

EXPERIMENTAL FLC DETERMINATION OF HIGH STRENGTH STEEL SHEET METAL

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Abstract

To assess formability in sheet forming, experimentally determined Forming Limit Curves (FLC) are often used. These conventional FLCs represent the forming limits (i.e. onset of necking) of a sheet material subjected to in-plane deformation or almost in-plane deformation. A widely used approach to experimentally determine the onset of necking of sheet material subjected to in-plane and almost in-plane deformation is formulated in ISO 12004. The aim of this work is to investigate limit strains for deep drawing quality sheet metal of HX180BD with nominal thickness 0.6 mm. The FLC curve has been measured by implementation of Nakajima test on universal testing machine Erichsen 145-60. The Nakajima test has been measured according to EN ISO 12004-2. Limit strains have been measured using 3D photogrammetric system ARAMIS by GOM. Forming limit curve was evaluated both the section method and the time dependent technique. The resulting experimental FLC curves were compared. With the time based method for the determination of FLC a greater strain values was achieved.

Keywords: material characterization, forming limit curve (FLC), forming process, high strength low alloy (HSLA) steels

1 Introduction

The complexity of the processes of plastic forming imposes a rigid and frequent characterization of the mechanical behaviour and formability of sheet metal used in these processes. In the last years, important development has been achieved based on new models, in experimental laboratory and industrial analysis. The forming limit diagram (FLD) was discovered and developed by Keeler and Goodwin, which has been widely applied in analysis of sheet metal forming. The FLD, which was consequently widely referenced in the sheet metal forming industry is now a standard characteristic in the optimization of sheet metal forming processes. The FLDs have enabled the prediction of which deformation can lead to the failure of the material for different strain paths and are considered an important tool in the die project as well as to optimize and correct problems in the line production [1]. Forming limit curve, the key feature of the FLD, records some pairs of in-plane limit strains (major and minor) and defines the boundary between safe zone (no necking) and dangerous zone (necking and splitting). The FLC is affected by many factors, such as the forming speed, the lubrication condition, the thickness of

sheets, the strain hardening, and the anisotropy of the sheet metals [2-5]. Despite the claim [6], that no standard methods have been developed for sheet materials with thickness below 0.5 mm, exists standard EN ISO 12004-2:2008 for determination of FLCs for sheet of thickness between 0.3 mm and 4 mm [7]. Many researchers [e.g. 8-12] are concerned with determining FLD of sheet materials using different methods. ARAMIS is a non-contact and material independent measuring system providing accurate surface strain values, for static or dynamically loaded test objects. On the basis of optical scanning it allows predicting critical areas which are taking places during forming process. ARAMIS is the solution delivering complete 3D surface, displacement and strain results where a large number of traditional measuring devices are required.

In this paper, the FLC curve was measured and constructed by ARAMIS system for each section of the HX180BD+Z100 during the Nakajima test. The common section based evaluation according to ISO 12004-2:2008 used in ARAMIS system was compared with time base method – linear best fit method. This research presents time dependent determination of the beginning plastic instability based on physical effects. The algorithm is based on the evaluation of the strain distribution based on the displacement field which is evaluated by optical measurement and treated as a mesh of a finite element calculation. The strain distribution with their time derivate for detecting the beginning of the localization were defined.

2 Experimental procedure and material

The essential aim of the paper was to measure the limit strains for high strength steel (HSS) sheet of HX180BD by Nakajima test. The HX180BD bake hardening steel can thus achieve higher strength in the finished part while retaining good forming performance. The gain in yield strength through the “bake hardening” (BH) effect is generally greater than 40 MPa. Thanks to this BH effect, this steels offer advantages compared to conventional drawing quality steels in improved dent resistance in all finished parts in the case of low forming strains (hood, roof, doors and wings) and substantial weight reduction potential at equivalent dent resistance (the decrease in thickness is offset by increased yield strength resulting from the heat treatment process). The basic mechanical properties of tested material are shown in **Table 1**.

Table 1 The mechanical properties of HX 180 BD +Z100 steel sheet (1.0914), thickness 0.6 mm

Direct.	R _{p0,2} [MPa]	R _m [MPa]	A ₈₀ [%]	A _g [%]	r[-]	n[-]	Δ r	BH2
0°	207.5	327.5	40.03	23.72	1.55	0.219	0.47	44.5
45°	215.1	334.6	36.75	21.99	1.19	0.208		44
90°	212.4	324	39.11	22.59	1.77	0.211		43.1
mean	212.5	330.2	38.2	22.6	1.425	0.212		43.9

The mechanical properties have been measured according to STN EN ISO 6892-1, the normal anisotropy ratio according to ISO 10112 and strain-hardening exponent according to ISO 10275. The values of material formability parameters have been measured in directions 0°, 45° and 90° to steel sheet's rolling direction on testing machine TiraTEST 2300 equipped with an automatic extensometer to measure the elongation and the second extensometer to measure the width of the specimen during the test.

