An alternative time-based strategy for the evaluation of forming limits using optical experimental measurements

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Abstract. Optical measuring systems allow to observe the sheet metal instability more precisely. The section method was first standardised and made available in commercial measurement systems in order to evaluate the forming limit curves almost automatically. The insignificant contribution of the necking area to the evaluated critical strains compared to the neighbouring volume of material led to alternative approaches such as the time-based evaluation criteria. The majority of these criteria take into account the strain evolution at the material necking location and are also suitable for evaluating other types of limits such as edge-crack sensitivity. Some advanced high-strength steels typically exhibit very short deformation after the onset of instability, which complicates the application of time-based approaches because they require sufficient amount of deformation after necking. The proposed approach is an attempt to reduce the dependence of the time-based approaches on the amount of deformation after necking by taking into account the local characteristics of the measurement curves. The approach is applied to some advanced high-strength steels to evaluate the forming instability and edge-crack sensitivity. The superiority of this identification approach is demonstrated in this paper by comparison with classical time-based approaches.

1. Introduction

Simplicity of the strain-based forming limit diagrams (FLD) makes them the most used tool in the assessment of the sheet metal formability. The probability of defects in terms of strain localization or rupture can be determined by the locations of principal strains relative to the forming limit curve (FLC). The implementation of digital measurement system took a long time in the online measurement of strains during a sheet formability test. With the use of digital online measurement systems, the forming limit curve is classically determined according to DIN EN ISO 12004-2 in a Nakajima or Marciniak test. The experimental determination of the critical deformation points is carried out according to DIN 12004-2 using the so-called line section method. In this method strain distributions along a section perpendicular to the rupture orientation at a measurement state just before the material separates is used to calculate the limit strains. As alternative evaluation scheme time-dependent methods have been extensively investigated to remedy the adverse effect of problematic strain distributions along sections [1], [2]. These however have their own difficulties especially in determining a clear and unique inflection point in time as the initiation of the instability. The majority of these criteria take into account the strain evolution at the material necking location and are also suitable for evaluating other types of limits such as edge-crack sensitivity.

The processing of high-strength and ultra-high-strength sheet metal steel grades poses new challenges for the automotive industry. In particular, high-strength dual-phase steels increasingly exhibit cracks at the component edges due to collar forming and body drawing processes [3]. The tendency of a material to develop early edge cracks due to extreme hardening effects while transversal shearing is

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also referred to as *edge crack sensitivity* (ECS). However, ECS is not solely dependent on the sheet materials used. The manufacturing process by which the edge of the semi-finished product was produced, as well as the associated cutting process parameters, also have a major influence on ECS [4]. If a component edge is produced by a shear cutting process, the formability of the sheet material at this edge degrades, hence the sheet metal edge exhibits increased ECS [3]. Those cracks are not directly predictable by common failure criteria e.g., the forming limit curve (FLC). Therefore, several approaches to test and predict edge cracks in simulation were developed in recent years [4], [5].

To critically analyze the most known testing methods for instability and ECS the German Association of the Automotive Industry (VDA) formed a group on a project called “Local formability and edge crack sensitivity”. Among many research institutes, sheet metal producers and sheet metal users, authors took part in performing the edge fracture tensile tests and the hole tension tests. As decided by the project group, the maximum principal deformation in these tests was determined at three different points in time: At the time of the 1% force drop relative to the maximum force $\phi_{1,1\%\text{Force}}$, at the time of the observed crack initiation $\phi_{1,Riss}$, and at the time of evaluated critical thinning of the material $\phi_{1,\text{Inst}}$ (localized instability).

In the tests performed to determine ECS, the maximum principal deformation change is preferably located directly at the specimen edge. Since the optical measurement data at the specimen edges are usually error-prone, a safety distance to the component edges is used to create the virtual mesh of the optical measurement to avoid possible errors. To generate an experimental dataset, demonstrating repeatability (intra-institution) and reproducibility (inter-institutions), various institutions took part in performing the same experiments. The special type of specimen for the edge-fracture-tensile-tests was proposed by the Chair of Metal Forming and Casting (UTG) of the Technical University of Munich [6], and these specimens are cut also by UTG for the mentioned VDA-Project using the introduced punching tool setup. In addition, the time-force-strain measurements recorded by all project partners are evaluated for the localized instability ($\phi_{1,\text{Inst}}$) by UTG using a script based on the method developed collaboratively by Volk and Hora [1] and probably further developed at UTG (see Figure 1). The most classical time-based approach proposed in this study uses the thinning rate slopes before and after the initiation of the instability to find the transition point.

![Figure 1](image)

**Figure 1:** A time-based evaluation method to identify the localized instability [6].

To justify the use of localized instability ($\phi_{1,\text{Inst}}$) in this study as a reliable approach, it is necessary to first discuss the alternative evaluation strategies mentioned above. Use of the maximum principal strain at a force drop of 1% beyond the maximum force $\phi_{1,1\%\text{Force}}$ has the advantage that it is clearly defined by the force curve. This improves the repeatability and reproducibility of the tests and also allows the use of a fully automated evaluation strategy. The disadvantage of this strategy is that a drawing force reduction is not necessarily coupled with the localized instability or edge fracture. The determination of the maximum principal deformation when the specimen is cracked $\phi_{1,Riss}$ has the advantage that there is a direct correlation of the measured value with the localized instability or edge failure. The disadvantage of this approach is that the point of time of the crack is specified visually by the operator and therefore is not automated and objective. This causes a degradation in repeatability and reproducibility.

