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An evaluation method for experimental necking detection of automotive sheet metals

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Abstract. In sheet metal stamping, the occurrence of strain localization in a deformed sheet is considered a failure. As so, sheet metal's formability is conventionally evaluated using the Forming Limit Diagram (FLD), which separates the principal strain space into safety and unsafety regions by a Forming Limit Curve (FLC). This study presents an evaluation method for detecting strain localization based on Digital Image Correlation (DIC) during the experiment. The commercial DIC software ARAMIS is adopted to monitor the strain-field distribution on the deformed specimen's surface. A detailed analysis of the proposed method is presented considering Nakajima tests conducted for two automotive sheet metals: AA6016 and DP800. The identified FLC based on the proposed method is compared with that of well-established methods such as ISO 12004:2-2008 and time-dependent methods. For both investigated materials, the proposed method presents a lower FLC than the others.

1. Introduction

Evaluation of the material formability or the forming limit is a crucial demand in sheet metal stamping processes. The forming limit is conventionally determined at the moment of strain localization on the deformed specimen surface. For a particular material, combining the forming limit with attainable strain states formulates the Forming Limit Curve (FLC). Accurate determination of the FLC is important not only for designing parts but also for validating the formed products.

Different methods have been presented in the literature for detecting strain localization. The ISO 12004:2-2008 standard is a well-established method for this purpose based on an inverse parabola fitted to the strain distribution along a section on the deformed surface. Volk and Hora [1] introduced an alternative by comparing the thinning rate of the necking area observed in the pre-necking and post-necking stages. The linearity of strain acceleration is quantified in the correlation methods (Merklein et al. [2] Hotz et al. [3]) in order to determine the strain localization. Martínez-Donaire et al. [4] suggested examining the strain rate evolution of a point located at the boundary of the necking region. Furthermore, the geometrical variations during a test were proposed to use for detecting the strain localization as well, see Wang et al. [5], and Min et al. [6].

The summarized methods successfully determined the FLC of several automotive sheet metals in the corresponding studies. Although their preliminary results are promising, examining their applications for a wide range of materials is necessary to validate their effectiveness. However, it is obvious that all of these methods are sensitive to the interpretations and prejudices of the practitioners. That always affects the robustness of a selected method.

This study presents an evaluation method for experimentally detecting the strain localization appeared on the specimen's surface. The proposed criterion is based on the evolution of the Coefficient of Variation (CoV) of the major strain rate observed in a region of interest (ROI). The proposed method is applied to investigate the FLC of two sheet metals, DP800 and AA6016, that are widely used in the automotive industry. The derived FLCs are compared to those of other common methods to verify the effectiveness of the proposed method.

2. Experiment procedure

2.1. Investigated materials

The tested materials in this study are Dual-Phase (DP) 800 and Aluminum Alloy (AA) 6016. Both of them have a thickness of 1.2 mm. They are well-known to be medium-to-high strength materials, which are used in making vehicle frames and chassis. Both materials used in this study were supplied by Volvo Cars (VCBC).

2.2. Nakajima test

To determine their FLC, a series of Nakajima tests are conducted for the investigated materials following the ISO 6892-1:2009 standard. Seven tests are carried out for each material to characterize the necking strains under different stress states, ranging from uniaxial tension to equi-biaxial tension. Fig. 1 shows the blank geometries used in these tests.

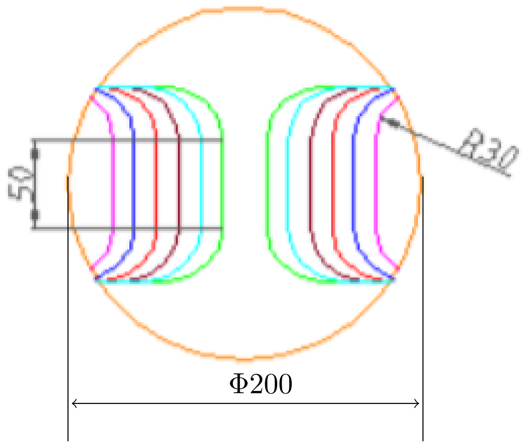

Figure 1. Geometry of the specimens used in Nakajima tests. Specimen widths (W): 25, 50, 75, 100, 125, 150, 200. Unit in mm.

