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Comparison of different testing approaches to describe the fracture behaviour of AHSS sheets using experimental and numerical investigations

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Abstract. The damage behaviour of Advanced High Strength Steel (AHSS) differs from conventional deep-drawing steels due to their microstructure. For example, shear fracture can occur unexpectedly without prior necking, leading to inaccuracies using Forming Limit Diagram (FLD). An improvement of failure prediction can be obtained by the use of stress state dependent damage models, which have to be parametrised by tests at different stress states for which a wide range of methods exists. Research is still needed regarding the choice of specimen, evaluation methodology and model accuracy. For that purpose, in this study two different experimental approaches are compared to analyse the fracture behaviour depending on the stress state of the complex phase steel CP800. Therefore, tensile specimens of various geometries are used on the one hand and butterfly tests in different orientations on the other. Subsequently, the modified Mohr-Coulomb (MMC) damage model is parametrised with the determined characteristic fracture values of the respective experimental methods. For additional comparison, also an FLD is determined. The different approaches are finally compared regarding their suitability for the parameterisation of stress state dependent damage models.

1. Introduction

Advanced High Strength Steels (AHSS) offer improved crash energy absorption capability compared to conventional steels. They combine high strength with relatively good ductility by means of a carefully adjusted multiphase microstructure, which consists of a soft and ductile matrix (e.g. ferrite) as well as additional hard constituents (e.g. martensite). Due to their properties, AHSS are used for lightweight design for example in crash-relevant vehicle components. In order to exhaust the formability potential, a careful process design is needed and especially forming limits considering the specific failure modes have to be precisely described.

For sheet metals, necking is widely accepted as the main failure mode. The forming limit predicted by necking is generally plotted in the space of major and minor strain and named as a forming limit diagram (FLD). However, the damage behaviour of AHSS is affected by the multiphase structures, in which morphological irregularities and hardness differences lead to high stress gradients. This results in a propensity for different crack appearances, without prior indication of necking, like exemplary shear fracture on tight radii and edge-fracture. These types of fractures cannot be predicted using an FLD, which was demonstrated for example in [1] and [2]. Moreover, FLD do not take the variation of the strain path into consideration.

To overcome these disadvantages phenomenological stress state dependent models can be used. Bai and Wierzbicki postulated that the existence of a failure locus in the stress space can be approximated using the Mohr–Coulomb yield criterion, which was originally used to describe the yielding behaviour of geomaterials [3]. The resulting failure locus in terms of the equivalent plastic strain, stress triaxiality, and Lode parameter is referred to as the modified Mohr Coulomb (MMC) model and has seen widespread adoption throughout the literature [4]. Other examples for that type of models are Xue-Wierzbicki [5] and CrachFEM [6]. Those type of approaches have shown good results for damage representation of high strength steels, for example TRIP690 [1] and DP600 [2]. By means of these models, the damage evolution is phenomenologically described dependent on the stress triaxiality η defined by the ratio of the Mises equivalent stress to the mean principal stress, as well as the normalised Lode angle $\bar{\theta}$, which corresponds to a function of the third deviatoric stress invariant [3]. In order to parametrise stress state dependent damage models, the fracture strain has to be identified within various tests in a wide range of stress states. However, tests for parameterisation of these kind of models are currently not standardised resulting in a variety of tests [7].

In this study, different approaches are compared in terms of the parameterisation of stress state dependent models. On the one hand, a special butterfly specimen geometry, which was developed at the IFUM [8] and showed good results for a DP600 steel, shall be tested at different loading angles in a stress range between shear and uniaxial tension. On the other hand, the fracture behaviour will be investigated by common uniaxial tensile geometries with a notch and a circular hole as well as two different simple shear specimen. The different approaches are used to investigate and model the fracture behaviour of a complex-phase CP800 AHSS. For each approach, characteristic fracture data in dependence of the stress state are identified by an experimental-numerical approach. Using these data, the MMC damage model is parameterised afterwards. For additional comparison purposes, also FLD, which are conventionally used for the description of forming limits in sheet metal forming operations, are determined. Finally, all approaches are discussed and current issues outlined.

2. Testing procedure

The investigations are carried out with a CP800 steel sheet of 1.6 mm nominal thickness provided by voestalpine Stahl GmbH. The chemical composition and the mechanical properties of the material can be found in [9], which were identified in the course of a previous work. In the current study, the fracture behaviour of the materials is investigated using the following described tests.

