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Failure prediction for nonlinear strain paths in sheet metal forming

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ABSTRACT

The Forming Limit Curve (FLC) is a conventional failure criterion to estimate sheet metal formability for proportional loading conditions in Finite Element Analysis. Previous studies found that a standard FLC is not suitable for predicting the influence of nonlinear strain paths. This paper introduces a new method for the description of failure behavior in two-step forming operations by using a metamodeling technique. The main objectives of this approach are the cost effectiveness of the required experimental calibration and its practical applicability. The predicted forming limits determined with the proposed method are presented and validated by experimental results.

1. Introduction

The prediction and evaluation of the material failure is one of the main tasks in sheet metal forming simulation. The most frequently used failure criterion in Finite Element Analysis (FEA) of sheet metal forming is the evaluation of Forming Limit Curves (FLCs). The calculated true strains ε_1 and ε_2 in FE simulation are compared to the theoretically or experimentally determined FLCs in post processing. The determination of FLCs is standardized in the international standard ISO 120042-2 [1] by two different experimental methods, the Marciniak [2] and the Nakajima test [3]. The ISO standardized evaluation method is currently the so-called intersection line method. Therein the failed specimen is analyzed and the strains of localized instability are calculated with a mathematical approach using the 2nd derivative of the thinning distribution. This method is robust but sometimes inaccurate since the forming limit strains are recalculated. In addition, it is sometimes inapplicable in case of multiple necking zones.

With the development of photogrammetric equipment it is nowadays possible to record the whole experiment and identify the onset of necking directly. Using optical measurement systems Geiger and Merklein [4] proposed a new analysis method for the determination of FLCs. However, this method was also based on the intersection line method. In order to overcome the drawbacks of the cross-section analysis method, the so-called time continuous evaluation method is suggested as an alternative. Volk [5] proposed the evaluation of the thinning gradient around the necking zone over time by a so-called frequency diagram. With this basic idea Eberle et al. [6] made further examinations and additional proposals. Volk and Hora [7] suggested a simple and fully automated evaluation algorithm. Merklein et al. [8] proposed the application of the 2nd derivative of the strain rate in an evaluation field around the necking zone.

According to the experimental studies of Müschenborn and Sonne [9], Kleemola et al. [10], Bergström and Ölund [11], Graf and Hosford [12,13] and others the traditional FLCs are only applicable to the forming processes with almost the same linear and unbroken strain paths. These proportional loading conditions are unlikely to occur in many forming operations with changing loading paths such as two-step forming operations. Typically each point of a two-step formed sheet is subject to a different shape of strain path and hence each point requires its own unique forming limit strain. Ofenheimer et al. [14] showed that the prediction quality of Arrieux's approach [15] decreases with higher prestrains when assuming isotropic hardening effects. For this reason many authors have proposed enhanced stress based criteria, e.g. Yao and Cao [16], Stoughton and Zhu [17], Hora and Tong [18] or Yoshida et al. [19]. A critical point of the stress based evaluation method is a reduced robustness, since the calculated failure limits depend strongly on the used stress–strain relationship. This is one of the main reasons, why the stress based evaluation methods are currently not widely used in practice. To overcome these limits a phenomenological approach to estimate formability effectively and applicably in two-step forming operations is proposed without changing the established a posteriori failure evaluation strategy.

In this paper the evaluation algorithm [7] and the strategy [14] are used for the identification of the beginning instability of a high strength steel HC300X in two-step forming operations. The failure behaviors in bilinear loading conditions are described with a function of true strain ratio ($\beta = \varepsilon_2/\varepsilon_1$) and true strain path length $l(\beta)$ at pre- and post-forming. As a result, the response surfaces of necking points are calculated, depending on the amount of total strain paths. The main objectives of this approach are the cost effectiveness of the required experimental calibration and its practical applicability. For this purpose the forming limit strains of another grade from the same material class (HC450X) in bilinear strain paths are also estimated using the proposed analysis method without any individual experiments for model fitting. The comparison with experimental results shows a good agreement with the predicted failure strains.

