Determination of Fracture Limit Line in Principal Strain Space by Shear Tests

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Abstract. The main goal of this paper was to define a new limit line, which expands Forming Limit Curve (FLC) more precisely Fracture Forming Limit Curve (FFLC). The new limit line was defined by damage models transformed from triaxiality-fracture strain space to the major/minor strain space and we focused on the shear area. Because FLC and FFLC have some limitations, for example, some Advanced High Strength Steels (AHSS) fractures before thinning. Another limitation can be seen on the left side of the diagrams in the shear region, where the part can break in the process without crossing the FLC or FFLC. The different shapes of samples were used for finding a new line of the FFLC and Deep Drawing Test (DDT) was used for verification. The fracture points from measurement were used for calibration of simple uncoupled damage models. The simple model means model, which is calibrated based on one or two measurements (tensile test or tensile test + shear test). This paper was used an Advanced High Strength Steel (AHSS) DP1000 sheet with a thickness of 0.8 mm for the experiments.

1 Introduction
Deep drawing is one of the most widely-used sheet metal working processes in the automotive industry. Special material has even been developed for this process which exhibits high elongation and reduced strength. The demands on them have been increasing over time, leading to the introduction of AHSS, including CP1000, DP1000, DP1200, and other grades. Materials such as DP1400 appear certain to be adopted in the coming years. These high-strength steels are mostly used for structural parts and not as appearance grades. Owing to the specifics of their manufacturing, they are not governed by the same principles as the deep-drawing materials of the past. Failure without appreciable necking is the primary problem. The reason is that necking, or local thinning, is normally an important indication of material behavior and represents a threshold that is plotted in Forming Limit Diagrams (FLD). In FLDs, limit values are plotted across a range of states from uniaxial tensile loading, through plane-strain states, to biaxial tensile loading with linear loading paths. Shear loading is not captured in these Forming Limit Curves (FLC). Also, a distinction must be made between in-plane shear and out-of-plane shear (Figure 1), [1]. The testing of standard specimens usually involves in-plane shear.
Figure 1. Definitions of shear mechanisms [1]

Figure 2. Translation between spaces

For practical purposes, the range should be expanded to include out-of-plane shear conditions, for instance by using a Deep Drawing Test (DDT). One of those who dealt with the out-of-plane shear region was Gorji [2]. He constructed FFLCs from data from a deep drawing test with small radii on the tooling. Hora [3] referred to the work of Wierzbicki and his collaborators Bai and Bao and their expansion of the Johnson-Cook damage model by incorporating Lode angle $\theta$ or Lode parameter $\xi$. This expansion brings the improved description of material behavior in different stress states.

Wierzbicki’s approach was previously studied and applied at COMTES FHT as part of a research project. The authors of this paper focused on the Fracture Forming Limit Curve (FFLC) which is defined in terms of fracture rather than mere thinning of the sheet. This paper deals with the shear deformation region, using simple damage models based on tensile test or tensile test + shear test for plotting the fracture limit line in this region. These models are defined in triaxiality-fracture strain space, therefore the limit curve was transformed to major-minor strains space, where was created the new line limit. These models will be compared with the result of DDT.

2 Fracture Forming Limit Curve

FFLC is determined using the same tests as those for FLC. However, the difference is that the test evaluation focuses on fracture and not just thinning of the sheet specimen. As a result, principal strain space can be populated in those regions where conventional Nakajima or Marciniak tests do not apply. Thanks to the mapping relationships published by Stoughton [2] and Lee [3] and elaborated in [4], one can translate fracture points to major/minor strain space (Figure 2). One can therefore acquire additional fracture points from conventional mechanical test data and extend the fracture limit line. The expression ‘conventional tests’ refers generally to standardized tests on both standard and non-standard test specimens.

