

# Finite Element Analysis of Size Effect for Forming-Limit Curves

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## Abstract

Nowadays, finite element (FE) methods are widely used for the analysis of Body in White parts production. An FE software applies the forming-limit diagram to predict the failure of the sheet metal. There are many new materials for weight reduction; for these new materials, the determination of forming-limit curves (FLC) is important to studying formability issues. There are some cases where the available material for the measurements is not enough or due to some specific measurement parameter, the standard test specimen cannot be used. In these cases, the geometry of the test pieces and the testing equipment should be reduced. In this paper, the material card for DC05 (1.0312) steel was determined based on a tensile test and the Nakajima test. With the material card, simulations were performed to investigate the size effect of the hemispherical punch used for Nakajima forming method. Based on the simulations, the difference between the FLC-s (determined with different equipment) was found to be negligible.

**Keywords:** *FLC, size effect, forming-limit curve.*

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## 1. Introduction

In recent years, development trends in the automotive industry have been determined by the reduction of harmful emissions. These aspirations can be realized by reducing the weight of automobiles. In order to decrease the weight of vehicles, it is not enough to simply reduce the amount of the applied materials; it is also necessary to increase their strength to fulfil safety requirements. As a result, nowadays, new high-strength materials such as boron alloyed manganese steels (e.g. 22MnB5), or high-strength aluminium alloys (AA7075) and related technologies (Press Hardening, Hot Forming and Quenching) [1] have been developed.

Nowadays, computer-aided design of sheet metal parts and finite element modelling of the technological processes are involved in the everyday practice. Accordingly, the software needs to have the possibility for applying the new materials and also the new technologies. For a simulation that adequately predicts the physical process, the behaviour of a material needs to be determined by the appropriate constituent equations. For sheet

metals these are the flow curves, which show how the material responds to plastic deformation, the yield-surfaces defining the limit of elastic deformation, and the Forming Limit Diagram (FLD). The FLD describes the limits of formability in the coordinate system of major and minor principal strains. These three properties of the sheet metal are collected in the so-called material cards.

Defining the behaviour of the material for conventional (cold) forming processes can be regarded as common practice. However, the high-strength materials - mentioned above - typically are formed by hot-forming technologies [2]. Nowadays, computer-aided design of sheet metal parts and finite element modelling of the technological processes are involved in the everyday practice. Accordingly, the software needs to have the possibility for applying the new materials and also the new technologies. For a simulation that adequately predicts the physical process, the behaviour of a material needs to be determined by the appropriate constituent equations. For sheet metals these are the flow curves, which show how the material responds to plastic deformation, the

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Defining the behaviour of the material for conventional (cold) forming processes can be regarded as common practice. However, the high-strength materials - mentioned above - typically are formed by hot-forming technologies [2]. In hot forming processes, the behaviour of the material is primarily determined by its dependence on temperature and strain rate, which clearly induces a change in the constitutive equations describing it. Dependence on these parameters makes the determination of material properties significantly more difficult.

Thus, in the case of hot forming, it is necessary to set up an experimental matrix to properly describe the deformation of the material where there are varying strain rates at different temperatures or different temperatures at a given strain rate. The increase in the number of tests makes it clear that material card for the hot forming simulation requires a larger amount of specimen than in cold forming. For newly developed materials, it is not always possible to produce large amounts of standardized size specimens that are typically required for testing, especially for a forming limit diagram.

Determining the FLC using the conventional Nakajima test causes considerable difficulties in a hot forming environment. In this case, in order to meet the requirements of the aforementioned experimental matrix in terms of temperature and strain rate, an equipment for FLD determination has been developed (Figure 1) that can be used with the GLEEBLE 3500 thermo-mechanical simulator at the Institute of Materials Engineering and Materials Technology, University of Miskolc, Hungary. This new device is a proportionally reduced equivalent to the tooling required for the standard Nakajima test.

The basic concept behind the tests presented in this paper is the well-known fact that in the case of the FLC tests performed in the equipment manufactured according to ISO 12004 standard [3], the positioning of the forming limit diagram changes in the coordinate system of the principal strains if the sheet thickness changes. This effect is more significant on the right side of the FLD ( $\epsilon_2 > 0$ ) but it is valid that increasing the sheet thickness the FLC will be shifted upwards along the  $\epsilon_1$  axis [4] (Figure 2).

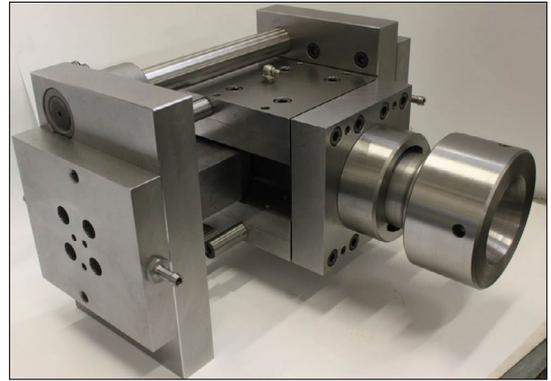


Figure 1. Proportionally reduced equipment for determining FLD.

