The anisotropy influence on the thickness of deep drawn cup

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Abstract:

Manufacture of press-formed parts often involves deep-drawing operations. Deep drawing, however, can be deemed an industrial branch in its own right. Today, many experimental as well as numerical methods are available for designing and optimizing deep drawing operations. The best option, however, is to combine both approaches. The present paper describes one such investigation. Here, experiment and numerical simulation were used for mapping the impact of anisotropy on thickness variation in a spherical-shaped drawn part of DC01 steel.

Variation in the sheet thickness was measured on the drawn part using two cameras, and evaluated by means of digital image correlation provided by the ARAMIS software from the company GOM. The forming experiment was carried out on an INOVA 200 kN servohydraulic testing machine in which the force vs. piston displacement curve was recorded. This experimental arrangement was then numerically simulated using the AUTOFORM software. For the purpose of this simulation, a series of mechanical tests was conducted to obtain a description of the experimental material of 1.5 mm thickness. Material models were constructed from the tests data, describing the work-hardening curve, the impact of anisotropy and the forming limit diagram. Specifically, these tests included tensile tests, the Nakajima test and stacked test which were carried out to determine materials data for individual models. Finally, the actual sheet thickness values were found by sectioning the spherical drawn cup and by measuring under a NIKON optical microscope.

The variations in thickness along defined lines were compared with the data from digital image correlation, numerical simulations, and measurements on the sectioned cup. The above-described experimental programme is suitable for calibrating a material model for any computational software which can correctly solve a deep-drawing problem.

Keywords: cup drawing; anisotropy; sheet metal forming; finite element simulation.

1 Introduction

The automotive industry is a sector with the strictest demands on lightweighting and highest pressure on prices. Consequently, various tools are employed by producers of deep-drawn parts for predicting the part's behaviour before the actual manufacturing operation. Generally, the available options are either simple trials on small-size parts or computer simulations. With intricate press-formed parts, the best choice is to combine both of these options.

Authors of this paper have measured fundamental properties of DC01 sheet, constructed a material model for computation with the aid of the AutoForm software, and ran a computer simulation of drawing of a spherical cup. The final steps of this investigation involved validation of the simulation by an actual test of drawing and measuring a spherical cup in a mechanical testing laboratory. The test was performed on a servohydraulic machine and the cup deformation was measured using digital image correlation.

Describing the deep drawing process by means of numerical simulation poses a complex non-linear problem. Deep-drawing grades of sheet tend to be anisotropic, exhibit a defined work-hardening behaviour, and their mathematical description requires up to 10 parameters. Using AutoForm, a special deep-drawing simulation software, parameters of a real-world test can be easily input into the simulation for evaluation. In this study, the amount of thinning in the sheet at the end of the process was compared between a computer simulation and an actual test.

2 Experimental material and method

In order to construct the material model of the DC01 steel, a set of mechanical tests had to be carried out. Anisotropy of the material was first mapped using a series of tensile tests on specimens oriented in various directions (0°, 45°, and 90°) with respect to the sheet rolling direction. Additional material parameters were found by conducting and evaluating stack tests. The outcome of these tests was a curve which describes the anisotropy of material properties.

2.1 Material model

The material model is highly dependent on accurate descriptions of the material´s mechanical behaviour, the selected constitutive model as well as the input data used for its calibration. Therefore, trying to create the appropriate description for the DC01 steel sheet (Tab 1.), the following material model was selected to describe as accurately as possible the material behaviour based on the hardening law and the yield criteria.

Tab. 1: Chemical composition steel DC01

element	C	Mn	P	S	N	Al
%	0.12	0.6	0.045	0.045	0.003	0.04

2.1.1 Yield criteria

The Von Mises is the most widely used yield criteria, but it is only describing isotropic metallic materials. One of the most implemented yield criteria is the one proposed in 1948 by Hill [7], that is the first orthotropic yield criterion.

In order to obtain a balance between the accuracy of the model and parameter identification costs, most of the advanced yield criteria are using a set of seven or eight experimental values. Usually, six input values are used for parameter identification: the three yield stresses (σ_0, σ_{45}, σ_{90}) and the three r-values (ratio between the strain in the width and the thickness) obtained from uniaxial tensile tests (performed with orientations of 0°, 45° and 90° to the rolling direction), calculated using the formula:

$$r = \frac{\varepsilon_w}{\varepsilon_t} = \frac{ln(\frac{w}{w_0})}{ln(\frac{t}{t_0})} \tag{1}$$

However, these six experimental values are insufficient to calibrate recent advanced yield criteria as BBC2008 [8]. The additional values needed, are commonly the balanced biaxial stress (σ_b) (measured from bulge test or equibiaxial tensile test) and the balanced strain ratio r_b-value (gained from stack test and the equibiaxial tensile test)[9].

