NOVEL APPROACH FOR PREDICTION OF LOCALIZED NECKING
IN CASE OF NONLINEAR STRAIN PATHS

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Abstract. Rising customer expectations regarding design complexity and weight reduction of sheet metal components alongside with further reduced time to market implicate increased demand for process validation using numerical forming simulation. Formability prediction though often is still based on the forming limit diagram first presented in the 1960s. Despite many drawbacks in case of nonlinear strain paths and major advances in research in the recent years, the forming limit curve (FLC) is still one of the most commonly used criteria for assessing formability of sheet metal materials. Especially when forming complex part geometries nonlinear strain paths may occur, which cannot be predicted using the conventional FLC-Concept. In this paper a novel approach for calculation of FLCs for nonlinear strain paths is presented. Combining an interesting approach for prediction of FLC using tensile test data and IFU-FLC-Criterion a model for prediction of localized necking for nonlinear strain paths can be derived. Presented model is purely based on experimental tensile test data making it easy to calibrate for any given material. Resulting prediction of localized necking is validated using an experimental deep drawing specimen made of AA6014 material having a sheet thickness of 1.04 mm. The results are compared to IFU-FLC-Criterion based on data of pre-stretched Nakajima specimen.

1. Introduction

Accurate prediction of localized necking is crucial for time, cost and quality effective production of advanced stretch- and deep drawing components. In the recent years, design of modern sheet metal components, especially for car body outer panels has become more complex. Due to increased customer demands regarding part design, weight and stiffness, robust process layout for such components has become more complex than ever. Forming of sharp radii and use of new lightweight sheet metal materials are current challenges for tool design and process layout. Since the late 1990s use of modern Finite-Element-Method (FEM) has become an industry standard for tool and process design in sheet metal forming. While computational time and modelling techniques have gradually advanced from the early models with many limitations like maximum number of elements, element formulation and contact definitions, the most commonly used criterion for prediction of localized necking is still the Forming Limit Curve (FLC) presented in the 1960s by Keeler et al. [1]. Determination of the FLC is standardized in ISO 12004-2 which can be applied for sheet thicknesses between 0.3 and 4.0 mm. Since the works of Müschenborn and Sonne [2] or Arrieux [3] it is well known that conventional FLC is not valid for complex forming processes exhibiting nonlinear strain paths. Contrary to lab scale determination of FLC using Nakajima- or Marciniak-Test setup most industrial sheet metal parts exhibit some critical nonlinear strain paths. This is even more the case when it comes to multi-step forming processes. Due to the fact that onset of localized necking in case of nonlinear strain paths cannot be assessed using conventional FLC, problems in production of such components may appear. Badly designed forming tools bear the risk of producing sheet metal parts with areas of localized necking or even fractures resulting in increased scrap production or not satisfying fulfilment of time, cost and quality expectations of tool production itself.

Up to now many approaches have been presented in order to take the effect of nonlinear strain paths into account. Some of the most commonly known approaches are Generalized Forming Limit
Concept (GFLC) presented by Volk et al. [5,6,4], Modified Maximum Force Criterion by Hora et al. [7,8] and Müschenborn and Sonne [2] approach as well as IFU-FLC-Criterion [9], [10]. Since the first publication of IFU-FLC-Criterion in 2012 work has focused on improvement of prediction quality of localized necking and reduction of experiments necessary for calibration. This is especially important for industrial application of this approach as time and cost effective calibration of the failure criterion have been the major drawback of this model.

2. Prediction of localized necking in sheet metal forming using Forming Limit Curve

Many approaches for prediction of onset of localized necking have been presented in the recent years. Most of them show promising results regarding improved failure prediction in sheet metal forming simulation. Despite these advances in modelling technology, improved failure prediction usually comes alongside with increased number of experiments necessary for calibration of these models. Regarding the IFU-FLC-Criterion for nonlinear strain paths, in the first version 165 Nakajima experiments were necessary for calibration of this model to be adjusted for one material. This huge number of experiments was the major drawback of this approach. In order to reduce calibration time and experimental costs, further variations have been presented, first by Werber et al. and then by Drotleff and Liewald in 2015 [11]. Experiments necessary for calibration of four approaches of IFU-FLC-Criterion presented are summarized in Table 1. Despite these efforts, number of experiments necessary for calibration of the criterion is slightly high. In case of version 2 only three extremal points of the FLC are considered and the FLC is determined using linear interpolation between these points. The number of experiments for calibration of version 2 could be reduced down to 39 instead of 165 in the first version. Versions three and four have been developed to combine very good prediction of localized necking based on a lower number of experiments for calibration of the criterion.