A hemispherical punch with a diameter of 100 mm is used to deform the blank during each test. To reduce the friction acting on the contact area, full lubrication of mild oil is spread out, and a thin polymer sheet is used to cover the punch. Moreover, a drawbead is used to prevent the unnecessary drawing of the blank edges. These tests are conducted under a constant ram-forming speed of 25 mm/s until rupture. During the tests, a commercial Digital Image Correlation (DIC) system ARAMIS is used to monitor the strain evolution on the top surface of the deformed specimens.

3. Evaluation method

3.1. ISO standard method

The evaluation method presented in ISO 12004-2:2008 is generally accepted to determine the FLC of sheet metals. In this method, the major and minor strains along sections perpendicular to the crack profile are interpolated by inverse parabola functions. The pole of these fitted functions determines the limiting strains. The method is implemented in the ARAMIS built-in function, which makes evaluating more user-friendly. Fig. 2 shows an example of selecting sections on the surface of a deformed AA6016-W100 specimen. Fig. 3 shows the identified necking strains of the considered specimen.

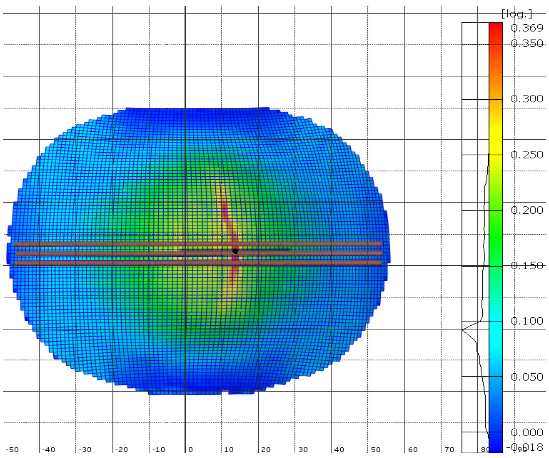

Figure 2. Selection of three sections for FLC calculation in ARAMIS.

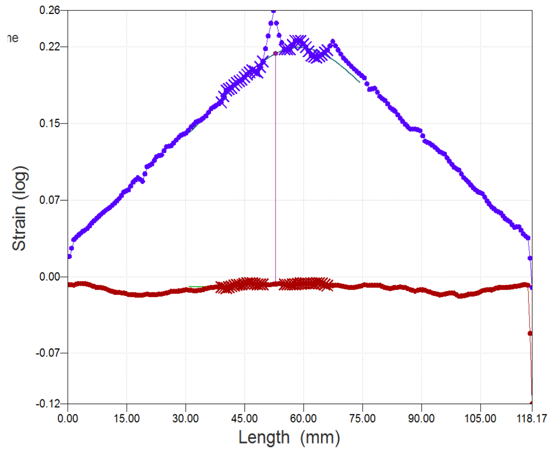

Figure 3. ARAMIS build-in function for FLC determination based on the ISO 12004-2:2008 standard.

3.2. Time-dependent method

Besides its benefits, the ISO standard method produces higher FLC than the forming limits observed in the production line of various automotive sheet metals [3, 7]. To overcome the drawback, Volk and Hora [1] presented a time-dependent method that takes into account the evolution of the thinning rate of a necking zone. The intersection of two linear curves, fitted to the necking zone's thinning rate evolution in the stable and unstable periods of deformation, indicates the instability.

This study adopts the time-dependent method (labeled "LBF method") to evaluate the FLC of the tested materials. In each specimen, a rectangular region of $2 \times 10\ mm^2$ in the necking zone is constructed in the second last image before visible fracture, which is equivalent to the recommendation of 5 elements for a 2 mm grid in the original article [1]. The arithmetic means of the thinning rate evaluated over the constructed necking zone are calculated for all stages of deformation. Based on the calculation, the necking strains of the corresponding specimen are determined following the procedure described in the cited work [1]. Fig. 4 presents the identified necking stage 81^{th} of the AA6016-W100 specimen based on the time-dependent method. It is noticeable that the thinning rates of the last four stages before visualized crack were ignored in the calculation since these values are higher than one.

