Sheet Thickness Reduction Influence on Fracture Strain Determination

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Abstract. Standardly, the FLC curve [11] is determined based on ISO12004 according to Nakajima test or Marciniak test [1]. There are two basic influences: the friction between the punch and the specimen and at the same time the pushing the punch on the specimen, which affects the strain distribution over the sheet thickness [17]. The main disadvantage of these tests is the measurement of the linear deformation paths only, but the real forming processes are usually formed in multiple steps processes and the loading path is strongly non-linear. The current trend for sheets formability assessment is investigation of non-linear deformation paths performed on cruciform specimens [2, 3] or using a combination of Marciniak and Nakajima tests [6], [7]. The cruciform specimens should have reduced thickness in the central part in order to assure main plastic deformation and fracture in this region [18]. However, there are indications that the thickness reduction can influence results of the formability assessment. The main goal of this present paper, is experimental investigation of effect of local material thickness reduction on FLC and on Fracture Forming Limit Curve (FFLC). The cruciform specimens with a reduced thickness is investigated with the use of the biaxial stand without friction and pushing the punch. All results are compared to the FLC values.

1. Introduction
The effect of thickness reduction thickness was investigated by other authors [10], when designing butterfly specimen, using tensile test with good agreement between standard and micro size specimen [19], [20]. Based on these works the thickness reduction doesn’t have influence on the material properties. This influence was investigated in other study [12] on material 5083 aluminium alloys as well. Moreover, another authors [13], [15] published the same conclusions, but only for uniaxial tensile tests. In this study, tensile test was used only for basic characterization of mild steel DC01 and the influence of sheet thickness reduction on fracture strain was investigated using biaxial tensile test and Nakajima test. In addition, all tests performed here were simulated and compared with experiments. The force-displacement, major-minor strain and fracture limits were analysed and compared between tests on cruciform specimens and Nakajima tests [4]. The differences found between the procedures are discussed here.

2. Basic characterization of mild steel DC01
Mild steel DC01 is used for internal research at COMTES FHT and some results were previously published e.g. [5],[8],[9] [14],[15],[16]. The uniaxial tensile test was used for basic characterization (Table 1) and description of hardening behaviour. The FEM simulation with Marc/Mentat version
2016 has been done with a material defined as von Mises with isotropic hardening without or with damage.

**Table 1. Mechanical properties DC01**

| Yield stress | Tensile strength | Elongation | Reduction area |
|--------------|------------------|------------|----------------|
| MPa          | MPa              | %          | %              |
| 180.4        | 293.8            | 49.2       | 87.5           |

3. Biaxial tests

Four biaxial tests were performed with different geometries of specimen and boundary conditions in order to determine the effect of thickness reduction on necking and fracture limits, these tests can be divided into two groups. The first group involves the Nakajima test which uses the hemispherical punch introducing biaxial loading during the test. The contact between the punch and the specimen is influenced by the pressure and the friction. These variables can shift the FLC curves. The second group are biaxial tests without contact between the punch and the specimen. For these tests we used our biaxial testing setup with four independent hydraulic pistons. For this test was developed the shape of the cruciform specimen that was optimized for mild steel DC01 [5]. This specimen has reduced thickness in the middle area in order to bring higher strains in the central region as discussed by many researchers [2],[3],[6],[18]. To sum up: four different specimen geometries were tested (Table 2). Three specimens were tested for each specimen’s geometry.

**Table 2. Geometries of tested specimen**

| 1 | 2 | 3 | 4 |
|---|---|---|---|
| Standard specimen according to ISO12004 [1] | Cruciform specimen according to Prantl [16] | Standard specimen with reduced area | Cruciform specimen with shorter arms |

Thickness of central part of the cruciform specimen was reduced with an initial thickness of 1.5mm and a minimal thickness of 0.3mm in the middle [16], Figure 1. This shape of reduction area was used for all specimen geometries except the flat standard specimen for Nakajima test – W200.

**Figure 1. Geometry of middle area with thickness reduction**

3.1. Nakajima test - standard specimen

The FLC is determined based on ISO12004 using the NAKAJIMA test. For this test specimens with a variety of widths from 40 mm to 200 mm were used. Experiments are carried out with hemispherical punch with a 50 mm radius and a die with a radius of 5 mm. The testing machine was an INOVA 200 kN hydraulic testing machine and the velocity of the punch was constant at 1mm/s. During all experiments, 3D displacement fields are captured with GOM Aramis DIC system. The
friction between the punch and the specimen was reduced using Teflon layers and lanolin. The results of the Nakajima tests were published [5], [13]. The most important specimen from previous studies for our case was the one with the width of 200 mm (Figure 2, W200).

![Figure 2](image2)

**Figure 2.** Forming Limit Curve for mild steel DC01 from Nakajima experiments [13]

3.2. **Biaxial test – cruciform specimen**

Our own cruciform specimen (Figure 3a) was optimized using FEM simulations in order to achieve a uniform and a maximum deformation in the central region and not in the shoulder area. Based on the literature survey and trial and error approach we found out the final shape for the 1.5 mm sheet thickness. The central thickness is 0.3mm and it gradually increases to the initial sheet thickness. During the optimization, damage models were not used and the suitability of the shape was evaluated on the basis of maximum deformation. The strain field is symmetric during the test (Figure 3a) and a few steps before crack the field changes to a non-symmetric (Figure 3b). This change is caused by exhaust plasticity and defects in the microstructure. Theoretically, the crack could be in both directions but the sample always breaks in one direction (Figure 3b).

