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Investigation of deep drawing of square cups using high-strength DP600 and DP800 steel sheets

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Abstract

This study investigated the deep drawing of square cups using high-strength dual phase DP600 and DP800 sheets via both experimental and finite element methods. The limiting drawing ratio (LDR) and wall thickness distribution were examined. The initial thickness of the materials used in the study was equal to 1-mm. The experiments were carried out at room temperature using both Teflon film and graphite spray lubricants at the same time. In terms of LDR, both experimental and numerical results corresponded with each other. A ratio of 1.97 LDR was reached for the DP600 steel and 1.92 LDR for the DP800. Given that the thickness distribution between the experimental and numerical results, an accord of over 90% was noticed. For the DP600 steel, the lowest experimental thickness value was 0.864 mm and the lowest numerical value was 0.87 mm. For the DP800 steel, the lowest experimental thickness value was measured to be 0.89 mm while the lowest numerical value was found to be 0.88 mm. In the conclusion, the present paper proves that the experimental results in the deep drawing of square cups can be achieved with very satisfying results by using numerical methods.

Keywords: High-strength steel, DP600, DP800, Deep drawing, Limiting drawing ratio

Research Article

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1. Introduction

Deep drawing is a plastic forming method using the action of a punch to shape sheet metals and it is widely used in sheet metal forming [1,2]. In this method, die elements are used to produce three-dimensional products with specific depths and profiles from two-dimensional workpieces having planar geometry [3]. A variety of simple and complex shaped parts can be manufactured via this method, and consequently, it has a very important place in metal forming applications [4–6].

In recent years, increasing competition and demand have made it a priority to produce safer, cheaper, and environmentally friendly automobiles with a lower weight / strength ratio, including both internal combustion vehicles and the increasingly popular electric vehicles [7–9]. To meet these demands, dual phase (DP), complex phase (CP), transformation induced plasticity (TRIP), and martensitic (MART) high- and ultra-high-strength steels have been developed. With the use of such new generation steels, great advances have been achieved in the automotive industry. In particular, the rise in the number of electric vehicles of recent highlights two important issues that need to be examined. The first is the development of car batteries and the second is the need to reduce the vehicle body weight. These issues call for the use of new generation steels and the improvement of forming ratios.

In this context, because they can meet both safety and lightness requirements at the same time, DP steels are primarily used in the production of the structural components of automobiles. As DP steel consists of the softer ferrite phase and the harder martensite phase, it exhibits a continuous yielding behavior, low creep rate, and high strain hardening rate [10,11]. Two of the most important indicators that steels can be shaped without damage are the LDR and the homogeneous thickness distribution. LDR can be determined by experimental, analytical, and finite element (FE) simulation. The most important material property affecting LDR is normal anisotropy or r-value. The strain hardening exponent, or n-value, is the other material property that affects LDR [12]. There are a number of parameters that affect forming, including the mechanical properties of the material, temperature, blank holder (pressure plate) force, friction, die clearance, etc.

Özek and Ünal [13] investigated the effect of the die surface angle on the LDR and wall thickness in the deep drawing of square vessels. In their experimental studies, they used 0 °, 5 °, 10 °, and 15 ° die surface angles and die/punch corner radii of 4, 6, and 8 mm. As a result of their studies, they reported that new types of square drawing dies used at different angles and radii provided a higher LDR compared to traditional dies.

Pepelnjak et al. [14] conducted a study on the warm deep drawing of DP600 steel using a non-isothermal heating method. In order to improve the LDR, they heated only the flange area. To determine the shaping property of steel, they carried out experiments at different temperatures ranging from room temperature to 300 °C. They stated that the LDR increased by 25.58% with the effect of heat and that the experimental and numerical results were in good agreement.

Wu-rong et al. [15] conducted a study on the LDR and formability of dual phase steels using 0.7 mm-thick SPFC340, 1.7 mm-thick DP600, 1.2 mm-thick DP800, and 1 mm-thick DP1000. They carried out deep drawing experiments on cylindrical vessels. They reported that they had achieved LDR values of of 2.30, 2.19, 2.15, and 2.07 for these materials, respectively. They also stated that the brittleness increased as the strength increased and that not only transverse, but also longitudinal cracks were seen in the DP800 and higher grades of steel. Olguner et al. [16] investigated the effect of press ram pulsation amplitudes on the deep drawability of dual phase steel sheet using frequencies of 5, 10, and 20 Hz. They reported that their proposed method had a significant effect both in terms of thickness reduction and drawing force compared to conventional ram presses.

