

# Understanding the FLC prediction thanks to fine simulation with damage modelisation

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**Abstract.** Nowadays, FLC is widely used to determine the feasibility of stamped parts. A FLC is usually determined by the experimental Nakajima trials. However, operating conditions can influence the value of the FLC. Experimental trials tend to suffer from result variability (scatters, errors ...) and it is rather difficult to interpret the results and find the root causes of such or such phenomenon.

The goal of this study is to investigate the influence of operating parameters of the Nakajima test on the FLC by using finite elements simulation. This paper is dedicated to the first phase of this study: define a rather reasonable model that is able to capture the main phenomena. Our goal is not to study and compare very complex plasticity models, that is a very important topic, but also an endless job. We want to build a robust, easy to understand, representative enough model. For that a solid element mesh as fine as CPU time allows was used (0.2 mm) in order to well represent the necking. The procedure used to identify the FLC is the same that for experimental determination. A virtual grid of 1 mm on the upper skin is used to compute the strains and the inverse parabola fitting methods of the ISO 12004-2 standard is used to determine the FLC points. Damage was also considered in the model, as it allowed to get closer to analytical and experimental prediction. The damage parameters were a combination of data found in literature and of fitting with an experimental FLC. With this model the effect of thickness was highlighted. Globally it was consistent with what we can observe in a real Nakajima test but we noted a strange behaviour around the uniaxial tension path that need further work to be explained.

## 1. Context

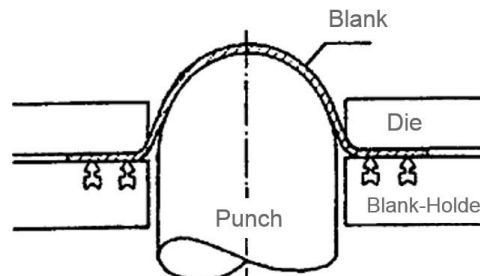
### 1.1. Why still studying the Forming Limit Curve?

Forming Limit Curve (FLC) is a generalized tool used to assess stamped part feasibility. This curve aims to divide admissible strains from strains leading to necking. However, FLC, which is of course dependent on the material and on the thickness, is not fully intrinsic to the material. There is no universal procedure to determine FLCs and the values are very influenced by the kind of test and the test procedure. In order to correctly assess part feasibility, understanding how the test procedure affects the FLC is essential. But this study is a first step to a wider concern: understanding the required conditions of necking onset in order to find out a general criterion able to assess stamping feasibility whatever the conditions are, nonlinear path, strain and stress gradient, part curvature, etc..



### 1.2. The motivation behind creating a numerical Nakajima model

Experimental trials are one way to determine FLCs. We chose to focus on Nakajima trial (Figure 1), as it is widely spread. Nakajima trial aims to determine FLCs by stamping a sample with a hemispherical punch until sample failure. Strains are then computed in order to determine strain at the onset of necking [1].



**Figure 1.** Nakajima trial tools.

Nakajima trial gives the user some flexibility in the choice of some operating parameters (i.e. punch diameter, blank thickness ...). FLC is very influenced by these operating parameters. Understanding how they influence FLC prediction could be a preliminary step to understand deep FLC mechanisms.

However, experimental trials have some limitations:

- Experimental trials are scattered. The dispersion can be related to experimental error (manipulation error, reading error, tolerances ...) and material scatter (every sample is different: material defaults ...). This scatter could misrepresent the interpretation of some phenomena.
- Changing one parameter can be complex as this parameter is not always under control (i.e. friction) or its variation may influence others.
- Experimentally, some data cannot be measured. Usually, we are limited to the strain measurement on the upper skin of the sample.
- The behavior of actual material itself is complex and it is difficult to link a given behavior to one material property.

In order to go beyond experimental limitation, we chose to develop a numerical medialization of the Nakajima trial. Numerical simulation offers these advantages:

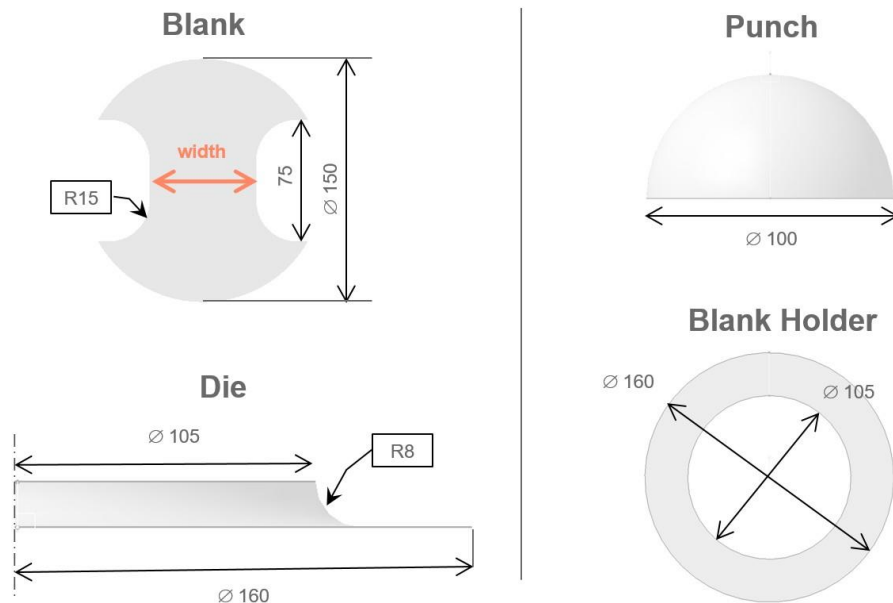
- There is no scatter or a controlled scatter can be introduced.
- The study of the influence of one parameter is facilitated as the change of its value doesn't affect affects others parameters.
- The results give access to a lot of information like strain or stresses through the thickness everywhere, every time.
- It is possible to choose the material properties to be taken into account (kind of plastic model, damage, strain rate sensitivity,...).

However, it must be clear that our purpose is not to look for “the best” and “more accurate” way to simulate the Nakajima test. We don't want to compare the effect of such or such yield locii, kinds of hardening damage models, or ways to extrapolate the stress/strain curve. We just want to have a not too bad modelization able to capture the influence of experimental parameters on the FLC.

## 2. Approach

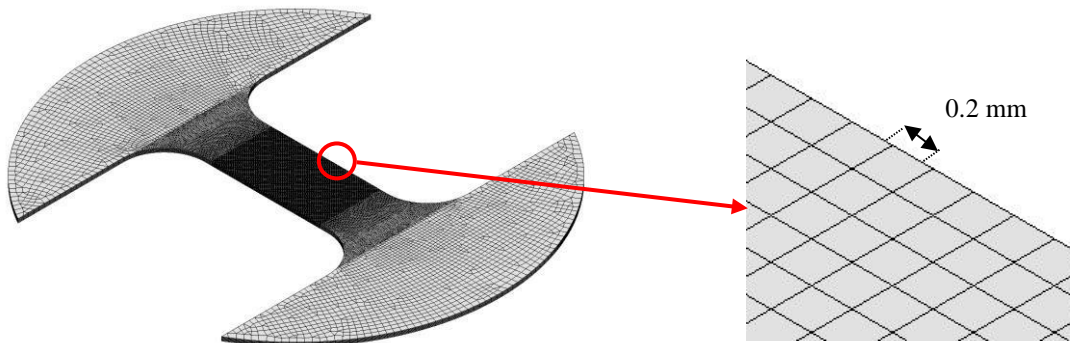
### 2.1. Model

The model was created on LS-DYNA software. Tool dimensions are similar to experimental ones (Figure 2).

