Formability Limit Curves under Stretch-Bending

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Abstract: A common strategy for stabilizing the greenhouse gas concentrations in the atmosphere was the introduction of new emissions limits for cars, and light commercial vehicles. For that reason the automotive industry is facing new challenges in order to fulfill these considerations. One of the strategies attained, is to employ new grades of Advanced High-Strength Steel (AHSS) to replace conventional steels in vehicle's body structures. These changes are intended to reduce the estimated total weight and increase fuel efficiency of vehicles. The main focus of this research is to derive a stability model which can encounter the enhanced formability obtained when simultaneous bending and stretching are applied to a sheet metal. Since experimental data is already available, it will be used for validation purposes. A sensitivity analysis in terms of different punch radii during the Nakazima test will be presented.
Keywords: FLC, AHSS, Stretch-Bending, formability.

1. INTRODUCTION

The use of advanced high strength materials in metal forming processes brought new defies predicting the material response under sheet metal operations. One of the techniques widely used to characterize this behavior is the Nakazima Test, which allows the generation of the Forming Limit Curve (FLC). This technique seems to be not accurate enough, and underestimate the formability limits for AHSS materials in cases where stretching and bending are combined. For this reason, in this study finite element simulations were developed to investigate further the effect of the introduction of these new materials into conventional metal forming processes.

It is known that sheet metal can only be deformed to a certain level before local necking, and subsequently failure occurs. The forming limit curve (FLC) or forming limit diagram (FLD) is a very common tool to determine the maximum principal strains that can be sustained by sheet materials prior to the onset of localized necking. However, the validity is limited to certain conditions, such as, regions with low curvatures, proportional deformations, in-plane stresses only, and the absence of bending, among others. Some of the first studies in relation to the influence of curvature during forming operations were realized by [Ghosh, 1974]. After analyzing data from an in-plane stretching test, with experimental results from a Nakazima type test, they determined that the formability of a metal sheet was positively influenced by the constrained deformation in contact with the rigid punch. In the same year, Charpentier [Charpentier, 1975] investigated the influence of the punch curvature on the stretching limits of steel sheets. Charpentier suggested that, as the sheet curvature increases, resulting in larger strain gradients, the limit strains also increases. He also demonstrated that, the limit strains increase with increasing punch curvature (1/R) at a constant material thickness by varying the nose radii of the punch during the experiments as in [Vallellano et al., 2008].

The use of advanced high strength steels in the following years made it more relevant and the influence of bending was more notorious. Some authors have shown that the formability, determined for a sheet, increases with decreasing radii to thickness ratio [Vallellano et al., 2008; Col, 2005; Till et al., 2008]. Till et al. showed that increased formability was seen especially for Advanced High Strength steels. More recent investigations predicted the necking behaviour of a metal sheet under combined stretching and bending by FEM simulations and an analytical method [Kruijf, 2008]. In FEM simulations for stretch-bending no necking was observed. In bend stretching the pre-bending promotes neck initiation during the subsequent stretching phase.

In one of the recent studies done by Fictorie [Fictorie, 2009], and made available to a wider public through [Fictorie *et al.*, 2010; Atzema *et al.*, 2010] two new setups were developed for a set of different punch diameters (20mm-50mm). They were tested with four different materials, and the main goal was to compare this data with the experimental information from the standardized Nakazima test (100mm). In that study, the formability of an aluminum alloy and mild steel was improved by increasing the curvature of the punch and its especially clear influence in the plane strain region. Part of the newest work in this matter was realized by [Hudgins *et al.*, 2010]. They developed an analytical model based on mechanics and material properties to predict instability expressed by maximum applied tensile stress as a function of die radius normalized by sheet thickness (R/t).

Forming limit curves are usually determined for membrane type deformations when FEM simulations are employed. Furthermore, the limit curves acquired seem to underestimate the limit values of strains and one reason may attributed to the effect of the thickness stress in the material. Also, the influence of simultaneous bending deformation on the forming limits has attracted renewed attention, and for that reason it is necessary that the determination of the forming limits curve should use solid elements in thickness instead of shell elements.

2. FORMING LIMIT CURVE DETERMINATION

For the FLC determination it is assumed that necking is one of the main failures in terms of formability. It is known that the FLC shows under which strain conditions the material becomes plastically unstable and consequently starts necking. In a tensile test necking will first be diffuse and then localized to promote fracture. In sheet metal forming mostly diffuse necking cannot occur and localized necking is the only necking mechanism. In this study as in a previous research the Bragard method will be used to determine necking [Fictorie *et al.*, 2010; Atzema *et al.*, 2010]. In this method the strain distribution of the necked points are eliminated and the necking point is reconstructed by the use of an inverse parabolic function. Furthermore, the application of this method has shown that the fitting window to determine the limit strain fail to remain in the contact zone between the blank and the punch, which means that only the contribution of the stretching part will be considered and not the combination of stretching and bending, see Figure 1.

