Alternative characterization method for the failure behavior of sheet metals derived from Nakajima test

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Abstract. One sustainability approach in sheet metal forming is to reduce costs by increasing the reliability of the forming process by applying numerical simulations. These are based upon the finite element analysis and require specific characteristic values of the material. To improve the accuracy of the numerical model regarding the failure behavior, forming limit curves (FLC) which display the conduct and failure boundaries of sheet metals are characterized. Optical measurement systems are used to analyze the strain distribution and to generate a material dependent FLC. To reduce the amount of testing, the tensile test, the plane-strain test and the hydraulic bulge test are combined to characterize the uniaxial, plane, and the biaxial strain area and the forming limit. The results are summarized in the presented FLC, which is consequently compared with results from the standardized Nakajima test. The method is validated with different materials to compare a ductile (DX54D), a brittle (DP800) and a lightweight sheet metal (AA5182). That approach is used for the validation of the alternative and cost-effective FLC characterization. This eliminates the need for the Nakajima testing facility and the high utilization of a testing machine can save costs and time in creating the specific material data.

1. Introduction

Innovative lightweight materials, such as high-strength steels or aluminum alloys, differ from conventional steels in terms of their specific properties such as higher strength values at lower density. Simultaneously, they have a lower forming capacity which requires a precise analysis of their failure behavior, for example in deep drawing processes. Preliminary numerical simulations of the forming process have the potential to save costs and time by allowing to simulate the process parameters in advance and reduces defects. For the simulation a correct material characterization, modelling, as well as an optimization of the design process by means of finite element analysis (FEA) and a correct definition of the forming capacity is mandatory. Otherwise, components often fail due to low formability or unadjusted process design. One way to display the failure limits of sheet metal in forming processes is the forming limit curve (FLC), which was introduced by Keeler et al. in 1963 [1]. They investigated the forming limits in stretching processes by analyzing the deformation of drawn circles on the sheet metal. The positive small strain area of a common FLC was shaped by their research. Modern FLCs additionally contain the negative strain area, as shown in figure 1b [2]. Goodwin [3] developed a universal and simple tool for this purpose by resetting the limits: Instead of diffuse necking and the onset of "surface depression", Goodwin utilized the fracture as the limit. The standardized procedure for determining the FLC is specified in DIN EN ISO 12004-2 [4] with the different procedures according to Nakajima [5] and Marciniak [6]. Both utilize a blank holder system and a punch. A specimen is
deformed till fracture, hemispherically for the Nakajima test and with a flat punch in the Marciniak test setup. The different strain paths are characterized by using adapted specimen geometries. The designation of the specimen geometry is based on the width (specified in mm) of the parallel shaft. After cleaning the surface of the specimens, a stochastic pattern is applied with graphite spray onto a white base color. By using a stereo camera system, the strain progression on the surface of the specimens during the testing can be measured, digitized and analyzed using the digital image correlation (DIC) technique [4]. In production an additional safety factor of 10 % is used to the major strain value of the created FLC [7]. Even though the procedure has proven to be reliable for ductile materials, it shows weaknesses for brittle materials without a defined necking phase [8]. The main material properties such as anisotropy, strain rate sensitivity, strain-hardening and strength are influencing the failure behavior [9]. According to the research in [10], higher minor strain values can be achieved by increasing the Nakajima punch, because the bending rises with decreasing punch diameter. The position of the FLC decreases in the deep-drawing area (negative minor strain $\phi_2$) with increasing punch diameter, whereas the curve is transferred upwards in the stretching (positive minor strain $\phi_2$) [10].