3.3. Volvo Cars method

An alternative method was developed and extensively used at Volvo Cars to determine the FLC of sheet metals. The basic idea of this method was presented in [8]. In deep, the minimum and maximum major strain rates (denoted by "Min-$\dot{\varepsilon_1}$" and "Max-$\dot{\varepsilon_1}$", respectively) observed in a ROI are compared to the lower and upper lines, which are constructed based on the mean (μ) and variation (σ) of the strain rates evaluated on the ROI. Crossing the boundary by either the Min-$\dot{\varepsilon_1}$ or Max-$\dot{\varepsilon_1}$ indicates the stage of necking initiation. Fig. 5 presents an example of the

VCBC method applied to determine the necking stage of the AA6016-W100 specimen, of which the derived result is stage 78^{th}.

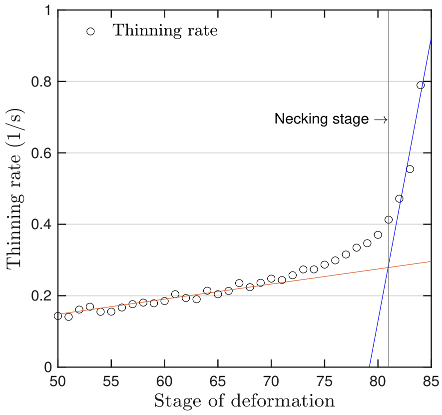

Figure 4. Evaluation of the linear best fitted method for AA6016-W100 specimen.

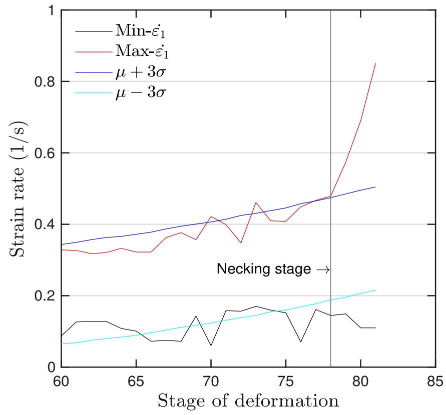

Figure 5. Evaluation of the VCBC method for AA6016-W100 specimen.

Implementation of this method in practice requires experienced experts who deeply understand the sensitivity of the method on the selection of ROI as well as the adjustment of the necking stage. In this study, the FLCs of two tested materials are evaluated by VCBC's experts and reported subsequently (denoted by "VCBC-FLC") for comparison purposes.

3.4. New method for necking detection

In statistics, mean, μ, is the average of the data set, while variation, σ, measures the spread of the data in the set. The Coefficient of Variation (CoV) of which the formulation is expressed in the equation below measures the dispersity of these values distribution.

$$CoV = \frac{\sigma}{\mu} \tag{1}$$

Motivated by the Volvo Cars method, it is suggested that the CoV of the major strain rate observed in a ROI can provide information regarding the necking initiation on the surface of the deformed specimen. Unlike a rectangular ROI preference in the previous studies, this study proposes to use a circular area located at the center of the necking region for this purpose. Therefore, a 5 mm diameter circle (denoted by "D5") is constructed on the surface of the deformed specimen at the last stage before the crack visualization for further investigation. The center of the circle is selected by the point that shows the largest equivalent plastic strain on the specimen surface at the last forming stage.