2.1. Butterfly tests

The geometry of the butterfly specimen used in the present work is shown in Fig. 1a. The design of the specimen is inspired by the butterfly geometry of Dunand and Mohr [10] and was designed in order to promote failure at the centre of the thickness reduced investigation area [8]. In a direct comparison with the specimen by Dunand and Mohr, a stronger strain localisation in the centre of the investigation zone can be achieved using this specimen, which increases the safety of fracture initiation at a specific stress state. Each surface of the investigation area of the butterfly specimen was symmetrically machined away with 25 % of the nominal sheet thickness. The outer contour of the specimen was taken from the sheet by wire cutting. Care was taken to ensure that roughness tolerances $R_a < 0.8$ and $R_z < 6.3$ were met. The specimen is designed to be tested in different orientations to the force direction. For this purpose, a special testing device based on the principle of Arcan [11] is used (Fig. 1b), which is able to rotate the central specimen holders in 15.5° increments permitting material investigations in a wide range of stress states from shear to plane strain tension. The experiments were performed under displacement control with a velocity of 0.02 mm/s for loading angles α (defined in Fig. 1a) of -3°, 12.5°, 28°, 43.5° and 59° until the onset of fracture. Digital Image Correlation (DIC) was used to analyse the strain distribution during the test and to measure exactly the relative displacement of the investigation area. Also the displacement of the grips was measured to capture boundary conditions for numerical models.

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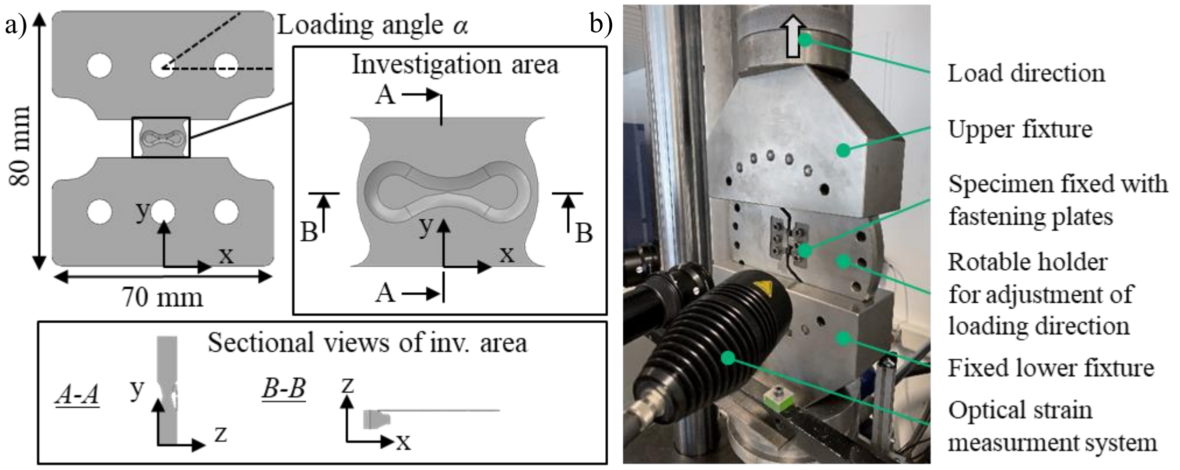

Figure 1. IFUM butterfly specimen (a), corresponding testing setup for uniaxial tensile machines (b).

2.2. *Tensile tests with various specimen geometries*

Tensile tests were carried out on flat specimen of different geometries. Specimens with a notched gage section and with a central hole were used. Furthermore, tests were performed with two different shear specimens, which are oriented on the standardised sample according to ASTM B831 [12] and the geometry published by Peirs et al. [13]. The geometries of the flat tensile specimens and their relevant dimensions are shown in Fig. 2. The specimens were produced by waterjet cutting. The tests were performed on a tensile testing machine S100/ZD by Dynamess. Before each test, the specimen alignment was carefully controlled to ensure even loading. The experiments were performed under displacement control with a velocity of 0.02 mm/s until the onset of fracture, and were repeated five times. In order to measure exactly the relative displacement in the centre of the gage section to analyse the strain distribution of the specimen during the test, DIC was used.