The limit strains have been measured by tool set for Nakajima test - **Fig. 1**.

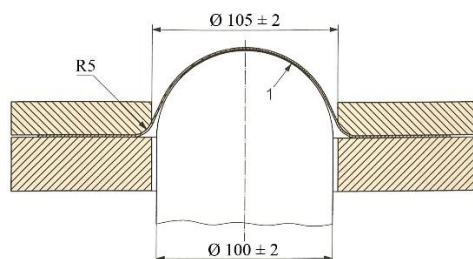


Fig. 1 Scheme of the Nakajima test according to EN ISO 12004-2

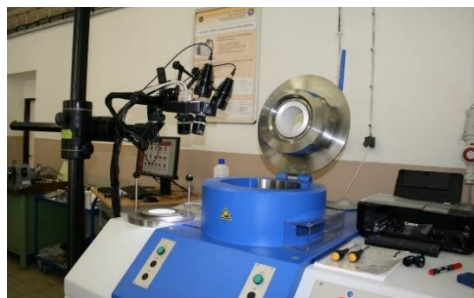


Fig. 2 Universal sheet metal testing machine Erichsen 145-60 with FLC tool and the ARAMIS system

The stretching of the testing samples has been performed on universal testing machine Erichsen 145-60 (**Fig. 2**) with the punch speed of 60 mm/min until the specimen fracture – **Fig. 4**. The matter of the test is stretching the specimens with different width that provide several strain paths (different ratios between strains φ_2 and φ_1).

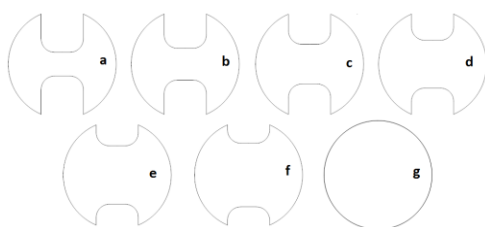


Fig. 3 Blank geometry for Nakajima test with blank width: a = 45 mm, b = 60 mm, c = 75 mm, d = 90 mm, e = 110 mm, f = 120 mm and g = 205 mm



Fig. 4 Dog bone shaped specimens with stochastic pattern after Nakajima test

The test conditions are specified in the EN ISO 12004-2 including the specimens shape. Waisted blanks (**Fig. 3**) with parallel shaft length of 50 mm and fillet of 25 mm have been prepared by milling. Stochastic patterns was applied by spraying paint onto the test piece surface. Paint adherence to the surface was checked before and after deformation.

3 The section method

Strain measurement was performed in the central test piece zone, close to the crack of the material. The measurement of limit strains have been done using ARAMIS photogrammetric system, which works on the principle of digital image correlation. The frame for evaluation of major and minor strains has been chosen a few steps before fracture occurred.

The GOM Company produces also ARGUS system, which can be used for this purpose also. However, the difference between these systems is the time of data collection. While ARAMIS system receives real-time data, ARGUS receives information discreetly in the state before and

after the test [13]. It was therefore concluded, that the ARGUS system cannot be used for time evaluation of the Nakajima test.

After the project is calculated and evaluated, it is necessary to define positioning of three parallel cross sections (Fig. 5) and subsequent determination of limit strains in forming limit diagram (FLD).

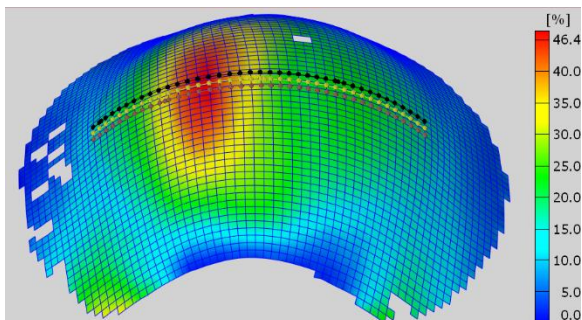


Fig. 5 Computed thinning of the sheet and cross sections created for exporting to the FLC mode of ARAMIS software

