EFFECT OF BENDING ON FORMABILITY LIMITS

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RESUMEN.

Con la finalidad de cumplir con las nuevas normativas en términos de reducción de emisiones de gases de efecto invernadero, nuevos grados de aleaciones de aceros avanzados están reemplazando los aceros convencionales en las estructuras de los vehículos automotores. Estos cambios tienen la finalidad de reducir el peso total del vehículo y reducir el consumo de combustible. Sin embargo, la implementación de estos nuevos materiales ha traído nuevos reto para predecir la respuesta del material ante operaciones de conformado de metal. Una de las técnicas más utilizada para predecir dicho comportamiento, es la gráfica de límites de formabilidad determinada a través del ensayo de Nakazima o la prueba de Marciniak. Al parecer estas técnicas no son lo suficientemente precisas y tienden a subestimar los límites de formabilidad de aceros avanzados en casos donde se encuentra simultáneamente tensión y un proceso de doblado. Por esta razón, en el presente estudio se desarrollaron simulaciones de elementos finitos para investigar a profundidad la determinación de las gráficas de formabilidad con distintos escenarios de lubricación.

ABSTRACT.

In order to fulfill new environmental regulations to reduce Greenhouse Gas Emissions (GHG), new grades of Advanced High-Strength Steel (AHSS) have been replacing conventional steels in vehicle’s body structures. These changes are intended to reduce the estimated total weight, and increase fuel efficiency of vehicles. Although, the implementation of these materials brought new challenges to predict the material response under sheet metal operations. One of the techniques widely used to characterize this behavior is the Forming Limit Curve (FLC), through the Nakazima or Marciniak test. These techniques seem 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 out of plane stress in the FLC determination. Also the investigation of the influence of different lubrication systems was accomplished.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>$\sigma_0$</td>
<td>Static yield stress</td>
</tr>
<tr>
<td>$\Delta G_0$</td>
<td>Maximum activation enthalpy (eV)</td>
</tr>
<tr>
<td>$\Delta \sigma_m$</td>
<td>Stress increase parameter for strain hardening</td>
</tr>
<tr>
<td>$m'$</td>
<td>Power for the strain rate behaviour</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Strain hardening parameter for large strain behaviour</td>
</tr>
<tr>
<td>$k$</td>
<td>Boltzmann constant = 8.617E-5 eV/K</td>
</tr>
<tr>
<td>$T$</td>
<td>Absolute temperature (K)</td>
</tr>
<tr>
<td>$\Omega$</td>
<td>Strain hardening parameter for low strain behaviour</td>
</tr>
<tr>
<td>$\epsilon_0$</td>
<td>Pre-deformation parameter</td>
</tr>
<tr>
<td>$\epsilon_p$</td>
<td>Actual strain</td>
</tr>
<tr>
<td>$\dot{\epsilon}$</td>
<td>Actual strain rate</td>
</tr>
<tr>
<td>$n'$</td>
<td>Exponent for the strain hardening behaviour</td>
</tr>
<tr>
<td>$\sigma_0^*$</td>
<td>Limit dynamic flow stress</td>
</tr>
<tr>
<td>$\dot{\epsilon}_0$</td>
<td>Limit strain rate for thermally activated movement</td>
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</table>

INTRODUCTION

The forming limit curve (FLC) or forming limit diagram (FLD) is a very common tool to determine the maximum major 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...
Some of the first studies in relation to the influence of curvature during forming operations were realized by Ghosh and Hecker [1]. 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 [2] 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 strain 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 [3].

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 such as, Col [4], Vallellano et al. [5], and Till et al. [6] that the formability, determined for a sheet, increases with decreasing radii to thickness ratio. 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 [7]. 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 et al [8], two new setups were developed for a set of different punch diameters (20 mm-50 mm). They were tested with two different materials, and the main goal was to compare this data with the experimental information from the standardized Nakazima test (100 mm). 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. [9]. 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 for small radii, and one reason may be 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 limit curve should use solid elements in thickness instead of shell elements.

**FORMING LIMIT CURVE DESCRIPTION**

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 with 1.4 mm in thickness of HCT600x steel with a 20 mm punch. In Figure 1, a schematic of the sensitivity of the material to different punch radii during the Nakazima Test is depicted.