For the definition of our material model, we will use the balanced biaxial strain ratio (r_b) obtained from the stack test and the biaxial test. The balanced biaxial strain ratio r_b-value can be calculated comparing the strain in two directions (rolling direction and transverse to rolling direction) and using the formula:

$$r_b = \frac{\varepsilon_{TD}}{\varepsilon_{RD}} \tag{2}$$

2.1.2 Hardening law

In order to define the hardening behaviour of the metallic sheet we decided to use the Swift hardening law. In the model of Swift law, three material constants, strength coefficient (K), strain-hardening exponent (n) and initial strain (ε_0) should be estimated by curve fitting the measured true stress-strain data before necking to the following equation:

$$\sigma = K(\varepsilon_0 + \varepsilon)^n \tag{3}$$

2.2 Uniaxial tensile test

The first step of the evaluation process has been the measurement of the tensile test in three directions (0°, 45° and 90°) related to the rolling direction (Fig.1). Three tensile tests have been performed for each direction using the universal testing machine Zwick Roel 250kN. The strain measurements of the tests have been performed by Digital Image Correlation (DIC) method [10] with the use of ARAMIS system [11]. The system is using two cameras that enable optical 3D strain measurements. The elastic and plastic behaviour of the material was obtained after the evaluation of the tests.

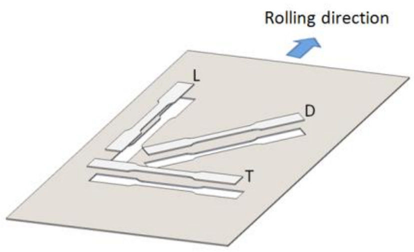


Fig.1 Sample directions related to the rolling direction

The mechanical properties evaluated from the uniaxial tensile test are the engineering strain (e) and engineering stress (s), these properties are obtained directly from measurements:

$$e = \frac{\Delta L}{L_0}, \qquad s = \frac{F}{A_0} \tag{4}$$

Finally the flow stress behaviour has been obtained rcalculating the true strain (ε) and true stress (σ). These parameters calculated directly from the engineering parameters before the necking and with an extrapolation after it.

$$\varepsilon = ln(1+e), \qquad \sigma = s(1+e) \tag{5}$$

We calculate these parameters for each direction (0°, 45° and 90°) to obtain the flow stress curves before necking, the flow stress beyond necking point can be extrapolated to fit the force-displacement curve. The flow stress curves are shown in the Fig.2:

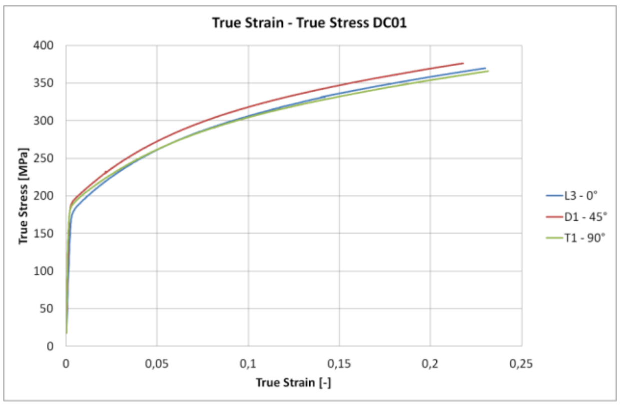


Fig.2 Flow stress curves for each direction

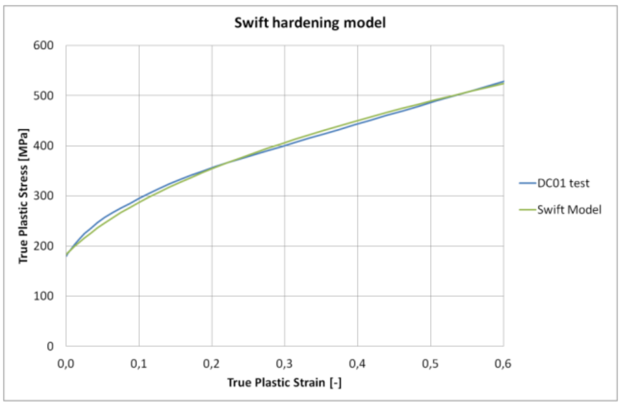


Fig.3 Swift model fitted to the tensile test

After the calculation of the true stress-strain we fitted the constants for the Swift hardening law for the rolling direction curve (0°), obtaining the following parameters:

