

CHAPTER 7 GENERAL CONCLUSIONS AND FUTURE WORKS

7.1 General conclusions

According to the current demands in the automotive industries, vehicles designed under consideration of light weight, crash performance, energy saving, and environmental aspect have been of special interest. Thickness reduction of steel sheets is desired in order to achieve lower fuel consumption. Thus, steel grades with higher strength and ductility such as AHS and UHS steels have been continuously developed and employed. By forming these steels, small post-necking deformation was observed or fracture could even occur before necking because of their complex failure mechanisms on the microstructure level. Due to complex microstructures of these steels describing failure behavior and predicting formability with the conventional tools like the forming limit diagram are no more sufficient. Accurate models for failure characterization are thus necessary for a successful manufacturing process of such steels. Hereby, influences of damage evolution must be considered by the prediction. In this work, failure criteria on both strain and stress spaces for formability description of AHS steels were developed under consideration of material plastic anisotropy, crack initiation and plastic instability.

In **the first part** of this work, anisotropic plastic deformation behavior of the TRIP780 steel sheet was investigated. Tensile tests of sheet samples with various notch geometries and hole expansion tests of the steel were performed. The influences of the constitutive models including various yield criteria, namely, von Mises, Hill'48 and Yld2000–2d as well as hardening model according to Swift and Voce on calculated local stress and strain distributions during deformation were discussed.

Influences of the constitutive models on stress–strain behavior

The engineering stress–strain curves resulted from corresponding FE simulations showed that the Swift hardening law provided breaking points of the curves at much higher strains than the Voce model for all tested notched samples, since the stress–strain curve described by the Voce model of the steel exhibited an earlier saturation point, which was not in the case of the Swift model. Obviously, the Voce model could more precisely represent the final failure states of the samples. Nevertheless, strain localization, which occurred much early in the extreme cross section of the U–shape notch sample was better predicted by the Swift model. The prior material softening of the investigated steel during plastic deformation could be defined as the states when experimental and numerical stress–strain curves started to deviate from each other. At this moment, damage initiation occurred and further developed until final fracture.

Influences of the constitutive models on local stress and strain distributions

Influences of the hardening models on calculated local stress and strain distributions were examined. The Swift hardening law exhibited higher local stress triaxiality values in all notched samples, which represented different states of stress, than the Voce model for the used yield criteria. The flow stresses modeled by the Voce model reached the saturation state at lower strain than those by the Swift model. On the other hand, local plastic strains predicted by the Swift model were much higher than those given by the Voce model under all applied yield criteria, especially in the case of the U–shape notch sample. It meant that the Swift hardening model more accurately described plastic strains of formed samples than the Voce model when large strain localization in extreme

shape was observed. Under consideration of yield criterion, the Yld2000–2d model showed higher stress triaxialities in all sample shapes, in particular the V–shape sample with a sharp–edged notch. The Yld2000–2d criterion considered yield stresses in 0° , 45° , 90° from the rolling direction and balanced biaxial yield stress in term of various anisotropic parameters. Thus, it could be used to well describe material behavior by large plastic deformation. The von Mises isotropic yield model, for which only yield stress in the rolling direction was taken into account, predicted stresses with the lowest magnitudes in all sample types. In contrast, in all samples with the exception of the radius–notch sample, equivalent plastic strains were slightly higher everywhere when calculated using the von Mises yield function, whereas the Yld2000–2d model provided the lowest plastic strains.

During **the hole expansion test**, punch load and stroke curves, final hole diameters in term of the hole expansion ratios as well as strain distributions along the hole circumference and specimen diameter in the rolling and transverse directions were investigated with respect to influences of the yield criteria and hardening laws. Principally, the Yld2000–2d model accurately predicted the experimental punch load and stroke curves when it was coupled with the Swift model and M exponent of 6 was applied. The Hill'48 model underestimated the experimental results, but correct tendencies according to the located direction from the RD were given as the resulted of hole expansion ratio. The results provided by the von Mises model, especially predicted local plastic strains showed the largest deviations. The hole expansion ratios and thickness strains along the hole circumference were more considerably affected by the applied yield models than the strains along the specimen diameter. Both hardening law and yield criterion noticeably influenced the prediction accuracies of the examined steel under hole flanging condition. The M exponent of 6 gave more reasonable results than other M exponent values. Therefore, appropriate anisotropic yield potential and hardening law were necessary for representing local plastic deformation behavior of the high strength steel.

In **the second part** of this work, formability prediction for the AHS steel sheet grade DP780 and TRIP780 were studied. It was found that fractures of the AHS steels could even occur before necking because of their complex failure mechanisms. This part commonly demonstrated the alternative tools for predicting failure onset of these steels. First, the FLCs of the steel sheets were experimentally determined by means of the Nakazima stretch–forming test. Subsequently, the FLCs and FLSCs based on the M–K model were numerically calculated on the basis of the Swift and modified Voce hardening law in combination with different yield criteria, namely, the von Mises, Hill's 48 and Yld2000–2d model. In addition, the FLSCs based on the FLC from the experiments were determined.