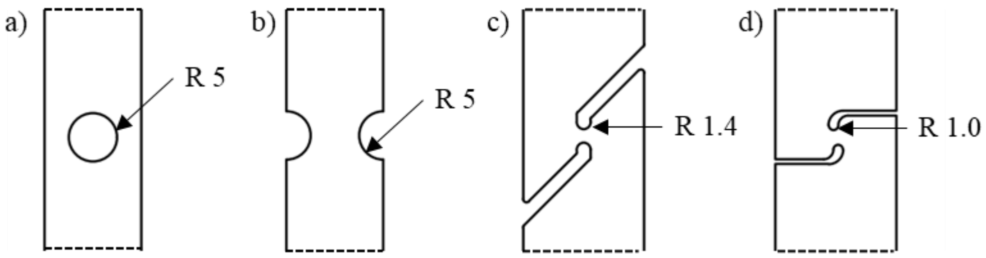

Figure 2. Various tensile samples for testing of different stress states: holed (a), notched (b), ASTM type shear [12] (c) and Peirs shear type sample [13] (d).

2.3. *Nakajima tests*

In order to determine FLD, Nakajima tests were performed according to ISO 12004-2 [14]. Six sample widths of 30 mm, 60 mm, 80 mm, 120 mm and 170 mm were tested with five repetitions for each sample. Before testing, a stochastic pattern was applied on the specimen in order to use DIC for the determination of the major and minor strain before the onset of fracture. The FLD in terms of the averaged minor and major strain determined by the standardised section method according to ISO 12004-2 is depicted in Fig. 3a, which can be interpreted as the necking limit. Additionally, an FLD was calculated using the highest section values of each test by the method “Section Max”, which is shown in Fig. 3a as the grey curve and describes the fracture limit of the material. For comparison purposes in the further chapters, the FLD were transformed into the stress triaxiality and equivalent plastic strain (Fig. 3b) using a definition of stress triaxiality dependent on the strain ratio for plane stress conditions as exemplary defined in [1].

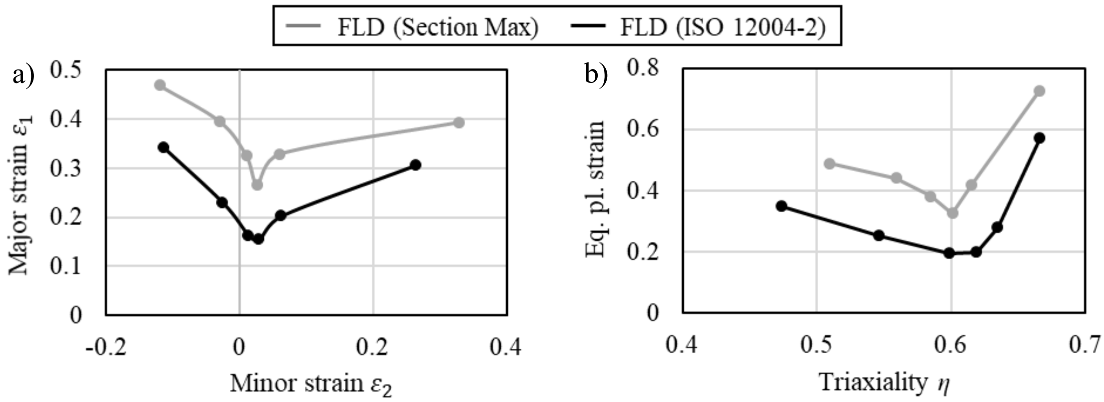

Figure 3. FLD determined by Nakajima-Tests for CP800 according to ISO 12004-2 (necking limit) as well as method “Section Max” (fracture limit): conventional representation in terms of the minor and major strain (a) as well as converted FLD dependent on stress state (b).