Table 1: Experiments necessary for calibration of IFU-FLC-Criterion

| Levels of pre-strain | Version 1 | Version 2 | Version 3 | Version 4 |
|----------------------|-----------|-----------|-----------|-----------|
| 0-FLC                | 1 FLC (5 points with 3 repetitions) | 1 FLC (3 points with 3 repetitions) | 1 FLC (5 points with 3 repetitions) | 1 FLC (5 points with 3 repetitions) |
| Secondary Nakajima-specimen | FLCs (5 points with 3 repetitions) with 10 different levels of pre-stretching | Plane-strain Nakajima-specimen (3 repetitions for one level of pre-strain) | Plane-strain Nakajima-specimen (3 repetitions for one level of pre-strain) | Plane-strain Nakajima-specimen (3 repetitions for one level of pre-strain) |
| Σ                    | 165       | 39        | 45        | 45 + 15 (FLC with high amount of pre-strain) |

For prediction of onset of localized necking for arbitrary nonlinear strain paths the criterion is calibrated using two step nonlinear strain paths created in lab scale specimen. Pre-stretching sheet metal specimen with a diameter of 340 mm in a scaled up version of the Marciniak-setup and cutting out secondary Nakajima-specimen is one way to create nonlinear strain paths. Since this procedure is very time and material consuming, there is a need for a new calibration strategy based on a reduced number of experiments. In this paper a new performed release of IFU-FLC-Criterion for prediction of localized necking is presented. This is achieved by combination of the approach for FLC determination using tensile test data presented by Held et al. [14] and a new version of IFU-FLC-Criterion for nonlinear strain paths [13]. Both criteria are shortly summarized in the following section.
2.1. FLC determination based on tensile test data

In 2009 Held et al. [14] published a promising method for determination of FLC using tensile test data. The results presented for different steel and aluminium grades were found in good agreement with conventional FLCs determined using Nakajima-setup. As described in that paper, for calculation of FLC parameters sheet thickness, yield strength and ultimate strength as well as maximum uniform elongation, elongation at rupture, hardening exponent and anisotropy need to be measured using conventional tensile testing machines. In 2013 Abspoel [12] published another method for prediction of Forming Limit Curve for various steel grades using only tensile test data. Comparison of experimental results from Nakajima-Tests with calculated FLC points from tensile test data using Held’s model is shown in Figure 1.

![Comparison of FLC calculated from tensile test data and FLC determined using Nakajima-test](image)

As can be seen from Fig. 1 the calculated FLC using the method presented by Held is in very good agreement with experimental data determined in the Nakajima-Test setup. The basic formulations for calculation of four FLC points can be found in [14]. The advantage of both approaches presented by Held and Abspoel is remarkably reduced number of experiments compared to the conventional methods for FLC determination. Despite this advantage, the lack of prediction accuracy in case of nonlinear strain paths remains unsolved. By combining the methods for calculation of FLC from tensile test data with IFU-FLC-Criterion for nonlinear strain paths this problem can be overcome.

2.2. FLC prediction for nonlinear strain paths

For prediction of localized necking in case of nonlinear strain path, IFU-FLC-Criterion uses effective strain according to von Mises to determine the shift of FLC in strain space. In [10] an empirical model has been presented to determine remaining formability of a sheet metal material based on the amount of effective strain the specimen has experienced up to a specific point in the forming process. This relation is described using a so-called displacement function in case of the IFU-FLC-Criterion as shown in Eq. 1. Considering the lowest point of FLC is in the plane strain area for most metallic materials, this function has been defined to describe the value of major strain of the lowest point of the FLC over effective strain as can be seen in Fig. 2.