This study investigated the deep drawing of square cups using high-strength dual phase DP600 and DP800 sheets via both experimental and finite element methods. The study aimed to determine the LDR and thickness variations of the high-strength sheets. We believe that this study will make a significant contribution to the work of academicians and manufacturers in the automotive industry.

2. Material and Methods

2.1 Material

Commercially available 1 mm-thick dual phase DP600 and DP800 steels were used in the experiments and their chemical compositions are given in Table 1. Tensile tests of the materials were carried out at room temperature using a 100 kN UTEST device at 0 °, 45 ° and 90 ° angles relative to the rolling direction. Tensile tests were carried out according to the ASTM-E8 standard, using test specimens prepared by cutting with a waterjet in order to prevent any heat input into the sepecimens. The stress-strain graphs obtained as a result of the tensile test are given in Fig. 1.

Table 1. Chemical composition of DP600 and DP800 materials

Material	Chemical composition (Weight%)			
	C	Si	Mn	P
DP600	0.097	0.225	0.823	0.0123
DP800	0.141	0.214	1.483	0.0106
	S	Al	Cr	Ni
DP600	0.0120	0.053	0.029	0.032
DP800	0.0156	0.085	0.020	0.032

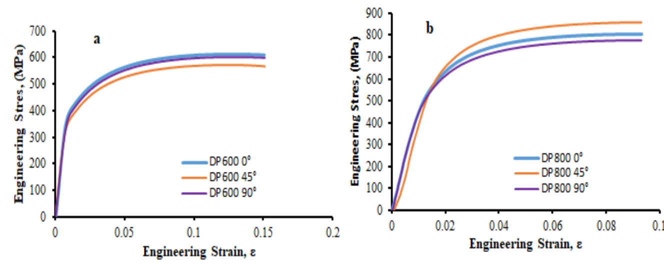

Fig. 1. Stress-strain variations of dual phase steel sheets: a) DP600, b) DP800

After mounting in bakelite, grinding, and polishing processes, the samples were etched with LePera. The microstructure images revealed the ferrite and martensite structure in both materials. When the images given in Fig. 2 are examined, the white regions show the ferrite phase, while the black regions show the martensitic phase.

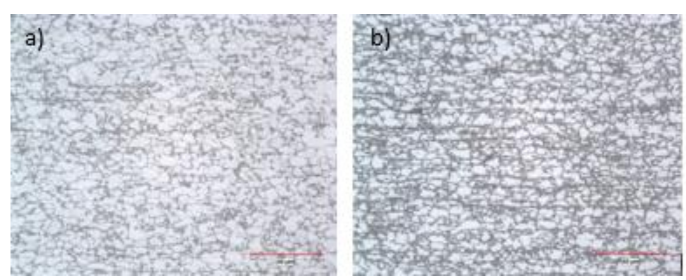

Fig. 2. Microstructural images of dual phase steels: a) DP600, b) DP800

2.2. *Method*

The test setup used for the deep drawing of square cups is given in Fig. 3 and the test parameters in Table 2. A PLC-controlled 50/20-ton capacity double-action hydraulic press was used in the study. In the experimental studies, the blank holder force and punch speed were kept constant. Within the scope of the study, the ideal blank holder force was determined by optimization using the finite element method (FEM). Experimental studies were carried out at room temperature to determine the LDR and wall thickness variations of the DP600 and DP800 materials.

In the study, the contact of the sheet material with both the blank holder and the matrix (die) was prevented by using a 0.25

mm thick Teflon film. In addition, the sheet material was lubricated with a graphite spray lubricant. This process facilitated the flow of the sheet sample into the matrix. Thus, by using a double lubrication system, the friction coefficient was significantly reduced. The fact that the Teflon film was not torn even after the forming process was completed indicated that the lubricant had preserved its properties. The blank holder force was determined as a result of optimization of the preliminary tests and was kept constant as 10 kN.