3. FE modelling

Experimentally, the onset of fracture initiation and the corresponding grip displacements were determined, which serve as boundary conditions for the numerical simulations. Numerical simulations of the tests are necessary in order to calculate non-linear stress developments that cannot be determined experimentally. In addition, strain evaluation of the butterfly specimens was not possible for all angles due to extensive shear deformation, which caused facet failures in the central field of the investigation area. For this reason, all experiments were uniformly evaluated using an experimental-numerical approach. Numerical models of the performed tests were developed in Abaqus to identify characteristic fracture data in terms of stress and strain states. Each FE model consisted of the specimen with the relevant tool parts. Continuum eight-noded elements with reduced integration (C3D8R) with an edge size of 0.1 mm were used for an adequate discretisation of the specimen, and the tools were modelled as elastic deformable solids. As boundary conditions, the experimentally determined displacement developments in x-y direction of the specimen for the onset of fracture were extracted from the DIC data and applied in the numerical simulation. The FE model of the butterfly tests can be found in further detail in a former publication by the authors [9]. For an accurate description of the material behaviour, data was used, which was also determined within the framework of the previous work [9]. The plastic material behaviour of the CP800 sheet was investigated in terms of tensile tests using specimens in three different orientations to the rolling direction. On this basis, the anisotropic Hill’48 yield criterion was parametrised. To identify the hardening behaviour, flow curves obtained from tensile tests were extended experimentally using hydraulic bulge tests and additionally extrapolated by an analytic approach after Hockett-Sherby. For more detailed information on the material model, please refer to [9].

4. Verification of FE model

The validity of the models was verified by comparing force-displacement data and strain distributions determined by DIC. In the experimental tests a good repeatability within five repetitions could be achieved. Fig. 4a compares the measured and finite element predicted force–displacement data of the tensile tests with various geometries in good agreement. Fig. 4b exemplifies the DIC-measured (left-side) and numerically predicted equivalent plastic strains (right side) on the surface of exemplary specimens at the onset of fracture. Good agreement between the two sets of images in terms of local distribution as well as quantitative values can be seen. Individual details of the sample edges cannot be evaluated with the help of DIC due to typical facet limits. A comparison of the FE model within the butterfly tests showed likewise a high accuracy, which can be seen in detail in the former work of the authors for this specific CP800 sheet material [9]. The Hill’48 yield criterion was able to reproduce the flow behaviour of the CP800 steel for different stress states ranging from shear to plane strain with good accuracy.

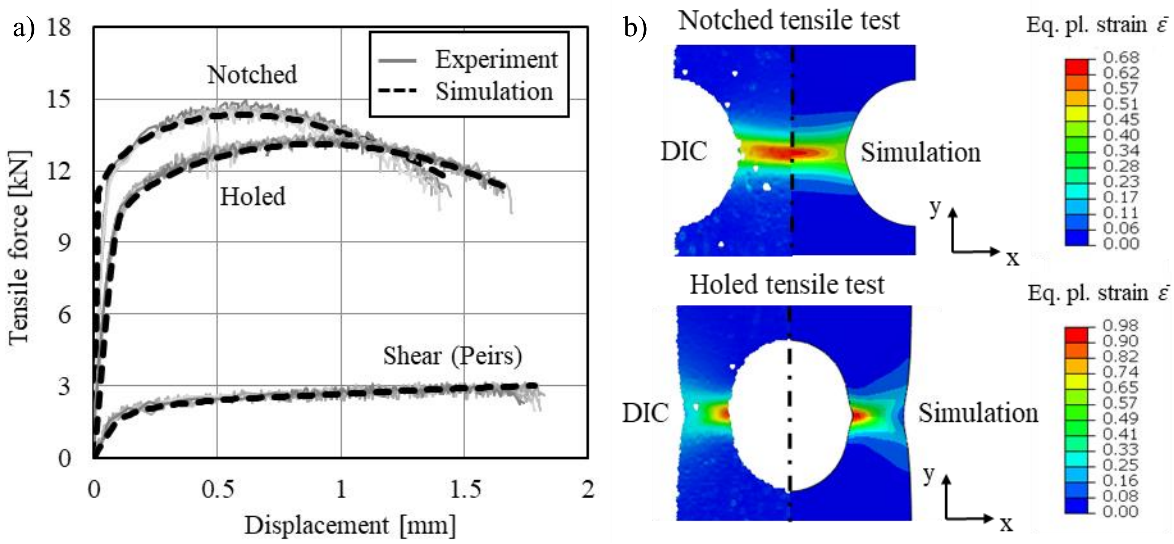

Figure 4. Verification of material model: comparison of experimental and numerical force-displacement data (a) as well as surficial distribution of eq. pl. strain at onset of fracture experimentally determined by DIC (left sample side) and predicted by FE simulation (right sample side) for notched and holed tensile specimen (b).