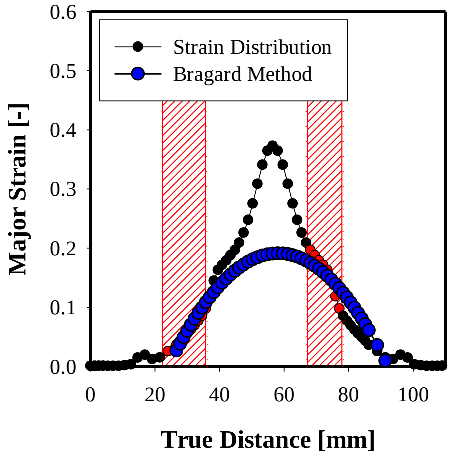

Figure 1; Bragard method illustration.

The main interest of this study is to derive a stability model which can encounter the enhanced formability obtained when simultaneous bending and stretching is applied to a sheet metal. In this particular case specimens of 0.7 and 1.4mm in thickness of steel DC06 and HCT600x respectively, will be used in accordance with the ISO-Standard [ISO, 2008], and with a 20mm punch. It was concluded from previous work [Fictorie, 2009], and literature review that some factors could be responsible for the improvement of formability in relation to bending in terms of the Nakazima Test. However, the previous FEM simulations of the process were not sufficient to fully capture the essence of the forming operation due to certain limits of the model itself. Summarizing these effects that could play a dominant role in the observed enhanced formability we encounter the following considerations: a) Pressure on the inside of the sheet, b) Friction between blank and punch, and c) Less ductile fracture behavior.

3. FINITE ELEMENT MODEL

In order to improve the results from the previous research and to consider some of the assumptions made in the past, a solid model would be used to encounter all the through thickness effects. A solid model would also lead to some disadvantages such as the number of elements needed and the increase in the overall computation time. The FEM simulation of the Nakazima Test was realized with the software ABAQUS/Standard and the elements were defined as C3D8R with enhanced hourglass control, see Figure 2.

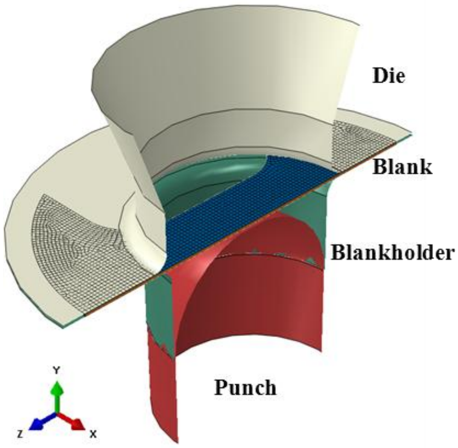

Figure 2; FEM Schematic of Nakazima test.

One of the influencing factors in the simulations is the friction between the bottom part of the blank and the punch. It is commonly assumed as a frictionless interaction when the localization is defined on top of the dome and slightly higher when the localization is not on top of the specimen [ten Horn, 2008]. In this study a frictionless interaction between the bottom and the blank and the punch was used. The representation of the friction between the following interactions: a) workpiece(top)-die and workpiece(bottom)-blankholder is also straightforward since the material should remain clamped. For interaction a, the value of friction was defined as 0.12, which is commonly used for metal to metal contact. Since the area of contact of the blankholder (interaction b) is usually fully serrated, it is expected to have a relatively high friction coefficient, in this case a value of 2 was set. The required blankholder force was varied between 100-200kN for the 20 mm (FLC20), and 300-500kN for the 100 mm (FLC100) punch simulations. The sample design for both punch dimensions was developed in [Fictorie, 2009], and based on the original size/shape of the samples used for the original Nakazima test (FLC100). The samples were scaled to fit the experimental setup and the two different punch diameters. A summary of all the sample parameters can be found in [Fictorie, 2009].

During the first attempt to obtain a stable FEM simulation, Abaqus/Standard was used. The specimen was 1.4 mm thickness and the material properties for HCT600X+Z (often referred to as DP600) and DC06 were obtained from literature [ten Horn, 2008]. The yield locus description is based on Hill´s 48, and the Bergström-van Liempt hardening equation. The description of the hardening equation and the parameters used in the simulations can be found in [Vegter and van den Boogard, 2006].