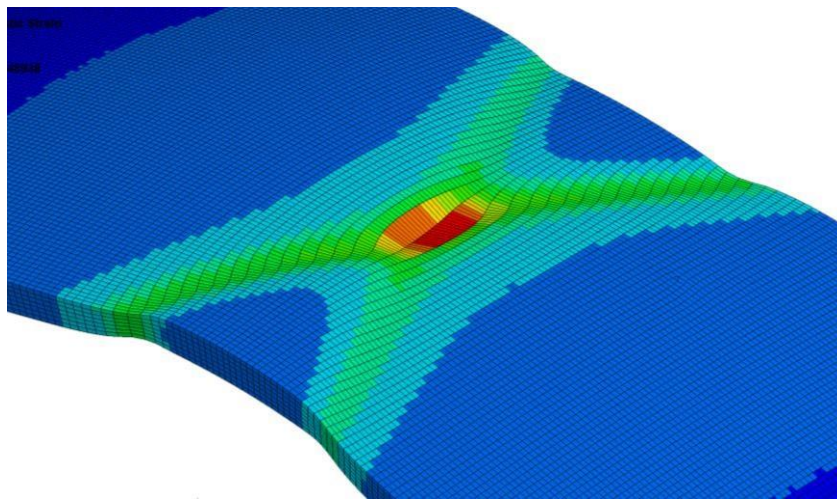


**Figure 2.** Nakajima tools dimensions.

Usually, shell elements are used for stamping simulation. Unfortunately, these elements don't allow to reproduce fine phenomena through the material thickness. With shell elements, necking onset is not correctly reproduced. Moreover, the mesh size needs to be finer than the "necking size" in order for the necking to precisely onset. Thus, we used a very fine solid mesh in the central area of the blank (Figure 3) (mesh size: 0.2 mm for 1.4 mm blank thickness). With this mesh size we are able to get several elements in the necking area that allows us to capture the necking effect even through the thickness (Figure 4).



**Figure 3.** A fine solid mesh was used.



**Figure 4.** Necking onset is finely reproduced.

The studied steel was a Dual Phase 600 (DP600). It is rather a formable High Strength Steel. A simple isotropic hardening law was used: Hollomon Law

$$\sigma = K\varepsilon^n$$

Even if this law doesn't allow to reproduce accurately the steel behavior compared to sophisticated laws (i.e. Swift-Voce), this law uses parameters which have a “physical” meaning (i.e. necking is mainly controlled by “n” value). Easy-to-interpret law parameters are essential to understand the influence of the hardening curve on the FLC.

The classical Hill 48 yield locus is also used even if we know that a non-quadratic yield locus with vertices can have a strong influence on the result.

A GTN (Gurson-Tvergaard-Needleman) damage model was chosen. We selected some GTN parameters from [2] and the last parameter ( $f_0$ ) was obtained by experimental trials and model calibration to fit analytical FLC prediction (Figure 7).

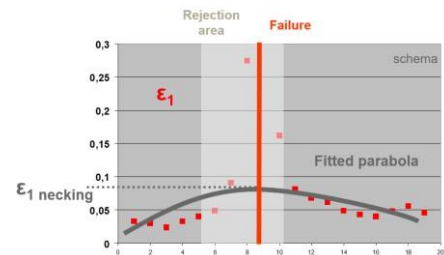
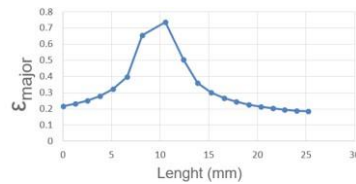
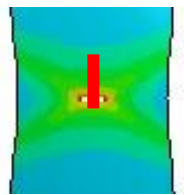
**Table 1.** GTN Parameters for DP600 <sup>[2]</sup>.

$f_0$	$f_c$	$q_1$	$q_2$	$q_3$	$\kappa$	$\epsilon_N$	$f_N$	$S_N$
0.0003	0.014	1.2	0.9	1.44	4	0.1	0.018	0.2

## 2.2. Post-processing

Post-processing methods are similar to experimental ones (Figure 5):

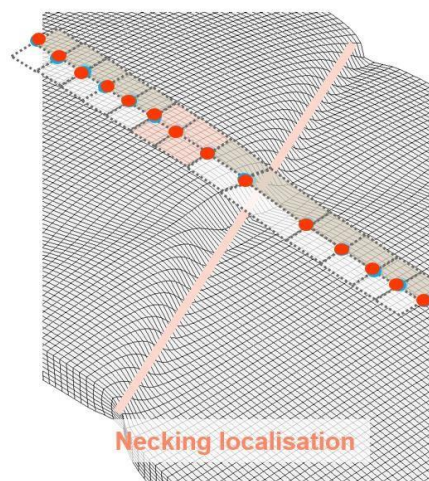
- Strains are measured on the upper skin of the blank through sections on both side of the failure.
- A grid of 1mm size is used to determine strains (Figure 6). It avoids reading directly the strain values on the elements and minimizes the mesh size influence on the strain measurements.
- Finally, the inverse parabola fitting methods of the ISO 12004-2 standard <sup>[1]</sup> are used to estimate strain at the onset of necking.
- The final strain value is the average of values obtained for four lines crossing the fracture area.