5. Fracture characterisation and modelling

As the finite element and material models were verified and accurately reproduced experimental data, they are suitable to be used to characterise reliable fracture data for further parameterisation of a damage model. For the evaluation of these data, the identification of suitable positions in the samples is required, which correspond to the location of fracture initiation. The butterfly specimens showed consistently for all investigated loading angles a fracture initiation in the centre of the investigation area. A continuous crack enlargement could be observed, so that besides the position of onset of fracture also the stage in time could be well identified. Based on the experimental observations as well as the numerically determined strain distribution, it can be stated that fracture is initiated on the surface of the specimens. Generally, it can be very challenging to determine experimentally at which position a crack is initiating. This was the case with the other tensile geometries. These specimens failed due to a sudden crack event without any prior signs of failure. In the case of the ASTM and Peirs type sample, the formation of edge cracks could not be excluded for the investigated CP800 steel. For evaluation of fracture data of all tests, the assumption was made that the crack initiates superficially at the position with the numerically predicted highest strain localisation. Based on this assumption, all relevant numerical data were obtained.

In Fig. 5 the strain-stress developments for thus indicated elements are depicted for the two testing approaches, butterfly tests (Fig. 5a) and tensile geometries (Fig. 5c). The stress histories of all tests revealed non-proportional developments. For this reason, relevant stress data for model parameterisation in terms of stress triaxiality η and normalised Lode angle $\bar{\theta}$ were averaged by calculating the centroid of the area, which are shown in Fig. 5a and 5c as the dashed lines. The overview on the stress states demonstrates that the entire range of positive stress triaxialities accessible in sheet materials ($0 \leq \eta \leq 2/3$) and in the full range of normalised Lode angle ($0 \leq \bar{\theta} \leq 1$) could be covered within the scope of all tests. Generally, the butterfly tests (Fig. 5a) show significantly more proportional stress developments in comparison to the tensile geometries (Fig. 5c). Furthermore, the stress developments of the butterfly tests correspond almost perfectly to plane stress conditions (Fig. 5b) in contrast to the developments in the conventional tensile specimen (Fig. 5d). Comparing the data with the work of others reveals that the calculated fracture strains are in good agreement for example with the study by Pathak et al. [15], where the failure behaviour of CP800 was investigated by shear, uniaxial, plane strain and biaxial tests.

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Nevertheless, due to the current lack of standardisation regarding testing conditions, simulation settings and evaluation procedure, data of different authors are basically difficult to compare.

The FLD describing the fracture limit evaluated according to the “Section Max” method agrees better with the fracture curve of the MMC model from the butterfly tests (Fig. 6a) than with that from the tensile tests (Fig. 6b). Since no calibration values were used in this area in the case of the MMC model determined by butterfly tests and purely analytical modelling is involved here, this may be just a coincidental incidence. The large discrepancies between the MMC model based on tensile tests (Fig. 6b) and the Fracture-FLD may well be caused by the influence of prevailing non-constant stress developments of the holed and notched specimen (see Fig. 5c).