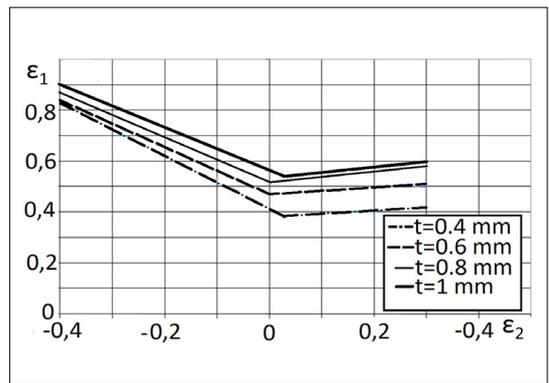


Figure 2. Effect of sheet thickness on the forming limit curves for DC05(1.0312) material grade. [4]

Thus, if we change the sheet thickness to punch diameter ratio, the position of the FLC in the coordinate system of the major deformations will change. In this paper, further experiments were performed to investigate the effect of punch diameter / sheet thickness ratio on the forming limit curve (FLC). In these experiments, the influence of the quotient on the FLC was tested by changing the diameter of the equipment rather than modifying the thickness of the sheet.

## 2. Material testing

As mentioned above, the basic prerequisite for accurate finite element modelling is the determination of a material card that precisely describes the deformation. For sheet metal parts, this can be achieved by performing the tensile test and the Nakajima test. The material quality to be tested was 1.4828 austenitic stainless steel with 1 mm sheet thickness, which is typically used for parts in exhaust systems.

The material was first cut by laser cutting process for performing tensile tests in three different directions i.e. in the rolling direction, 45 degrees and perpendicular to it. The tensile test was performed with an MTS universal electro-hydraulic device at the Institute of Materials Engineering and Materials Technology, University of Miskolc, Hungary. In addition to the longitudinal and transverse size change of the specimens, the corresponding force values were continuously recorded. By converting the values of force and changes in length, true stress and true strain values are determined. Further, the yield curve was determined from the section of these values within the range of plastic deformation.

The onset of plastic deformation of the material in the main stress plane  $\sigma_I$ – $\sigma_{II}$  is determined by an origin-centred ellipse, i.e. the yield surface. The yield surface varies continuously as a function of deformation, which can be derived from the flow curve. In order to integrate the yield surface later into the software, the plastic anisotropy coefficients describing the direction dependence of the sheet rolling is also determined from the records of tensile tests.

The third part of the material card used in finite element modelling is the Forming Limit Diagram, and more specifically the Forming Limit Curve (FLC) itself, which is the curve connecting the points of fracture in the coordinate system of major strains. To obtain the FLC basically five (Figure 3), but a minimum of three specimens of different bridge widths are required. The specimens of different bridge widths were laser cut, as mentioned for the tensile test, and were machined from a 1 mm sheet. During the experiments, the test specimens were fixed temporarily between a die and a blank-holder to avoid any movement, and then loaded with a hemispherical punch in the direction of the sheet thickness until cracking occurred. During loading, the displacement of the points of the 1 mm quadrilateral mesh applied to the surface of the specimens was continuously recorded by a four-camera optical measuring system.

The displacement of the mesh points relative to one another is automatically converted by the measuring system into a deformation, thanks to the continuous recording, which provided the accurate picture of the entire process of deformation. The FLC was determined based on the deformations associated with the fracture.

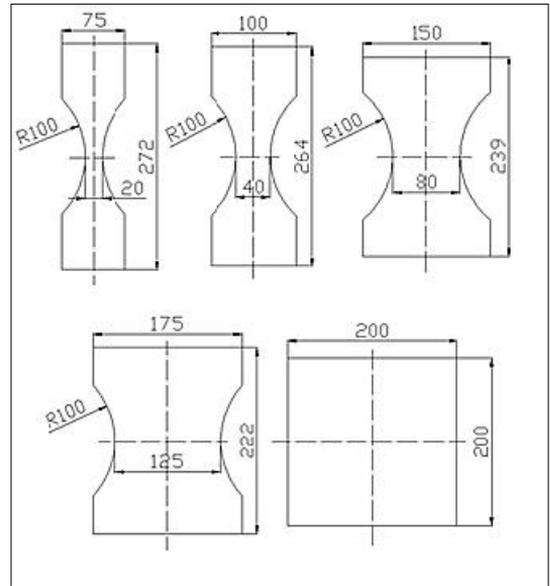


Figure 3. Specimen geometries with different bridge widths for determining FLD-s.

### 3. Finite element modelling

After performing the physical measurements, finite element modelling was used to investigate the effect of deviation from the standardized tooling. The simulations were performed in AutoForm R8 software, where first the material card [5], and then the tooling was defined.