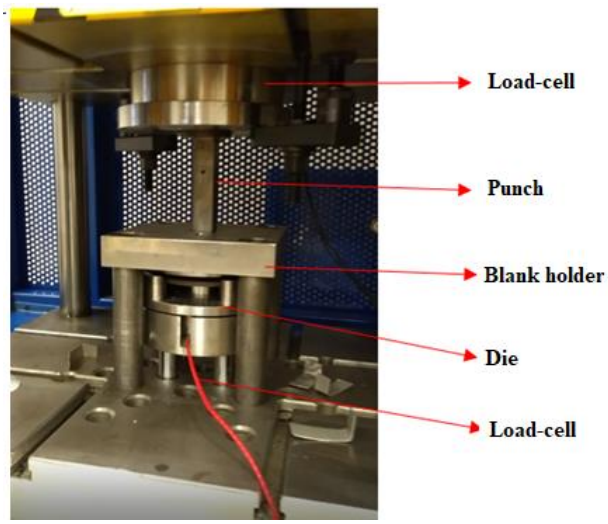

Fig. 3. Experimental setup

Table 2. Drawing tool geometry and process parameters

Parameter	Dimension	Unit
Die radius	5	mm
Punch radius	5	mm
Punch speed	10	mm/s
Punch diameter	37.56	mm
Die diameter	39.98	mm
Sheet thickness	1	mm
Die clearance	1.21	mm
Blank holder force	10	kN

When determining the LDR (β) for the deep-drawn square cup, the punch diameter was calculated by averaging the inner tangent diameter and the outer diagonal diameter of the square punch. According to Fig. 4, (β) values were determined using Eq. (1) and Eq. (2).

$$\beta = D_{max}/d_{punch} \tag{1}$$

$$d_{punch} = (d_{it} + d_{ot})/2 \tag{2}$$

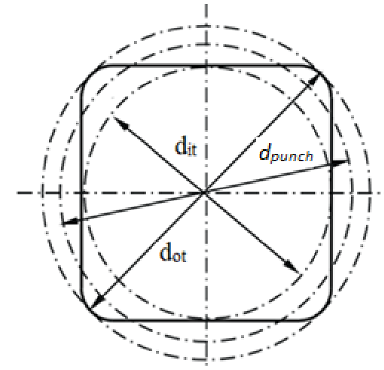

Fig. 4. Determination of the average punch diameter (d_{punch}) for a square cup [17]

Here, D_{max} is the original sheet diameter, and d_{it} and d_{ot} are the inner tangent diameter and the outer tangent diameter of the square punch, respectively. An ATOS 3D scanner was used to determine the variations in thickness of the deep-drawn square cups. The scanned cups were cut in a virtual environment and measurement operations were carried out. The thickness of the test samples was measured at an accuracy of 0.001 mm from the measurement points specified in Fig. 5.

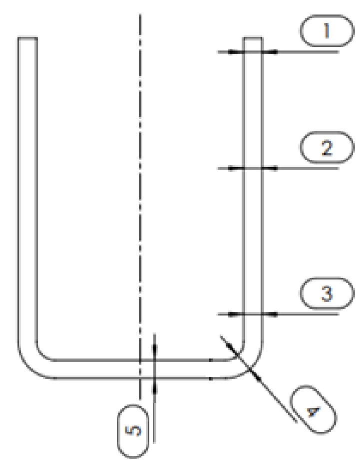

Fig. 5. Measurement points for thickness variation

The analysis of the deformations on the test sample was carried out with FEM using Simufact Forming R16 package metal forming software, which is known to be a highly reliable metal forming simulation program for analyzing forming operations. Before starting the analysis, after designing the die elements, the models of the sheet materials to be used in the experiments were created, and an isotropic material model was used for the created model. Using the stress-strain curve obtained from the tensile test results, the yield point and tensile strength required for the material model were transferred to the system. FEM analysis has been conducted by the FLD criteria.

Before starting the square deep drawing experiments, mesh structures were created for the matrix, blank holder, punch, and sheet material. The mesh structures of the matrix and the punch are presented in Fig. 6, and those of the blank holder and sheet material in Fig. 7. The parameters used in the finite element analysis are given in Table 3.