4. SIMULATION RESULTS

No fracture criterion was employed, so no element deletion was applied to the workpiece. In order to asses when the material becomes unstable, a similar criterion to the Marciniak-Kuczynski or M-K models was used [Marciniak and Kuczynski, 1967]. The criterion is based on the strain rate of the top, and bottom surface of the sheet in the history elements. It is assumed that the necking starts if the strain rate ratio localizes in a set of elements and is limited by:

$$\frac{\dot{\varepsilon}_{top}}{\dot{\varepsilon}_{top-/+4elements}} \geq 20 \qquad \text{Eq. 1}$$

A comparison was made for the strain rate values over time for the top elements, and the bottom elements in the region where the crack in the simulations is expected (strain rate localization). In Figure 3, is shown how the Top elements are referred as the elements with the highest strain rate value on the top surface on the sheet. Furthermore, the Top-/+4 are defined as four elements away from the Top element. The same applies for the bottom sheet surface, which in this case was found to be symmetric.

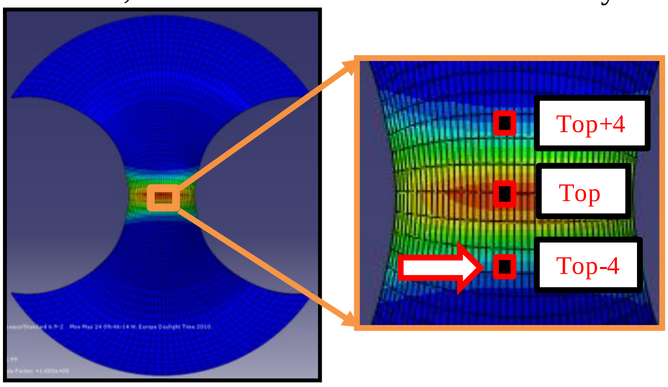

Figure 3; Schematic of elements selection for strain rate localization.

Different strain paths were followed to be able to determine the forming limit curves for the right, and left hand side of the FLC, see Figure 4.

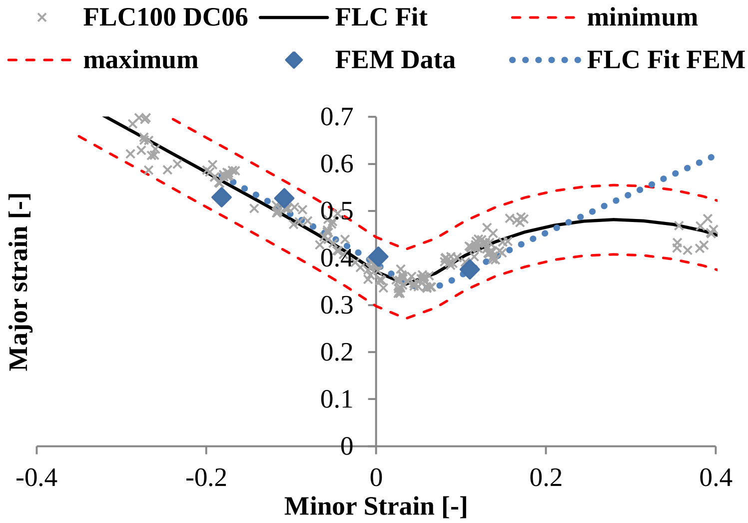

Figure 4; FLC experimental and FEM results for DC06 and 100 mm punch.

The same procedure to determine the forming limit function as in the experiments was employed to determine the forming limit function for the FEM simulation data. The simulations of DC06 and DP600 for the 100 mm punch were used as validation of the finite element model. The following step was to model the 20 mm punch and determine the FLC function as close as possible to the ISO Standard. It can be seen that in Figure 4 and Figure 5 the FLC function determined for the both FEM data is in well agreement with the FLC function determined for the experimental points.

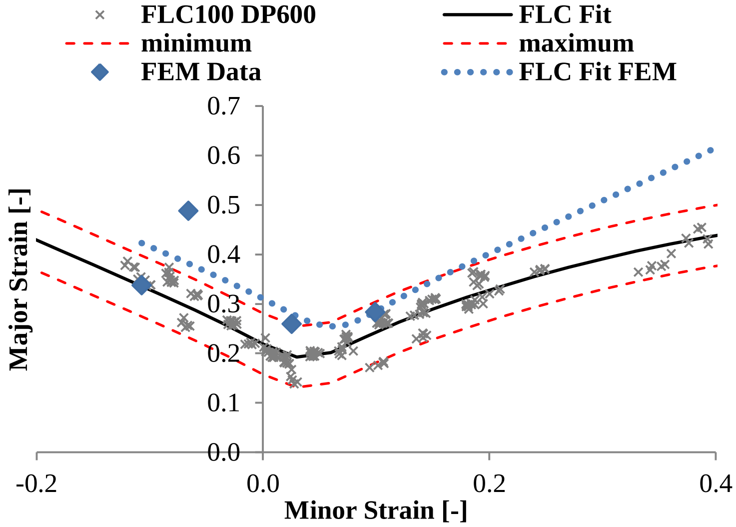

Figure 5; FLC experimental and FEM results for DP600 and 100 mm punch.

