

## Determination of Forming Limit Curves - Strain Path and Failure Analysis

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**Abstract.** With the goal to define a cost-effective and efficient process to identify adequate materials for sheet metal forming processes, it is crucial to evaluate the formability of materials. Forming limit curves (FLC) are used to analyze the forming and failure limits of sheet metals and dependence of the major ( $\epsilon_1$ ) and minor strain ( $\epsilon_2$ ) from the uniaxial stress-strain area through the plane-strain point to the biaxial strain area. According to ISO 12004-2, the FLC is performed by Nakajima or Marciniak tests. Due to the experimental setup and the preconditions, pre-stretching occurs in the specimens and bending and friction effect are the result. The determination of the onset of necking (FLC) results mathematically from a “best-fit inverse parabola” on section lines. In addition, the failure point, i.e. the maximum strain value one frame before failure, is also analyzed. In contrast, tensile, notched tensile and hydraulic bulge tests, which are known in the literature as basic tests for the determination of the FLC, exhibit a linear strain path evaluation. These tests are used in this investigation as an alternative for the determination of the FLC. The behavior of the various strain paths of Nakajima and the alternative methods are examined for necking and cracking. Furthermore, the fracture surfaces are investigated by confocal laser scanning microscopy to identify influences of the different FLC methods on the fracture mechanics. FLCs were conducted with the Nakajima and the alternative FLC characterization method for a ductile steel (DX54D). To ensure transferability, the tensile tests are also performed with a high-strength steel (DP800). The FLC of the ductile steel, generated through the alternative method, exhibits a similar shape to the Nakajima generated FLC with the advantage of a constant strain rate leading to linear strain paths and a lower number of tests. The same results are achieved for the uniaxial strain tests with DP800.

### Introduction

An efficient process design for sheet metal forming in industrial applications can cut down on costs and save material. The utilization of a numerical process analysis can contribute to this end. In order to achieve an accurate numerical model to implement the forming process, a material characterization is required. This includes the determination of the maximum formability of a material. Gensamer [1] studied the value of the relationship between the measured mechanical characteristics of metals and their mechanical behavior in 1946, by creating a diagram depicting information on deformation at various loading conditions. One way to determine the formability and consequently the failure limits of a sheet metal is the forming limit curve (FLC). The FLC was introduced by Keeler et al. in 1963 [2]. Based on his research the methodology to generate a FLC was improved and extended through subsequent investigation, e.g. by Goodwin [3] and Col [4]. The FLC represents the onset of necking as the failure, since it constitutes as the stage before undesirable cracking. Fig. 1 shows the FLC schematically and represents the different strain areas, from the uniaxial to the plane until the biaxial. The common setup for standardized FLC determination is described in ISO 12004-2 [5] and is based on the test setups on Nakajima [6] and Marciniak [7], both utilizing a blank holder system and a punch. To generate the FLC, a position-dependent online evaluation, the so called “cross-section evaluation” method, is used and is based on the digital image correlation (DIC) technique [5]. DIC is an optical methodology that is used to record 2D or 3D measurements of changes in sequential images by using a calibrated camera system. For the