3 Translation of FLC data into Triaxiality-Lode angle space

Using the following relationships, FLCs can be translated into other spaces [2], [3], [4]. Plastic strain increments are defined by equation (1). Where $\alpha$ is a ratio of principal strains (2), more precisely principal strain increments, assuming that the material is incompressible and isotropic. The material can then be characterized in terms of von Mises equivalent stress $\bar{\sigma}$ as in equation. Where $\sigma_{ij}$ are stress components, $\sigma_1$, $\sigma_2$, and $\sigma_3$ denote principal stresses, $S_{ij}$ is stress deviator components, $d\Lambda$ denotes the plastic multiplier, and $d\varepsilon_{ij}$ stands for plastic strain increments (3). In equation (2), the range of values of $\alpha$ is expected to include both negative and positive values. Relevant stress ratios (1) have been defined for further work. Triaxiality $\lambda$ can be formulated using stress ratio $\beta$ and the following equations, where $\sigma_{\text{in}}$ is the mean stress and $\bar{\sigma}$ denotes equivalent stress. The equivalent strain increment is defined in terms of increments of principal strain components. Substituting equation (1) produces an expression for the equivalent strain (5). Under plane stress conditions, the strain ratio $\alpha$ is constant. Equivalent strain $\bar{\varepsilon}$ can then be expressed in terms of principal strain $\varepsilon_1$ and parameter $\alpha$ (6). FLD can be translated into the space of $(\varepsilon, \lambda)$ using equations (6) and (4). The
procedure involves the use of equation (4) and elimination of the $\beta$ parameter among the three equations. Besides the above approach, one can also explore material behavior in other spaces. In the present case, the single most important alternative is the translation from triaxiality-strain space to principal strain space using a rearranged version of (4). Once the stress ratio $\beta$ has been determined using triaxiality, ratio $\alpha$ can be expressed. Based on the equivalent strain, the major strain was found using (6), and the then minor strain was determined from (1) as described in the literature [2], [3], [5].

$$\alpha = \frac{d\varepsilon_2}{d\varepsilon_1} = \frac{\sigma_2}{\sigma_1} = \beta$$

(1)

$$\sigma = \frac{1}{2} \left[ (\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 \right]$$

(2)

$$d\varepsilon_{ij} = d\Lambda \frac{\partial \sigma}{\partial \sigma_{ij}} = \frac{3}{2} \frac{d\Lambda}{\sigma} s_{ij}$$

(3)

$$\lambda = \frac{\sigma_0}{\sigma} = \frac{\beta + 1}{3\sqrt{\beta^2 - \beta + 1}}$$

(4)

$$d\varepsilon = \frac{4}{\sqrt{3}} \left[ \frac{1}{\lambda} + \lambda^2 \right] d\varepsilon_1$$

(5)

$$\varepsilon = \frac{2\varepsilon_1}{\sqrt{3}} \sqrt{1 + \alpha + \alpha^2}$$

(6)

4 Material
Fracture limit lines in the shear region were determined for the AHSS DP1000 sheet 0.8 mm in thickness. Material characteristics of the steels were determined using tensile testing (Figure 3a) on specimens oriented in three basic directions: Rolling Direction (RD), Diagonal Direction (DD), and Transverse Direction (TD). They are reported in the following Table 1, there is basic material characterization, as yield strength $\sigma_y$, ultimate tensile strength UTS, elongation A and reduction area RA. The purpose was to obtain fracture points for fitting material damage models, which were transformed into the major/minor space.

| Material | $\sigma_y$ [MPa] | UTS [MPa] | A [%] | RA [%] |
|----------|-----------------|-----------|-------|--------|
| RD       | 730             | 1049      | 14    | 11     |
| DD       | 706             | 1018      | 15    | 16     |
| TD       | 740             | 1048      | 9     | 12     |

5 Shear tests
Data for plotting the fracture limit line in the shear region were gathered by shear testing. These tests were performed on the various shape of specimens with in-plane shear being the dominant mechanism. One of them conformed to ASTM B831–05 (Figure 3b). The second specimen (Figure 3c) was specially modified for DP1000 steel because the crack initialized in the narrow part of the sample body instead of in the side bridges. Tests were carried out under quasi-static conditions (approximately $0.0001 s^{-1}$) and at room temperature. The effects of the different deformation rates in the shear tests and the Nakajima test were not taken into account. Two shear specimens from DP1000 steel were tested. Their fracture strain values were similar (Figure 4) The goal of the measurement was to obtain load paths for individual specimens and compare each other. Fracture points were another result of the measurement. They were used for fitting curves from various fracture models, ensuring that the resulting curve is continuous and smooth in its separate parts.
6 Damage models

The following models were used for plotting the fracture limit line: Bao-Wierzbicki [6] and MAX shear [7]. They were only applied to the triaxiality range less than 1/3 to provide a continuous description from pure tension through shear to compression.

