A microstructure based modelling of high strength steel sheet under stretch-bending

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Abstract. In the automotive industry, advanced high strength (AHS) steel sheets are widely used for various structural and safety parts in car body. Such AHS steels exhibit complex microstructures containing different phase constituents. The yield and tensile strength of these steel sheets are significantly increased, but the formability is very restricted due to earlier occurred local damages. Their fracture behaviours are thus strongly governed by the microstructure characteristics and interplays between various phases. Besides, the forming processes of AHS parts mostly showed a non-linear strain history, for which the conventional forming limit curve (FLC) could not be properly applied. In this work, stretch-bending tests were carried out for the AHS steel sheet grade 980 after subjected to different pre-strains. FE simulations on the micro-scale of the forming experiments were performed by using 2D representative volume element (RVE) model, which was generated from the real microstructure of examined steel. Hereby, local crack occurrences in the microstructure of steel were described. Furthermore, the FE results by using isotropic and kinematic hardening law were compared. Finally, the bending limits of steel grade 980 after varying pre-strains were predicted.

1. Introduction

Nowadays, in the automotive industries, vehicles with increased load carrying capacity and lightweight design are aimed. Thus, various advanced high strength (AHS) steel sheets have been continuously developed to find a new concept of car body structure and to meet these challenged requirements [1,2,3]. To manufacture a body part of such AHS steel sheets, sheet metal forming is yet the most important and frequently used process. One major problem by forming AHS steels like dual phase steels is the earlier fracture occurrence and thus restricted formability [2,4,5]. This was due to the particular microstructure characteristics and interplays between various phases. Hence, the prediction of deformation and fracture behaviour of AHS steels is still needed to be improved. On the other hand, complex multi-step or successive forming procedures are often employed to successfully achieve the final shape of a part [6,7]. Basically, forming limit curve (FLC) is used in FE simulation to compare with occurring strains for evaluating the feasibility of defined forming processes of sheet metal part. A prediction with high accuracy is only possible for proportional linear strain paths [7,8].
For industrial forming operations with non-linear strain paths, the conventional FLC is not acceptable [7,8,9]. In some cases, FE simulations taking into account the microstructure effects have been carried out [10,11,12]. Hereby, representative volume element (RVE) was defined and micromechanical models were used for describing the stress-strain responses of each participating phases. However, only basic forming procedures as tensile deformation were investigated. In this work, AHS steel sheet grade 980 was investigated under non-proportional forming histories. Firstly, uniaxial and biaxial tensions were applied to the steel sheets. Afterwards, the pre-strained samples were subjected to a stretch-bending until failure. FE simulations on the macroscopic and microscopic scale using 2D RVE model were performed similar to those experiments. Local deformation on the microstructure level of the examined steel, which could strongly affect its formability, was studied. The simulation results from different strain paths were compared and discussed.

2. Experimental investigation

2.1. Materials
In this work, the AHS steel grade 980 with the initial thickness of 1 mm was used. Table 1 shows the chemical compositions of the examined steel. The microstructure of the steel sheet was characterized by optical microscopy (OM) and scanning electron microscope (SEM), as shown in figure 1. It was found that the microstructure of steel consisted of about 48% ferritic matrix, 46% hard martensite and 6% bainitic phase.

Table 1. Chemical compositions of the investigated steel sheet (in wt.%).

| C   | P   | Si  | Cu  | S   | Cr  | Mn  | P   |
|-----|-----|-----|-----|-----|-----|-----|-----|
| 0.176 | 0.015 | 0.467 | 0.008 | 0.003 | 0.002 | 2.42 | 0.015 |

2.2. Experiments
To obtain mechanical properties and stress-strain curve of examined steel sheet, uniaxial tensile test at room temperature with a velocity of 2 mm/min was conducted. Tensile specimens according to the standard DIN 50114 with the gauge length of 25 mm were prepared. The strain developments of sheet specimens during the tests were gathered by using a digital image correlation (DIC) technique. The determined stress-strain response is illustrated in figure 2. In addition, a non-proportional forming test including uniaxial tension and subsequent stretch-bending was performed for verifying the FE results.

![Figure 1. Observed microstructure of the investigated steel grade 980 by SEM](image)

![Figure 2. Determined true stress-true strain curve of steel grade 980](image)
3. FE modelling

For the simulations, the Marciniak forming test [13] was conducted to generate different pre-strains under biaxial deformation. Then, a stretch-bending test was applied to the pre-strained sheet samples. Such bending deformation mode with small punch radius could lead to a critical failure of AHS steel sheets at rather low elongation and fracture would thus occur without a significant necking [11,14].

3.1. Macroscopic simulation

FE simulations of the Marciniak test with successive stretch-bending were carried out for the examined steel, in which von Mises yield criterion coupled with both isotropic and nonlinear isotropic/kinematic hardening model was used. Note that the r-value of the steel was close to 1. The FE models of Marciniak test were defined according to the experiments in [13], which consisted of punch, die and blank holder, as depicted in figure 3. The dies were modelled as rigid body and shell element was defined for the blank. A draw bead with a height of 5 mm was applied to prevent sliding of specimens. At failure of stretch-bending process, fracture was expected to occur in the middle of specimen. Hence, a finer mesh was assigned to this area. The FE models of stretch-bending contained die, blank holder and punch, as seen in figure 4. A punch radius of 2 mm and punch angle of 35 degree were applied [15]. The Marciniak tests were carried out until reaching the different punch depths of 10, 12 and 15 mm. Afterwards, all in-plane plastic strains calculated for the formed specimens from the last step of Marciniak test were gathered and further given as the pre-strains of specimen in the stretch-bending step. The friction coefficient of 0.1 was assumed for all macroscopic simulations.