application of this technique, the optical measurement system Aramis (GOM GmbH, Germany) is used. To that end, a white base color and a stochastic pattern with graphite spray is applied on the surface of the specimen, which is then deformed until fracture, hemispherically in the Nakajima and with a flat punch in the Marciniak test setup. To realize the different strain paths, the specimens have a specific geometry and are differentiated by their widths of the parallel shaft, e.g. S030 represents the uniaxial strain area with a parallel shaft of 30 mm. The FLC standard evaluation is suitable for materials with pronounced necking zones, but the method shows weaknesses for materials without a defined necking phase, like high-strength steels [8]. Besides this criterion, the tribological properties between punch and sheet play an important role in the Nakajima test setup. It is known from literature [7] that the deformation history has an influence on the forming limit. The Nakajima FLC is based on the assumption of linear strain paths, which is only partially present in reality. The bending effect through the bulged punch, the friction and the biaxial pre-stretching influence the strain paths negatively. In the standard, a correction of the nonlinear deformation, curvature and contact pressure is recommended [5]. To analyze the influence of specimen curvature in FLC, Kuppert [10] examined the Marciniak and Nakajima specimens with tensile and hydraulic bulge tests (HBT) with respect to their strain paths. Metallographic investigation of Nakajima specimens and their microstructure profile towards fracture were performed by Tasan et al. [11]. Their work contribute to the physical understanding of sheet metal micro-mechanics by different strain path histories. The relationship between microstructure evolution, localization of necking and the fracture was investigated. Affronti et al. [12] examined different strain stages and drawing depths of Nakajima experiments. The specimens were examined with scanning electron microscopy (SEM) in order to find a correlation between the surface evaluation of the material and the FLC to define the onset of necking. In [13], an alternative characterization method for FLCs was introduced, in which the failure limit curve for ductile steels are well represented. Here, the Nakajima tests with their respective specimen geometries (S030, S110 and S245) were replaced by tensile, notched tensile and hydraulic bulge tests. The advantages of these experiments are the constant strain rate, the almost frictionless forming and the fact that these tests are part of standardized material characterization to determine the elastic-plastic material behavior.

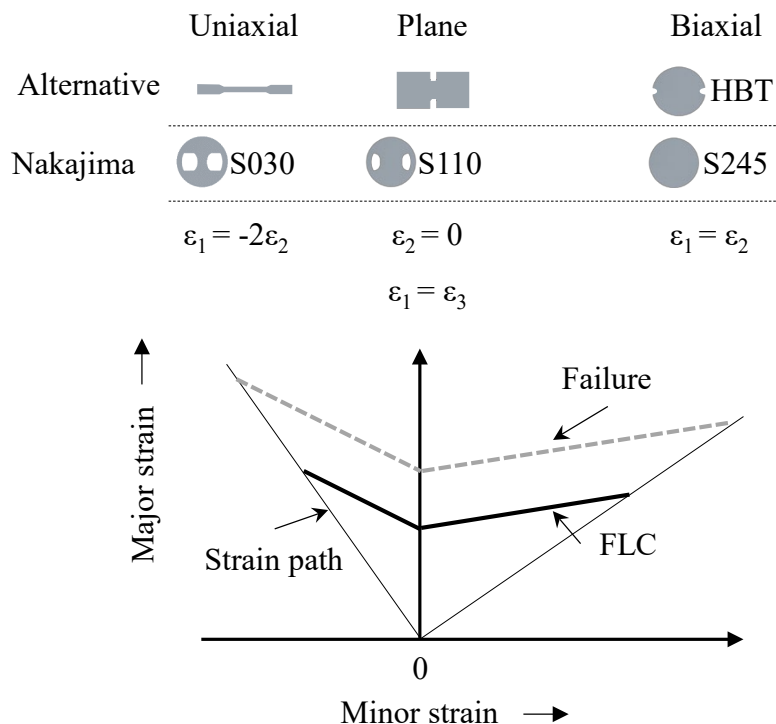


Figure 1: Schematic setup of the forming limit curve (FLC) and the failure curve with Nakajima and alternative specimens (tensile, plane-strain and HBT)

Within this contribution, the strain path histories from Nakajima tests and the tensile, notched tensile and HBT are compared and investigated in regards to their different forming histories and influence on the forming limits and fracture. The FLC is determined according to the standard with the "best-fit inverse parabola". In addition, the maximum strain value is referred to as the failure limit. To this end a ductile steel DX54D is used for the verification. To analyze the forming limit and the strain path in the uniaxial strain area of a less ductile sheet material, the steel DP800 is utilized. All experiments were conducted until failure. The recordings are made with the optical strain measurement system Aramis. In addition, microscopic height profile measurements of the crack structures of the individual specimens are performed to analyze the fracture mechanics. The height profile measurements were conducted with the digital microscope VHX-2000 (Keyence Corporation, Japan) with a 10 x magnification. The plane-strain test can map the minimum support points of the standard method. The reduced number of tests and materials, as well as a linear strain path of the alternative method, make it a viable option for generating cost-effective FLCs.