Tab. 2: Swift model parameters

K	ε_0	n
625.1	0.005	0.412

The anisotropy parameters have been calculated after the initialization of the straining and before the necking of the specimen. The results obtained after the evaluation of the uniaxial tensile tests are:

Tab. 3: Anisotropy parameters gained from uniaxial tensile tests

σ_0[MPa]	σ_{45}[MPa]	σ_{90}[MPa]	r_0[-]	r_{45}[-]	r_{90}[-]
178.7	192.7	184.8	1.78	1.25	2.15

2.3 Stack test

To complete the characterization of the anisotropy model it is necessary to obtain another parameter in order to create a material model more reliable for advanced yield criteria. This parameter is the balanced biaxial strain ratio r_b-value that is obtained from the disk compression test (stack test), the bulge test or the biaxial test.

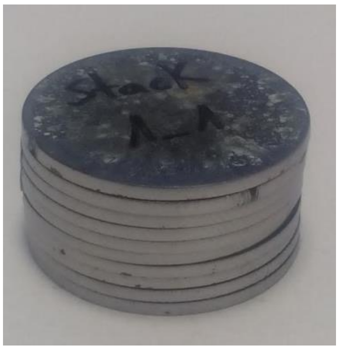


Fig.4 Compression stack test sample

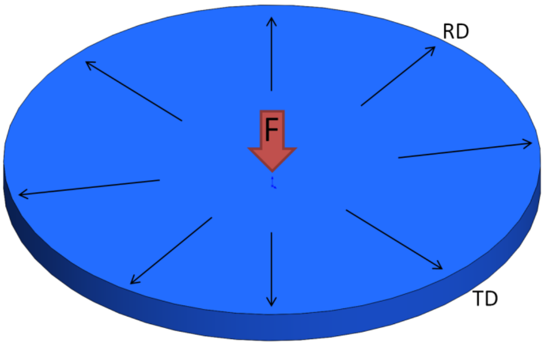


Fig.5 Compression and force and strain distribution during stack test

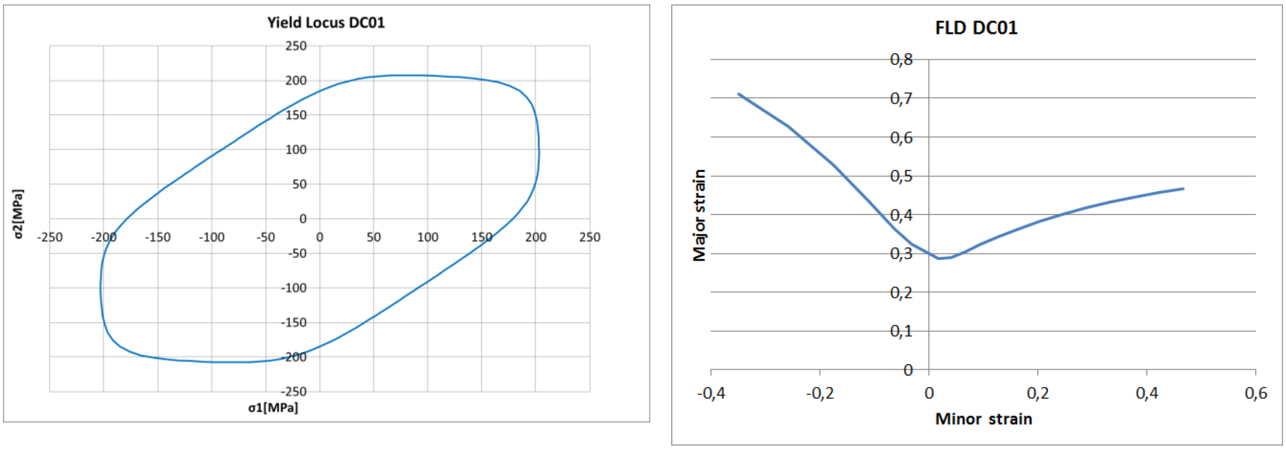
To obtain this parameter the stack test has been performed, using disks of 25mm diameter and stacking a total of 10 disks [12]. To conserve the anisotropy properties, the disks were piled considering the rolling direction. To reduce the friction between the stacked specimen and the compression plates of the tool, a Teflon-foil acting as a solid lubricant is placed at each end of the specimen.

