high strength and great energy absorption. Most AHS steels exhibit microstructures containing several phases and constituents with different morphologies and mechanical properties. In this work, the dual phase (DP) steel grade 780 was investigated under dynamic tensile loading by means of a finite element modelling on the micro-scale. A representative volume element (RVE) model was applied to take into account the effects of microstructure characteristics on the mechanical behaviour of steel sheets at high strain rates. For the RVE modelling, the Johnson-Cook constitutive model was applied to describe the stress-strain response, whereas the Johnson-Cook damage model and damage locus were employed for predicting failure development of each individual phases of examined steel. The RVE simulations were performed under varying strain rates and states of stress and the results were subsequently compared.

1. Introduction

By designing a new vehicle, lightweight and passive safety of structural parts must be taken into account. Therefore, understanding material deformation at high strain rates is necessary for achieving the improved crashworthiness of vehicle. Dual phase (DP) steel is one of the most important AHS steel grades that show superior formability and energy absorption behaviour. The DP steels have been successfully employed in such crash-resistance components, by which weight reduction, lower fuel consumption and enhanced safety features of vehicle could be attained. The DP steel is a multiphase steel which has ferritic-martensitic microstructure. The ferritic phase is soft and exhibits good elongation, while the martensitic phase is hard and contributes to strength of DP steels. During the plastic deformation of DP steels, these both phases have strong interactions on the microstructure level. Hence, a micro-scale based model is needed for characterizing the micro-mechanical behaviour
of steel so that representative volume element (RVE) FE simulations were taken into account in this work. However, the accuracy of numerical results significantly depends on the used constitutive models and their parameters. The Johnson-Cook (JC) model has been widely applied for predicting plastic deformation of material under high strain rate loading. Besides, various models based on accumulative damage mechanisms could be used as a fracture criterion. For example, the Gurson-Tvergaard-Needleman (GTN) model was successfully employed to describe ductile failure of metals at high stress triaxiality condition [1]. Moreover, the Johnson-Cook damage model has been developed for incorporating the effects of stress triaxiality, strain rate, and temperature [2]. In addition, Bao and Wierzbicki [3] examined the relationships between different fracture strains and stress triaxialities including shear fracture phenomenon and introduced then the damage locus.

In this study, RVE FE simulations in combination with the JC constitutive model were conducted to describe the local high strain rate deformation of DP microstructure. Additionally, the JC damage model and damage locus were applied to predict the fracture behaviour of DP steel on the micro-scale under dynamic loading. The material parameters for each individual phase were identified and provided. The resulted microstructure developments were compared and discussed.

2. Material
The dual phase steel sheet grade 780 with the thickness of 1 mm was investigated in this work. The chemical composition of the as-received steel sheet is given in Table 1.

| Steel grade | C   | P   | Si  | Cu  | Ni  | Cr  | Mn  | Mo  |
|-------------|-----|-----|-----|-----|-----|-----|-----|-----|
| 780         | 0.114 | 0.012 | 0.010 | 0.008 | 0.008 | 0.183 | 2.648 | 0.062 |

2.1. Microstructure
Microstructure of investigated steel was characterized by optical microscopy and the obtained micrograph is presented in figure 1. It was found that the used DP steel grade 780 consisted of about 36% martensitic phase fraction and 64% ferritic phase fraction.

2.2. Uniaxial tensile test
Quasi-static uniaxial tensile test of the examined steel sheet was carried out by a universal testing machine. The ASTM E8 standard specimen was used and the test was performed at room temperature with the strain rate of 0.001 s⁻¹. The stress-true strain curves of steel specimens were determined and are provided in figure 2. The yield and ultimate tensile strength of steel sheet were 497 and 791, respectively, while the total elongation of around 22.5 % was achieved. It is seen that the steel showed rather low yield strength to tensile strength ratio which is typical for DP steel.

Figure 1. Observed microstructure of steel grade 780.

Figure 2. Determined stress-true strain curves of investigated steel grade 780.
3. FE analysis
In the case of numerical analyses, FE simulations were conducted to predict microstructure behavior of the examined steel under dynamic loading. The strain rate of 500 s\(^{-1}\) was taken into account. The macroscopic simulations of tensile test under high strain rates were firstly carried out at varying states of stress. A multi-scale approach was applied, in which local strain fields of deformed tensile specimens were taken as the boundary condition of micro-scale model. Note that on the micro-scale a 2D RVE model based on real micrograph was used. The strain rate dependent flow stress curves of DP steel were incorporated by the JC model. Furthermore, the JC damage model and damage locus were applied on the micro-scale for each phase in the RVE. More details will be given later.

3.1. Macroscopic model

3.1.1. Macroscopic model. The geometries of tensile specimens were defined in order to obtain varying states of stress. Three different specimens, namely, pure shear, uniaxial, and U-notched [4] were thus employed. Then, FE models of the specimens were generated by using a two-dimensional plane stress (CPS4) element.

3.1.2. RVE model. In this work, 2D RVE model was generated on the basis of a random area of real two-phase microstructure of investigated DP steel. Hereby, a micrograph with the size of 50 x 50 µm\(^2\) was used and the element size of RVE model was 0.5 x 0.5 µm\(^2\). The used RVE model consisting of ferritic and martensitic phase is presented in figure 3. For the RVE model, the CPS4 element was also defined. In addition, the sub-modelling technique was employed to gather the boundary conditions of RVE model from the critical areas of the various macroscopic tensile specimens subjected to tension load.