There are some considerations in order to be able to generate the FEM data points for the calculation of the FLC Fit for the 20 mm punch. The first one is related to the fitting window for the calculation of the inverse parabola. Since the distance is in relation with the 100 mm punch the fitting window tends to be considerably large for the smaller punch radii resulting in significantly lower values of strain. For that reason a scaling of the size (distance between green lines) of the fitting window parameter was scaled in order to try to overcome this situation, see Figure 6.

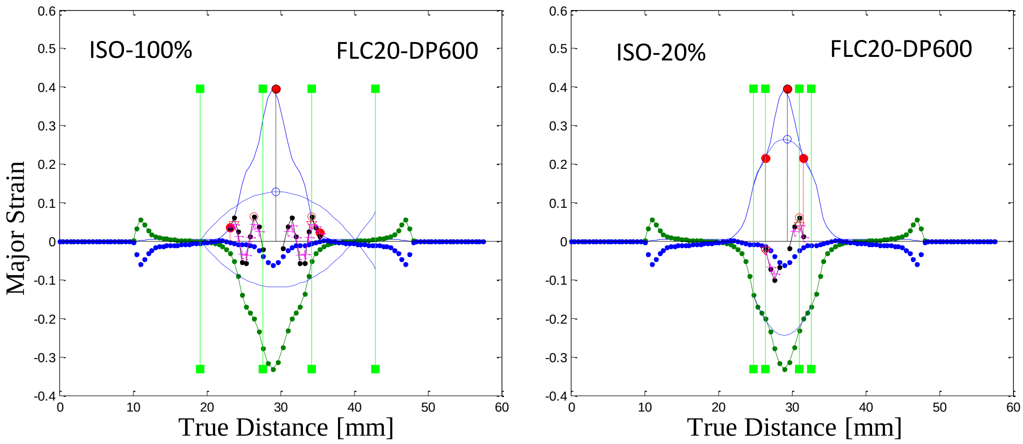

Figure 6; Fitting window considerations.

The final results for the 20 mm punch for the case of the DP600 reveals that the current methodology cannot determine accurately the forming limit predictions, see Figure 7. The values of the FLC are underestimated and the shape of the FLC does not correspond to the actual results of the experiments. The values of the limit strains of the experimental results are considerable higher compared with the values of the 100 mm punch for the case of DP600. New alternatives to determine the FLC fit should be addressed.

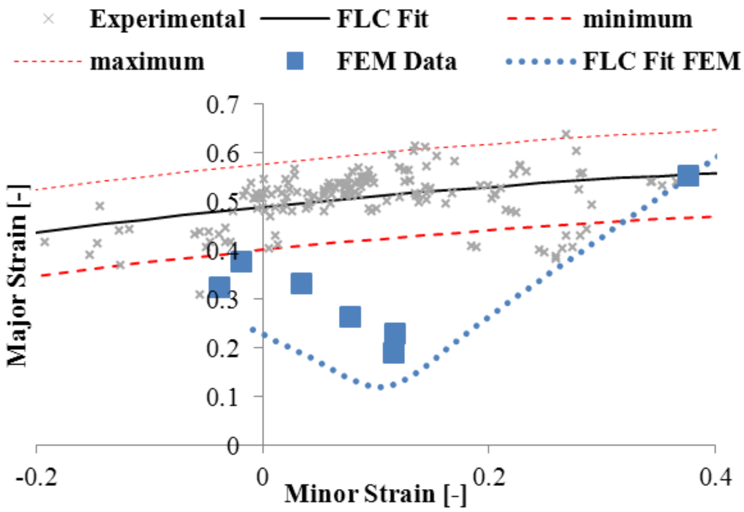

Figure 7; FLC experimental and FEM results for DP600 and 20 mm punch.

5. CONCLUSIONS

In this work, the numerical determination and comparison with experimental data for the Nakazima test with two different punch diameters was accomplished. The effect of bending was pointed as critical for the appropriate determination of the formability limits through FEM simulations. In terms of the 100 mm punch the simulations are in reasonable agreement with the experiments, but more work is necessary for the 20 mm punch.

6. ACKNOWLEDGMENTS

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