During the test, the force was gained from the universal testing machine Zwick Roell 250kN and the strain and displacement values were gathered by another DIC method using MERCURY system [13]. Two independent cameras were arranged with an angle of 90° to each other, one of them in the rolling direction and the other one perpendicular to the rolling direction. With this setup it was possible to cover more than the half lateral surface and to measure the strain in the rolling direction and in the transversal direction. Using the formula previously described we have obtained the value $r_b = 0.951$ gathering the strain values of the central disks of the pile, where the strain field is homogeneous.

In order to calculate the yield locus for the DC01 steel sheet, the BBC2008 yield criterion was used [8]. The material parameters used as in put in the BBC2008 identification procedure [15] are the previously calculated:

- Three Yield stresses for each direction (σ_0, σ_{45}, σ_{90})
- Three r-values (r_0,r_{45},r_{90})
- Balanced biaxial stress (r_b)

The calculated BBC2008 yield locus is shown in the figure 6a. In our case was used 7 parameters BBC2008 yield criterion plotted on the yield locus graph (fig. 6a) [11]. Based on the results, a forming limit curve as a function of ε_1 and ε_2, true strain values on the sheet surface, was constructed, as illustrated in Fig. 6b [11]. Functions obtained in this manner were input into numerical simulations of the spherical cut drawing process in the AUTOFORM software.



a) Yield surface b) Forming limit diagram

Fig. 6: Material properties of DC01.

3 Verification measurement

The test was carried out in an INOVA 200 kN hydraulic testing machine. The purpose was to assess the effects of lubrication between the spherical punch and the sheet. In the present case, no lubricant was used, which led to tearing away from the top of the spherical cap. By means of a spherical-end male punch of 100 mm diameter, the initial 200 mm-diameter blank was drawn at a velocity of 2 mm/s.

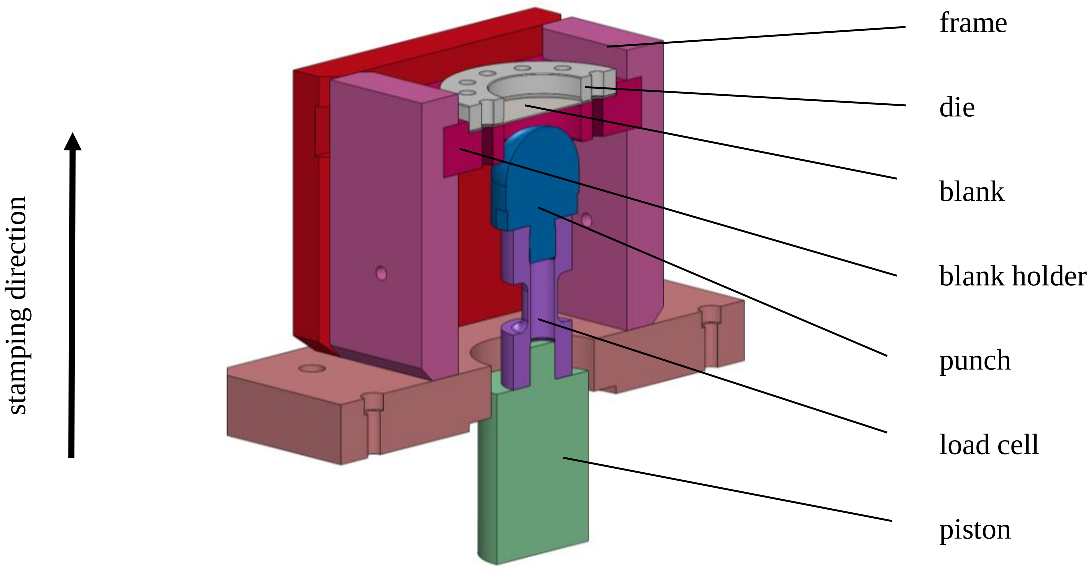


Fig. 7: Configuration of tool and blank before forming

The main outcome of the test was validation of the computational model which focused on the thinning of the sheet upon the test. During the test, the forming force was recorded by means of a load cell, and the cup shape was monitored using the ARAMIS digital image correlation system from the GOM company. Tearing in the sheet occurred at a 45° angle with respect to the rolling direction.