FLCs

By comparison between experimentally and theoretically obtained FLCs for both investigated steels, it was found that the M–K model in combination with the Swift hardening law and the Yld2000–2d yield criterion provided the most accurate formability prediction, in particular in the strain range from plane strain to biaxial tension, since the balanced biaxial r –values, r_b were incorporated in the calculations. On the other hand, the FLCs predicted by all yield criteria slightly underestimated the experimental results in the uniaxial tension range. The M–K model was based on the

localized necking theory and limit strains in that range, where diffused necking was supposed, were therefore not correctly represented. The calculated FLCs were significantly affected by the applied yield criteria and hardening models. The Voce model exhibited the FLCs with lower limit strains than the Swift model. Deviations of the FLCs predicted by using different yield functions were observed from the plane strain to biaxial tension state, since localized necking based on the applied M–K model strongly influenced by yield surface.

FLCs vs. FLSCs

The determined stress based criterion, FLSCs were significantly affected by the applied yield criteria and hardening laws. The Swift model provided higher forming limit stresses than the modified Voce model in the entire states of stress. The yield criterion showed strongly effects on the shape of the calculated FLSC. The FLSCs derived from the FLCs predicted by the M–K model in combination with the Yld2000–2d yield criterion and Swift hardening model better agreed with the FLSCs based on the experimental FLD data than other models. Note that the FLSCs calculated by the M–K model with all used yield criteria somewhat overestimated the FLSCs based on the experimental FLCs in the biaxial stress state. The hole expansion test was performed for verifying the determined FLCs and FLSCs. It was found that the FLSCs could more precisely describe failure and local deformation at fracture of both investigated steels by stretch–flanging condition rather than the conventional FLCs. The prediction accuracies of the FLSC strongly depended on the yield surface and hardening law applied in the calculations.

In the **final part**, damage criteria based on crack initiation and plastic instability of the AHS steel grade JAC780Y were experimentally determined by tensile tests of sheet samples with different notches and geometries in combination with the DCPD method and FE simulation. The developed damage curves exhibited a wide range of stress triaxiality value between 0 and $2/3$. For the investigated steel, the damage curves for crack initiation were definitely lower than those for plastic instability depending on governing state of stress.

Influences of yield criterion on the damage curve

The damage curves obtained by the Yld2000–2d model for both crack initiation and plastic instability were higher than those by other yield criteria in the entire range of stress triaxiality value. Larger deviations between the determined damage curves for plastic instability by different yield criteria were observed at large deformation degree than those curves for crack initiation. Regarding the state of stress, the DCs for plastic instability by various yield criteria showed larger discrepancies in the low stress triaxiality range (pure shear and combined loading sample).

Applicability of damage curves

The developed DCs for both crack initiation and plastic instability were verified with the Nakazima stretch–forming test and an industrial stamping part.

The Nakazima tests using various sample shapes were experimentally performed and corresponding FE simulations applying different yield functions were carried out. Calculated stress and strain paths were strongly influenced by the sample geometries and used yield criteria. The predictions of the DCs for crack initiation fairly agreed with experimental observations, in which microcracks in each sample were identified at the described states by SEM. Additionally, achieved dome heights of all formed Nakazima

samples were predicted for both states of crack initiation and plastic instability and compared with the experimental results. The predictions were acceptable and however considerably depended on the yield criterion.

On the industrial scale, real automotive component was formed and the determined DCs were applied to describe its formability behavior.

The industrial part was pressed until material failed on purpose. The stress-strain paths of the critical areas observed as failure on stamped part were calculated by FE simulations coupled with different yield criteria. It was found that the determined stress-strain paths strongly depended on the yield criterion and observed locations. The calculated paths of the areas P1 and P2 intersected the crack initiation DCs and plastic instability DCs successively. It meant that fracture was predicted at these areas. On the other hand, there was no fracture observed in other critical areas. Correspondingly, their stress-strain paths crossed over the crack initiation DCs, but not meet the instability DCs. These instability DCs can be applied successfully to formability prediction of industrial sheet metal forming process.

Applicability of DCs based FLCs

The four used Nakazima samples and the industrial stamping part were used to evaluate the applicability of the determined DC based FLCs. From the FE simulations, major and minor principal strains were obtained from the identified crack initiating element up to the instants of failure or maximum load in the experiments. The strain paths of all Nakazima samples exhibited continuous linear characteristics until fracture in different ranges of state of strain crossed over the instability DC based FLC could more precisely describe plastic instability state of the investigated DP steel than the Nakazima based FLC. In other words, formability prediction of the determined DC based FLDs was more satisfactory than that of the conventional FLD. In the same manner as aforementioned for the industrial part was performed, consequently.

7.2 Future work

Based on the current work, three main parts could be improved regarding formability prediction of the AHS steels.

- The FE simulation of the hole expansion test should be performed by using solid element combined with advanced development of anisotropic yield function.
- The newly ductile damage criteria are used to evaluate crack initiation and final failure on the hole expanding process for describing anisotropic plastic behavior of these steels.
- The calculated FLDs and FLSDs using the M-K model should be developed based on microstructure modeling to large strain deformation by the physically based hardening model or anisotropic hardening model and kinematic hardening model coupling with advanced yield function.
- The local strain distribution in critical areas of tensile notched tests should be measured and compared by using the digital image correlation (DIC) method through optical strain measurement system.
- The damage curve should be developed to cover more a broad range of stress state in minus and plus of stress triaxiality with the equivalent plastic strain. Consequently, the DC based FLCs also developed in the same manner.
- The damage curves based on microstructure modeling have to be obtained through FE simulation coupled with ductile damage criteria in micro scale modeling.

- The damage curves based on localized necking state should be confirmed by the other method such as measured strain or DIC method by optical system.
- More the high grade of Advanced High Strength Steel should be conducted to perform tests and developed the damage curves, FLDs and FLSDs, such as DP1000.