INTERNATIONAL JOURNAL OF
AUTOMOTIVE SCIENCE AND TECHNOLOGY

2023, VOL. 7, NO: 2, 104-111 www.ijastech.org e-ISSN: 2587-0963

# Assessment of Conical Die Deep Drawability of DP800 and MART1400 Advanced High Strength Steels

Nuri Şen[1*], Tolgahan Civek[1] and Ezgi Tongü[1]

0000 0002 6501 5858, 0000 0002 1487 5903, 0009 0006 3179 9558

[1] *Mechanical Engineering Department, Faculty of Engineering, Duzce University, Duzce, 81000, Turkey*

**Abstract**

Deep drawing is one of the most important and vastly conducted sheet metal forming method. Thus, even small improvements achieved on the deep drawability of sheet metals significantly increases the ability of sheet metal to be formed into more complex products. Advanced high strength steels (AHSSs) are one of the most popular steels in the automotive industry due to their high strengths. However, their low ductility causes considerable splitting problems near the cup punch region. In this study, deep drawing experiments have been conducted in conical dies with four different angles (0º, 7.5º, 12.5º, and 20º) for DP800 and MART1400 steels to observe whether a higher deep drawing ratio (DDR) can be achieved by deep drawing in conical dies for AHSSs. In addition, finite element analysis (FEA) has been utilized to estimate the DDR for each types of steels in different conical die setups. It has been observed that the deep drawability of MART1400 steel has not improved in any of the conical die setups. However, DDR of DP800 has slightly increased by 2.46% by deep drawing with 20º die angle. A good agreement with the numerical and experimental results has been achieved.

Keywords: Conical die deep drawing; Deep drawing ratio; DP800; MART1200

**Research Article**
https://doi.org/10.30939/ijastech..1278573

Received 07.04.2023
Revised 18.05.2023
Accepted 23.05.2023

* Corresponding author
Nuri ŞEN
nurisen@duzce.edu.tr
Address: Mechanical Engineering Department, Faculty of Engineering, Duzce University, Duzce, Turkey
Tel: +903122028653

## 1. Introduction

Weight reduction and strength improvement are one of the main tasks for the original equipment manufacturers (OEMs). Thus, the use of AHSSs is continuously rising among the sheet metal forming industries in order to obtain parts with high strength and less weight [1], [2]. However, the lower formability of AHSSs as compared to high strength low alloy (HSLA) steels requires well optimization of the forming process in order to obtain sound products.

DP steels are one of the most preferred AHSS due to their reasonable formability and high energy absorption capabilities [3]. Thus, it mostly is used in parts that require impact resistance and good energy absorption ability. The reasonable formability and the high strength of DP steels are achieved through their unique microstructure, which comprises ferritic and martensitic structures [4]–[6]. While the ferrite provides good formability to DP steels, the martensitic structure improves its strength. Hence, various types of DP steels can be achieved by changing the ferrite and martensite ratios coexisting in the microstructure. On the other hand, MART steels are one of the strongest steels among the AHSSs due to their fully martensitic microstructure and are highly used for impact resistance parts such as bumpers [7], [8]. The significantly high strength of MART steels causes in severe springback and low formability, which considerably limits their use for complex parts [9].

In literature, many attempts have been carried out to assess the deformation behaviour of both DP and MART steels and improve their formability in order to expand their use for more complex shaped parts. In some studies [10], [11], [12], [13],[14],[15] researchers have found considerable improvements on the deep drawability, springback reduction and total elongation capacity of AHSSs by using warm forming methods. Some researchers [16], [17], [18], have focused on the importance of proper lubrication in forming since a suitable lubrication in between the die and sheet interfaces plays a vital factor for achieving parts with low surface roughness and few seizure errors. Due to incredibly high strength levels of AHSSs, these surface errors further deteriorate during forming operation. Abe et al. [16], have investigated the effects of die coatings on the seizure errors for 980 and 1180 MPa AHSSs. They have shown that VC-coated die has caused smaller surface roughness and eliminated the seizure error, while TiN-coated die hasn't been suitable for AHSSs. ŞEN et al. [17], have applied the minimum quantity lubrication (MQL) method for incremental forming process. The authors have obtained higher surface quality of the formed products about 14.60% with the MQL assisted incremental forming method. The behaviour of sheet metal under deformation is significantly related to its microstructure properties. Thus, some critical factors of sheet metal such as strain hardening and strain rate sensitivity indexes, deformation behavior of constituent phases and damage evolution in the microstructure have drawn a considerable interest of researchers in the literature [19], [20].