Fig. 8: Photo of sample after test

Fig. 9: Cut sample

4 FEM simulation in AUTOFORM

The AutoForm software was developed for modelling deep drawing processes. It relies on the finite element method and uses no other than shell elements. In the program, the mathematical descriptions of materials properties are tailored to deep drawing simulations. The data and the graphs listed above (Figs. 2, 3, and 6) were used as inputs into the numerical simulation of the sheet behaviour. Drawing on hands-on experience and expertise from sheet-forming industry, the program is intended mainly for the automotive sector. Every step in the sequence can be analyzed and optimized separately as an independent solution. The program features a built-in function which provides a full-scale solution for the entire manufacturing process. Default variables evaluated by the program include the sheet thickness, % thinning, wrinkling, and other values associated with deep drawing.

The input into the AutoForm simulation was a CAD file with the geometry of the Nakajima test fixture shown in Figure 7. Only a single-action draw was simulated, where the positions of the punch, the die and the blank holder are precisely defined. In this test, the blank was bolted down firmly. Therefore, the blank holder in the model was fixed. The velocity of punch was set in accordance with the completed validation test. Results of the computer simulation show the thinning of the spherical cup, as well as the indication of thinning in the graph.

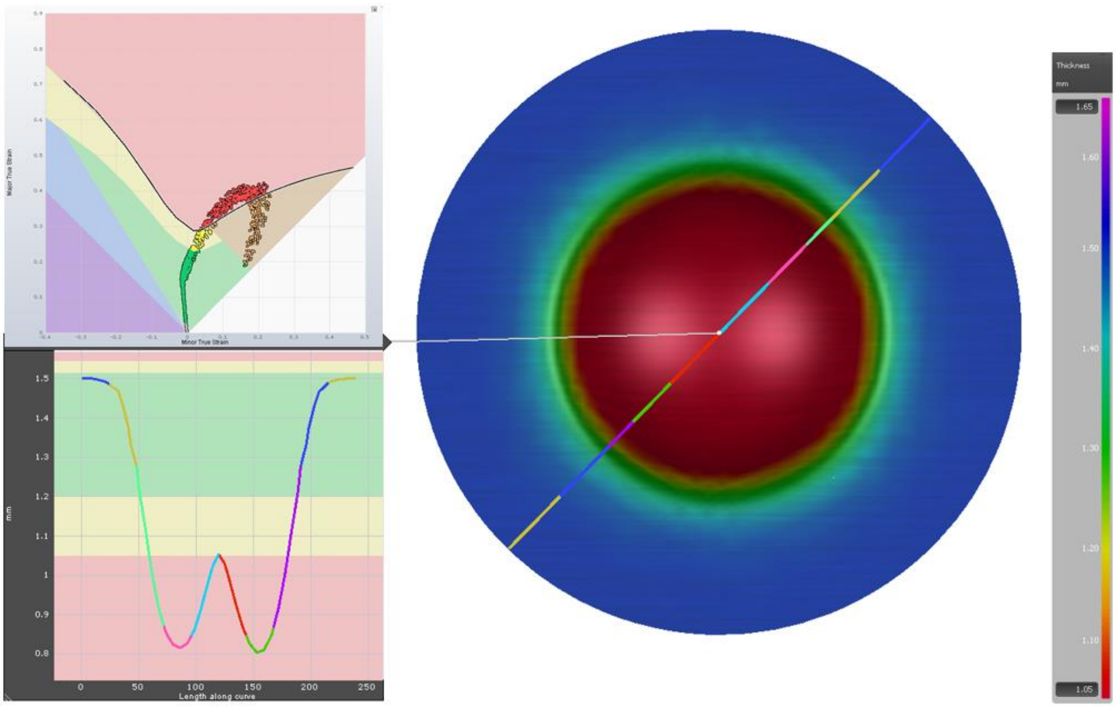


Fig. 10: Thinning in the simulated drawn cup

5 Comparison and discussion

The key outcomes of these simulations were the shape of the drawn part and thickness variations along defined cross-sections. Other variables which were compared between the actual test and the numerical simulations included the behavior of the drawing process, the force required for drawing the part and the impact of anisotropy on strain distribution.