Fig. 6 depicts the evolution of mean and variation of the major strain rates evaluated on the ROI of the deformed DP800-W50 specimen. In addition, the corresponding CoV evaluated in this area is also plotted in this figure. A magnified view of this figure is presented in Fig. 7 focused on the identified necking stage. These figures show that μ always increases as the deformation continues. In contrast, the evolution of σ can be classified into two periods or ranges: (i) varying around a fixed value in the stages of small deformation and (ii) increasing significantly at later stages of deformation. As a result, the CoV decreases in the first period and increases in the latter. It is reasonable to assume that the deformation of the whole ROI is homogeneous in the first period, while strain localization occurs in the second period. Thus, the

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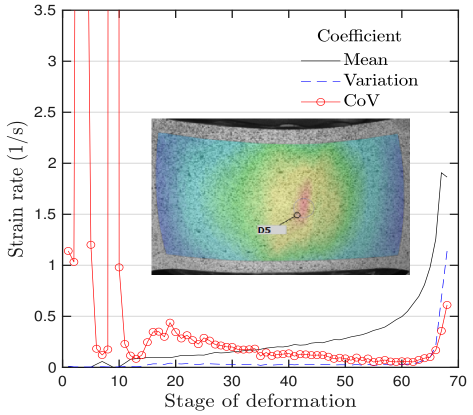

Figure 6. Statistic coefficients monitored at the necking region.

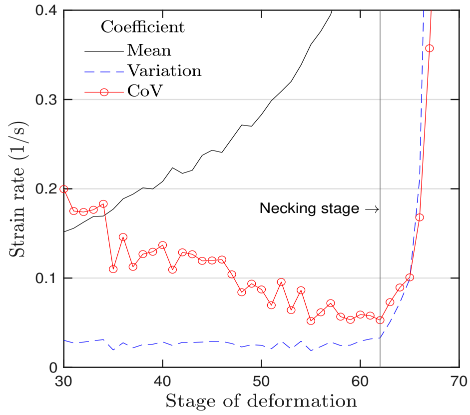

Figure 7. A magnified view of Figure 6 with the identified necking stage.

global minimum of CoV evolution indicates the strain localization established on the deformed specimen.

As seen in Fig. 7, the CoV curve exhibits various bumps due to inevitable noises contained in the measured data. One may consider a smoothed curve, which is a numerical approximation for the measured one, to identify the global minimum and the relevant necking stage. Although investigating the smoothing method and its influence on the derived results is omitted in this work, that will be the scope of a forthcoming study. To deal with the bumpiness of the curve, it is assumed that the last local minimum before a steep increase of the CoV indicates the necking stage, as shown in Fig. 7. An in-house Matlab code is developed to determine the necking stage based on the proposed method.

In order to study the sensitivity of ROI selection to the derived results, two additional ROIs (denoted "D3" and "D10") are constructed on the specimen surface, which have the same center as the D5 but with different diameters of 3 mm and 10 mm, respectively. In addition, a "D5-sub" region is constructed with the same diameter of 5 mm and 5 mm away from the other's center point, as shown in Fig. 8.

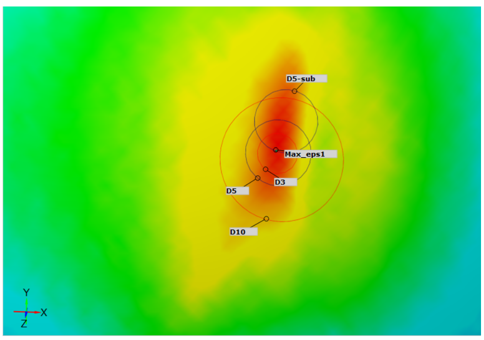

Figure 8. Location of different ROIs for sensitive study.

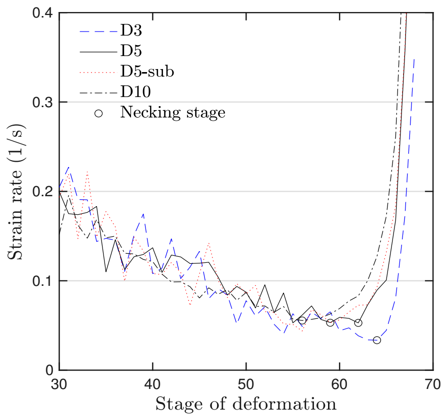

Figure 9. Evolution of the CoV observed in different ROIs.

