Prediction of limit strains during non–proportional load paths with a change in loading direction

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Abstract. Many different models have been published to predict failure after non-proportional load paths. Most of those models are phenomenological and heuristic models. They require a profound knowledge about the material. Examples are the enhanced Modified Maximum Force Criterion (eMMFC), the Polar Effective Plastic Strain-model (PEPS) or the Generalized Forming Limit Concept (GFLC). In addition to the load path, the loading direction has a significant influence on the formability of sheet metals. The mentioned models currently neglect this influence. By extending the GFLC-model by the parameter of loading direction, this influence is taken into account. By analyzing an acceptable number of bi-linear experiments, it is possible to calibrate the proposed model for a micro-alloyed steel HC340LA. Therewith an arbitrary load path with a change in loading direction can be evaluated. The results of this contribution show the effectiveness of this approach by different experiments.

1. Introduction

The prediction of localized necking is topic of many different research projects. For linear load paths the Forming Limit Curve (FLC) is widely used. Graf and Hosford [1] have found, that the loading history has a significant influence on the formability of AL2008-T4 sheet metal. A biaxial pre-forming state generally lowers the FLC, while a uniaxial pre-forming increases the FLC. They confirmed the results of Bergström and Ölund [2] who investigated an aluminium alloy and an AK – steel. Both investigated materials showed a significant influence of pre-forming on the remaining formability. The prediction of necking after a non – proportional load history has been in the focus of research for several years. Different models have been published based on different approaches. Stoughton and Yoon [3] used the Polar Effective Plastic Strain – model (PEPS) to predict non-linear effects. They found, that a big merit of the PEPS-diagram is the strain path independence. Nevertheless, the constitutive law has a strong influence on the effective strain. Hora et al. [4] presented the Modified Maximum Force Criterion (MMFC-model) which was extended to the enhanced Modified Maximum Force Criterion (eMMFC-model) [5]. The presented approaches are theoretical models and therefore require a very accurate description of the material behaviour [6]. A different model was published by Volk et al. [7]. The Generalized Forming Limit Concept (GFLC-model) is a phenomenological model to predict bi-linear strain paths. It has already been extended to arbitrary strain paths [8]. In this model, a database of multiple linear and non-proportional load paths are used to predict necking of arbitrary load paths accurately.

All the presented models are limited to strain-paths with no change in loading direction. However, industrial applications show that especially these changes significantly influence the remaining
formability. Therefore, a novel approach is presented in this contribution. The GFLC-model is extended by the parameter of loading direction. By creating a database with multiple experiments, an accurate prediction of failure is possible.

2. Experimental setup

In this investigation, a micro-alloyed steel HC340LAD with an initial thickness of 1.0 mm was used. The presented database for the linear GFLC, as in [8], is extended by conducting experiments with a new specimen geometry. Within this new geometry pre-strain ratios $\beta = 0.5$ ($\beta = \varphi_2/\varphi_1$) can be created. This allows a more precise prediction of strain paths in between the plane strain and biaxial strain state. The used specimen geometries can be found in Figure 1. These geometries have to be adapted for each material individually. Using the same geometry for different materials, will lead to deviations in the resulting strains. To pre-form the specimens a modified Marciniak tool, proposed by Weinschenk and Volk [9], was used. The punch speed was set to 15 mm/s. To reduce the friction between the punch and the specimen, deep drawing oil was applied on the punch and the specimen.

![Figure 1](image1.png)

**Figure 1.** (a) Tool used for the pre-forming, (b) uniaxial specimen geometry, (c) plane strain geometry, (d) $\beta = 0.5$ geometry and the biaxial specimen geometry (e).

The initial specimens for the pre-forming step were manufactured by laser-cutting under three different directions (0°, 45° and 90°) with respect to the rolling direction. A total of 10 different initial specimens are manufactured. These specimens are pre-formed to two different strain heights. The height of the strain is approximately 25 % and 50 % of the linear FLC. After the pre-forming step, four different Nakajima specimen geometries were extracted by laser-cutting from the formed specimens. This allows the identification of the pre-forming influence on a complete FLC. The Nakajima specimens were rotated with regard to the initial forming direction, see Figure 2.

![Figure 2](image2.png)

**Figure 2.** Schematic pre-forming process for a uniaxial specimen (a) and the specimen extraction under different angels with respect to the initial forming direction (b) 0°, (c) 45° and (d) 90°.