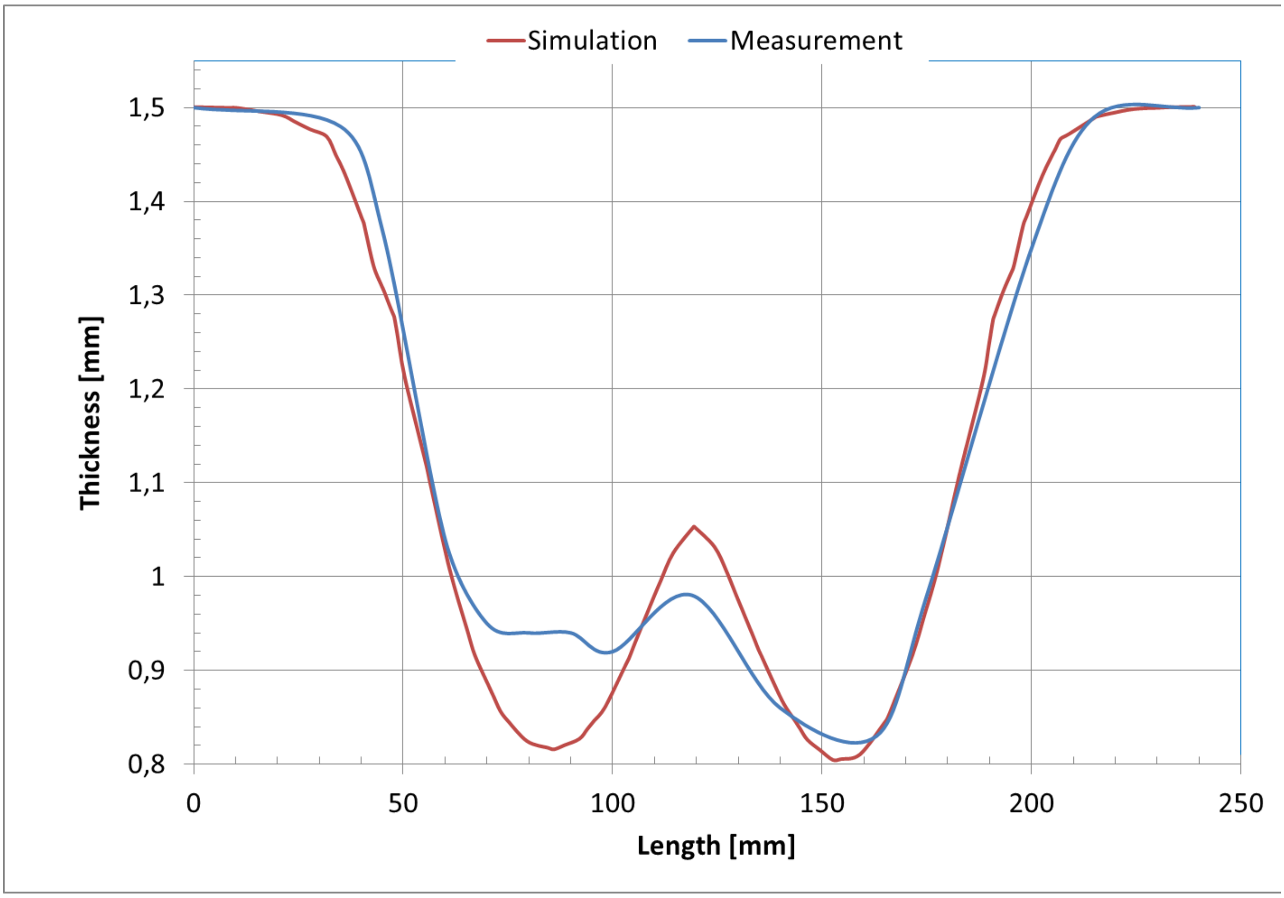


Fig. 11: Comparison between simulation data and readings from verification measurement

Figure 11 compares the thickness variation in the drawn part along a line across the tear. The simulation indicates uniform thinning in the sheet, whereas the validation test shows led to a non-symmetric profile caused by tearing. In the FLD diagram from the simulation (Fig. 10), the limit curve was exceeded at the top of the drawn part, which corresponds to the initiation of tearing in the validation test.

As evidenced by the results, the material model which had been constructed using data obtained from basic mechanical tests can be used for simulating drawn parts of relatively intricate shapes.

6 Conclusion

This paper evaluates sheet thickness variation in a spherical drawn part of DC01 deep-drawing steel. Based on mechanical testing data, a material model was constructed and input into numerical simulations in AUTOFORM software. Real-part measurements and numerical simulation data were compared. The study produced a material model for DC01 steel which describes the anisotropy of properties and its effect on sheet thickness variation in Nakajima drawing test.

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