Fig. 9 compares the evolution of CoV of the major strain rate observed in these ROIs. In addition, the calculated necking stage based on these ROIs is depicted in this figure. These CoV curves appear in a similar tendency in the decreasing period. However, their distinction is obviously displayed in the increasing period where the smaller ROI produces the later stage of increasing line. Consequently, adopting a smaller ROI yields a later necking stage, which is explainable as follows. Increasing CoV indicates an increase of the inhomogeneous strain distribution over the ROI due to the concentrated deformation on the necking area. In other words, the minimum of CoV indicates the last stage of homogeneous deformation over the ROI. As a result, the size of ROI is directly related to the size of the "identified" necking area or the "necking band". Since a size of 2 mm to 3 mm of the necking band is commonly reported for automotive sheet metals [9, 10], a circular area with a 5 mm diameter of ROI is recommended in this study.

4. Comparison

Fig. 10 and Fig. 11 show comparisons between the FLCs of AA6016 and DP800 sheets evaluated based on different methods. As seen in these figures, the ISO standard method provides the highest FLC for both tested materials, while the results of the VCBC method are always the lowest curves. It is noticed that the VCBC-FLCs are considered the ground trust since they are actually used in a production line. The time-dependent method results in an intermediate FLC for both tested materials. The difference between the perceived curves in Figs. 10-11 demonstrates the significance of developing a new evaluation method instead of the ISO 12004-2:2008 standard.

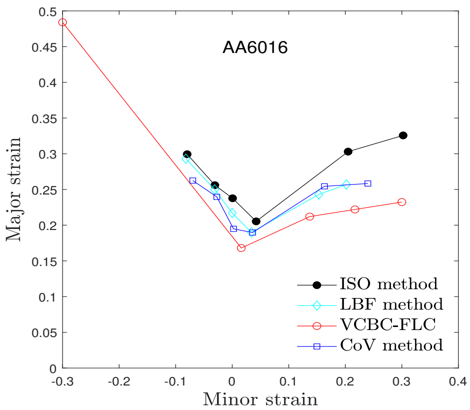

Figure 10. Comparison between predicted FLCs of AA6016 sheet based on different methods.

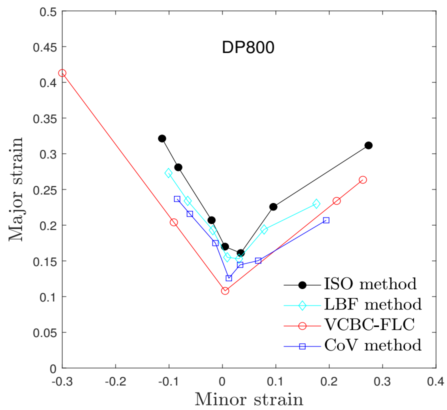

Figure 11. Comparison between predicted FLCs of DP800 sheet based on different methods.

Compared to the time-dependent method, the proposed CoV method derives lower FLC for two examined materials, except for the right side of the FLC of AA6016. Although the evaluated FLC of the proposed method is higher than the VCBC-FLC, the comparison demonstrates its potential in determining the FLC of sheet metals. Moreover, implementing the CoV method is programmable since it seeks a minimum event. That is a substantial benefit in the current era of big data.

Many factors could influence the derived result of the proposed method, which will be considered in a forthcoming study. Some of the foreseeing factors can be listed as the region of interest (i.e., the location, shape, and size of the investigating area), the mesh size of the ROI, and the different sources of quantification (i.e., the major strain rate and the thinning rate). Adopting acoustic emission measurement techniques is a promising approach for validating the accuracy of the proposed method [11, 12], which deserves further investigation. It is necessary to investigate the applications of the proposed method for different materials and various test batches to verify its robustness and effectiveness.

5. Conclusion

A new evaluation method for experimental detecting strain localization of sheet metals is proposed in this study. The method seeks the minimum of the CoV observed in the major strain rate field spreading in a region of interest, which makes its implementation programmable. The proposed method is applied to determine the FLC of AA6016 and DP800 sheets, of which the derived FLCs are lower than that of the well-established methods, such as, ISO 12004:2-2008 standard and the time-dependent method [1]. Compared to an industrial used curve, the VCBC-FLC, the proposed method presents closer results than the others.

Acknowledgments

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