Table 3. FEM simulation parameters

Parameters	Values
Material	DP600, DP800
Object type	Material: Elastoplastic Die: Rigid Punch: Rigid
Mesh properties	Mesher: Sheet mesh Element type: Hexahedral Element size: 0.69912 mm
Friction coefficient	0.05
Punch speed	10 mm/s

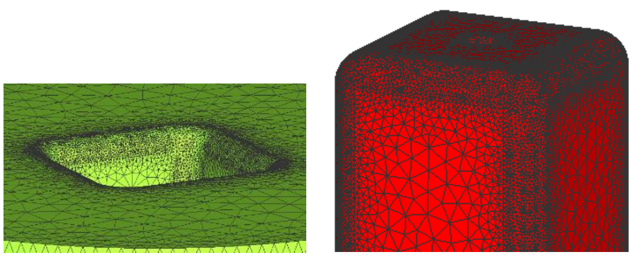

Fig. 6. Matrix and punch mesh structures

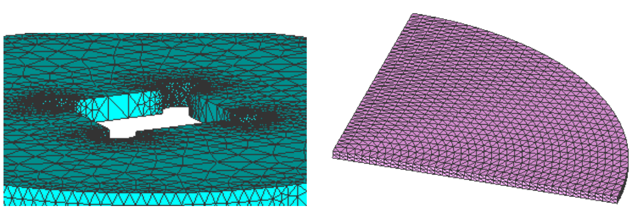

Fig. 7. Mesh structures of blank holder and sheet sample

3. Results and Discussion

3.1 Limiting drawing ratio (LDR) results

The LDR as an indicator of material formability refers to the largest cup depth that can be drawn in one try without damage and is determined by the ratio of the diameter of the sheet material to the diameter of the punch [15,18]. Within the scope of the study, in order to determine the LDR, the materials were prepared in 2-mm increments starting from a 68-mm diameter. Results of the tests to determine the LDR of the dual phase steels in the deep drawing of square cups are given in Fig. 8 (DP600) and Fig. 9 (DP800). The LDR was obtained as 1.97 for the DP600 and 1.92 for the DP800.

Fig. 8. DP600 deep-drawn square cups

Fig. 9. DP800 deep-drawn square cups

The deep-drawn square cups obtained as a result of the numerical analysis of the DP600 and DP800 materials used in the study are shown in Fig. 10 (DP600) and 11 (DP800). Again, the ratios of 1.97 for DP600 and 1.92 for DP800 could be drawn without failure. These results correspond exactly to the experimental results. The simulation results demonstrated their importance in terms of reducing die production costs and saving time without the need for experimental studies.

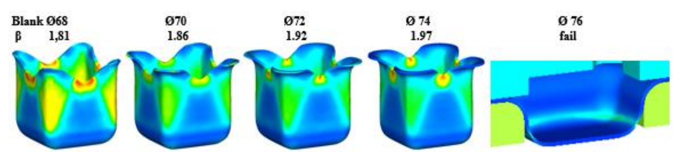

Fig. 10. DP600 deep-drawn square cups

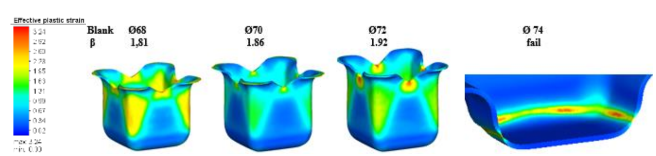

Fig. 11. DP800 deep-drawn square cups

According to the studies on the deep drawing of cylindrical cups, the LDR of DP steels with 600-1000 MPa tensile strength is approximately 2.00–2.1 and the LDR of DP steels with a strength level of 500 MPa is around 2.1–2.15 [18,19]. One of the most important ways to increase the LDR is by forming under the effect of heat. Pepelnjak and Kaftanoğlu [20] increased the drawing ratio of DP600 steel from 2.15 to 2.54 under the influence of heat.