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2. Formability prediction of nonlinear strain path

2.1. Time continuous evaluation method

According to the previous studies it has been shown that the thinning rate is a suitable physical quantity to identify localized necking [5]. The concentration of the remaining plastic deformation in small shear bands will lead to high thinning rates, while the thinning rates outside the shear bands will stay nearly constant. The algorithm to detect the beginning instability makes use of this effect [7]. Deformation begins stable and nearly homogeneous. The localized necking is generated during instable deformation and before crack initiation. The stable and instable areas are fitted with two linear trendlines by using the least square method. The intersection point of these two straight lines will be defined as the beginning instability. Previous studies show the validity and applicability of this method with linear and unbroken strain paths. In two-step forming operations the time dependent method can be also applied to the identification of the localized necking. With the aid of the time dependent method the localized necking of the bilinear strain path is estimated by using the intersection of two straight lines. In Fig. 1 this evaluation method is applied to a dual phase steel HC300X with thickness of 1 mm, in order to determine the FLCs with linear and nonlinear strain paths. The determination of the FLCs is realized by taking one-step experiments and two-step experiments with the same strain ratios. In this paper all strains indicate true strain. The six prestrains of Fig. 1 are realized by oversized tensile tests (points 1 and 2) and oversized Marciniak tests (points 3–6), respectively. Afterwards standard Nakajima tests are performed in four post strain directions with 3 samples in each case. These are in sum 72 experiments which are evaluated with the time continuous analysis method [7]. In the next step the experimental results are parameterized with the strategy proposed by Ofenheimer et al. [14].

2.2. Metamodeling

Based on the experimental data it is concluded that loading histories have a great influence on the forming limits in nonlinear strain paths. The main objective of the paper is the development of simple evaluation strategy for bilinear strain paths. It is very robust and simple to implement the evaluation method in commercial software programs with acceptable experimental efforts.

At bilinear strain paths each forming limit strain can be parameterized with a function of strain ratio and strain path length. Here the FLC of linear strain path is set as reference data. Each strain ratio ($\beta = \varepsilon_2/\varepsilon_1$) of the beginning instability has the unique strain path length l_{FLC} (β) as intersection point with the common FLC. Continuously, each strain path length ratio λ_{pre} and λ_{post} of the first and second forming operation is calculated for a corresponding strain ratio β_{pre} and β_{post}, respectively ($\lambda = l/l_{\mathrm{FLC}}$). By these means a metamodel of total strain path length ratio λ is established and its mathematical function is built up as follows:

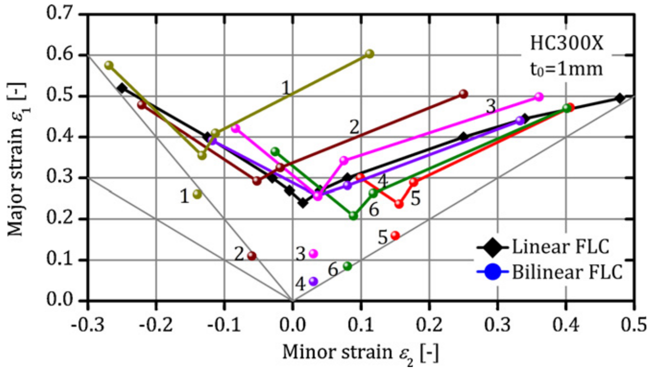

Fig. 1. Experimental forming limit diagram for bilinear strain paths using time continuous evaluation method for six different prestrains.