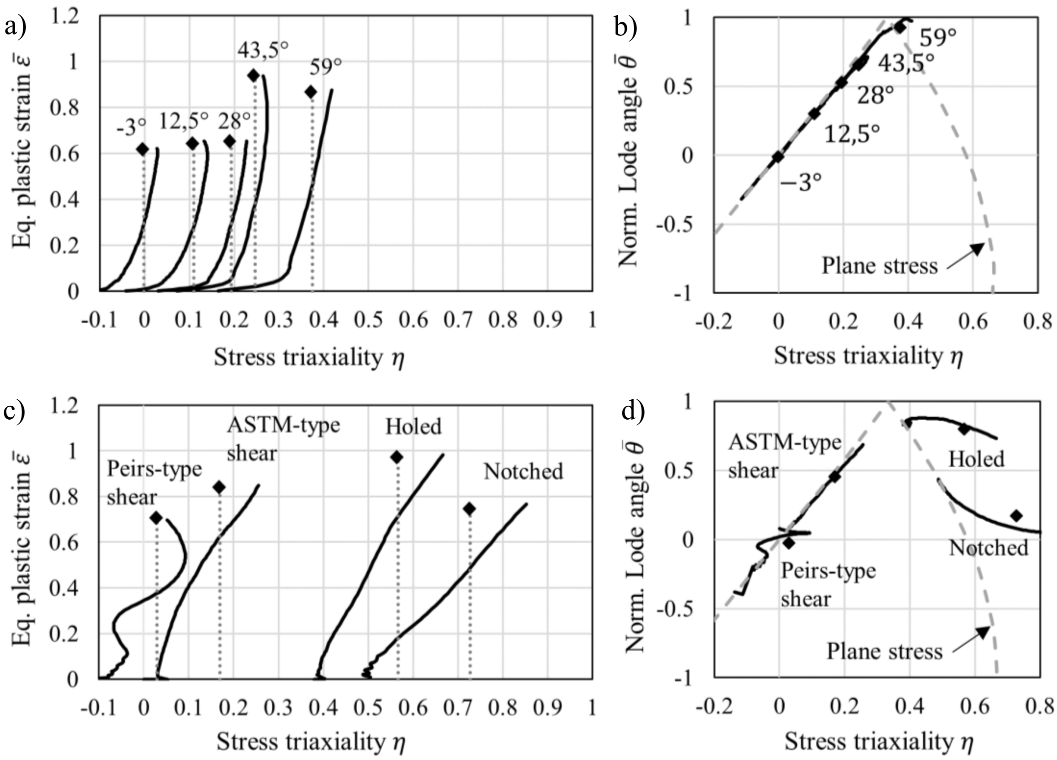

Figure 5. Numerically determined stress evolution until fracture: eq. plastic strain as a function of the stress triaxiality (left column) and normalised lode angle as a function of the stress triaxiality (right column) of butterfly tests for varied loading angles (a) and (b) as well as tensile geometries (c) and (d).

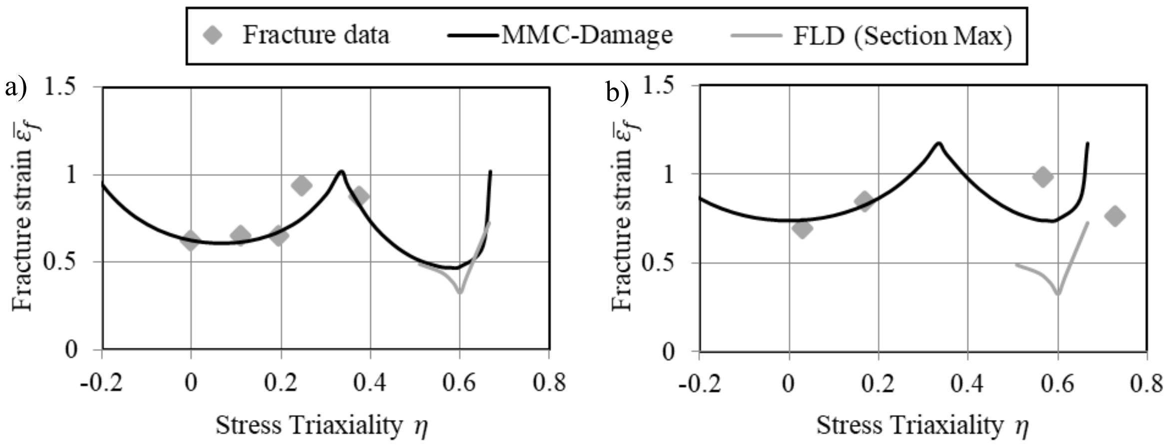

Figure 6. Parametrised MMC damage model by butterfly tests (a) and various tensile specimen (b) as well as FLD determined by method “Section Max”.

6. Discussion of results

Comparing the FLD (Fig. 3b) with the parametrised MMC models (Fig. 6), the range of validity of the FLD is very limited. For example, observed failure of AHSS under shear conditions around $\eta \approx 0$ cannot be predicted with this approach.

An alternative is the use of stress state dependent damage models, which have to be parametrised appropriately in a wide stress range. For characterisation of the fracture behaviour of metallic sheets under shear conditions, ASTM type shear specimen are widely used. Particular attention has to be paid regarding the strain distribution for this specimen, because studies comparing three different AHSS with each of three thicknesses showed that the highest strain localisation is strongly thickness and material dependent [7]. In Fig. 7, the global distribution of the eq. plastic strain for three different shear testing approaches in terms of the ASTM and Peirs type shear specimen and the butterfly specimen for α = -3° are shown for the experimentally determined boundary conditions at the onset of fracture. Both, the ASTM and the Peirs type shear specimen, show the highest global strain localisation at the specimen edge ($\bar{\varepsilon}_{max}$). A local maximum at the surface of these specimen is pronounced at the surface near the edge of the specimen, which is defined as $\bar{\varepsilon}_{max,surf}$. In contrast, the butterfly specimen shows a centrally localised strain distribution.