1- Failure 2- Strain Measurement 3- FLC point determination:

Inverse Parabola Fitting

**Figure 5.** Nakajima post-processing stages.

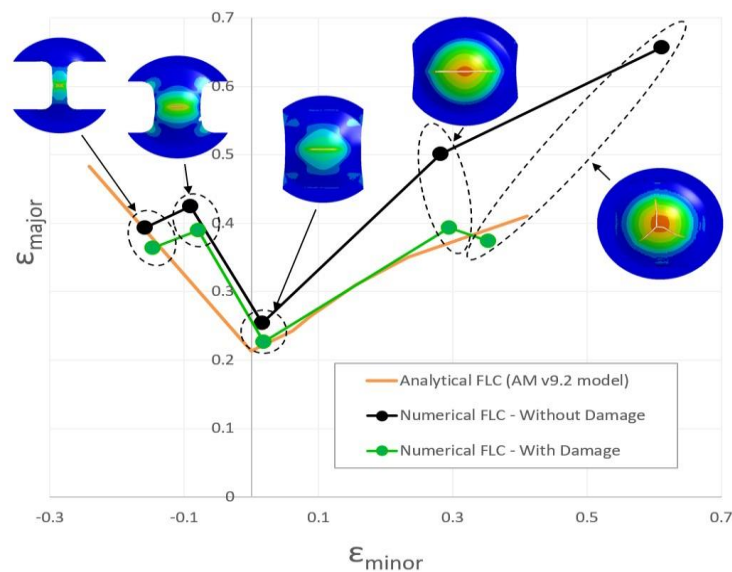


**Figure 6.** A grid is used to avoid the mesh size influence during the strains determination.

### 3. Results

#### 3.1. Influence of the damage

Damage was also considered in the model. Such models are rarely implemented in stamping simulation. This is due to the lack of available parameters that are difficult to identify. However, in our study, damage consideration presents a main advantage: normally the inverse parabola fitting methods must be applied on a broken specimen but, without damage, the elements in the necking area can become very long (without breakage). Additionally, damage allows the material to show a soften behavior before necking. Thus, strain gradients would be different and it could influence the necking onset.



**Figure 7.** Damage influence is stronger in the right-side than in the left-side FLC.

Simulations with and without considering damage in the model confirmed that the expansion side of the FLC (right side) is strongly influenced by damage (Figure 7). On the contrary, the FLC left side is less influenced by damage. The 2 curves, with and without damage, are quite close in this area. For this FLC left side, the failure material behavior is controlled by necking and instability, which appear at low damage growth.

Moreover, adding damage to the model also allows to reproduce the typical 3-branches EBE failure shape experimentally observed (Figure 8). Without damage consideration, necking only onsets on a single branch (not at the top of the blank).



**Figure 8.** The failure shape of EBE simulation with damage (right) is closer to experimental shape (middle) than without damage (left).