3.2 Wall thickness results

The stresses that occur on the cup during deep drawing directly affect the wall thickness of the cup [21,22]. Therefore, one of the points to be considered during deep drawing is the variation in wall thickness. The success of the forming process depends on the success of the wall thickness variation. The variation in the thickness of the vessel walls also affects the geometrical completeness and life of the workpiece [2]. Damage to the deep-drawn part usually occurs from thinning, so it is important to identify critical areas and determine the stress variation in the thickness direction during deformation [23]. Fig. 12 shows 3D scans of DP600 sheet samples and Fig. 13 presents graphs of thickness variations. The Fig.s show that the thickness increased as the flange diameter increased toward the cup mouth. It can be seen that the lowest wall thickness occurred in the area just above the punch radius. Material flow became difficult due to the friction generated during forming, so the tensile stress on the sheet caused thinning at the corners of the punch and immediately above it [23]. A similar situation was observed with the DP800 results given in Fig.s 14 and 15. No wrinkling was seen at the mouths of the DP600 samples, but there was a significant buckling in the DP800 samples. This could be attributed to the strength of the material and also to the inadequacy of the blank holder force.

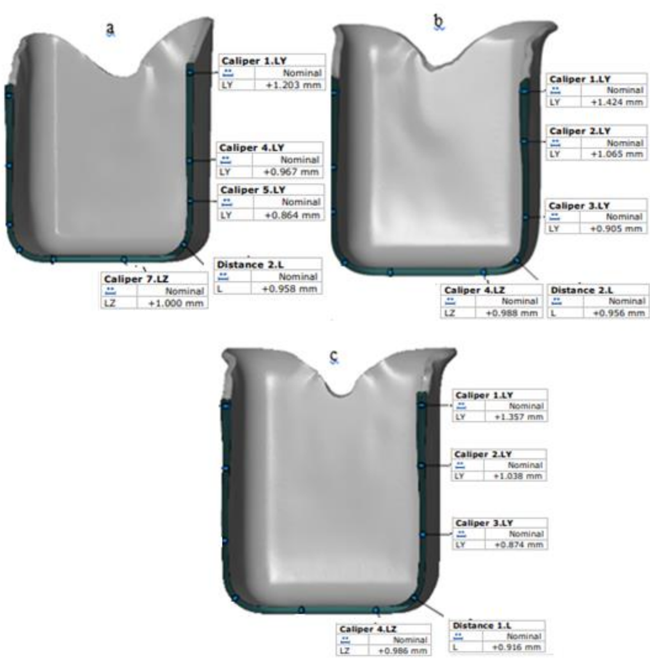

Fig. 12. 3D-scanned DP600 samples: a) Ø70, b) Ø72, c) Ø74

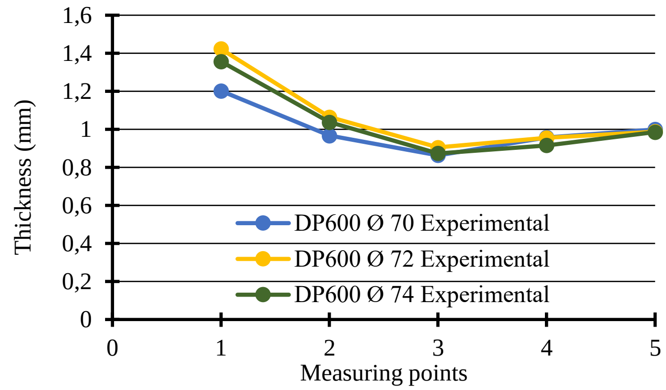

Fig. 13. Thickness variation of DP600 sheet (experimental)