3.2. Flow curve modelling

3.2.1. Static flow curves of single phases. The true stress-true strain curve of ferrite and martensite in the investigated steel sheet were firstly described by considering the carbon partitioning and a dislocation theory [5]. The predicted flow stress curves of both phases under quasi-static loading are illustrated in figure 4.

![Figure 3. 2D RVE of the investigated steel.](image)

![Figure 4. Predicted flow stress curves for the individual phases of steel grade 780.](image)

3.2.2. Dynamic flow stress curve. The JC constitutive model was used to describe the strain rate dependent flow stress curve of examined steel sheet. Note that, in this work, the JC model parameters were obtained by calibrating with the static flow stress curve and taking from the previous investigations [6-8]. For the macroscopic simulations of tensile specimens, the static stress-strain
curve in figure 2, while for the micro-scale RVE simulations, the predicted single flow stress curves of ferrite and martensite, as shown in figure 4, were used to calibrate the JC parameters of DP steel and each individual phase, respectively. However, the strain rate sensitivity parameters C of the JC model for DP steel were taken from the literatures [6-8], whereas for ferrite and martensite they were defined as those of the ferritic mild steel and fully martensitic quenched boron steel [6-8]. Note that the carbon contents of both steel sheets were similar to those in ferrite and martensite of the examined DP steel. The identified JC model parameters of DP steel, containing ferritic and martensitic phase are listed in Table 2.

| Material  | A [MPa] | B [MPa] | n   | C      | \( \dot{\varepsilon} \) [s\(^{-1}\)] |
|-----------|---------|---------|-----|--------|-----------------|
| Steel 780 | 575     | 750     | 0.410 | 0.0090 | 0.001           |
| Ferrite   | 418     | 700     | 0.500 | 0.0220 | 0.001           |
| Martensite| 1226    | 6       | 0.001 | 0.0053 | 0.001           |

3.3. Damage modelling

In addition, the JC damage model and damage locus were applied for the individual phases in the RVE model in order to describe the damage initiation of DP microstructure under various states of stress. Both ductile damage criteria represented the relationship between the equivalent plastic strain to fracture and governed stress triaxiality. Nevertheless, the damage locus criterion differed from the JC damage model, in which the relationships for low and high stress triaxiality regions were distinguished. To obtain the parameters of JC damage model the damage curves of ferrite [6,9] and martensite [10] determined from previous works were referred. The applied JC damage curves of each phase are given in figure 5. On the other hand, the used damage loci with two triaxiality zones of each single phase were adapted from the damage curves provided in the former investigations [9,10] and literatures [11], which are also demonstrated in figure 5 for a comparison. To describe fracture behaviour on the micro-scale under high strain rate deformation, the corresponding strain rate sensitivity must be taken into account. In this work, the strain rate sensitivities of JC damage model for both phases were assumed to be similar to that of the DP steel grade 780 [9-11]. It is noted that the damage loci for various strain rates were defined by employing this strain rate sensitivity term of JC damage model.

Figure 5. Comparisons of damage curves for ferrite and martensite in DP steel represented by the JC damage model and damage locus criterion.

4. Results

FE simulations of tensile specimens under varying states of stress were carried out at the strain rate of 500 1/s. The local stress triaxialities of each formed sample were calculated and are shown in figure 6-
7. It was found that the averaged stress triaxiality values of the critical area of pure shear, uniaxial and U-notch samples were 0.05, 0.34 and 0.58, respectively. Afterwards, RVE simulations under different states of stress were performed with the same loading of those critical areas from the corresponding macroscopic simulations. The local damage initiations in the examined DP microstructure under different deformation modes at high strain rates could be predicted and are also illustrated in figure 6-7. It was seen that the crack initiation sites and crack propagations were significantly different when the overall state of stress was changed. Furthermore, the RVE simulations using damage locus with two triaxiality zones noticeably showed fracture behaviour different from those using the JC model, especially in the case of shear loading. For the DP microstructure under uniaxial tensile loading at high strain rate, crack initiations and propagations occurred within the ferritic phase that was well in accordance with the results in [12], as illustrated in figure 8. Note that the calculated local strain rates of RVE were much higher than the overall strain rate of macroscopic specimens. With regard to the JC damage model constant strain rate sensitivity was assumed. However, the dependency between damage and applied strain rate can be certainly varied that will be considered in the future work.

![Figure 6](image1.png)

**Figure 6.** Calculated local stress triaxiality distributions on deformed specimens and damage initiation behaviour of DP microstructure under pure shear deformation at the strain rate of 500 1/s.

![Figure 7](image2.png)

**Figure 7.** Local stress triaxiality distributions on deformed specimens and calculated local damage initiation behaviour of DP microstructure under tensile deformation of notch sample at the strain rate of 500 1/s.
5. Conclusions
FE simulations of tensile specimens under varying states of stress and high strain rate of 500 1/s were performed for the DP steel grade 780. Subsequently, RVE simulations on the microstructure level were carried out for the corresponding samples. The JC model was used to describe the stress-strain responses at high strain rates, in which their parameters were obtained by calibrating with the static flow stress curve of DP steel and containing individual phases. In addition, two damage criteria with and without consideration of low stress triaxiality region were applied to the micro-scale simulations and the predicted damage developments were compared. It was found that the damage initiation and propagation of DP microstructure under shear deformation at high deformation rate predicted by both criteria were significantly different. Local fracture behavior under low triaxiality must be particularly taken into consideration. Additionally, the predicted results will be validated with experimental observations in the future works.

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