As an interesting example on the use of the time-based localized instability ($\phi_{1,\text{Inst}}$), Figure 2 shows the thinning rate and the principal major strain as a function of time recorded at the most-critical point (for this case the most critical interior point and not a point on the edge of specimen) on a classical
tensile test of the material HR660Y760T-CP. The shown thinning rate has several straight regions, resulting in two possible evaluation times (Point 1 and Point 3). The evaluation performed by UTG determined for this case the Point 1 as the point of time of critical thinning and beginning of instability. This results in a relatively low prediction for the principal deformation of approx. $\varphi_1 \approx 0.12$. Since these reference specimens, having both edges milled, are cracked in the center of the specimen, this value should be approximately located on the FLC of the material in the forming limit diagram (see Figure 3). The values for major and minor strain at the evaluation times are plotted in the forming limit diagram as shown in Figure 3. The FLC data was taken from the material libraries provided by AutoForm and Dynamore simulation programs and provided by the manufacturer of this material. It can be seen in this figure that the Point 1 is located significantly below the FLC. With manual intervention the same algorithm can produce Point 3 or even Point 2 (as the closest point to the intersection of the linear interpolations on first and third segments of the curve) which are almost located on the FLC and thus better represents the state of the critical thinning. This example shows the need to reconsider the assessment strategies for the instabilities within or at the edge of the specimen. To obtain a conservative, reliable estimate of the failure time, the determined time of the critical thinning should be defined at the beginning of the significant increase of the thinning rate, which is the Point 2, for this specific case.

**Figure 2:** Evaluation points for the time-based method using a reference tensile test (HR660Y760T-CP).

**Figure 3:** Evaluated points in the forming limit diagram of the material HR660Y760T-CP.
2. New approach for the automated evaluation of the point of critical thinning

This section develops an alternative strategy for the automated evaluation of the point of critical thinning based on the time-strain method with data obtained during stretching of conventional tensile test specimen. The strain values are to be measured at the most critical point of the specimen, i.e. at the failure point or at the nearest measurement point if the failure is at the edge of the specimen. If this point lies on the edge of the optical measurement mesh, the criterion provides the strain values for the ECS of the tested material. This strategy is tested for the hole tensile test and the edge-fracture-tensile-test but also generally applicable to other procedures. The algorithm for determining the critical thinning strain value is given in Figure 4 and the details are explained afterwards on the basis of a punched hole tensile test for the material CR780Y980T-CP and the and edge fracture tensile test for the material HR660Y760T-CP.

The thinning rate $\dot{\varphi}_3$ is used to determine the correct point of time of critical thinning. The states of the optical measurement system are used as the quasi-time in the approach and all measurements are made as a function of this integer number. In a first step, the thinning rate is subjected to smoothing using B-Splines. The maximum achieved thinning rate refers to the state number, up to which the calculations explained below are based on. In other words, data measured beyond this state is not considered. In the next step, the state (i.e., time) of the critical thinning or the instability point is found. Looking at the thinning rate curve in Figure 2, a human observer searches for the point of instability in the region of maximum curvature. For this purpose, the scales of the axes are usually normalized optically. For the same reason, the calculated values of curvature in such a plot do in fact make more sense after numerically normalizing the scale of the one axis with respect to the one of the other. Therefore, we re-scaled the x-axis, the integer numbers corresponding to the state number. Numerous
test calculations using the curvature $\kappa$ of the modified graph of the thinning rate as a function of rescaled state numbers revealed the fact that not only the curvature of the imagined continuous curve but also the distances between the points of the underlying discrete representation are influential in the curvature calculation. This phenomenon is explained in Figure 5, in which the use of curvature is shown on the left side and the alternative use of angular divergence is shown on the right. The greater distance (usually observed with increased thinning rate) between the second and third points of interest inversely affects the calculated curvature value. This conclusion demonstrates that human perception can be better represented by angular divergence than curvature on the discrete representation. As shown in the Figure 5, the angular divergence can be calculated in the simplest way by calculating the angle between the two line-segments connecting the first and second points and the second and third points. An extended version for the calculation of the angular divergence can be achieved by considering many before and after points and fitting lines to these before and after points. It has been shown that the approach based on angular divergence remains stable and always indicates the same critical point, up to 5 before and after points.

![Figure 5: Use of curvature vs. angle change in finding the instability point based on three measurement points.](image)

The calculated $\alpha$ values are then used to evaluate the instability point, being the state corresponding to the last peak of the $\alpha$-plot. This state number is associated with the measured major and minor strains, which can then be used as the critical strain point.