The present paper focuses on the development of an alternative FLC using the stress-dependent characteristic tests and eliminates the Nakajima test. A minimum of three supporting points and associated tests are required to create the alternative FLC with quasi-linear strain paths: The negative small strain area is represented by an uniaxial tensile test, the plane strain area by a plane-strain test and the positive strain area is represented by the biaxial hydraulic bulge test (HBT). These tests replaced the Nakajima specimens S030, S110 and the S245. The difference between the required samples is shown schematically in figure 1b. With the characteristic values determined from the tensile tests in all three rolling directions (0°, 45°, 90°), the HBT and the respective anisotropy, material models according to Barlat 2000 (Yld20002-2d) [11] can be identified. The FLC can be determined without Nakajima tests by carrying out plane-strain tests and using the Nakajima-based evaluation method for the tensile specimens of the weaker rolling direction. Compared to the conventional method, the introduced FLC is carried out in a strain controlled manner in the uniaxial and plane-strain area. The alternative FLC is validated through comparison with the typical FLCs, according to DIN EN ISO 12004-2, generated from Nakajima tests [4].

![Figure 1](image_url)

**Figure 1.** Schematic setup a) of the Nakajima testing method with optical deformation measurement system and b) of the FLC with Nakajima and alternative specimens, according to [2]

2. Materials, experimental setup and procedure

2.1. Materials

For the present study three materials were investigated. As a ductile steel DX54D with a sheet thickness of 0.8 mm is selected as a reference material. DX54D is a mild steel for cold deep-drawing processes with a very good formability. Usually used in automotive industry for interior and exterior applications.
For the investigation of the failure behavior of brittle materials DP800 steel is used. This high strength steel is often applied for crash-relevant structures in the automotive industry. The sheet thickness is equal to 1.0 mm. The chosen lightweight material is an aluminum alloy AA5182 with a sheet thickness of 1.0 mm. This material is a naturally rigid alloy. These are in high demand for use in non-visible areas like structural components in automotive engineering. The three materials offer the chance to investigate a wide range of material properties due to their different material parameters. The material properties are given in table 1.

**Table 1.** Thickness ($t_0$), yield strength (YS), tensile strength (TS) and uniform elongation (UE) of the tested DX54D, DP800 and AA5182 sheets. The number of tested specimens, $n = 3$ in each case.

| Material   | $t_0$ [mm] | YS [MPa] | TS [MPa] | UE [%] |
|------------|------------|----------|----------|--------|
| DX54D      | 0.8        | 166.49   | 292.28   | 38     |
| DP800      | 1.0        | 580.15   | 872.35   | 12     |
| AA5182     | 1.0        | 120.54   | 265.22   | 21     |

**Figure 2.** Flow curves of DX54D, DP800, AA5182 from tensile tests (T) and schematically illustrated Portevin-Le-Chatelier-Effect (PLC) by AA5182

### 2.2. Nakajima test setup

Nakajima tests for the metals were performed on the Nakajima test setup in order to validate the FLCs in relation to the major and minor strain value [4]. To create a FLC with reduced number of tests, at least three geometries must be performed. A smaller number of geometries can be used as it is not necessary to describe a complete FLC [4]. Circular blanks with a diameter of 245 mm are cut out with a central parallel shaft with a defined width. In a simplified version the support points of the uniaxial (S030), the plane (S110) and the biaxial strain (S245) are essential. The Nakajima tests are performed on a standardized test facility and later compared with the alternative method for validation purposes. The test setup and a small FLC with the necessary specimen geometries are schematically shown in figure 1. The sheet is clamped between the blank holder and the die with a constant pressure of $F = 500$ kN to prevent material flow. The punch ($\phi 100$ mm) moves in a vertical direction with a test velocity of $v = 1.5$ mm/s to deform the specimen until it cracks. For the digital calculation of the characteristic strain values, the tests are recorded by using the optical strain measurement system Aramis from GOM (Germany). Like the specified range of the DIN EN ISO 12004-2 the sampling rate of the process is higher than 10 Hz [4]. The pictures per seconds of the Nakajima test setup are adjusted to 30. The notches of the Nakajima specimens depend on the failure direction of the material to be tested. In this respect, the notches for aluminum specimens are arranged parallel to the rolling direction, while they are placed perpendicular to the rolling direction for steel specimens. In the Nakajima test setup, special requirements regarding the tribological system are made. The friction should be close to zero in the bulge, therefore the lubrication system used is a sandwich system of teflon foils, polyvinyl chloride
(PVC) pad and grease. It also influence the location of the cracks in the specimens and is crucial for the validity of the tests and depends on the strain. Valid cracks must be located at a distance of less than 15 mm from the maximum dome height.