Although the lubrication conditions, microstructure and temperature plays a dominant role during a deep drawing process, geometrical features of the die setup such as die shoulder radius, punch edge radius and die angle have deterministic effects on the deep drawing process [21]–[24]. In literature, it has been stated that the use of a conical die for the deep drawing process may enhance the DDR [25], [26]. Savas and Secgin [27], have used the conical die design with different angles (0º , 2.5º, 5º, 10º , 15º) to deep drawn the DIN EN 10130-91 steel sheet. They have observed that DDR has improved from 1.75 at 0º die angle to 2.175 at 15º die angle. Özek and Akkelek [28], have applied the similar conical die design with various die angles (0º, 3º, 6º, 9º, 12º, 15º) for the deep drawing of rectangular shaped cups from St37 steel. In their results, they have shown that the DDR can be improved to 1.55 at die angles from 3º to 15º as compared to conventional deep drawing die

A careful die design for the sheet metal forming process may result in considerable improvements regarding either surface quality or formability. There have been many studies emphasizing the formability improvement achieved with the use of a conical die design for variety of materials. However, there are only few studies related with the deep drawing behaviour of AHSS, when drawn through a conical die. Moreover, there are only few studies regarding the deep drawability of MART steels. Thus, in this study, the effect of conical die concept on the deep drawability of DP800 and MART1400 steels have been investigated. The main focus of the study has been to improve the DDR of both kinds of steels by means of a conical deep drawing die setup. Conical dies with five different angles (0º, 7.5º, 12.5º, 20º) have been manufactured and used for the deep drawing experiments. Finite element analysis (FEA) method has been used to model the deep drawing process and correctly estimate the DDR achieved for both kinds of steels by the conical die deep drawing setup.

## 2. Materials and methods

### *2.1 Materials*

In this study, DP800 and MART1400 steels with 1 and 1.5 mm thicknesses, respectively, were used for the deep drawing experiments. The chemical composition of both steels have been given in Table 1.

### *2.2 Tensile test experiments*

Tensile test specimens with the dimensions shown in Figure 1 were cut by water-jet cutting method in the rolling direction for each steels. Tensile test experiments were conducted at 0.005 s-1 with the Zwick/Roell Z600 tensile test device according to TS EN ISO 6892-2 standard. The true stress – strain graphs of each steel have been given in Figure 2.