The stress developments for the elements with the global and surficial maximum strain value are evaluated in Fig. 8. The strain distributions of the ASTM and Peirs type shear specimen show large fluctuations and deviations of the stress state. The effect of predominant strain concentrations at the specimen edge, where a pressure superimposed stress condition prevails, and the accompanying influences on the onset on fracture have to be investigated. For parameterisation of stress state dependent damage models, in the best case only constant stress states should be used. Especially strong non-linear stress developments due to the appearance of necking appeared in the notched and the holed tensile tests (Fig. 5c). Further work is needed in order to assess the influence of non-proportional strain paths for calibration of stress state dependent fracture criteria.

For those reason, the interpretation of a specific characteristic value describing fracture initiation is accompanied with difficulties and inaccuracies, which occur due to undefined position of fracture initiation and averaging of the stress development. The butterfly sample, compared to the other samples, showed significantly more proportional stress developments. In addition, the stress developments correspond to plane stress conditions (see Fig. 5b). Also, fracture initiated slowly at the surface in the centre of the investigation zone for all tested load angles. Considering the strain distribution of the butterfly specimens before the failure point, it can be seen that the highest deformation occurs on the specimen surface. This position corresponded well with the experimentally identified locations of crack initiation for all loading angles.

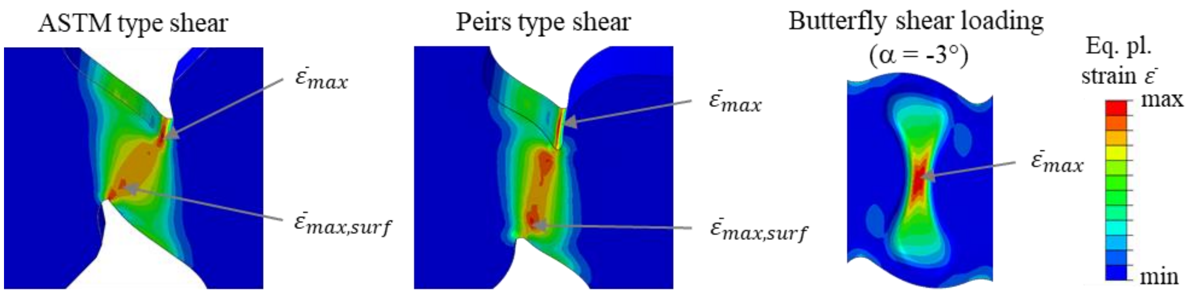

Figure 7. Local distribution of eq. plastic strain for different testing approaches (onset of fracture).

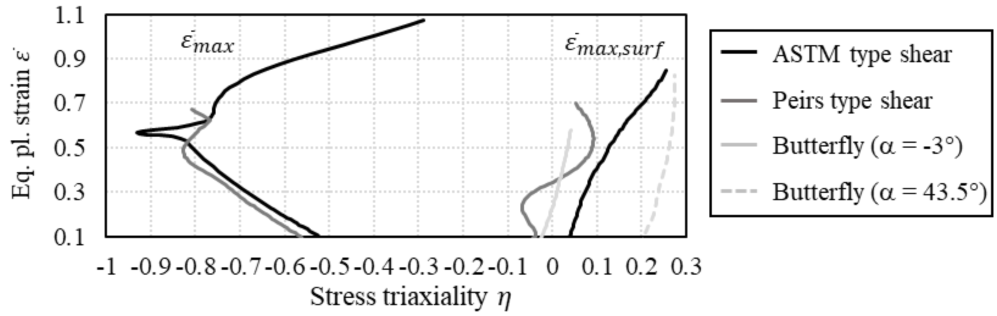

Figure 8. Stress developments for various testing approaches until onset of fracture at global and surficial highest eq. plastic strain $\bar{\varepsilon}_{max}$ and $\bar{\varepsilon}_{max,surf}$ as defined in Fig. 7.