2.3. Tensile test setup

The uniaxial tensile test is standardized according to DIN EN ISO 6892-1 and is used to determine the flow curve for the identification of material models and is a decisive factor for simulations [12]. Tensile specimens with a test length of 50 mm were drawn to failure on a Z100 universal testing machine from Zwick AG (Germany). The constant strain rate for the steels is 0.400 %/s and 0.667 %/s for the aluminum alloy. The Aramis optical strain measurement system from GOM was used for the DIC with a sampling rate of 30 Hz. The tensile tests are carried out with the three materials. Following the Nakajima guideline, the rolling directions are selected depending on the materials. The steel specimens were cut out of sheets at 90° and the aluminum specimens 0° in the rolling direction.

2.4. Plane-strain test setup

For the analysis of the plane strain area, which is the lowest point of the FLC, notched tensile specimens were used. The radii are \( R_{PS} = 3 \text{ mm} \) with a parallel length of 1 mm. A plane strain area is generated in the center of the parallel shaft (30 mm) the minor direction of deformation. These tests were also performed on the universal test machine Z100 with strain rate of \( \frac{d \varepsilon}{dt} = 0.400 \%/s \) for the steels and \( \frac{d \varepsilon}{dt} = 0.667 \%/s \) for AA5182. Digital images of the entire test up to the crack were also taken with a sampling rate of 30 Hz and evaluated with the software Aramis. The notched area of the plane-strain specimens is schematically shown in figure 3a after forming.

2.5. Hydraulic bulge test setup

The hydraulic bulge test depicts a pure yield deformation state with an almost frictionless forming of the specimen up to the crack. Higher degrees of forming can be realized without considering the plane anisotropy. The circular blank with a diameter of 395 mm is clamped between the blank holder and the die (\( \varnothing 200 \text{ mm} \), \( R_{die} = 28 \text{ mm} \)) with a pressure of \( F = 3500 \text{ kN} \) and is bulged up to the crack by increasing the pressure of the oil. In the present study the hydraulic bulge tests were performed strain rate independent because of a modified maximal sampling rate of 6 Hz. The strain measurement is carried out optically on the surface with Aramis according to DIN EN ISO 16808. The tool is mounted onto a hydraulic press HPDZb 630 from Hydrap (Germany) [13].

2.6. Evaluation method

The position-dependent online evaluation method is based on the principle suggested by Bragard [14], using the DIC techniques and the collection of images from the beginning till fracture. On the image where the crack is visible, a line is positioned vertically to the crack, which is then transferred to the last image before the crack. The first cutting line is placed through the center of the crack. More cutting lines can be created. Nakajima specimens are created with up to two additional cutting lines on each side with a spacing of 2 mm. The analysis of the measured deformation distribution is carried out via these fixed
cross-sections lines. The number of lines can be adjusted to the geometry and size of the specimens. For the tensile tests, three lines with 1 mm spacing each were set throughout the specimen. For the plane-strain specimens, seven lines with equal spacing were selected, as shown in figure 3a. For the HBT, seven lines with 5 mm spacing were selected due to the larger size of the sheet in comparison of the others. This method is a modified Bragard method and schematically illustrated in figure 3b. The detailed evaluation method is provided in DIN EN ISO 12004-2 [4].

3. Results and discussion

The detailed values of the Nakajima tests and alternative FLCs are shown in figure 5. For the presentation of the FLCs, each experiment was conducted three times (n = 3) to calculated the mean value. The dashed line represents the FLC determined through the Nakajima method with three geometries (S030, S110 and S245), which describe the stress-strain ranges of the support points. The solid line depicts the FLC with the investigated alternative test procedure (T, PS and HBT) and the cross-section evaluation.