It was concluded from previous work [8], and literature review [10] 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:
During bending operations of a sheet metal, the outer layer of materials is severely stretched in comparison with the inner layer. In the case of the Formit Limit Curve (FLC) determination through the Nakazima tests, this behaviour of bending while stretching is also encountered. Normally, the deformation is assumed to be plane stress, where the stress over the thickness is assumed to be zero. Although, there are some indications that the stress may be higher and it could affect the process considerably. It is known that adding a surface pressure, the equivalent von Mises stress will increase on the inside bend postponing the onset of necking, and thus increasing the formability. According to Fictorie [8], the effect of the inside pressure is possibly non-linear with the punch radius, so it will have no effect for large punch sizes and a large effect for sharp punches.

In Figure 2, the 3D model for the Nakazima test and the experimental device used are shown. More detail regarding the sample dimensions and machine settings can be found in (3, 8).

Since the inside pressure on the sheet can only be modelled by using solid elements, the priority for the start of the project was to develop a model able to reproduce this phenomena using solid elements instead of shell elements, which are very popular in literature. These modifications will allow us to investigate which parameters of the sheet are relevant.

b. Friction between blank and punch

In the experimental phase it was noticeable the effect of the PUR pad (friction device) to promote the crack generation at the top of the specimen, see Figure 3. It seems that the strain distributions obtained over the samples were influenced in a positive way, and the material was driven away from the top. The strain distributions showed a single peak where the necking occurred. From the simulations it became clear that the lubrication system can be an influencing factor for the strain distribution and thus special care has to be taken when modelling it. For the PUR pad solid elements must be used, containing several layers over the thickness controlling the hourglassing effect.

c. Less ductile fracture behaviour

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. Necking will first be diffuse and then localized to promote fracture. In previous research to determine necking the Bragard method was used. From the strain distribution the necked points are eliminated and the necking point is reconstructed by the use of an inverse parabolic function [8].

Some researchers [10] attribute failure not only to necking, but fracture, as the main mechanism. They had shown that the fracture curve is close to the instability line of HCT600X steel, but always above of it. This information was used for FEM modelling in combination with experimental data to determine for a specific material the different failure limits together in one diagram called CrachFEM.

**FINITE ELEMENT MODEL**

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In order to improve the results from the previous phase and to consider some of the assumptions made in the past, a solid model would be used to encounter all the through thickness effects, see Figure 3. A solid model would also lead to some disadvantages such as the number of elements needed and the increase in the computation time for the finite element model.

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. The experimental data related to the material properties will remain confidential. The representation of the friction between the sample and the die and blankholder is less important and more straightforward. For metal-to-metal contact, in the smooth region, a friction coefficient of 0.12 is used. The friction coefficient used for the serrated areas was set to 2, and the required blankholder force to 100kN.

During the first attempt to obtain a stable FEM simulation, Abaqus/Standard was used considering the tools as analytical rigid. The specimen was 1.4 mm thickness and the material properties for HCT600X (DP600) were obtained from literature [12]. In the previous simulations the Corus-Vegter yield locus was used in combination with the Bergström-van Liempt hardening equation [13], see Equation 1.

$$\sigma_y = \sigma_0 + \Delta\sigma_y \left( \beta \left( \dot{\varepsilon}_p + \varepsilon_0 \right) \right) + \ldots$$

$$\ldots \left[ -e^{-\frac{1}{\Delta\sigma_y + \dot{\varepsilon}_0}} \right] + \sigma_0 \left( 1 + \frac{kT}{\Delta G_0} \ln \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \right)^n$$

In the actual simulations the hardening rule is the same but the yield locus is based on Hill’s 48 [14]. The adaptation of the Abaqus model to implement the Corus-Vegter yield locus is still not defined yet since its complexity is very time consuming. The hardening equation was included in Abaqus/Standard as tabular data, but the final goal is to set it up in a separate subroutine called UHARD.

**SIMULATION RESULTS**

It is necessary to mention that all the forming simulations have a refined mesh in the area of contact with the punch. The computation time was in a range of 2 to 10 hours using an Intel Core 2 Duo E8400 Processor with 4Gb of RAM. For the FEM simulations, the die, blankholder, and punch were defined as analytical surfaces in order to reduce to the minimum the computation time. No fracture criterion was employed, so no element deletion was applied to the workpiece. In order to assess when the material becomes unstable, a similar criterion to the Marciniak-Kuczynski or M-K models was used (15), see Equation 2. 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:

$$\frac{\dot{\varepsilon}_{\text{top}}}{\dot{\varepsilon}_{\text{top}+4\text{elements}}} \geq 20$$

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 4, 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.
It is necessary to mention that different strain paths were followed to be able to determine the forming limit curves for the right, and left hand side of the FLC. In Figure 5a, and 5b, the strain rate, and strain rate ratio are evaluated for the sample near the uniaxial strain. The complete range of punch displacement was used and it will be identified in two different regions below for sake of comparison. It can be seen that the maximum punch displacement can be determined by the onset of necking or necking initiation (red line in Figure 5b) as any value of strain rate ratio above that limit (Equation 2). It shows how after the necking criterion is met, the strain rate ratio shows a rapid major increase which moves toward infinite.