ARAMIS system used for this purpose a predefined script that will determine these values. Positioning of cross sections on deformation map and also calculated values of major and minor strains (Fig. 6) was achieved according to [7]. Inner limits for the best-fit curve through experimental points was determined by a best fit of a parabola according to (1):

$$f(x) = a x^2 + b x + c \quad (1)$$

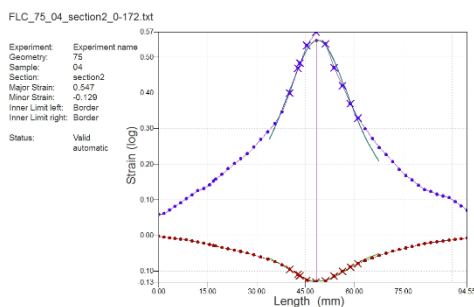


Fig. 6 Determining of limit strain by interpolation method

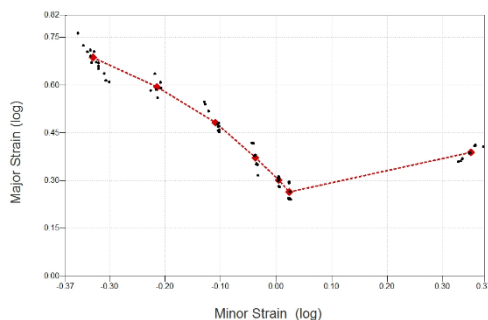


Fig. 7 The FLC curve constructed by section method

The limit major and minor strains for each section of the test piece have been calculated according to EN ISO 12004-2 [7] when section data have been imported into the FLC mode of the ARAMIS software. From each test piece shape was carried out several tests. The subsequent statistical evaluation was used only from valid samples, i.e. samples, where the crack occurred in distance of 15% of the diameter of the punch from the center of the dome. During the tests, some problems have been found concerning the lubrication. When the polyethylene foil have been used, for specimen No. 4, 5 and 6 the fracture didn't occur in the center of the dome or max.15

mm away from the top. Thus, the foil was lubricated with oil from both sides and then the fracture occurred within the limits. The final forming limit curve is illustrated in **Fig. 7**. The other problem was wrinkling at the sides of the specimen's neck for test piece No. 5. As had been found in [6], that wrinkling didn't affect the position of limit strains, i.e. the forming limit curve. Thus, the specimen have been evaluated.

4 Time dependent methods

The time dependent determination is looking for the change in deformation of the strain points around the fracture from the side of the time sequence. Points far away from failure will decelerate with proceeding forming and after a certain time (deformation) will stop to deform. Points near the crack will continuously accelerate until fracture. The algorithms used in this technique try to quantify this effects with the aim to find out the time (the image) when the first points on the sample are beginning to deform in an unstable way (beginning of unstable necking) [15]. Basically four different time dependent methods are commonly used [13, 15]. The "Correlation coefficient method" [16, 17] is using the second derivative of the major strain values with respect to time and the "Linear best fit method" [18] using the first time-based derivative of the thinning rate have shown promising results. Using time dependent methods the resulting FLCs are showing greater strain values than FLCs determined according to ISO 12004-2:2008 [14].

According to the Correlation coefficient method [16, 17] the determination of instable necking is based on the analysis of the acceleration of the major strain or thinning results with evaluating the second time-based derivative of these measures. With this method the instable necking is detected using correlation coefficient r . This correlation coefficient is always defined from the first used point in time to all subsequent points. In the beginning of this time based evaluation the correlation coefficient is zero. It will end in a maximum when the curve continuously change from a constant value and results in a drop of the coefficient when instable necking is reached. The corresponding major strain and minor strain values at the point in time according to the maximum of the correlation coefficient are then used as measures for the forming limit curve.

Determination of the correlation coefficient r using a gliding concept is described in the Gliding correlation coefficient method. To overcome the mathematical instability of the correlation coefficient at $r = 0$ a linear function in time with slope n between 0.1 and 1 is added to the acceleration curve of the major strain or thinning. If a gliding correlation coefficient is used, where always the same amount of points are used for the correlation coefficient acting in a similar way to a gliding filter, the value for the correlation coefficient is always $r > 0$. At the beginning of the evaluation the coefficient r is approximately 1 due to the fact that the acceleration scatters around the constant slope n . The coefficient r will be smaller than 1 when the acceleration deflects to high values and grows again towards 1 when the acceleration again becomes linear. The onset of instable necking is identified for forming states from uniaxial to biaxial reasonably stable [15].