The chosen specimen geometries have a specimen width of 30 mm, 100 mm, 130 mm and a circle with a diameter of 235 mm for the biaxial specimen. The Nakajima tests were conducted on a BUP1000 from ZwickRoell™. For the strain measurement an ARAMIS™ 4M system with a measuring frequency of 10 frames per second was used. To reduce the friction between the Nakajima punch and the specimens, lubrication paste in combination with a PVC-pad was applied. The punch speed was set to a constant value of 1.0 mm/s. To determine the onset of localization, the Time Dependent Evaluation Method was used [10]. A minimum of three valid experiments for each specimen combination was tested.
In a first validation step Nakajima experiments with geometries not used for the meta-model were performed. To validate the proposed model, also experiments with a tool proposed by Eder et al. [11] were conducted. This tool allows the creation of a wide spread strain distribution by forming sheet metal strips. The tool geometry can be found in Figure 3. As this tool is also used on the BUP1000, the same experimental setup with a measuring frequency of 10 frames per second and a constant punch velocity of 1.0 mm/s as for the Nakajima experiments was used. To reduce the friction deep drawing foil and lubrication paste was applied on the punch.

![Figure 3](image3.png)

**Figure 3.** Used tool geometries for the Nakajima experiments (a) and the validation experiments as well as the specimen geometry (b)

3. Results

3.1. Pre-forming

The specimens are pre-formed to 25 % and 50 % of the linear FLC. To pre-form all directions of the specimens equally, the linear FLC is determined for the three different directions. The resulting pre-forming states can be seen in Figure 4. A total of 20 pre-forming states is needed for a sufficient database. The nomenclature of the pre-forming states is “P” for pre-forming, followed by the pre-forming state (U for uniaxial, PS for plane strain, BZF for the $\beta = 0.5$ strain state and B for biaxial), the angle with respect to the initial rolling direction and the height of the strain (25 % as low and 50 % as high). Due to the different punch geometry in the pre- and post-forming experiments, the biaxial pre-strains of the linear FLCs are corrected by the GFLC according to [12].

![Figure 4](image4.png)

**Figure 4.** Different pre-forming states in comparison to the linear FLCs.
3.2. Post-forming Nakajima experiments

The Nakajima test results show a significant influence of the pre-strain height, the pre-form state and the change in loading direction on the formability of the investigated material. A uniaxial pre-forming leads to failure beyond the linear FLC while a biaxial pre-forming leads to failure below the linear FLC, shown in Figure 5. The post-forming direction is denoted as PF0°, PF45° and PF90° with respect to the initial rolling direction.

![Figure 5](image)

**Figure 5.** Influence of the pre-forming state for the specimens in rolling direction on the FLC for the 25 % pre-formed specimen (a) and the 50 % pre-formed specimen (b) for specimens with no change in loading direction.

The onset of necking for specimens with no change in loading direction and the same strain state are in good agreement with the linear FLC, as expected. The higher the pre-strain the more significant the influence of a change in loading direction is, see Figure 6. It is also noticeable, that the left hand side of the FLD is stronger affected than the right hand side.

![Figure 6](image)

**Figure 6.** Influence of the pre-forming height on the formability, (a) 25 % uniaxial pre-formed, (b) 50 % uniaxial pre-formed specimens in rolling direction.

As the biaxial specimen has a circular shape, the biaxial necking point is the same for all tested loading directions. The conducted Nakajima experiments are used as the database for the proposed extension of the GFLC-model.

4. Prediction of necking by the modified GFLC-model

To use the database in the extended GFLC-model, the strain paths have to be parameterized. Hence, each strain ratio \( \beta \) has a strain path length \( l_{FLC} \). The strain path length ratio is calculated with a corresponding strain ratio and a corresponding loading direction. The total strain path ratio \( \lambda \) is defined as:

\[
\lambda = f(l_{pre, \beta_{pre, \varphi_{pre}}, l_{post, \beta_{post, \varphi_{post}}}}) = \lambda_{pre} + \lambda_{post} = \frac{l_{pre(\beta_{pre, \varphi_{pre}})}}{l_{FLC(\beta_{pre, \varphi_{pre}})}} + \frac{l_{post(\beta_{post, \varphi_{post}})}}{l_{FLC(\beta_{post, \varphi_{post}})}} \tag{1}
\]