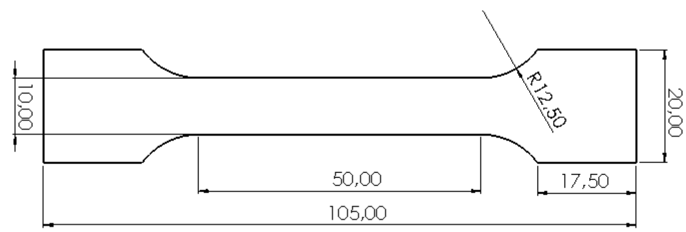


Fig. 1. Dimensions of the tensile test specimens

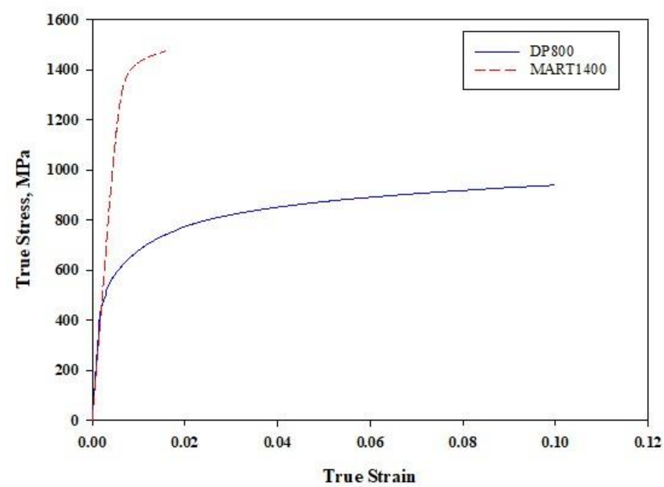


Fig. 2. True Stress – Strain graph of DP800 and MART1400 steels at 0.005 s-1

Table 1. The chemical composition of DP800 and MART1400 steels

| Materials | Fe | C | Si | Mn | P | S | Al | Ti | Nb | V |
|---|---|---|---|---|---|---|---|---|---|---|
| DP800 | 97,9 | 0,142 | 0,190 | 1,489 | 0,007 | 0,003 | 0,038 | 0,001 | 0,016 | 0,012 |
| MART1400 | 98,1 | 0,179 | 0,168 | 1,201 | 0,010 | 0,004 | 0,038 | 0,032 | 0,001 | 0,018 |

### *2.3 Deep drawing experiments*

Circular specimens were cut by water-jet cutting method from DP800 and MART1400 sheets. Dies with four different angles (0º, 7.5º, 12.5º, 20º) were manufactured and used in the deep drawing experiments. A flat punch were used to draw the circular specimens into the die cavity. Around 7.5 tons and 15 tons of forces were applied by the blankholder on the DP and MART specimens, respectively, to prevent them from wrinkling during deep drawing process. The determination of the blankholder force was done by preliminary deep drawing tests, in which the blankholder force was increased until reaching to a successful drawing without tears or wrinkles. After each successful deep drawing operation, the specimen diameters were incrementally increased by 2 mm. DDR were then calculated by dividing the largest successfully deep drawn specimen diameter to punch diameter as shown in Eq. (1) Deep drawing experiments were conducted with three different lubrication condition (Teflon film, graphite, Teflon film + graphite) to select the effective lubricating method and Teflon film were selected to be used in the deep drawing experiments since it resulted in lower forming force than graphite condition and was easier to apply as compared to Teflon film + graphite condition. The Teflon films were placed on the top and bottom surfaces of the flange regions of the sheet metal and its thickness was 0.25 mm.

$$DDR=\frac{d\emptyset_f}{d\emptyset_p} \quad (1)$$

Where, $d\emptyset_f$ and $d\emptyset_p$ represent the final successfully deep drawn specimen diameter and punch diameter, respectively.

The geometrical features of the die setup have been given in Table 2. The experimental setup and its schematic representation have been given in Figure 3

### *2.4 Finite element analysis modelling*

#### *2.4.1 Optimization of the constitutive model for DP800 and MART1400*

Finite element analysis are mainly used for die designing processes in order to eliminate or reduce the trial and error stages. In this study, Voce type hardening model as shown in Eq. (2) were used to predict large deformation stresses. Due to its stress saturation behavior, the Voce hardening model is able to predict the stress-strain responses at higher strain levels and used for variety of materials including steel and aluminum [29], [30]. The parameters of the Voce hardening model were optimized by simulating series of the tensile test experiments and comparing the obtained load – displacement curves with experimental values. In the tensile test simulations, gauge length of the specimens were meshed with hexahedral elements in 0.3 mm size and three elements were used through the thickness. Grips that are used to hold the specimen in place were selected as rigid bodies and glued to the specimen.

The tensile test simulation model has been shown in Figure 4. The comparison of the experimental and simulated flow curves of DP800 and MART1400 steel have been shown in Figure 5.

$$\sigma=\sigma_0+V_1[1-\exp(-V_2\varepsilon)] \quad (2)$$

Where, $V_1$ and $V_2$ represent the Voce hardening model parameters and $\sigma_0$ the initial yield strength