7. Conclusion and outlook

The fracture behaviour of an AHSS CP800 sheet was investigated in this study within different testing approaches. On the one hand butterfly tests for different loading angles were performed, and on the other hand tensile tests with various geometries in terms of a notched, a holed and an ASTM type as well as a Peirs type shear sample. By means of those two experimental approaches, MMC models were calibrated. For further comparisons FLD were determined according to ISO 12004-2 as well as by evaluation of the highest section values.

The study shows the great dependence of the testing procedure on the results with regard to damage modelling. In terms of the used ASTM and the Peirs type shear specimen, the identification of the location of crack initiation is challenging. Both samples exhibit the highest strain localisation at the centre of the edge, where a pressure-superimposed stress condition is predominant. The notched and the holed tensile specimen show high stress variations, which needs strong averaging in order to identify one specific stress value going along with inaccuracies.

In contrast, butterfly specimen, which were carried out for varying loading angles in a wide stress range, showed a considerably more linear development of the stress state and each corresponds to plane stress conditions. Also the position of fracture initiation is clearly defined in the centre of the investigation zone for a specific stress state.

The influence of non-linear strain paths on failure behaviour is still undisputed. Further investigations in this regard are therefore planned for the future.

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References

[1] Li Y, Luo M, Gerlach J and Wierzbicki T 2010 Prediction of shear-induced fracture in sheet metal forming *J of Mat Proc Tech* **210** pp 1858–1869
[2] Behrens B-A, Bonk C and Peshekhodov I 2017 On modelling of shear fracture in deep drawing of a high-strength dual-phase sheet steel *J of Physics: Conf Series* **896** p 12125
[3] Bai Y and Wierzbicki T 2008 A new model of metal plasticity and fracture with pressure and Lode dependence *Int J of Plasticity* **24/6** pp 1071-1096
[4] Beese A M, Luo M and Li Y and Bai Y and Wierzbicki T 2010 Partially coupled anisotropic fracture model for aluminum sheets *Eng Fracture Mech* **77** pp 1128–1152
[5] Wierzbicki T and Xue L 2005 On the effect of the third invariant of the stress deviator on ductile fracture *Impact and Crashworthiness Lab Report 136*, Int J of Fracture
[6] Dell H, Gese H and Oberhofer G 2007 CrachFem - A Comprehensive Approach For The Prediction Of Sheet Metal Failure *AIP Conf Proc* **908** pp 165-179

[7] Peshekhodov I, Dykiert M, Vucetic M and Behrens B-A 2016 Evaluation of common tests for fracture characterisation of advanced high-strength sheet steels with the help of the FEA *IOP Conf Ser: Mat Sci Eng* **159** p 12014
[8] Peshekhodov I, Jiang S, Vucetic M, Bouguecha A and Behrens B-A 2016 Experimental-numerical evaluation of a new butterfly specimen for fracture characterisation of AHSS in a wide range of stress states *IOP Conf Ser: Mat Sci and Eng* **159** p 12015
[9] Behrens B-A, Brunotte K, Wester H and Dykiert M 2021 Fracture Characterisation by Butterfly-Tests and Damage Modelling of Advanced High Strength Steels *Key Engineering Materials* **883** pp 294–302
[10] Dunand M and Mohr D 2011 Optimized butterfly specimen for the fracture testing of sheet materials under combined normal and shear loading *Eng Fracture Mech* **78** pp 2919-2934
[11] Arcan M, Hashin Z and Voloshin A 1978 A method to produce uniform plane-stress states with applications to fiber-reinforced materials *Exp Mech* **18** pp 141-146
[12] ASTM B831 Standard test method for shear testing of thin aluminum alloy Products
[13] Peirs J, Verleysen P, Van Paepegem W and Degrieck J 2009 Novel pure-shear sheet specimen geometry for dynamic material characterization *DYMAT - Int Conf Mech and Phy Beh of Mat Dyn Loading* **1** pp 35-41
[14] International Standard ISO 12004-2 Metallic materials – guidelines for the determination of forming-limit diagrams
[15] Pathak N, Adrien J, Butcher C, Maire E and Worswick M 2020 Experimental stress state-dependent void nucleation behavior for advanced high strength steels *Int J of Mech Sc* **179**