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# Development of a new and simplified procedure for the experimental determination of forming limit curves

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ABSTRACT

This study aims to eliminate the off-centric initiation of localization caused by friction in the Nakazima testing of forming limit curves (FLCs). Our proposed approach uses an ordinary Nakazima testing equipment and standard Nakazima geometries for specimens. The principle is based on a layer of relatively thick, flexible and durable polyurethane disc, whose coherent deformation ensures strain localization at the pole. The main advantages of this approach are the simplicity of the equipment and testing, inexpensiveness, and yet the coverage of the entire strain range relevant to sheet metal forming. The technique is validated by experimental and numerical FLC investigations.

## 1. Introduction

Prediction of formability is one of the important issues in sheet metal forming practice and its simulation. Although alternative approaches are increasingly investigated in the academic community, the forming limit curve (FLC) is still the main instrument for the quantitative description of sheet metal formability. In this respect, various experimental approaches and evaluation techniques have been developed for the experimental determination of FLCs.

Starting from the pioneering investigations of Gensamer [1], Keeler [2] and Goodwin [3], the milestones of the related studies in the literature have been summarized by Banabic et al. in [4–6]. The IDDRG has proposed a standard FLC evaluation procedure recommending the use of Marciniak [7] or Nakazima [8] tests which is standardized later on under ISO 12004.

In today's practice, the Nakazima test remains the most widely used FLC testing approach due to its simplicity, short application time, economy and commercially widespread and available equipment. It obviates the need for a dummy or carrier specimen as proposed by Marciniak et al. [7] and Banabic et al. [6], eliminating the 5 to 10-time lengthy equipment cleaning burden when the hydraulic burst of the specimen or the carrier sheet is involved. On the other hand, the weaknesses are: First, the problematic distribution of strains due to the existence of friction; and, second, the non-linear strain path due to biaxial pre-strain artefact caused by localized initial stretching around the pole of the hemispherical punch. The former downside may cause off-polar tearing and, hence, the exclusion of test data when ISO 12004 evaluation procedure is applied. Whereas, the latter may cause a change in the shape of the FLC, especially near the plane-strain point as reported by Leppin et al. [9] and Abspoel et al. [10]. These two drawbacks have been eliminated in the works by Marciniak et al. [7] and Banabic et al. [6] at the cost of increasing the testing time in addition to an excessive use of dummy specimens.

In the present paper, the authors propose a new and simplified approach for FLC experimentation, reducing the aforementioned two weaknesses. The methodology is based on the utilization of a relatively thick polyurethane disc placed in between the specimen and the hemispherical punch. The remainder of the experimental approach is similar to the Nakazima test and, as such, covers the entire strain-ratio range of the FLC. The coherent deformation of the polyurethane disc provides a desirable strain distribution, even better than any available enhanced tribo-system, to reduce the parasitic effect of the friction. Furthermore, the initial biaxial pre-strain artefact is reduced since the polyurethane disc reflects the initial spherical touch of the punch smoothly onto the specimen. Finally, the cost of the polyurethane pad is at most around 0.3 € per FLC experiment. This is the case when a single polyurethane disc is used only for a single FLC set of 8 Nakazima geometries. For the most of the sheet material types tested by the authors, a single polyurethane disc proves to remain functional for more than two complete FLC sets.

## 2. Proposed experimental approach for FLC testing

### 2.1. Comparison of various approaches

It is demonstrated in Banabic et al. [6] that the standard Nakazima test cannot yield a strain localization in the polar region of the Nakazima specimen due to the existence of friction. Even the utilization of enhanced tribo-systems between the hemispherical punch and the sheet specimen such as Teflon foils separated by copper-based lubricants or placement of merely a coin-sized paraffin wax, which is better than the first one according to the authors' experience, cannot completely eliminate this drawback. A further deficiency of the Nakazima test as shown by Leppin et al.

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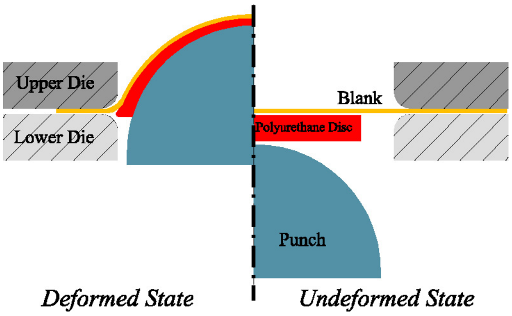

**Fig. 1.** Schematic view of the proposed testing approach.

[9] and Abspoel et al. [10] is the nonlinear strain path due to the biaxial pre-strain artefact caused by initially localized stretching around the pole of the hemispherical punch. To eliminate these deficiencies, Banabic et al. [6] proposes a novel approach based on the hydraulic bulging of a carrier blank placed under the pierced test specimen. The bulging carrier-blank builds a growing dome, over which a specially designed specimen stretches to develop different load paths, making it possible to examine the whole deformation range of an FLC. In this way, strain localization in the polar region is achieved at the cost of a dummy carrier-blank and 5 to 10-time lengthy equipment cleaning and preparation burden due to hydraulic bursts.

Aiming to overcome the disadvantages mentioned above and, yet preserving the achieved superiorities in the previous studies, the authors propose a new experimental approach based on the placement of a relatively thick polyurethane disc in between the standard Nakazima specimen and the hemispherical punch, as shown in Fig. 1. In this way, first the coherent deformation of the polyurethane disc enables a desirable strain distribution with a strain localization in the polar region; second, the non-linearization of the strain path due to biaxial pre-strain artefact caused by localized initial stretching is reduced; third, the experimentation time is unvaried compared to that of a Nakazima test; and, fourth, the complete deformation range of an FLC is kept intact by utilizing the entire family of the standard Nakazima specimens.