After the maximum punch displacement is determined, the major and minor strain at the specified displacement can be extracted and used to determine the FLC for all the strain paths (uniaxial to biaxial strain). A more detailed description of Figure 5a, is presented in Figure 6a, and Figure 6b. Analyzing Figure 6a, it can be visualized how for the initial contact (0-2 mm) the strain rate is relatively high at the beginning for the bottom elements but it drops quickly. The top elements follow a similar behavior, but it is clearly postponed since the first parts in contact with the punch, are the bottom elements. It can be understood that the strain rate drops till it reaches steady state (0.6-0.7 mm) and starts increasing again (>2.5 mm) due to the deformation. In Figure 6b, the localization starts taking place around 7.25 mm, and can be seen how the Top and Bottom (Bot) elements continue with an increase in the strain rate while the adjacent elements (Top+4 and Bot+4) tend to zero.
Taking in consideration Figure 4b, a more detailed set of plots was defined in Figure 7a, and 7b. For the first case an unusual point (red circle) is devised around 0.6 mm which is still under review, but it is possible that this point corresponds to the transition between the elastic, and the plastic part of the material. It is also remarkable that this effect is only observed on the surfaces in contact with the punch which leaves the door open to the possibility that the responsible of this point is the contact algorithm from the FEM module. More analysis in this matter will be presented in future work.

In Figure 7b, is depicted the strain rate ratio for the range of 6-8 mm of punch displacement. It is shown how the bottom elements see a rapid increase followed by the top elements. This behavior indicates that the localization will start first in the bottom part of the sheet and later on at the top.

In order to make a comparison for different friction scenarios three friction coefficients (μ=0, 0.01, and 0.05) were employed between the punch, and the bottom of the sheet, see Figure 8a-8b. A frictionless process is considerable close to reality since in the experimental part two Teflon’s layers are used to reduce friction. It has been estimated in previous work (12) that a friction coefficient value around 0.01 for the simulations is closer to the encountered during the experimental part. Also an extra set of simulations with a higher friction coefficient (0.05) was realized.

It can be seen that for the left hand side (LHS ) of the FLC, the major strains are higher for the bottom elements in comparison with the simulations results of the top elements. It is also clear that all the data points from the experimental part are below the forming limits for all three friction models. The effect of the friction in the
LHS is evident in figure 8a where the frictionless model reaches lower strain values. This effect is not visible in the Top elements as it was expected, see LHS of Figure 8b. It can be appreciated from Figure 8a, and Figure 8b that considering the limit strains only in the top of the sheet will underestimate the forming limits. For the right hand side (RHS) there are factors such as, yield locus, hardening type, Lankford R-value of the material, and the strain rate dependence that may have an impact in the shape of the curve for the limit strain calculations. Especially near the biaxial region the values of major strains tend to be higher for lower levels of $R$ (16). For the RHS, the results from simulations with zero friction coefficient show that near the plane strain region the model is unable to capture all the data points from experiments. As soon as friction is added to the model, the limit strains for both friction coefficients (0.01 and 0.05) are able to capture all data points.

CONCLUSIONS

A comparison was made between the experimental data from literature and FEM simulations results to simulate the behavior of the Nakazima test for steel HCT600X. The samples tested the uniaxial, plane strain, and biaxial strain paths for a 20mm punch.

The results of the left hand side (LHS) of the FLC are in good agreement with the experimental data. The effect of friction is only shown in the bottom elements where is critical for this forming process.

Only the models with friction were able to capture all the data points from experiments in the right hand side region.

The results of forming limit curves are relatively sensitive to the constitutive model of the material, the yield function, strain rate and other factors.

FUTURE WORK

As future work, it is necessary to find a methodology capable to generate the FLC’s without the need of extensive experimental tests, to enhance the practical utility of FEM metal forming simulations.

It is also intended to extend the work to different punch diameters such as 50, 75, and 100 mm.

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