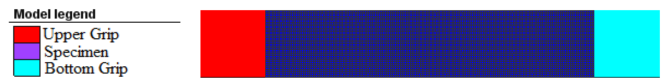


Fig. 4. Numerical model used for the tensile test simulation

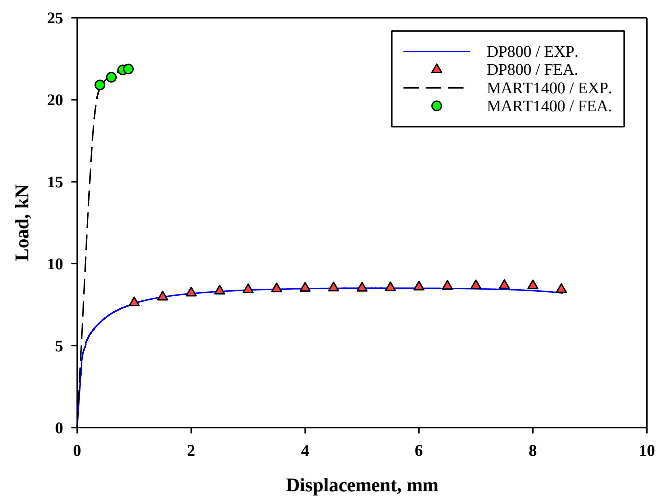


Fig. 5. The comparison of simulated and experimental flowcurves for DP800 and MART1400 steel

#### *2.4.2 Deep drawing analysis*

In the deep drawing analysis model, dies were imported as rigid bodies into the FEA model and the sheet specimens were meshed with hexahedral elements in 0.43 mm size and three elements were used through the thickness. Only one quarter of the circular specimen was simulated to reduce the calculation time. 0.07 Coulomb friction coefficient was given between the die and sheet surfaces. Determination of the friction coefficient was done by carrying out iterative deep drawing simulations for different friction coefficients until a good agreement was reached on the experimental and simulated force – displacement graphs. The comparison of the experimental and simulated force - displacement graphs have been shown in Figure 6. The lower force prediction during the ironing stage of flange regions of the sheet metal might have been resulted because of lower clearance in the flange regions due to the thickness of Teflon films. The failure diagnosis of sheet metals was assessed by theoretical Keeler forming limit diagram (FLD).

Table 2. The geometrical features of the die setup for the deep drawing process

| Materials | Geometrical Features | | | | |
|---|---|---|---|---|---|
| | Punch diameter | Die angle | Die radius | Punch edge radius | Clearance |
| DP800 | 37.6 mm | 0º, 7.5º, 12.5º, 20º | 5 mm | 5 mm | 1.21 mm |
| MART1400 | 36.4 mm | 0º, 7.5º, 12.5º, 20º | 5 mm | 5 mm | 1.81 mm |

a) b)

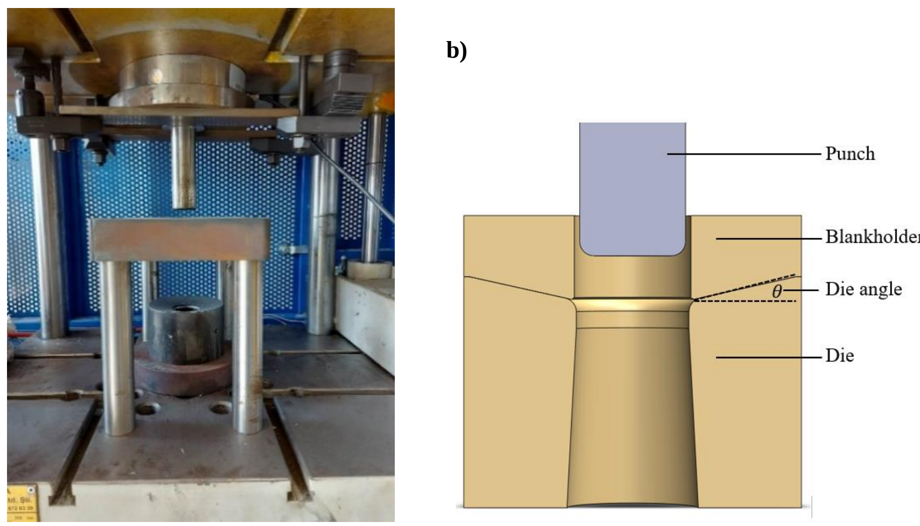


Fig. 3. a) The experimental setup for conical die deep drawing and b) its schematic representation

In the derivation of FLD for DP800, the given strain hardening coefficient, n, and thickness, t, were 0.16 and 1 mm, respectively. In the derivation of FLD for MART1400, the given strain hardening coefficient, n, and thickness, t, were 0.11 and 1.5 mm, respectively. The derived FLD curves obtained for DP800 and MART1400 steels have been shown in Figure 7.