### 2.2. Mechanical properties of the polyurethane disc

Table 1 provides the mechanical properties, shore hardness, thickness and diameter of the circular Sarcoprene-ST-70A polyurethane disc utilized throughout this study. This is a high performance polyester polyurethane. Such elastomers provide properties generally not available with rubbers. They show improved oil resistance, better thermal stability, higher abrasion and tear resistance, better load-bearing capacity, better toughness and resilience than most general-purpose rubbers. In order to generate the model parameters for the polyurethane disc to be used in the numerical simulation of the proposed testing approach, simple tensile and strip drawing tests are performed. An engineering stress–strain diagram given as in Fig. 2 is used to generate the parameters of the Mooney-Rivlin material model MAT-27 in Ls-Dyna (see Table 1). The density and the Poisson's ratio are defined as 1.25 g/cm$^3$ and 0.499, respectively.

A strip drawing test is performed using a sheet strip made of DC04 with the hydraulic oil of the Nakazima testing device sprayed on it. As shown schematically in Fig. 2, the sheet strip is squeezed between two polyurethane pads, where the compression force is created by a leaf spring. Afterwards, the strip is pulled at least twice the length of the polyurethane pad by the crosshead of the tensile testing device. The temporal values of the compression force and the pulling force are recorded, and half of the ratio of the pulling force to normal compression force is plotted with respect to drawing distance, as in Fig. 2. It is deduced that the Coulomb's friction coefficient can be roughly estimated at 0.09 for this case. These friction tests are performed for low-to-high compression forces, and it is observed that the friction coefficient varies by only 20% around this value. To make the numerical modelling simple, the value of 0.09 is used as a constant coefficient of friction.

**Table 1**
The properties and dimensions of the polyurethane disc used for the Nakazima test with 100 mm punch diameter and ∅ 105 mm die aperture.

| Hardness | Diameter | Thickness | Mooney-Rivlin const. A & B |
|---|---|---|---|
| Shore A 70 | 90 mm | 8 mm | 1.7 & 0.23 |
| Tensile strength | Elongation | Resilience | Cured-density |
| 40 MPa | 675% | 42% | 1.25 g/cm$^3$ |
| Viscosity at 80 °C | Mix-ratio | Curative temp. | %NCO |
| 1700–2300 | 7.9% curative | 100 °C | 2.5–2.75 |

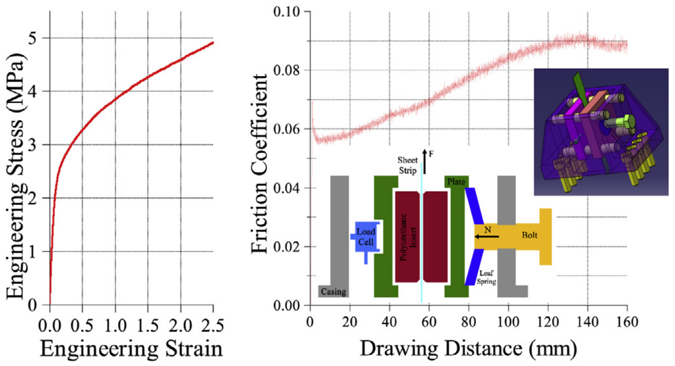

**Fig. 2.** Tensile test of the polyurethane specimen with 5.24 mm thickness, 19.8 mm width and 30 mm gauge length (left) and coefficient of friction between the DC04 sheet metal and the polyurethane obtained by a strip drawing test (right).

### 2.3. Simulation of the stretching over the polyurethane disc

Numerical analysis of the process is conducted to gain insight into the process details. The experimentally not visible deformation of the polyurethane disc can be observed in the numerical analysis. Furthermore, the numerical analysis can also be used to reveal the effect of the friction coefficient and the mechanical properties of the polyurethane disc on the strain distribution in the specimen. In this context, Ls-Dyna is used as the simulation environment. The MAT-27 Mooney-Rivlin material model is used to model the polyurethane disc, as also explained in Section 2.2. A constant Coulomb's friction coefficient of 0.09 is used since this value corresponds roughly to the case of lubricated contact interface. Initially, DC04 is considered for the Nakazima specimens since DC04 was found to be one of the most sensitive materials against friction in revealing the tearing at the polar region. DC04 is modelled using MAT-133, BARLAT-YLD2000, and the experimental findings for this material is given in Table 2.

**Table 2**
Mechanical characterization results for the utilized 0.8 mm thick DC04.

| $E$ | $\nu$ | $Y_0$ | $Y_{45}$ | $Y_{90}$ |
|---|---|---|---|---|
| 206 GPa | 0.3 | 134.82 MPa | 145.96 MPa | 143.80 MPa |
| $Y_b$ | $r_0$ | $r_{45}$ | $r_{90}$ | $r_b$ |
| 121.34 MPa | 2.38 | 1.87 | 2.77 | 0.96 |

The strain paths are recorded at the polar location until tearing occurs at the three major Nakazima geometries. The corresponding simulation results up to the recorded punch heights as well as experimental measurements are compared in Fig. 3. This figure demonstrates also the experimental measurements obtained by the conventional approach where the Teflon foils separated by copper-based lubricants are used on the bare punch. Looking at the experimental and simulated strain paths developed until the corresponding punch heights, it can be concluded that the simulation results are in acceptable agreement and the proposed approach provides better strain paths when compared to the conventional approach. Strain distributions for these three cases are also demonstrated in Fig. 4, such that the arc-length values for

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