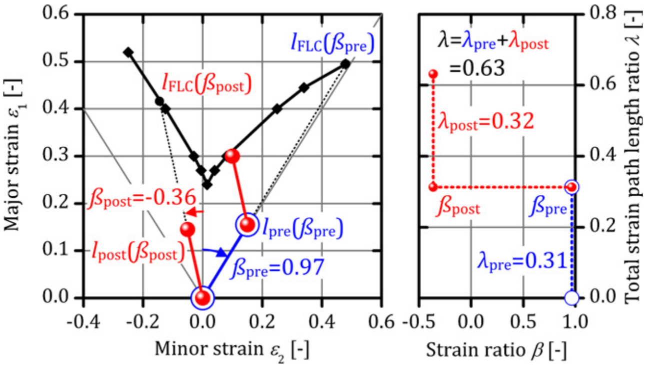

Fig. 2. Parameterization of bilinear strain path with biaxial pre-forming (ε_1 = 0.18, ε_2 = 0.167, β_{pre} = 0.97) and uniaxial post-forming (ε_1 = 0.12, ε_2 = −0.04, β_{post} = −0.36).

$$\lambda = f(l_{\mathrm{pre}}, \beta_{\mathrm{pre}}, l_{\mathrm{post}}, \beta_{\mathrm{post}}) = \lambda_{\mathrm{pre}} + \lambda_{\mathrm{post}} = \frac{l_{\mathrm{pre}}(\beta_{\mathrm{pre}})}{l_{\mathrm{FLC}}(\beta_{\mathrm{pre}})} + \frac{l_{\mathrm{post}}(\beta_{\mathrm{post}})}{l_{\mathrm{FLC}}(\beta_{\mathrm{post}})}$$

The benefit of this procedure is that λ is a dimensionless value in combination with a self-scaling effect when changing the FLC. Hence experimental results can be transferred to other material grades with different FLCs in a limited range, see Section 3.

Fig. 2 shows exemplary the parameterization of a bilinear strain path with biaxial pre-forming (ε_1 = 0.18, ε_2 = 0.167, β_{pre} = 0.97) and uniaxial post-forming (ε_1 = 0.12, ε_2 = −0.04, β_{post} = −0.36). As a result the pre, post and total strain path length ratio λ_{pre}, λ_{post} and λ amounts to 0.31, 0.32 and 0.63, respectively. Thus, each forming limit strain can be represented with strain ratio and total strain path length ratio. For example, Fig. 3 presents how the four experimental derived necking points of prestrain number 5 with biaxial pre-forming are recalculated using the proposed parameterization. Furthermore, it is highlighted that the major and minor strains for pre- and poststrain are calculated individually and the major strain must be higher than the minor strain for pre- and poststrain.

With the presented parameterization of the experimental results it is possible to establish a metamodeling procedure for the evaluation of any bilinear strain path. This strategy is based on the isoparametric approximation using the transformation of a four-node Lagrange element of FEM, see Fig. 4. There one can see the diagram that consists of the experimental prestrain points 1–6 in Fig. 1 and six additional points 7–12 based on the conventional FLC. On the one hand a prestrain path length of 0 indicates that the whole FLC is available as poststrain (points 7–9). On the other hand the poststrain path length is equal to 0 if the prestrain is equal to the FLC (points 10–12). Every base point has an individual post-forming FLC containing four experimental points, which are interpolated linearly between them as displayed in Fig. 3. With these 12 base points the diagram of (β_{pre}, λ_{pre}) can be divided into several domains with four nodes.

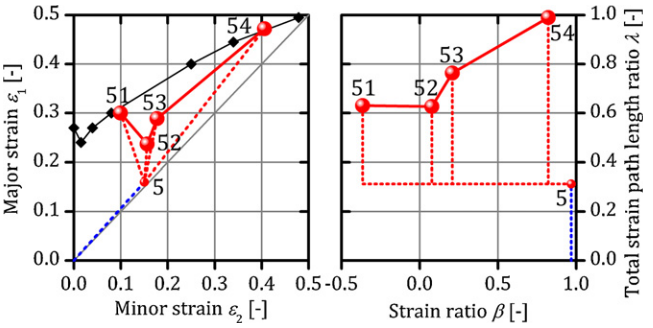

Fig. 3. Parameterization of the four experimental derived necking points at prestrain point 5 with biaxial loading condition and linear interpolation between necking points.