Each strain increment can be described with the parameter \( \beta \), \( \lambda \) and \( \varphi \). The following meta-model is shown in Figure 7. Compared to the standard GFLC-model, the 3D-GFLC is extended by the parameter of loading direction. The shown diagram consists of 48 data points. 24 of them are from the linear FLC while the other 24 are determined by the pre-forming. The database is therefore significantly bigger then the database for the linear FLC. The strain path length of a bi-linear strain path is calculated by linear
Lagrange interpolation of the surrounding data points of the element. The resulting post strain path length ratio $\lambda_{\text{post}}$ is approximated by the scalar product of the calculated path length ratio and the interpolation function of the used data points. The onset of necking is calculated inversely.

**Figure 7.** Meta-model of the 3D-GFLC (a) and the schematic prediction of necking (b).

For a given pre-forming state with a certain strain path length ratio $\lambda$, strain ratio $\beta$ and loading direction $\phi$, the remaining formability for an arbitrary strain path can be calculated, see Figure 8. The reduced formability for a change in loading direction is clearly visible, where a biaxial post-forming leads to an increased formability compared to the linear FLC. A strain path length ratio of 1 indicates the formability of the linear FLC. Therefore, the value can be bigger as 1.

**Figure 8.** 3D-Surface to predict the remaining formability after a pre-forming of $\lambda = 0.35$, $\beta = 0$ and $\phi = 0^\circ$.

### 5. Validation of the proposed 3D-GFLC model

To validate the proposed 3D-GFLC model, different validation experiments are conducted. For a strain path with no change in loading direction, the onset of necking can accurately be predicted, see Figure 9. A biaxial post-strain is applied to a plane strain pre-formed specimen. The plane strain pre-forming has used 38 % of the formability. The remaining formability until necking is therefore 62 % of the linear FLC.

**Figure 9.** Predicted failure for a plane strain pre-formed specimen with a biaxial post-forming.
The validation for the 3D-GFLC is done by experiments which are not used for the meta-modelling. Pre-forming height and the loading direction for the post forming step are therefore changed. A uniaxial post-strain is applied to a biaxial pre-formed specimen. The loading direction is changed from 90° to 22.5°. The small deviation of the strain path length ratio shows, that an accurate prediction of the necking is possible as shown in Figure 10.

![Predicted failure for a β = 0.5 pre-formed specimen under 90° with a uniaxial post forming under 22.5°](image1)

**Figure 10.** Predicted failure for a β = 0.5 pre-formed specimen under 90° with a uniaxial post forming under 22.5°

To proof, that also more complex forming operations are accurately predicted, a tool proposed by Eder et al. [11] is used. Specimens are uniaxial pre-formed under 0° to the rolling direction. The specimens are formed until fracture and the strain path of the necking zone is investigated. The influence of a change in loading direction on the drawing depth is clearly visible in Figure 11.

![Influence of a change in loading direction on the draw depth (a) and the necking zone (b)](image2)

**Figure 11.** Influence of a change in loading direction on the draw depth (a) and the necking zone (b)

The higher the change in loading direction, the smaller is the remaining formability. Also the necking zone is affected by the pre-forming and the change in loading direction. Thus all three investigated loading directions show a different necking zone. To predict this behaviour accurately the usage of the standard GFLC-model is not possible. The formability for strain paths with a change in loading direction would be overestimated. By using the proposed 3D-GFLC method the different failure points are predicted accurately.
6. Conclusion and outlook

The influence of the strain path history on the remaining formability of sheet metals is well investigated nowadays. In this contribution the significant influence of a change in loading direction on the remaining formability of a micro-alloyed steel HC340LA has been investigated. It is found, that the bigger the pre-forming, the bigger the influence of a change in loading direction is on the remaining formability. A change of the loading direction of 45° or 90° leads to a significant reduction in remaining formability. To predict this material behaviour, the GFLC-model is extended by the parameter of loading direction. As the GFLC-model is a phenomenological model, the extension is possible with only little effort. To proof the accuracy of the proposed 3D-GFLC, validation experiments have been conducted. The different strain paths are predicted accurately.

In future investigations the influence of a change in loading direction has to be shown for more materials. Also the reason for the significant loss of formability has to be further investigated. Nevertheless, as the 3D-GFLC model is a phenomenological model, only a solid database without any further knowledge about the material is needed to predict necking accurately. The significant influence has to be taken into account for industrial forming operations.

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