### Materials, Experimental Setup and Procedure

**Materials.** In the present study, two materials were investigated. As a ductile steel, DX54D with a sheet thickness of 0.8 mm was selected. It is regularly used for deep-drawing processes for interior and exterior applications in automotive industries due to its good formability. Additionally, Nakajima and tensile tests were performed with a less ductile steel DP8000 with a sheet thickness of 1.0 mm. This material finds usage in crash-relevant structures, e.g. the A-pillars of cars. The material parameters are given in Tab. 1.

*Table 1: Thickness ( $t_0$ ), yield strength (YS), tensile strength (TS) and uniform elongation (UE) of the tested DX54D and DP800 sheets;  $n = 3$*

Material	$t_0$ in mm	YS in MPa	TS in MPa	UE in %
<b>DX54D</b>	0.8	166.5	292.3	38
<b>DP800</b>	1.0	580.2	872.4	12

**Nakajima test setup.** FLCs of the materials were generated using the Nakajima test setup in order to validate the here presented alternative FLC characterization method. The standardized Nakajima test is performed on a test facility according to ISO 12004-2, including a blank holder, a die and a punch ( $\varnothing$  100 mm). The sheet is clamped with a constant pressure of  $F = 500$  kN to prevent material flow, while the punch moves in vertical direction ( $v = 1.5$  mm/s) to deform the sheet until failure. In [5] at least five support points are specified for the generalization of a FLC but a minimum of three support points is sufficient and will be used in this context. The specimens are 245 mm diameter circular sheets, cut out with a parallel shaft of different widths to represent different strain conditions. The used specimen geometries are, the negative minor strain (S030: parallel width of 30 mm), the plane-strain (S110: parallel width of 110 mm) and the biaxial strain condition (S245: full test specimen) and are schematically depicted in Fig. 1. The notches of the specimen depend on the weaker rolling direction of the sheet. For steel specimens, these are thus perpendicular to the rolling direction [5]. The Nakajima tests were conducted until fracture of the material with attention to a valid crack location. Therefore, a lubrication system of a sandwich system with Teflon foils, polyvinyl chloride pad and grease is used to reduce friction. The tests were recorded with the optical strain measurement system Aramis with a constant sampling rate of 30 Hz.

**Alternative FLC.** The tensile, plane-strain tests and HBT are combined to an alternative characterization method derived from Nakajima tests and are able to map the FLC with three different specimens and two different test setups. All tests were carried out with DX54D whereas with DP800 only the tensile tests were performed. Focus was set on the investigation of the strain paths in the

uniaxial area. The presented negative minor strain area of each forming limit diagram (FLD) was performed by the uniaxial tensile tests according to ISO 6892-1. The specimen geometry with a test length of 50 mm, according to DIN 50125 was prepared with a stochastic pattern to measure the point shifting in Aramis. As the standardized FLC represents the onset of necking, the Nakajima specimen geometry is designed according to the weakest rolling direction [5]. Therefore, the presented tensile tests were performed according to this configuration. The lowest point of the FLC, the plane-strain area, is depicted by notched tensile specimens (plane-strain specimens), with a radii of  $r_{ps} = 3$  mm and a parallel length of 1 mm and are cut parallel to the rolling direction. The tensile and the plane-strain tests were performed using a Z100 universal testing machine (Zwick AG, Germany) with a constant strain rate of 0.400 %/s for the steel specimens, according to SEP1240 [14]. The frequency differentiating are not investigated in this contribution. An Aramis system serves as the optical strain measurement method of the specimens with a fix sampling rate of 30 Hz for the DX54D steel and 6 Hz for DP800. For the alternative FLC, the biaxial strain area was mapped through the hydraulic bulge test, using a tool mounted onto a hydraulic press HPDZb 630 (Hydrap Pressen Maschinenbau GmbH, Germany). The circular blank ( $\varnothing$  395 mm), which is clamped between the blank holder and the die ( $\varnothing$  200 mm,  $r_{die} = 28$  mm) with a force of  $F = 3500$  kN, is bulged up to the crack by increasing the oil pressure. Due to the test setup, it is an almost frictionless forming process. According to ISO 16808, the constant strain rate is measured optically in Aramis.