3. Experimental Setup

The edge fracture tensile tests and hole tensile tests were carried out based on the tensile test according to DIN EN ISO 6892-1. The specimen geometry corresponds to that being used for the tensile test according to ASTM standard. The hole tensile test specimen were punched with a hole diameter of 10 mm in a specimen of 20 mm width. In case of an edge-fracture-tensile-test, the samples were milled on one edge and shear cut on the other edge by UTG for all project partners, so that a study of the repeatability and reproducibility of the evaluation of the edge cracking behavior on a shear cut edge became feasible. The relative cutting gap was reported as 12.0% of the sheet thickness. Reference tests are also carried out with edges milled on both sides. The drawing direction during the tests was perpendicular to the rolling direction (90°), since this is where the smallest changes in shape occur when the specimen cracks and a conservative assumption is therefore made [7]. The drawing speed during the tests was constant and is 12.0 mm/min as specified by the VDA project team. For statistical validation, seven specimens per test material and edge condition were tested. The 5M GOM-ARAMIS was used as a DIC system for capturing strain values from test specimens. The reference length for strain calculation
was recorded to be 0.6 mm. The shape changes are recorded on the burred face of the cutting edge in case of the shear-cut specimens. The materials used in this study are CR780Y980T-CP and HR660Y760T-CP being only a subset of the whole materials considered in the scope of the VDA project. The material parameters of the aforementioned materials are presented in Table 1.

| Material            | t [mm] | Yield Strength [MPa²] | UTS [MPa] | Frature Strain min. [%] |
|---------------------|--------|-----------------------|-----------|------------------------|
| CR780Y980T-CP       | 1.5    | 889.8                 | 987.9     | 8.2                    |
| HR660Y760T-CP       | 3.0    | 759.8                 | 889.6     | 11.6                   |

4. Results and Discussion

The use of the proposed approach is shown in Figures 6 and 7 for the materials CR780Y980T-CP and HR660Y760T-CP with the classical ISO tensile specimen geometries used also for the edge-fracture-tensile-test and the hole tensile specimen. The plot of the angle α calculated as explained above is given in Figure 6 for a classical tensile test. The last highest point of the plot of angle α then corresponds to the point in time of the critical thinning of the specimen. This plot also demonstrates the estimation by the method proposed by [1] using exactly the same measurement data performed by the owner of the script. The major strains corresponding to the evaluated states are comparatively shown below in Figure 6. A further comparison is performed using a hole tensile test with a punched hole as shown in Figure 7, demonstrating also the calculated critical major strain values near the punched edge. In Figures 6 and 7, the divergence angle α is also calculated using 5 pre- and post-points. As explained in section 2, the specified critical point remains unchanged regardless of the number of pre- and post-points used for the angle calculation. Such critical major strain is important in evaluating an extended FLC curve valid for the punched edges of a blank.

Figure 8 shows the simplified forming limit diagram for the material HR660Y760T-CP as a comparison for the evaluated critical major strains φ₁,Inst,IFU and φ₁,Inst,UTG. The results of the proposed criteria are labeled with “IFU” and the results of the method introduced by [1] are labeled with “UTG”. Using the provided experimental data, UTG evaluated the critical values for all project partners using the script explained in [1]. Reference tests referred to the specimens with both edges milled. Shear-cut specimens are labeled as “Punch”. The principal strain values evaluated by the proposed approach φ₁,Inst,IFU for the reference specimens lie close to the FLC of the material. The shear-cut specimens, however, are found significantly below the FLC curve, showing a remarkably reduced edge crack sensitivity of this material. In comparison, the principal strains φ₁,Inst,UTG determined by UTG were calculated significantly below the forming limit curve.
Figure 6: Calculated values for critical thinning and the major strain in case of a classical tensile specimen with even edges. The used material is HR660Y760T-CP.
Figure 7: Calculated values for critical thinning and the major strain for punched hole tensile test specimen. The used material is CR780Y980T-CP.
Figure 8: Forming limit diagram for the material HR660Y760T-CP with determined forming limit strains

5. Conclusion and Outlook
The proposed approach for the time-based evaluation of instability strains in case of far-edge localisation or edge crack sensitivity is shown to yield proper results for the advanced high strength steels considered in the scope of the VDA Project on “Local formability and edge crack sensitivity”. The shortcomings arising due to the three stable regions for the evolution of the thinning rate, compared to the two stable regions assumed by the most classical time-based strategies, are eliminated. The plausibility of the results is demonstrated by comparing the evaluated strain values with the forming limit curves of these materials. The introduced evaluation procedure until now is fully automated, it does not require manual interventions. The required strain values are measured at the most critical point, and the time history of the entire strain distribution on the specimen is not required for the calculations. As it relies on a discrete calculation strategy, the proposed approach also requires a sufficient amount of measurement points properly representing the continuous behavior of the material. This strategy, developed within the framework and time span of mentioned VDA project, has not yet been tested for the classical evaluation of FLC curves with Nakajima test setups. A comparison with the classical approaches in this context also is planned as a follow-up study by the authors.

Acknowledgements
The material provided in the scope of the VDA Project “Local formability and edge crack sensitivity” is highly appreciated. The preparation of the EFTT specimens and the evaluation of the critical strains using a proprietary time-based calculation strategy by UTG is gratefully acknowledged.

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