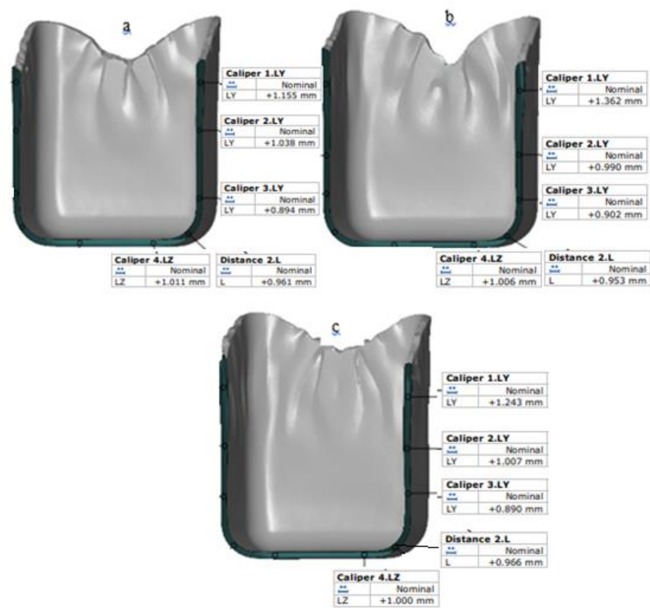

Fig. 14. 3D-scanned DP800 samples: a) Ø68, b) Ø70, c) Ø72

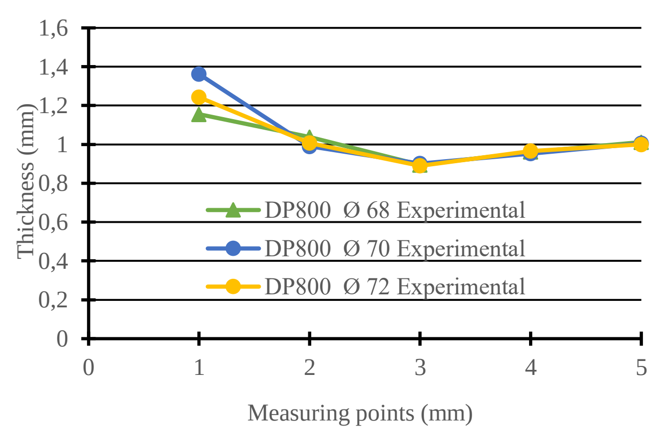

Fig. 15. Thickness variation graph of DP800 sheet (experimental)

Thickness measurement result graphs of the square cups obtained via the simulation studies are given in Fig. 16 for DP600 and Fig. 17 for DP800.

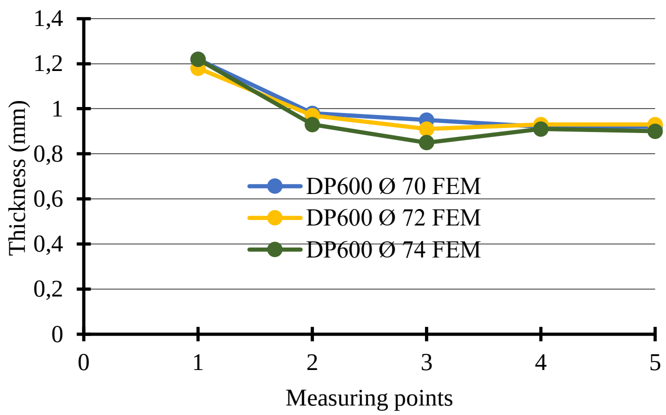

Fig. 16. Thickness variation graph of DP600 sheet (simulation)

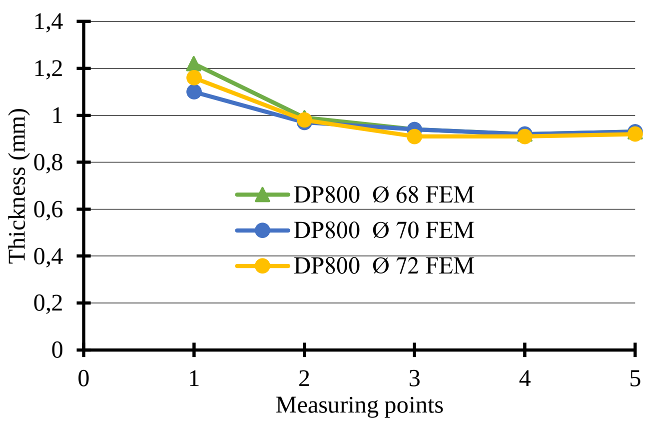

Fig. 17. Thickness variation graph of DP800 sheet (simulation)

Analysis of the thickness measurement of the cups obtained as a result of the finite element experiments revealed that the greatest thinning was in the area in contact with the punch curvature and in the area just above it. This can be explained by the fact that the flow of the material into the die clearance was entirely completed by the punch radii. In addition, the increase in thickness towards the mouth of the cup and the drawing effect on the material were the reasons for the excessive thinning at measuring point number 2.

3.3 Comparison of experimental and simulation results

The LDR results of the deep-drawn square samples produced by the Simufact Forming V16 metal forming program and by the experiments performed in the real environment of the laboratory were compared. For DP600, material with a maximum diameter of Ø74 mm was formed using both methods without tearing, while for DP800, material with a maximum diameter of Ø72 mm was formed using both methods without tearing. These results show that the FEM and experimental studies were perfectly compatible.