In order to calibrate the model, this displacement function needs to be parametrised using pre-stretched plane-strain Nakajima-specimen. By pre-stretching of oversized Marciniak-specimen and cutting out secondary Nakajima-specimen, it is possible to create two step nonlinear strain paths on a lab scale to calibrate the criterion. Strain measurement is done using modern digital image correlation systems.
In Fig. 2 displacement function for AA6014 material is shown. Circles represent biaxial pre-stretching, squares and triangles account for plane strain and uniaxial pre-stretching of the respective material. As can be seen from Fig. 2 the influence of pre-stretching direction has only very little effect on major strain value determined in Nakajima-test. Therefore pre-stretching up to 5% effective strain, Nakajima-specimen stretched in uniaxial-, plane strain and biaxial direction have nearly the same value of major strain in the diagram.

This fact can be used for determining the displacement function for IFU-FLC-Criterion using only tensile test data. This approach was first presented in 2015 by Drotleff and Liewald. Detailed description of determination of displacement function can be found in [11]. Rectangular specimens are pre-stretched up to 20% then secondary specimens are cut out for determination of maximum uniform elongation using tensile test setup. The displacement spline determined using this model is shown in Fig. 3 and is in good agreement with the conventional one using Marciniak- and Nakajima-setup.

![Fig. 2: Displacement function of IFU-FLC-Criterion describing shift of FLC for increasing levels of pre-stretching](image)

**Fig. 2:** Displacement function of IFU-FLC-Criterion describing shift of FLC for increasing levels of pre-stretching

![Fig. 3: Comparison between experimental data points determined in the tensile test (square) and Nakajima-Test (diamond) for AA6014](image)

**Fig. 3:** Comparison between experimental data points determined in the tensile test (square) and Nakajima-Test (diamond) for AA6014
If the displacement function shown in Fig. 2 is combined with a conventional forming limit curve, a
three dimensional failure surface can be generated for prediction of localized necking in case of arbit-
rary nonlinear strain paths [11]. For assessment of material formability in post processing of FEM
simulation, the user needs to determine critical nonlinear strain paths from the simulation, determine
von Mises effective strain $\varphi_{eff}$ and calculate the lowest point of the according FLC using the follow-
ing formulation:

$$\varphi_1 = \frac{AB}{C\varphi_{eff}^D + B}$$  \hspace{1cm} \text{Eq. 1}

Variables A, B, C and D need to be determined using a best fit to the experimental data shown in Fig.
3. A is chosen to be the major strain value of the plane-strain point of the FLC. The variables B, C and
D are used to adapt the displacement function to the experimental data points shown in Fig. 3. Failure
prediction procedure can also be automated and used in post processing of modern FEM-Software
tools. In order to further reduce number of experiments necessary for calibration of IFU-FLC-
Criterion, this approach can be combined with modern methods for calculation of FLC from tensile
test data. This may be an easy-to-use, industrial approach for failure prediction in complex deep draw-
ing or multi-step forming processes.

3. Prediction of localized necking in sheet metal forming for nonlinear strain paths
The combination of Held’s or Abspoels approach with IFU-FLC-Criterion gives a model for pre-
diction of localized necking in sheet metal forming for arbitrary nonlinear strain paths which can be
calibrated using only tensile test data. In total only 27 tensile tests need to be conducted in order to
calibrate the model. Resulting failure surface can be seen in Fig. 4. This model is in good agreement
with failure surface of conventional IFU-FLC-Criterion, but can be calibrated using only very few
experiments. Since level of effective strain according to von Mises should be below 15% for most
deep drawing processes where parts are formed in one single drawing operation, prediction quality
should be reasonably good. For high levels of pre-strain (>15% effective strain), deviation between the
new presented approach and conventional IFU-FLC-Criterion is increasing. This is due to the fact that
uniaxial pre-stretching in general does not reach as high strain values as biaxial pre-stretching. There-
fore, the values determined for high effective strain values show more scatter.