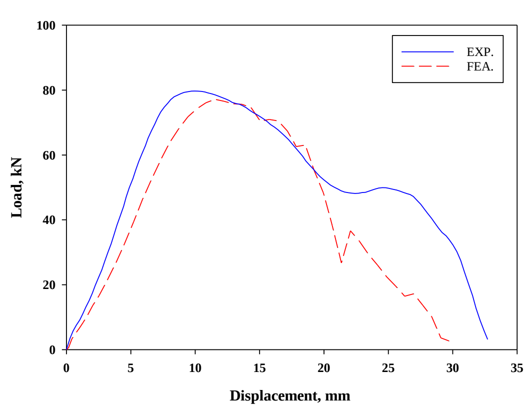


Fig. 6. Comparison of the experimental and simulated force - displacement graph for deep drawing of DP800 steel in 70 mm diameter

## 3. Results and Discussions

### *3.1 Effect of conical die deep drawing method on the DDR of DP800 and MART1400 steels*

DDR is one of the characteristic methods of assessing the formability of sheet metals. Mainly, DDR value indicates how deeper products can be formed. Thus, improvement of DDR lets the forming of products with higher complexity or depth. In Figure 8 and 9, the deep drawn samples of DP800 and MART1400 steels with conical dies with different angles have been shown, respectively. It can be seen that the increase of die angle has not resulted in a significant improvement on the DDR for each steel type. However, the DDR of DP800 has slightly improved by 2.46% at 20º die angle. The highest achieved DDR has been 2.18 and 1.97 for DP800 and MART1400 steels, respectively. In conventional deep drawing operations, the cup walls are bent and unbent while drawing through the die radius. This bending and unbending deformation of the cup walls cause the work hardening of the cup walls. On the other hand, since the cup nose region only goes through a single bending deformation it less work hardens as compared to cup walls. Therefore, this work hardening gradient in between the cup nose and wall regions limits the amount of wall length that can be supported by the cup nose during deep drawing operation. However, when sheets are drawn through a conical die, bending and unbending of the cup walls are reduced with the increase of die angle, which results in the reduction of work hardening gradient in the cup nose and wall regions and consequently improve the DDR. Although many improvements have been observed by the conical deep drawing method for materials such as cold rolled low carbon steel [31] brass and aluminum [22], [32], in the case of DP800 and MART1400 steels, increasing of die angles up to 20º have not considerably contributed to increasing the DDR. One of the main reasons of such independence of DP800 and MART1400 steels to conical die deep drawing in between 0º to 20º angle observed in

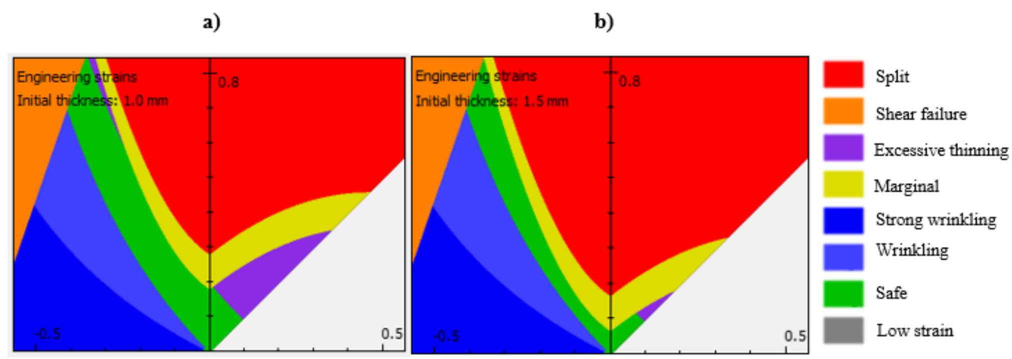


Fig. 7. Obtained FLD curves according to theoretical Keeler method for a) DP800 and b) MART1400 steels

This study may have been caused due to using of insufficient die angles to reduce the work hardening of the cup walls. Hezam et al. [33], have observed a considerable increase in the DDR by using a conical die, however, they have also noted that the DDR achieved at lower die angles has been lower than that achieved at higher die angles.