3.2. Microscopic simulation with RVE model

2D RVE was generated from a micrograph of investigated steel grade 980 with the area of 50×50 μm², as shown in figure 5. A plane strain element was defined for the RVE. To describe the mechanical properties of each individual phase, the micromechanical models, which are based on a dislocation
theory and local chemical composition, were taken into account. More details about the models for the individual phases can be found in [12]. Figure 6 demonstrates the modelled flow stress curves for ferrite, bainite and martensite of the steel grade 980. Furthermore, it is seen that the stress-strain curve predicted by RVE simulation under tensile loading agreed well with the experimental result. Therefore, these individual stress-strain responses were given to each phase in the RVE model by using the J2 plasticity. For the forming tests, the deformation fields from the critical area of formed specimens subjected to the Marciniak and successive stretch-bending was taken as the boundary conditions of the RVE model. The RVE simulations were performed under different pre-strains and the deformations of examined microstructure were calculated and studied.

4. Results and discussion
Firstly, for verification, strain distribution at failure of specimen after the tensile pre-strain and stretch-bending was evaluated by the DIC and compared with the results from macroscopic FE simulation, as depicted in figure 7. It was observed that the local plastic strains from both experiment and simulation were in good agreement. Thus, the strain fields of the critical area of specimens were taken and used as the boundary condition for RVE simulation on the micro-scale.

RVE simulations were carried out for the critical region of sample under tensile pre-strain with following stretch-bending by using both isotropic and kinematic hardening laws. Then, the overall stress-strain curves and local strain distributions from the RVE simulations were determined and compared with the experimental tensile curve, as illustrated in figure 8. It is seen that the isotropic hardening model led to resulted microstructure with too early strain localization and thus deviated stress-strain behaviour. Note that the critical plastic strain of RVE coupled with kinematic hardening at the state of macroscopic fracture identified from specimen after tension and stretch-bending was gathered and used as a criterion for failure prediction.

![Figure 7](image1.png)

**Figure 7.** Measured and calculated plastic strain distribution on sample after tensile pre-strain and subsequent stretch-bending of steel grade 980 at failure

![Figure 8](image2.png)

**Figure 8.** Overall stress-strain curves and local strain distributions predicted by RVE simulations using isotropic and kinematic hardening model for specimens subjected to stretch-bending after a tensile pre-strain
Furthermore, macroscopic and RVE simulations were performed for the Marciniak tests with different punch depths and following by stretch-bending. The calculated strain distributions of investigated microstructure for the critical areas of samples after stretch-bending with the same punch depth of 3.7 mm are depicted in figure 9. It was found that the strain developments of steel grade 980 on the microstructure level were noticeably different and the localization bands occurred in dissimilar manner according to the applied loading type. The resulted microstructure in case of the uniaxial tensile pre-strain showed obvious localized bands developed under 45 degree to the loading direction. By the biaxial pre-strain, the local strains mostly accumulated in some regions of ferrite phase and they spread throughout the entire microstructure when the drawing depth was increased.

![Figure 9. Local strain distributions in microstructure of steel grade 980 under stretch-bending to the punch depth of 3.7 mm after a pre-strain of (a) uniaxial tension (b), (c) and (d) Marciniak test with the drawing depth of 10, 12 and 15 mm](image)

Figure 9 shows the calculated strain paths up to their corresponding failures predicted by RVE simulations for the critical areas of specimens subjected to various pre-strains and subsequent stretch-bending in comparison with the FLC of the examined steel. Obviously, the strain paths for Marciniak tests located in the biaxial region and those for subsequent stretch-bending developed in the area between uniaxial and plane strain region. It was shown that the amount of pre-strain by Marciniak test strongly affected the resulting forming limits. The pre-strain with the punch depth of 15 mm would lead to sample failure at a plastic strain lower than that of the FLC. In addition, the failure moments described by the RVE simulations were plotted in the force vs. displacement curve of bent specimens after different biaxial pre-strains, as depicted in figure 11.

![Figure 10. Strain paths until failure predicted by RVE simulation for specimens subjected to different pre-strains and subsequent stretch-bending in comparison with the FLC of the examined steel grade 980.](image)
Figure 11. Force vs. displacement curve until predicted failure point of 980 steel samples subjected to stretch-bending after various biaxial pre-strains by Marciniak test.

5. Conclusions
2D RVE simulation for specimens of steel grade 980, which were subjected to Marciniak tests and subsequent stretch-bending, were conducted. Firstly, it was observed that the stress-strain behaviour and local strains of samples after uniaxial tension and stretch-bending, which was predicted by using RVE simulation coupled with a kinematic hardening model, better agreed with that obtained by experiment than those using isotropic hardening. The strain distributions and localizations in the complex microstructure of examined steel under various non-linear strain histories were rather distinguished. It was found that the predicted in-plane strains at failure by forming processes with non-linear strain path could be significantly deviated from those of the FLC that were in dependence on the type and level of applied pre-strain.

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