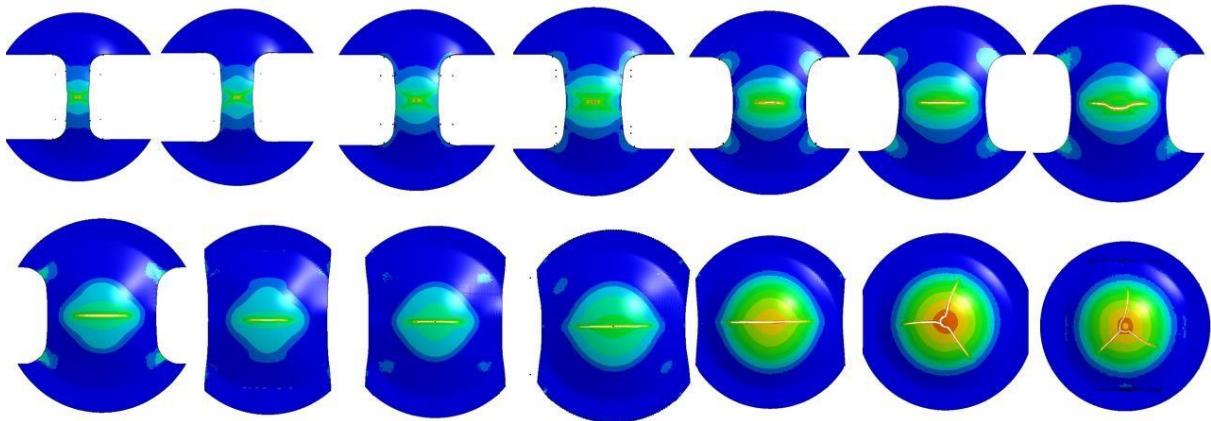


### 3.2. Influence of Blank thickness

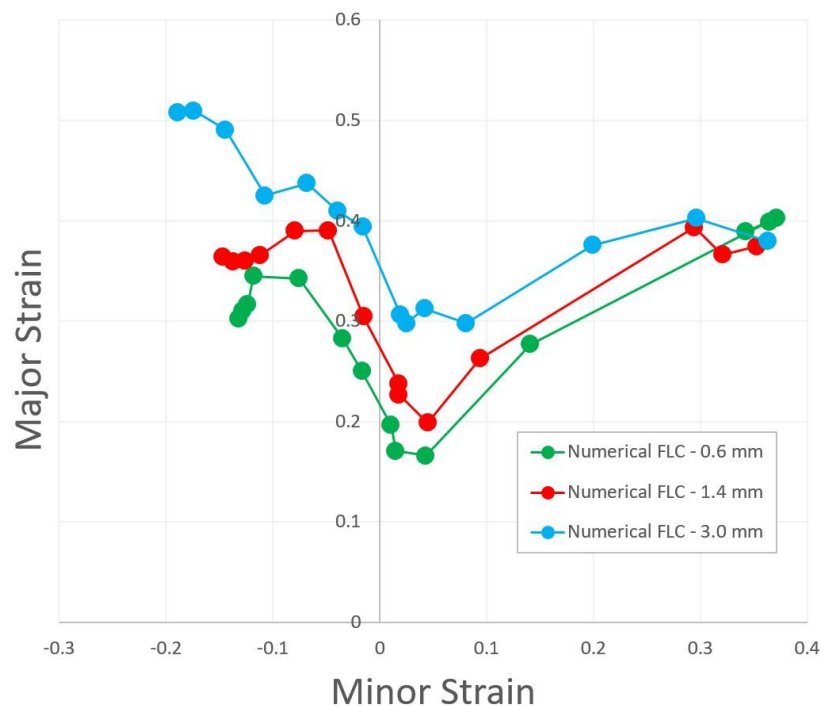
Thickness is a major parameter for stamping. Feasibility may vary according to the blank thickness, but the understanding of its influence remains vague.

The numerical model allowed us to determine the FLC for 3 different blank thicknesses. All other parameters stayed the same (tools dimensions, material ...).

Usually, experimental FLCs consist of 5 points. Each point represents a different strain path according to the blank width. We chose to determine numerical FLCs with 14 points (corresponding to 14 different blank widths for each FLC) (Figure 9). This choice was the opportunity to assess the accuracy of 5 points FLCs.



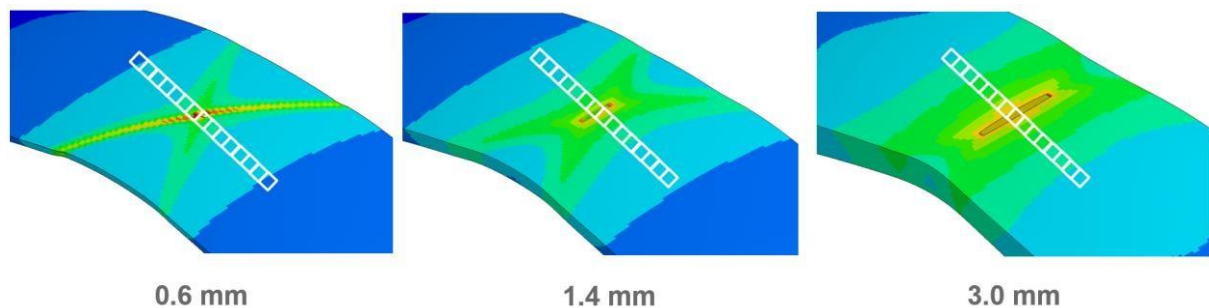
**Figure 9.** Nakajima blanks.



**Figure 10.** Thickness influence on the FLC prediction.

First thing to notice is the difficulty of obtaining some points in the expansion area, as in the experimental trials (right side of FLC) (Figure 10).

The thicker the blank, the higher FLC will be. Moreover, the left side of the FLC seems more sensitive to a thickness modification. A possible explanation to this relationship between thickness and FLC increase could be related to the strain measurement grid size. For each thickness blank, the same strain measurement grid size was used (1 mm at initial stage). However, the thicker the blank, the wider the necking area (Figure 11). Usually, the necking area width and the thickness have the same approximate size. For the 0.6 mm thickness blank, the necking area width is around 0.6 mm. The localized area will be included in a 1 mm grid. So, the strain measurement won't be very localized. On the contrary, for the 3.0 mm thickness blank, several 1 mm grid will be in the necking area. In this case, the strain measurement will be very localized.