![Fig. 4: Failure surfaces of AA6014 generated by use of conventional displacement function (red surface) and newly determined failure surface estimated from tensile test data (blue)](image)

![Fig. 5: Failure prediction using IFU-FLC-Criterion in comparison to conventional FLC](image)

Prediction of localized necking is done in the same way as described in [11, 15, 9] and is in reasonably
good agreement with experimental results as determined in [15]. The new approach has been applied
to experimental deep-drawing part “Tunnelverstärkung” exhibiting nonlinear strain paths in four areas during deep-drawing leading to localized necking which cannot predicted using conventional FLC. As can be seen from failure prediction is in good agreement with conventional IFU-FLC-Criterion.

4. Conclusion
Accurate failure prediction for complex deep drawing processes is an important field of research for cost, time and quality fulfilling production. Using advanced failure criteria for determination of critical part geometries in a very early design stage is a key factor for future success of sheet metal forming. The model presented may be a way to improve prediction quality in forming simulation without increasing experimental costs for calibration to inestimable amounts. Further research should especially focus on validation of prediction quality and transferability of this approach to multi-step forming processes.

References
[1] Keeler S P 1961 Plastic Instability and fracture in sheets stretched over rigid punches MIT D.Sc. thesis Cambridge, 84 pp
[2] Müschenborn W and Sonne H-M 1975 Einfluß des Formänderungsweges auf die Grenzformänderungen des Feinblechs Archiv des Eisenhüttenwesens 46 pp 597–602
[3] Arrieux R 1997 Determination and use of the forming limit stress surface of orthotropic sheets J Mat Pro Tech 64 1-3 pp 25–32
[4] Volk W and Suh J 2013 Prediction of formability for non-linear deformation history using generalized forming limit concept (GFLC) NUMISHEET 2014: The 9th International Conference and Workshop on Numerical Simulation of 3D Sheet Metal Forming Processes Part B General Papers (Melbourne Australia) AIP pp 556–561
[5] Volk W, Hoffmann H, Suh J and Kim J 2012 Failure prediction for nonlinear strain paths in sheet metal forming CIRP Annals - Manufacturing Technology 61 (1) pp 259–262
[6] Volk, W Jocham D, Gaber C and Böttcher O 2015 Neue Methodik zur Vorhersage des Materialversagens bei nicht-linearen Dehnwegen 35. EFB-Kolloquium 2015 Intermezzo der hybriden Werkstofflösungen T40 pp 201–214
[7] Hora P, Tong L and Berisha B 2013 Modified maximum force criterion, a model for the theoretical prediction of forming limit curves Int J Mater Form 6 pp 267–279
[8] Hora P and Tong L 2006 Numerical prediction of FLC using the enhanced modified maximum force criterion (eMMFC) Proceedings of the FLC Zurich pp 31–36
[9] Werber A 2015 Einfluss nicht-linearer Dehnpfade auf Bauteileigenschaften und Versagen von Aluminium-6xxx-Legierungen Dissertation (Bonn) XVIII
[10] Werber A, Liewald M, Nester W, Grünbaum M, Wiegand K, Simon J, Timm J and Hotz W 2013 Development of a new failure prediction criterion in sheet metal forming Int J Mater Form
[11] Drotleff K, Liewald M and Mosebach J-T 2015 Improved Failure Criterion for Nonlinear Strain Paths Forming Technology Forum (Zurich)
[12] Abspoel M, Scholting M E and Droog J M 2013 A new method for predicting Forming Limit Curves from mechanical properties J Mat Proc Tech (5) pp 759–769
[13] Fallahiarezoodar A, Drotleff K, Liewald M and Altan T 2015 Lightweighting in Automotive Industry Using Sheet Metal Forming–Advances and Challenges 5th ICAFT Conference (Chemnitz)
[14] Held C, Dadrich J, Denninger R, Schleich R, Weidenmann K A and Liewald M 2009 Semi-empirische Berechnungsmethode zur Bestimmung des Grenzformänderungsdigramms auf Basis mechanischer Kennwerte Mat-wiss u Werkstofftech 40 (11) pp 831–835
[15] Liewald M and Drotleff K 2016 Bewertung von Umformgrenzen bei nicht-linearen Beanspruchungen in der Praxis EFB-Forschungsbericht Nr. 428 (Hannover)