**Evaluation method.** An overview of the current method for evaluating a standardized FLC can be found in ISO 12004-2. The here presented method for evaluating the results is the so-called “cross-section” method, which uses the DIC techniques and is based on the research of Bragard et al. [15]. It is a position-dependent online method by analyzing the images: A cutting line is positioned vertically to the center of the crack on the first image where the crack is visible and transferred to the last image before the crack. More cutting lines, can be created depending on the geometry of the specimen. Via these fixed cross-section lines, the analyses of the measured deformation distribution and an interpolation to locate the major and minor strain values to map the FLC is carried out. The Nakajima specimens are evaluated with three cutting lines with a distance of 2 mm. The same evaluation method is used with the alternative method. Both tensile tests were set with three lines and 1 mm spacing. The HBT was set with seven lines with 5 mm spacing because of the larger size of the specimen in comparison to the others. The cutting lines are also used to map the maximum point of strain before failure. The first cutting line is placed through the maximum strain value in the image before crack. Therefore, this value is named failure point (FP) in this context and represent the failure.

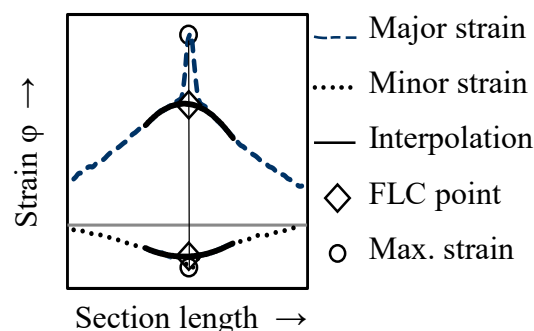


Figure 2: Schematic cross-section evaluation with the FLC point, maximum strain value represents the failure point (FP) measured by the last picture before failure

## Results and Discussion

The FLCs of the ductile steel (DX54D) produced with the standard Nakajima experiments and the alternative tests are shown in Fig. 3. The black lines represent the alternative method (tensile strain, plane-strain and biaxial strain), the gray lines show the standard method (S030, S110 and S245), where the course of the strain paths can be traced by the dashed lines. The FLCs are depicted as solid

lines in their respective color. The maximum strain value via Aramis is shown as circles and represents the failure of the sheet metal. Each experiment was conducted three times ( $n = 3$ ) and are shown as smaller points as the mean value. Due to its ductile behavior, the material DX54D achieves a high major strain value, which indicates its good deep-drawing properties. Considering the standard FLC support points, the alternative method reproduces the onset of necking well, with a maximum deviation of  $\Delta\epsilon_1 = 0.049$  and  $\Delta\epsilon_2 = 0.009$  for the uniaxial strain area. As a consequence of the biaxial pre-stretching of the Nakajima specimens with notches (S030, S110), higher minor strain conditions are achievable with the alternative method. In contrast, the tensile specimens experience no friction and bending which leads to no curvature, so the linear strain path occurs right at the beginning of the deformation in the uniaxial area. It should be noted, that for the uniaxial strain area a S030 Nakajima geometry is compared with a tensile test specimen with a web width of 12.50 mm. Other web widths can be created for approximation but without difference at the start of the strain path (pre-stretching). The plane-strain specimens of the alternative method exceeded the S110 geometry in its major strain value with a difference of  $\Delta\epsilon_1 = 0.038$ . Similarly, this can be attributed to the pre-stretching of the Nakajima specimen into the biaxial area at the strain path. The difference between the onset of necking (FLC) and the maximum strain value (failure) is higher for the S110 ( $\Delta\epsilon_1 = 0.163$ ) than for the alternative method ( $\Delta\epsilon_1 = 0.020$ ) which presents the challenges of the plane-strain test. Here, special attention must be paid to the boundary conditions otherwise, crack location will not be central and therefore hard to detect. At the biaxial strain area for the Nakajima test the failure lies clearly above the onset of necking in major strain direction. This can be due to the friction and the greater curvature of the bulge. This lies in contrast to the results achieved via the alternative method where the onset of necking (FLC) and the maximum strain value (failure) from the HBT are located very close and linear (almost frictionless test setup).