Since, at lower die angles, the conical deep drawing die approaches to the conventional deep drawing die, advantages of using a conical die over conventional deep drawing die considerably reduces. Thus it can be deduced that a higher DDR may have been obtained at higher die angles. However, the incapability of using a blankholder plate at higher die angles should be taken into consideration since it may cause in wrinkling failures for especially steels with high strengths and low thickness [25].

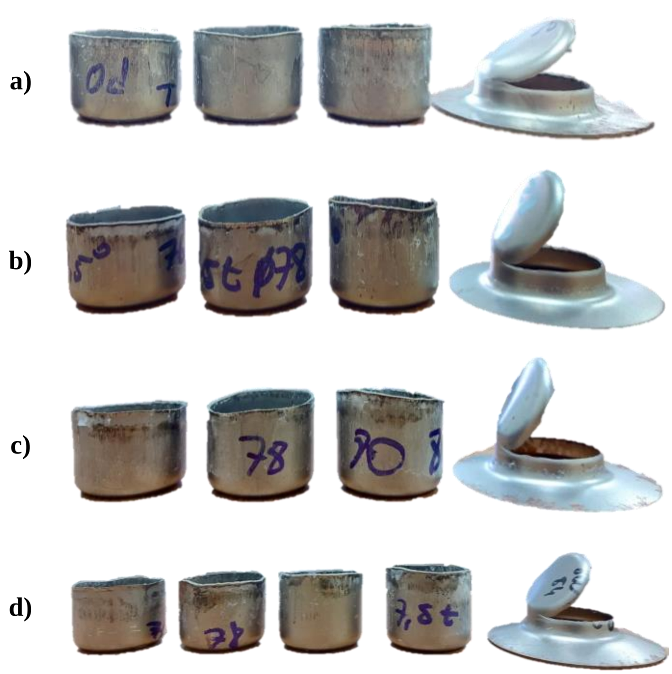


Fig. 8. Deep drawn DP800 samples with conical dies with different angles: a) 0º , b) 7.5º, c)12.5º, d) 20º, the initial diameters of the samples shown in a), b), c) are 76, 78, 80 and 82 mm, and for d) are 76, 78, 80, 82 and 84 mm from left to right

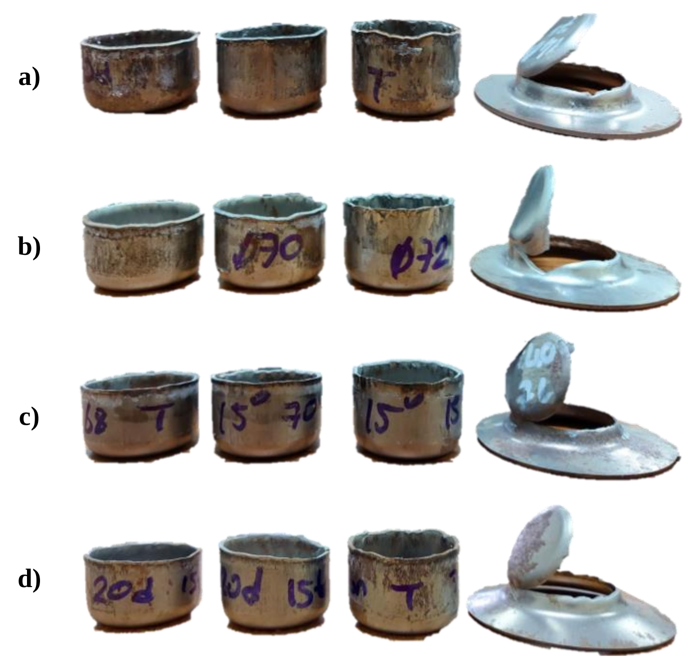


Fig. 9. Deep drawn MART1400 samples with conical dies with different angles: a) 0º, b) 7.5º, c)12.5º, d) 20º, the initial diameters of the samples shown in a), b), c) and d) are 68, 70, 72 and 74 mm from left to right