6.1 Simplified Bao-Wierzbicki fracture model in the shear region

The Bao-Wierzbicki fracture model was calibrated against tensile tests only. Regions II and III were used, i.e. the triaxiality range of \(-1/3 < \eta < 1/3\) was covered. The fracture initiation locus for the Bao-Wierzbicki model is defined in terms of equations (7). Constant \(a\) is the plastic strain at fracture in pure shear (\(\eta = 0\)). Constant \(b\) is the plastic strain at fracture under uniaxial tension (\(\eta = 1/3\)). Constant \(b\) can be derived from tensile test data. It is the ratio of the cross-sectional area before the test \(A_0\) and at the fracture location after the test \(A_f\). Width and thickness after the test were measured by microscope. Constant \(a\) is calculated using the following formula. Details and the method by which the formula was derived are described by Lee [8].

\[
\varepsilon_{f,BWII} = b + (a-b) \left( \frac{\eta}{\eta_0} \right)^2 \quad \varepsilon_{f,BWIII} = \frac{a}{1+3\eta} 
\]

(7)

\[
\bar{\varepsilon}_{f,MSII} = C \left( \frac{1 + \alpha - \alpha^2}{1 - \alpha} \right)^{1/n}
\]

(8)

6.2 Simplified Max shear fracture model in the shear region

The MAX shear fracture model was calibrated against the shear test only (8). The model is also referred to as the Tresca criterion. It postulates that fracture occurs when the highest shear stress reaches a certain threshold. The model was applied over the triaxiality range \(-1/3 < \eta < 1/3\) where \(C\) is a material constant, which was calibrated by measurement.

7 Evaluation and transformation

Curves for both models were fitted to the fracture strain points found by mechanical testing (Figure 5). These points were obtained from the tensile test on the flat specimen and two shear tests (ASTM and optimized smile samples). Calibrated damage models as Bao-Wierzbicki and MAX shear were transformed into the principal strain space and it was produced a new segment of the fracture limit line in this space. With these models, the line appears smooth and continuous.
8 Deep drawing tests

Accuracy of the above-characterized models was validated against a test in a Deep Drawing Test Device (DDTD). The part drawn in the test was a triangle cup, as defined by Hora [3]. The purpose of the test was to assess fracture strain in the drawn part. Its shape produces various types of strain in the part, which enables the researcher to assess in-plane shear and out-of-plane shear states. A schematic illustration of the DDTD is shown in Figure 7.

The resolution of strain on the shape of the drawn cup is presented in Figure 8. The tooling in this experiment had a larger radius in the punch and the die than that published by Hora [5]. The R10 radius facilitates the drawing process and is acceptable for high-strength materials, but we are working on the dies with a smaller radius like Hora. The strain on the cup was evaluated using ARGUS and quality was dependent on the size of etched points and distance between them on the undeformed sheet. The used size was 1mm and the distance was 2mm.

9 Results and discussion

The main goal of the paper was defining a new fracture limit line, which expands Fracture Forming Limit Curve (FFLC). The new limit line was defined by damage models transformed from triaxiality-fracture strain space to the major/minor strain space and we focused on the shear area. These simple models could predict cracks in the shear area and their verification was performed by DDT. As noted, DDT produces various types of strain in the part and predominantly shear in the out-of-plane region, which cannot be measured by specimens, which were shown in Figure 3. A comparison of new fracture limit lines and strain distribution after the test draw was shown in Figure 6. The new fracture limit line from the Bao-Wierzbicki model provides an opportunity to used known damage models in principal strain space. The prediction of fracture was successful for
steel DP1000. Bao-Wierzbicki model has a good prediction, but its applicability will have to be verified for various conditions, such as holding force, strain rate, temperature, punch shape, etc.

10 Conclusions
A method for finding a fracture limit line for the shear strain region using fracture models was presented. It was derived from the definitions of the individual models. The models were calibrated against data from mechanical tests. These tests included tensile tests on flat specimens and specimens with a hole, shear tests, and plane strain tests. The measured fracture strains were plotted against triaxiality values. Fracture limit lines derived from the models were then translated into principal strain space. The line obtained with the Bao-Wierzbicki model was validated against a deep drawing test with a triangle cup. Thanks to the special shape of the cup, fracture occurred at the desired points. The procedure presented above was applied to the AHSS DP1000 sheet 0.8 mm in thickness.

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