Due to the high forming capacity the FLCs of the ductile steel (DX54D) achieves a high major strain range and differs only minimal when compared to the Nakajima FLC, shown in figure 5a. The discrepancy occurs in the plane-strain area of the major deformation grade: According to the Nakajima method, the plane strain support point is $S_{110\varphi_1} = 0.401 \pm 0.011$ and $S_{110\varphi_2} = 0.007 \pm 0.002$. The minimum point of the FLC with the alternative method is $PS_{\varphi_1} = 0.439 \pm 0.026$ and $PS_{\varphi_2} = -0.009 \pm 0.001$ and is therefore displaced marginally into a higher major area, which corresponds to a later failure. The minimal standard deviation $sd = 0.002$ of the minor strain value of each method can be neglected. The crack of the alternative plane-strain specimen starts to propagate in the plane-strain area in the center of the parallel shaft. The crack location of both specimens, as shown in figure 4a (plane), are valid and represent the plane-strain support point of the FLCs. The uniaxial strain range, represented by the Nakajima specimen S030 and the tensile test, differ by a value of $\Delta \varphi_1 = 0.042$ and $\Delta \varphi_2 = 0.076$. In each specimen, a clear necking zone can be identified, as shown in figure 4a (uniaxial). The deviation of the biaxial points are $\Delta \varphi_1 = 0.026$ and $\Delta \varphi_2 = 0.030$. Despite the differences of the major and minor strain values, the FLCs overlap significantly and display only a lengthening in the uniaxial area and a shortening of the FLC in the biaxial area. The region between applicability and damage is the same for both FLCs and the alternative FLC is within the safety factor. From the present results, it can be assumed that the alternative method is applicable for the investigation of ductile steels.

The alternative FLC of the high-strength steel (DP800) is shifted with the support point of plane-strain of $S_{110\varphi_2} = 0.024 \pm 0.002$ to a more minimal minor strain value of $PS_{\varphi_2} = 0.006 \pm 0.001$ and under the safety factor of 10%. Deduced from figure 4b (PS-DP800), the crack initiation in the plane-strain specimen originates from the radii and is therefore invalid. Geometry S110 of DP800 reveals the formation of a multiple peaks in the strain distribution, illustrated by a second crack. Weaknesses appear in the performance of the tests for plane strain. Considering the displacement of the lowest support point, the major and minor strain values of the uniaxial region of S030 and the tensile test are almost superimposed. The biaxial strain area matches well and varies only minimally from $S_{245\varphi_1} = 0.263 \pm 0.010$, $S_{245\varphi_2} = 0.247 \pm 0.010$ to HBT$\varphi_1 = 0.266 \pm 0.011$ and HBT$\varphi_2 = 0.243 \pm 0.012$. In addition, the crack location of both tests is at the maximum dome height, which indicates a good test performance. In this material state, the alternative FLC shows deficiencies and more than 10% differences in the plane-strain area and resultant in the uniaxial area. Due to its brittle behavior and the formation of multiple peaks, DP800 shows weaknesses in both methods [8].