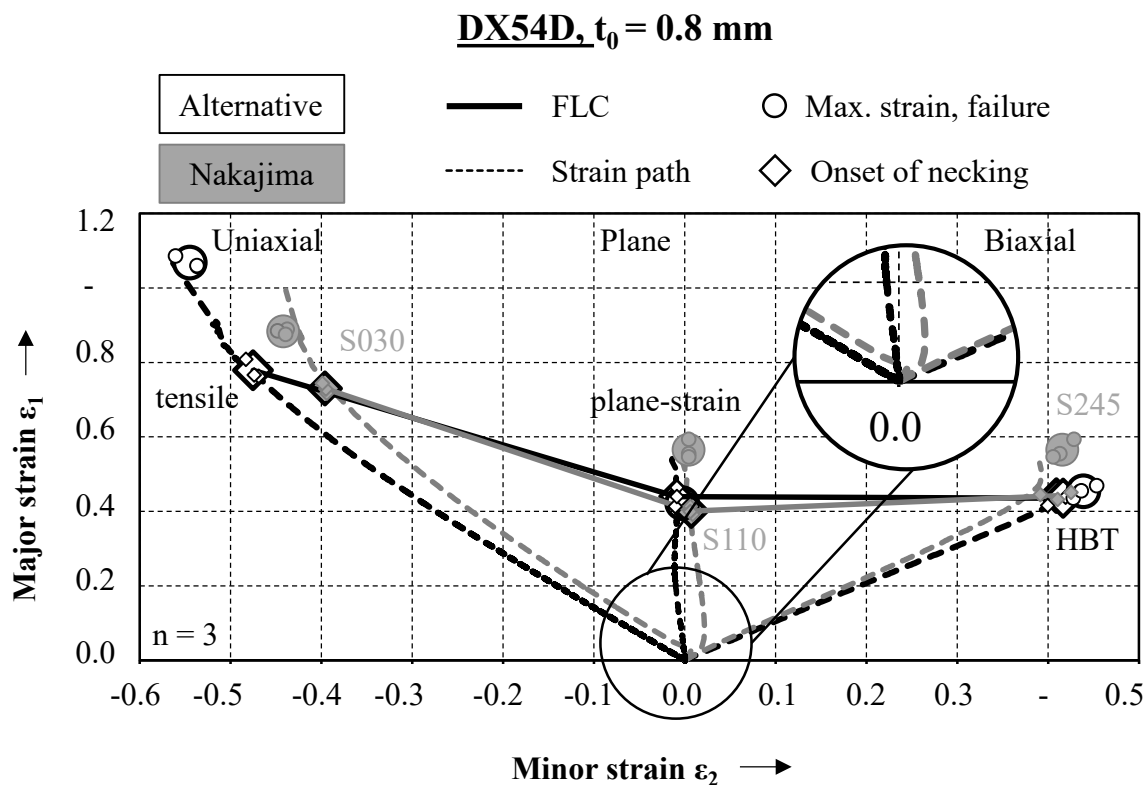


Figure 3: Results of the investigation of DX54D,  $n = 3$

The uniaxial strain area of the high-strength steel DP800 depicted by the tensile and the S030 Nakajima specimens ( $n = 3$ ) are shown in Fig. 4. For this material, only the experiments for the negative minor strain area were performed for the strain path analysis, where the FLC point  $\epsilon_1 = 0.275$ ,  $\epsilon_2 = -0.092$  for the S030 geometry and  $\epsilon_1 = 0.276$ ,  $\epsilon_2 = -0.112$  for the alternative method was reached. The tensile tests were carried out with a sampling rate of 6 Hz and the Nakajima tests with 20 Hz. The uniaxial FLC point of the tensile tests shifted further towards the negative minor

strain value due to the uniaxial strain condition in length. Furthermore, the strain progression of the Nakajima tests are not continuously linear. At the beginning, a pronounced pre-stretching into the biaxial area can be observed. After pre-stretching, when the minor strain values decreases, until the onset of necking (FLC) the curve is almost linear. This pre-stretching occurs due to punch geometry and clamping of the Nakajima test setup. This pre-stretching is non-existing in the tensile tests. For the Nakajima specimens the value for the major strain from the point of the onset of necking increases sharply compared to the decrease in minor strain until failure. The weaker transverse necking of the Nakajima test setup is cause for this. The curve from the FLC point and the maximum strain value of the tensile tests in comparison is relatively linear.