AutoForm provides the ability to import into the software the points defined in the previous section for each deformation characteristic. A drawback of the flow curve determination with the tensile test is that the points thus obtained cover only a small range of deformation. To overcome this problem, the software performs extrapolation using a mathematical function added to specific points. Several known mathematical models are available for extending the physical points of the flow curve; in this case, we applied a combined Swift and Hockett-Sherby approximation widely used in the field of sheet metal forming, which uses the mathematical form as described in equation (1). In this equation  $\varepsilon_{pl}$  and  $\varepsilon_0$  are strains,  $\sigma_{sat}$  and  $\sigma_i$  are stresses,  $a$  and  $m$  are exponents in the strain hardening law.

$$\sigma = (1 - \alpha) \left[ C \cdot (\varepsilon_{pl} + \varepsilon_0)^m \right] + \alpha \left[ \sigma_{sat} - (\sigma_{sat} - \sigma_i) e^{-a \varepsilon_{pl}} \right] \quad (1)$$

To describe the yield surface, the Hill48 model was selected for which the anisotropy coefficient value was derived from the tensile tests.

Once the material card was defined, the appropriate tool geometries were imported. The standardized tooling model is illustrated in **Figure 4**, where the punch diameter marked  $D_b$  was 100 mm. In order to examine the size effect, it was necessary to reduce the diameter of the stamp, so that the diameter of 100 mm was first reduced by half and then by one-fifth, so that all other dimensions of the test equipment were reduced proportionally.

After the FE modelling of the equipment was completed, the first necessary step was to determine the parameters of the simulation. Friction also influences the location of rupture (particularly in the region of positive deformation on the FLD) as well as the deformation path of the specimen [6]. In order to get appropriate results, the friction parameter was set for the largest bridge width piece with standard-shaped tools, because of the large contact areas, which is the most important factor to consider in this case.

After defining the characteristic friction coefficient, simulations were performed for the next four bridge widths with the given settings. In the evaluation, the physical thickness measurement of the maximum thickness at rupture was taken as the basis of the physical measurement and the main deformation was determined at this FE node.

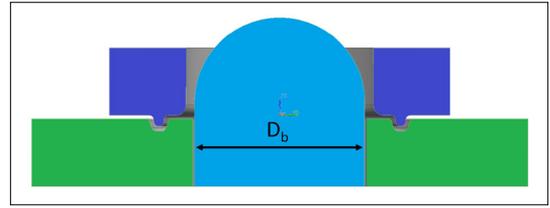
The deformation points for the fracture thus obtained are illustrated in **Figure 5**. On the basis of these results, it can be stated that the FLC achieved by physical measurement and finite element modelling shows a good correlation.

Since the simulations on the 100 mm diameter punch are considered correct, it is further continued to compile the simulations for the proportionally reduced 50 mm and 20 mm stamps. It is also important to note that in these cases the geometry of the specimens shown in **Figure 3**, is reduced proportionally to the given diameter at constant plate thickness.

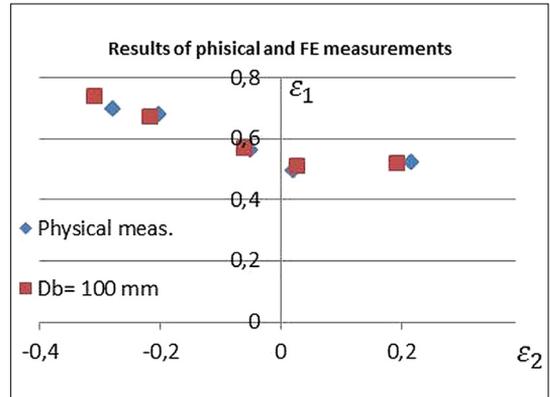
#### 4. Results and discussion

After running the simulations, the deformation of each specimen was evaluated for each of the three punch diameters. The strain distribution is the same for each bridge width. Calculating the fracture points was based on the sheet thickness measured at the 100 mm diameter punch and the strain in the thickness direction. The FLC-s for each punch diameter are illustrated in **Figure 6**.

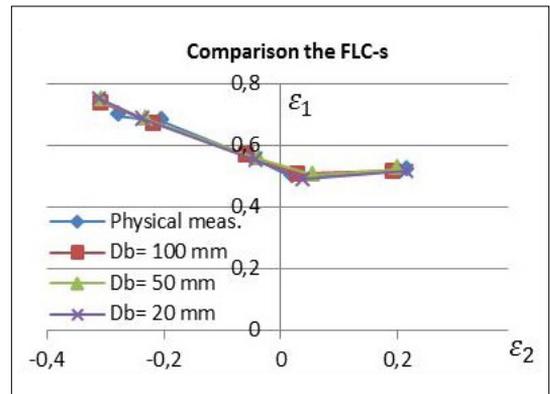
From the corresponding correlation of the curves in **Figure 6** it can be stated that if the size



**Figure 4.** Standardized tool geometry.



**Figure 5.** Comparison the FLC points of the simulation and the physical measurement.



**Figure 6.** Results of the size effect created by diameter change of hemispherical punch.

of the punch is reduced proportionally, the FLD is not affected by the dimensional change at a given sheet thickness. So the punch diameter to sheet thickness ratio has no effect on the Forming Limit Curves, but only the sheet thickness.

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