Gliding difference of mean to median method. The difference between a gliding mean and a gliding median over a defined number of points from 7 to 15 depending on the frame rate used is utilised to determine the change in the thinning rate defined as the beginning of instable necking. The nature of a gliding median evaluation reduces the effect of noise while the mean evaluation is calculating the average change of thinning over a specific window of time. The difference between the mean and median evaluation has a maximum at the moment when the thinning rate is accelerating [15].

4.1 Linear best fit method

The linear best fit method is based on a technique analyzing the “rate of thinning” of the material within a local area where the instable necking will occur [18]. This local area is showing a large increase of thinning with time in respect of the surrounding areas which is an indication of the beginning of instable necking [19]. For the linear best fit approach the thinning rate is considered as the basis for the determination of the point in time of instable necking instead of the thinning acceleration. The latter suffers from increased noise due to the second derivative. To reduce the influence of noise in the determination of slope of the thinning, the derivative is determined using a fitting window of typically 7 images representing 7 points in time [20]. This fitting window can be adjusted depending on the frame rate used and might be larger for higher frame rates. The beginning of instable necking is evaluated for this method using two best fit straight lines, one fitted through the area of stable deformation in the beginning and one fitted through the thinning rate results just before specimen failure (**Fig. 8**). In order to normalize time-axis for different punch velocities, the punch position instead of time was taken. The punch velocity was set to 1mm/s. The intersection of these two lines identifies the point in time when instable necking starts and the corresponding major and minor strain values for the forming limit curve are taken at this point in time.

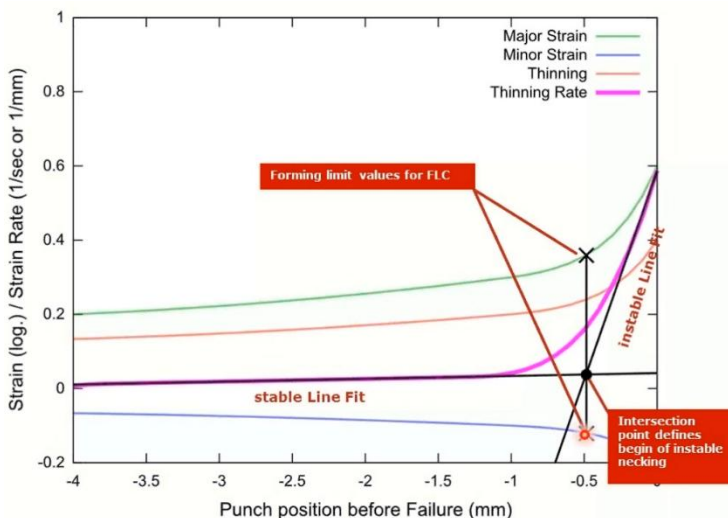


Fig. 8 Determination of instable necking using the linear best fit method [13]

The method described in [18] was modified by [15] to calculate more reliable result values. The first best fit straight line fitted through the area of stable deformation is calculated in the area of 4mm to 2mm before specimen failure. To determine the second fitting line through the thinning rate results just before specimen failure a gliding straight line fit is calculated for each point in time based on the change of punch position considering a fit windows size of ± 0.1 mm (typically 3 points in time). This results in one straight line for each point in time and the second fitting line is defined as the one with the largest gradient. In this case the modified straight line fit represents the real thinning rate more accurate for a bigger range than the approach described in [18]. Using the modified method a later onset of necking is determined and thus greater forming limit values are derived.

All considered time dependent methods are evaluating results which are related to the change of the strain rate of the specimen before failure occurs. Usually, in the beginning of a Nakajima test, a test specimen is showing relatively uniform deformations and thus a constant strain rate. Later, during the test, areas of the specimen located further from the failure area are exhibiting decreasing speed of deformation before deformation slows down these areas stop. The main principle of all time dependent methods is based on the fact that the strain rate of a local area of the test piece in the necking area rises quickly before specimen failure. Therefore these time dependent methods are used to determine the point in time during the test when the specimen starts to show instable necking.

5 Comparison of the results based on the different evaluation methods

On the basis research [15] realized on 30 different materials from steel and aluminum alloys, where the FLCs were determined the following conclusions can be drawn:

- The correlation coefficient method sometimes shows not stable evaluations typically resulting in too high strain values for the FLC
- The gliding correlation coefficient, compared to the correlation coefficient shows a better reproducibility but the resulting strain values by trend are too low.
- The gliding difference of mean to median has the smallest accuracy while the resulting strain values by trend are too high but not as high as sometimes with the correlation coefficient.
- The linear best fit method shows the most accurate evaluation, in terms of reliability and reproducibility, with strain results values close to those achieved in real formed sheet metal components.