A comparison of the thickness variations of the deep-drawn square samples produced by the Simufact V16 metal forming program and by tests performed in the real environment of the laboratory is given in Fig. 18 for DP600 and Fig. 19 for DP800. Both graphs show that the variations in the measurement points are minimal. These results once again reveal the compatibility of the simulation and experimental work for thickness change.

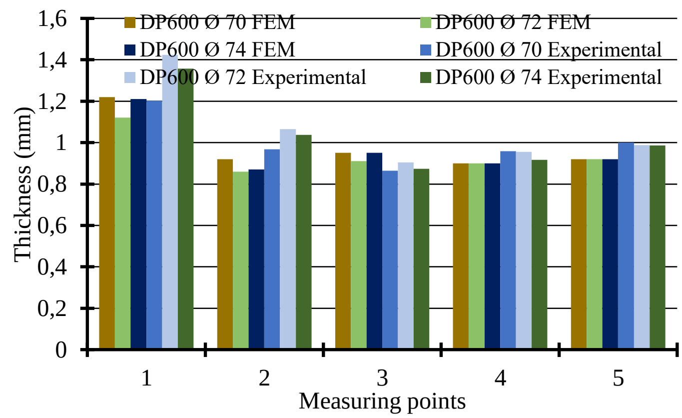

Fig. 18. Comparison of thickness variations of DP600 sheet as a result of experimental and numerical studies

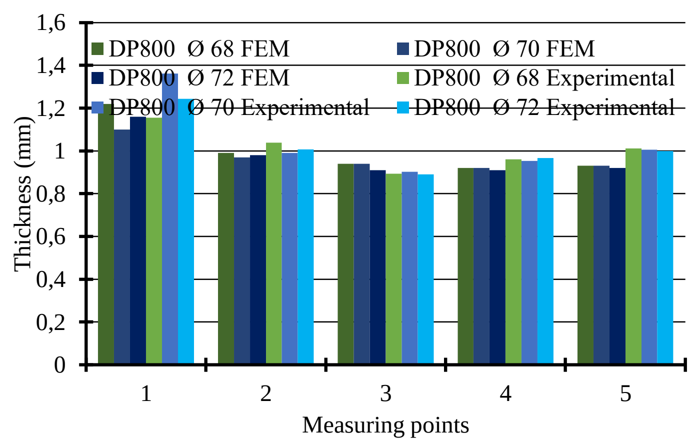

Fig. 19. Comparison of thickness variations of DP800 sheet as a result of experimental and numerical studies.

4. Conclusions

The use of high-strength steel sheet materials is steadily expanding in the automotive industry. In this study, square deep drawing of high-strength steel sheets under room temperature conditions was investigated in detail experimentally and numerically using the Simufact Forming V16 metal forming program. The results obtained by the study are summarized as follows:

- The similarity of the experimental and numerical results can greatly reduce the trial-and-error rate. As they are quite similar to those of the experimental results, appropriate dies designed by the numerical programs can be used to help reduce the high cost of dies and to save time.

- The results show the importance of transferring material properties and test conditions to a simulation environment in order to obtain accurate and compatible results.
- In terms of the LDR, both the experimental and the numerical results corresponded, with the ratio of 1.97 for DP600 steel and 1.92 for DP800.
- In terms of thickness distribution, the experimental and numerical results corresponded by more than 90%. The lowest thickness values for DP600 steel were 0.864 mm (experimental) and 0.87 mm (numerical). For DP800 steel, the lowest thickness values were 0.89 mm (experimental) and 0.88 mm (numerical).
- The highest thickness increase occurred at the cup mouth because the effect of the blank holder force created difficulty for the material flow into the die clearance.
- In the experimental studies, more wrinkles occurred in the DP800 after forming than in the DP600.
- This study can be further expanded using different parameters such as heat effect, different blank holder forces, different punch radii, and so on.

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Conflict of Interest Statement

The authors declare that there is no conflict of interest in the study.

CRediT Author Statement

N. Şen: Conceptualization, Finite element analysis, Writing, Validation, Data curation,
İ. Çolakoğlu: Experiments, Measurements,
V. Taşdemir: Writing-original draft, Finite element analysis, Formal analysis

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