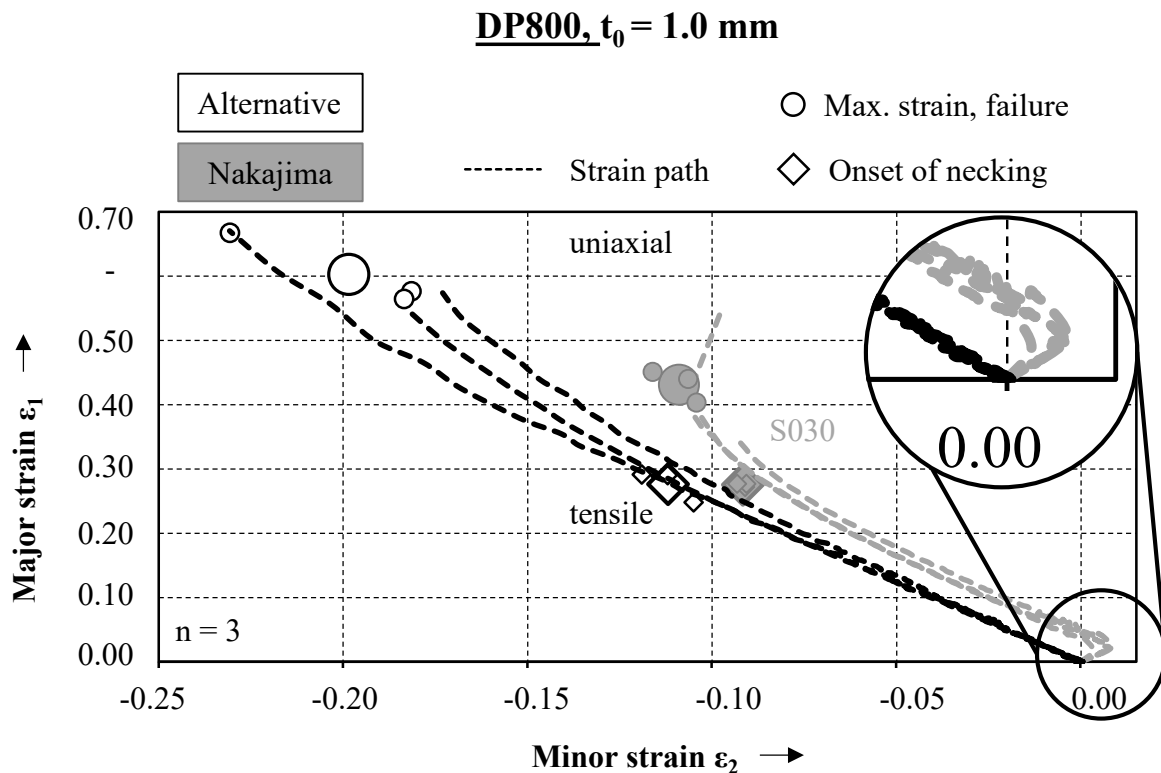


Figure 4: Uniaxial strain area of DP800 steel with Nakajima specimens S030 and tensile tests,  $n = 3$

In [13] the focus was set on the valid crack initiation of the specimens. In this paper the fracture profiles generated through the alternative FLC method and the Nakajima tests setup are analyzed and displayed in Fig. 4. Results from the height profile measurements indicate that the behavior of the DX54D steel is evidently distinguishable from the behavior of the DP800 steel. DX54D exhibits a sharper fracture surface due to stronger necking in direction of the sheet thickness compared to the DP800 steel. Evaluating the measurements performed on the tensile, plane-strain and HBT experiment specimens, a sharper fracture is noticeable in contrast to the standard geometries. This can be ascribed to the test setup and the stronger necking in the direction of the sheet thickness. Especially in the standard tensile tests, a strong pronounced necking is noticeable compared to the S030 geometry. The Nakajima specimens have a relative planar fracture surface, which indicated a sudden crack initiation. These specimens experienced a combined strain and bending deformation due to the higher bending effect on the upper surface. The cracks grow in the direction of the inner surface. As depicted in Fig. 3, the increase of the major strain in S245 of DX54D after necking leads to abrupt failure, while the HBT specimens experiences uniform stretching.