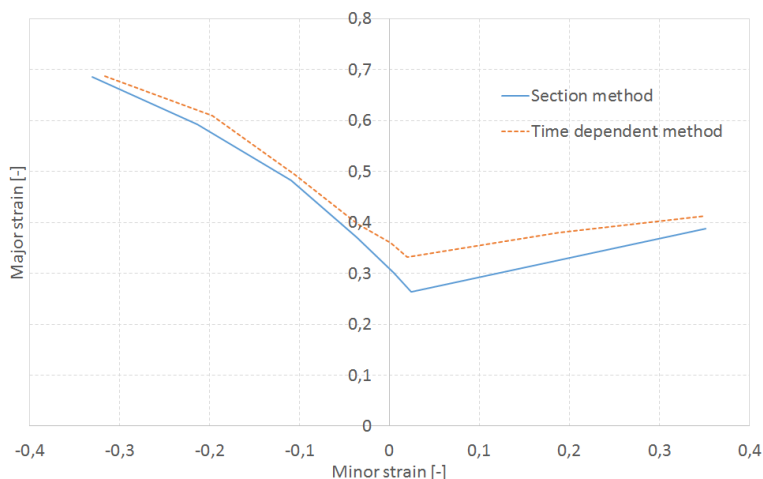


Fig. 9 Comparison of FLC between section method and linear best-fit method

Based on these facts, a comparison between the common sections based evaluation of the forming limit curve according to ISO 12004 and time dependent method evaluated according to linear best fit method using the same measurements within a Nakajima test series was carried out. For the tested material of HX180BD, the section based forming limit curve determination (ISO 12004) results in the lowest curve while the time dependent methods lead to a shift of the

forming limit curve to greater strain values. In particular the variants of the linear best fit method are showing the largest shift in the plain strain region and biaxial deformation conditions of the forming limit curve. **Fig. 9** shows the comparison of the forming limit curves between the section based and linear best fit method for HX180BD steelgrade.

In general, as mentioned above the forming limit curve based on the linear best fit method shows a shift to larger values in the plane strain and biaxial deformation areas. A more detailed examination of the plane strain area shows a questionable reliability in determining the FLC strain values with the section based method, while the linear best fit method leads to a much closer fit to the real values (**Fig. 10**). From the **Fig. 10** (left) are evident two peaks of major strain curve. This indicates above all a problem with the lubrication. Similar results were achieved for the biaxial loading state, where the section based method leaves much more questionable results than the linear best fit method.

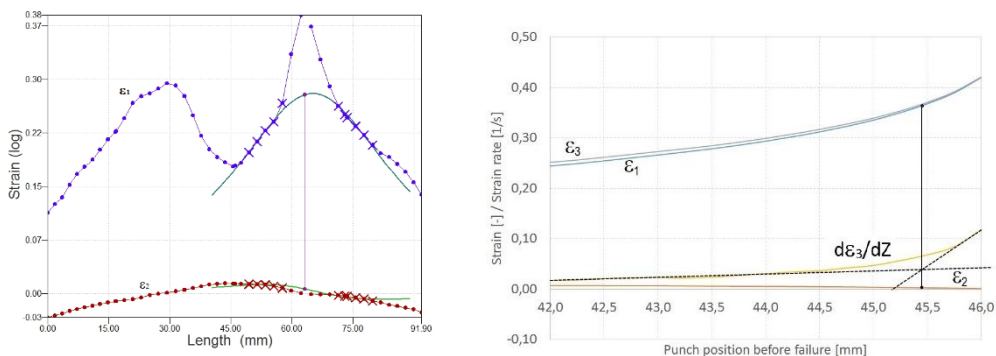


Fig. 10 Detailed comparison for plain strain state between section method (left) and linear best fit method (right)

6 Conclusion

In this experimental method for determination of forming limit curves were used the most advanced technology of measurement and testing. Using these devices the experimental FLC curve of high strength steel applicable in automotive industry was obtained in a short time. The forming limit curve for high strength steel sheet of HX180BD was determined in order to establish material model in simulation software and implement the testing method in our laboratory. The Nakajima stretching test was applied to a 0.6 mm thick steel sheet according to EN ISO standard.

The time based methods for the determination of FLCs are typically leading to a shift to greater strain values. Compared to measurements and experience with real formed sheet metal components are closer to the realistically expected forming limits for different materials. The linear best fit method turned out to deliver the most stable mathematical evaluation with forming limit results matching closely real formed parts for a large variety of different materials.

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