![Figure 3](image3)

**Figure 3.** The field of major strain on cruciform specimen (a)FEM simulation (b) DIC ARAMIS

3.3. **Nakajima test – standard specimen with reduction middle area and cruciform specimen with shorter arms**

These two specimens in apparatus (Table 2, Figure 2) for the Nakajima test were tested. Initial and boundary conditions were the same as for Nakajima test except the velocity of punch was 0.3 mm/s. 3D displacement fields are captured with GOM Aramis DIC system as well. The goal of these tests was to complete the portfolio of specimens and to describe the behaviour of specimens during the test, especially to determine the necking and fracture limit. The fracture limit was evaluated using a
combination of measurement and numerical simulations. The simulation of all tests was in good agreement with the experiments (Figure 4).

![Figure 4. Force–displacement comparison during experiment and simulation](image1)

![Figure 5. Micrograph of central part](image2)

4. Microstructure analysis of reduction area
The influence of sheet thickness reduction process on a microstructure is insignificant. The cross section cut in the central part has been performed to show the depth influenced by the machining. From the Figure 5 it can be seen that the influenced layer is quite small and represents 1/13 of the central part thickness. The hardness measurement did not show any change compared to the arms region [16].

5. Result and discussion
Simulations of tests were conducted with the nonlinear finite element solver MARC version 2016. A three-dimensional modelling approach was used to simulate these tests. The interaction between the rigid tools and the specimen was kept as node to element contact with a Coulomb bilinear friction coefficient of 0.12. The specimen was a deformable body with solid elements number 7 (linear 8-node hexahedron). Finer mesh (element thickness 0.06 mm at a minimum thickness) was applied in the central area of the sample, while the body of the specimen was meshed with coarse elements with a size of 1 mm and 3 elements were used the through thickness of sheet. In the reduced area five elements through the thickness were used in order to predict the necking accurately. Cockroft-Latham damage model was used for fracture strain effect description (1). The biaxial stress state was in all geometries of specimen (triaxiality about 0.6) therefore this simple damage model was used with one material constant, threshold for damage $C$ and variables are only the maximum principal stress $\sigma_1$, the effective von Mises stress $\bar{\sigma}$ and the effective plastic strain rate $\dot{\varepsilon}_p$. The punch velocity was 1 mm/s and influence of strain rate was not considered. Initial values of damage model was obtained from the tensile test and calibration was performed based on the Nakajima test.

$$\int \frac{\sigma_1}{\bar{\sigma}} \dot{\varepsilon}_p dt \geq C$$

Table 3. Damage thresholds

| Specimen name                              | Standard specimen | Cruciform specimen | Standard specimen with reduction area | Cruciform specimen with shorter arms |
|--------------------------------------------|-------------------|--------------------|---------------------------------------|-------------------------------------|
| Damage threshold $C$ [-]                   | 0.725             | 0.416              | 0.459                                 | 0.447                               |
By analysing the result (Figure 6), it was noted that, the determined fracture limit was dependent on the testing method. The damage threshold increases using the hemispheric punch, specifically in the cruciform specimen increases from 0.416 to 0.447 (Table 3). This effect can be explained by different values of the individual stress components (biaxial stress vs. stress through the thickness) evaluated from FEM simulation. This result is full compliance with observation made by Wu [21], it is that superimposed hydrostatic pressure delays on set onset of inhomogeneous deformation. In other words, a superimposed hydrostatic pressure increases the uniform strain. Thanks to the reduction in the thickness of the standard specimen (Nakajima test W200), the fracture strain decreased. The upward trend of specimens 2 and 4 (Figure 6) was due to the change of field biaxial strain to plane strain. This change is due to a local thinning of the sheet. The same effect is seen at specimen 1, (Figure 6).

6. Conclusion
In order to understand the differences between the tests for sheets characterization, experiments using a cruciform specimen and a flat standard FLD specimen and their combinations were conducted (i.e. FLD standard specimen with a middle area reduction and cruciform specimen with shorter arms). In all tests, the parameters were kept as similar as possible. All tests were further simulated in Marc/Mentat software. From the results, it was found that plotted force-displacement curves of all samples are different but the biaxial strain paths during the test were the same for all tests. The comparison between the tests and the simulation was also in good agreement. The results analysis shown that, using hemispherical punch the drawability is higher than those ones for the cruciform test using the multiaxial stand. Additionally, the sheet metal is pressurized by punch during the Nakajima test, thereby increasing the softness of the material, which increases the ductility. This is an agreement Nikhare [12] findings. Overall, it was concluded that, due to punch pressure on metal sheet a radial stress is induced and, the material deforms more during punch pushing than in the course of cruciform specimen pulling in the multiaxial stand. However, the experimental tests using the cruciform specimen on multiaxial stand eliminate the pressurization factor and bring the pure forming limits. But these forming limits were smaller than traditionally determined FLDs. Reduction sheet thickness on fracture strain was shown in Figure 4, where the specimen 1 a 2 was same geometry, only specimen 2 had reduction thickness in the middle. This reduction reduced elongation and damage occurred at a lower strain of 0.459 compared to a standard FLC sample of 0.725.
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