The fracture behavior of DP800 differs significantly from the DX54D results due to the brittle behavior of the material. Necking and sheet thinning is not as pronounced with DP800. In the Nakajima test, an abrupt failure in the form of a planar fracture is visible, while in the tensile tests a

discontinuity between the edge and the center of the sheet thickness is evident. Again, there is a slight higher profile on the side facing the punch, due to the bending effect in the S030 geometry.

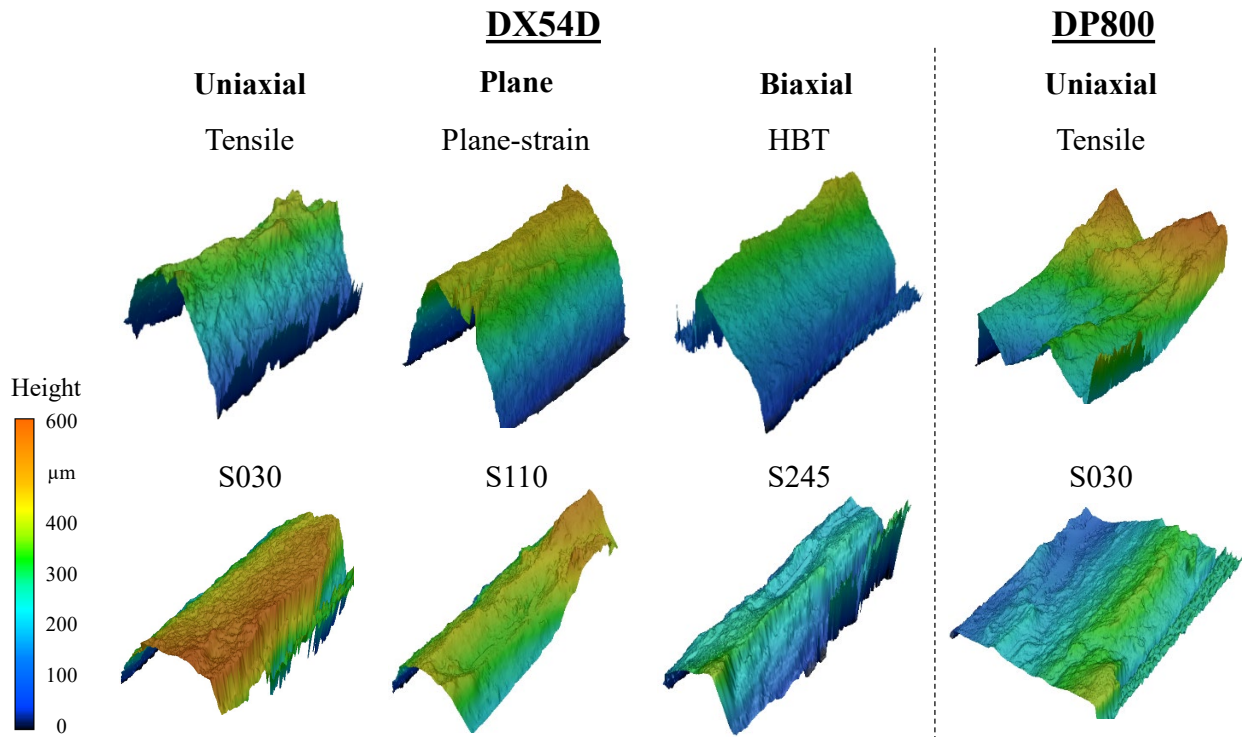


Figure 5: Height profile measurements of the Nakajima and the alternative FLC experiments (tensile, plane-strain and HBT) with DX54D and DP800