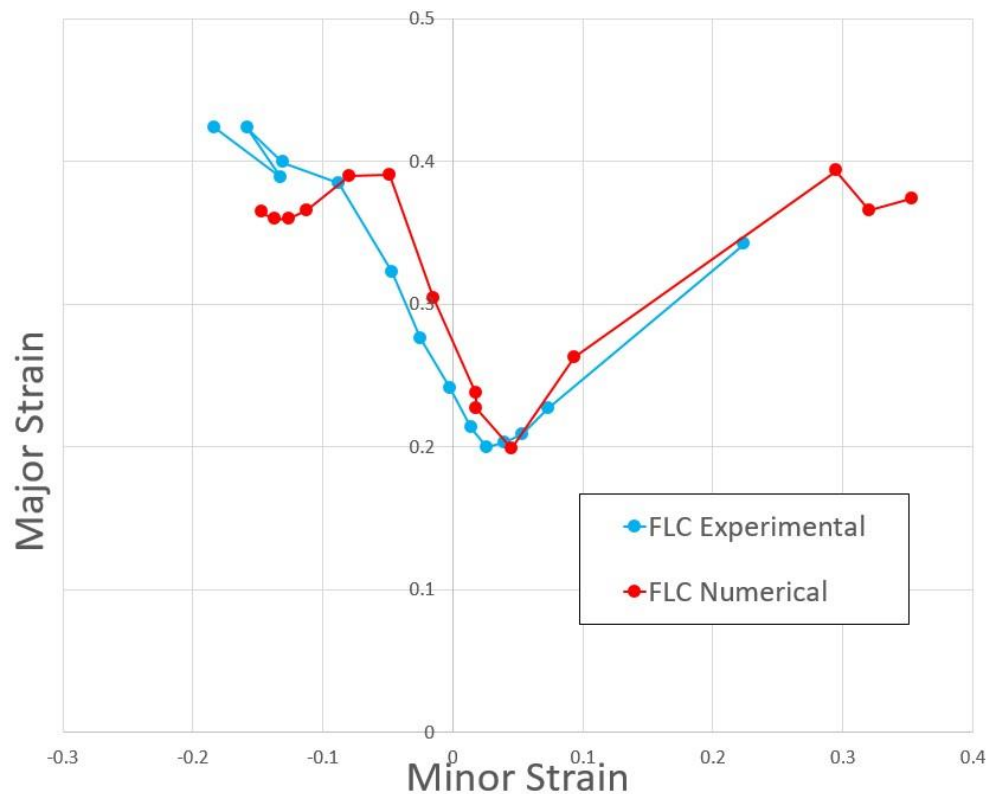
**Figure 11.** Thickness influence on the necking width area.

To conclude, strains will be measured in more localized areas for the thickest blanks.

### 3.3. *The model still needs to be improved ...*

While studying the thickness influence on the FLC, an unusual phenomenon was observed: the numerical FLC left side points are not aligned (Figure 12) (between Uniaxial Traction and Planar Traction). As said before, FLC are experimentally determined with less different blank widths (~5). Therefore this phenomenon could be experimentally unobserved. In order to clarify this phenomenon an experimental FLC with 14 different blanks was determined (1.4 mm thickness). Comparison between numerical and experimental FLC confirms that this observation is not reproduced experimentally (Figure 12).





**Figure 12.** Experimental and Numerical FLC for 1.4 mm blank.

Further investigations are needed to understand this behavior difference. The model could be improved with parameters such as strain rate effect. The damage model could also be enhanced: GTN model doesn't reproduce shear phenomena which appear especially on the FLC left side.

#### 4. Conclusion

Modeling approach is a way to better understand the influence of experimental parameters when determining a Forming Limit Curve. It allows parameter variation and should avoid experimental scatter.

The model developed in this paper simulates a Nakajima trial. We showed that damage consideration is important to correctly simulate the right side of the FLC. We obtained a global good correlation with experimental data and failure shape. However, unusual behavior was observed in the left side of the FLC that should be understood.

We showed the influence of some parameters (i.e. blank thickness) and other ones are being under investigation (tool dimensions, specimen shape, ...).

This modeling approach will be used with other experimental methods of FLC construction, like strain rating method.

#### References

- [1] ISO 12004-2, *Metallic materials — Sheet and strip — Determination of forming-limit curves Part 2: Determination of forming-limit curves in the laboratory*, 2008
- [2] Ole WEST, Junhe LIAN, Sebastian MÜNSTERMANN and Wolfgang BLECK, *Numerical Determination of the Damage Parameters of a Dualphase Sheet Steel*, 2011  
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