The most significant difference between the presented alternative FLC and the standardized Nakajima method is obtained for the aluminum alloy AA5182 with an exceeding of 10% safety factor from the Nakajima method, as shown in figure 5c. The FLC of the alternative method consequently exhibits a lower failure characteristic and the forming process is not fully exploited with this alternative FLC. The material fractures at lower major strain values with these test conditions. The support point in the plane-strain area is almost at minor strain equal to zero, $PS_{\varphi_2} = -0.001 \pm 0.001$ and thus differs by a value of $\Delta \varphi_2 = 0.026$ from the plane-strain region ($S_{110\varphi_2} = 0.027 \pm 0.001$) of the Nakajima.
experiment. With these three support points, the alternative FLC shifts to a minimized major strain area. The crack initiation of the plane-strain specimen of the aluminum alloy also shows the limitations of the test setup, as shown in figure 4c (PS-AA5182). The failure starts from the radii and not from the center region where the plane-strain is located. The uniaxial area differs mainly in the minor strain values from $S030\phi_2 = -0.075 \pm 0.004$ to $PS\phi_2 = -0.103 \pm 0.002$ and only marginally in the major strain area of $\Delta \phi_1 = 0.001$. The failure of the specimens occurred in a relatively sudden manner, without clear necking. The cracks of the HBT and Nakajima S245 specimens are nearly the same, as can be seen in figure 4c (biaxial). Also, in the biaxial area a lower alternative FLC is obtained compared to the Nakajima method which is reflected in the values $S245\phi_1 = 0.354 \pm 0.010$, $S245\phi_2 = 0.341 \pm 0.013$ to $HBT\phi_1 = 0.296 \pm 0.004$, $HBT\phi_2 = 0.282 \pm 0.008$. In each case a relatively biaxial range is present ($\phi_1 = \phi_2$). The weaknesses of the alternative method are probably due to the Portevin-Le-Chatelier (PLC) effect \[15\]. The PLC effect is responsible for the formation of instabilities in the strain distribution of this complex material. Flow figures are formed during deformation, which are caused by dynamic strain ageing and which could establish instabilities in the strain distribution, as shown in the flow curve of AA5182 in figure 2 \[8\]. Due to this Effect, 5XXX aluminum alloys are not used for decorative purposes.

Various specimen geometries, materials and machines were used to validate the alternative FLC with the Nakajima test setup. The different test setups resulted in varying tribological conditions. The friction sandwich system of the Nakajima tests differs from the friction influence of the HBT. No influential friction is present in the tensile test and plane-strain test. In addition, the bending effects on the respective examinations must be determined. The validation of the FLCs refers to varies materials as well as to

![Figure 4](image-url)

*Figure 4.* Investigated specimens of Nakajima test setup (S030, S110, S245), tensile (T), plane-strain (PS) and HBT specimens with the rolling direction of the material a) DX54D, b) DP800 and c) AA5182
different sheet thicknesses. No conclusion can be made about dependencies of the sheet thicknesses in relation of the alternative FLC.

4. Summary and outlook

In order to provide material parameters for a numerical simulation, such as Young’s modulus, the yield curve, the yield locus and the forming limit curve, different characterization tests are required. For the correct representation of the failure behavior, a forming limit curve can be generated by standardized Nakajima or Marciniak tests. In order to reduce costs and time in the generation of specific material data a new method was presented. The alternative FLC with the support points are modelled by the tensile test, the plane-strain test and the hydraulic bulge test, thereby eliminating the need for the Nakajima testing setup. In contrast to the Nakajima method, quasi-linear strain paths are achieved with the alternative FLC. According to the material model of Barlat 2000 (Yld2000-2d), the tensile tests and the biaxial stress-state test (HBT) can also be utilized for the material model. The comparison of the FLC of the standardized Nakajima method and the representation by the three stress and strain based characterization tests shows a varying consistency, depending on the different materials. The alternative FLC can represent the failure limits for ductile steels comparatively well. Weaknesses of the method are

Figure 5. Results of the investigation of a) DX54D, b) DP800 and c) AA5182 different sheet thicknesses. No conclusion can be made about dependencies of the sheet thicknesses in relation of the alternative FLC.
revealed for brittle and lightweight materials, which is a shared shortcoming of conventional Nakajima test.

Especially in the plane-strain area, further investigations like applications of other geometry parameters or of edge processing are required to achieve a more accurate replication of the Nakajima FLC. Sheet thickness variations also should be analyzed more detailed in further studies. The alternative FLC with the modified test method and the high sampling rate of the data offers additional potential to be applied for improved characterization of the failure behavior of sheet metals using pattern recognition methods. In addition, researchers are working on a time-dependent evaluation method for Nakajima methods. The results should be investigated in this regard. In the following investigations, bending effects on the individual tests should be analyzed.

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