## Summary and Outlook

Within this contribution, the strain path evaluation of the standard Nakajima tests and an alternative method by using tensile, notched tensile and hydraulic bulge test specimens for generating a forming limit curve were investigated. The alternative FLC characterization method persuades with a linear strain path progression in comparison to the Nakajima generated FLCs. This is substantiated by the results of the fracture surface measurements, where lesser bending effects are visible in the height profiles of the alternative method specimens. The uniaxial and plane-strain area of the alternative method is displaced further to the left due to the non-existent pre-stretching of the specimens. The biaxial point (FLC) lies in a larger minor strain range in contrast to the standard. The area between FLC and failure point is more linear than the Nakajima specimens in all alternative experiments. This conclusion could be drawn for both, the DX54D and the DP800 material. Although generating promising results, the alternative methods exhibits limitation especially in mapping the plane-strain area where the localization of the crack is dependent on strict boundary conditions. The plane-strain support point should be investigated by another experimental setup, e.g. other geometries of the notched tensile specimen.

Further investigations on strain rate sensitive materials such as AA5182 are required to complement the results of the ductile and brittle steels and to qualify the alternative method for a wider range of materials. In the research, different frequencies were recorded with Aramis. A variation of alignment could be investigated with respect to the maximum strain value.

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**References**

- [1] M. Gensamer, Strength and Ductility, 1946, Transactions of the American Society for Metals, 36, pp. 30-60
- [2] S.P. Keeler, W.A. Backofen, Plastic instability and fracture in sheets stretched over rigid punches, 1963, ASM Trans Q., pp. 25–48
- [3] G.M. Goodwin, Application of Strain Analysis to Sheet Metal Forming Problems in the Press Shop, 1968, SAE Technical Paper Series
- [4] A. Col, FLCs: past, present and future, Japanese Deep Drawing Researg Group, Japan Society for Technology of Plasticity, Iron and Steel Institute of Japan, IDDRG 2002, Global Enviroment and Sheet Metal Forming, 2002, pp. 107–125
- [5] International standard ISO 12004-2:2021, Metallic materials –Determination of forming-limit curves for sheet and strip – part 2: Determination of forming-limit curves in the laboratory
- [6] K. Nakajima, T. Kikuma and K. Hasuka, Study on the formability of Steel Sheets, 1968, Yawata Tech Report 264, pp. 8517-5830
- [7] Z. Marciniak, Stability of plastics shells under tension with kinematic boundary condition, Arciwum mechaniki stosowanej, 1965, pp. 577–592
- [8] E. Affronti, Evaluation of failure behaviour of sheet metals, Erlangen: FAU Studien aus dem Maschinenbau, vol 342, 2020
- [9] W. Müschenborn, H.-M. Sonne, Einfluß des Formänderungsweges auf die Grenzformänderungen des Feinblechs, Steel Research International, vol.46, 1975, pp. 597–602
- [10] A. Kuppert, Erweiterung und Verbesserung von Versuchs- und Auswertetechniken für die Bestimmung von Grenzformänderungskurven, Erlangen: FAU Studien aus dem Maschinenbau, vol. 267, 2015
- [11] C.C. Tasan, J.P.M. Hoefnagels, C.H.L.J. ten Horn, M.G.D. Geers, Experimental analysis of strain path dependent ductile damage mechanics and forming limits, in Mechanics of Materials 41, 2009, pp. 1264-1276
- [12] E. Affronti, M. Merklein, Metallographic analysis of Nakajima tests for the evaluation of the failure developments, 17<sup>th</sup> International Conference on Sheet Metal, 2017
- [13] D. Kohl, M. Merklein, Alternative characterization method for the failure behaviour of sheet metals derived from Nakajima test, IDDRG, Germany, 2021
- [14] Stahlinstitut VDEh. Prüf- und Dokumentationsrichtlinie für die experimentelle Ermittlung mechanischer Kennwerte von Feinblechen aus Stahl für die CAE-Berechnung(1240). Düsseldorf: Stahleisen GmbH, 2006
- [15] Bragard A, Baret J C and H. Bonnarens, Simplified Technique to Determine the FLD on the Onset of Necking, 1972, C.R.M, pp. 53-63