### *3.2 Comparison of FEA and Experimental Conical Die Deep Drawing Results*

FEA methods have been extensively used for sheet metal forming designs to prevent the waste of time and resources expended during trial and errors. However, sheet metal material properties such as flowcurve, anisotropy, forming limit etc. needs to be well characterized and defined in order to approximate the analysis results to that of observed in the real forming process. Forming limits of a sheet metal are generally defined by FLDs, which can be obtained by Nakazima test. However, obtaining of FLD for a sheet metal requires excessive amount of repetitive experimental tests. Thus, theoretical methods such as Keeler are usually preferred in the sheet metal industry as to obtain the limiting strains. The comparison of the FEA and the fractured specimens have been shown for MART1400 steel in Figure 10. In the FEA model, the fractures have occurred along the punch nose region for 74 mm initial diameter, which resonates well with the experimental results. Similar to the experimental results shown in Figure 9., the largest initial diameter for MART1400 steel that has been able to be numerically deep drawn has been 72 mm as shown in Figure 11. The comparison of the FEA and the fractured specimens has been shown for DP800 steel in Figure 10. The fractures in the FEA model have always occurred along the punch nose region as have been observed in the experimental results. However, in the numerical results, the fractures have occurred in 82 mm initial diameter size for 0º and 7.5º die angles, while it occurred in 83 mm initial diameter size for 12.5º and 20º die angles. The largest initial diameters that have been numerically deep drawn for DP800 steel at different die angles have been shown in Figure 12. It can be seen in the numerical results that a high proximity have been reached as compared to the experimental deep drawing results, which validates the applicability of Keeler theoretical FLD in deep drawing analysis for MART1400 and DP800 steels.

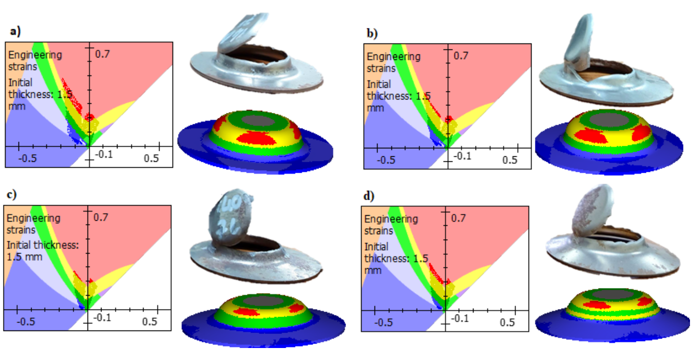


Fig. 10. The comparison of experimental and numerical deep drawing analysis for MART1400 steel in 74 mm initial diameter, a) 0º, b) 7.5º, c) 12.5º, d) 20º

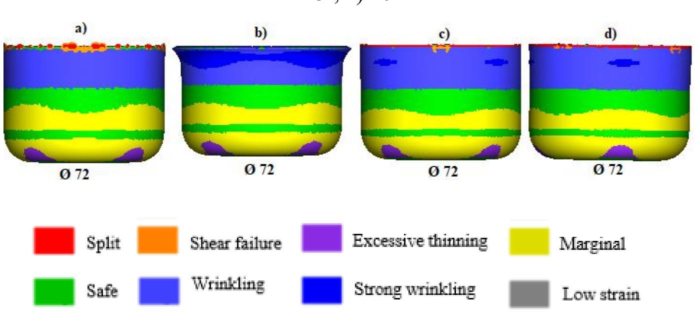


Fig. 11. Numerical deep drawing results for MART1400 steel in 72 mm initial diameter, a) 0º, b) 7.5º, c) 12.5º, d) 20º

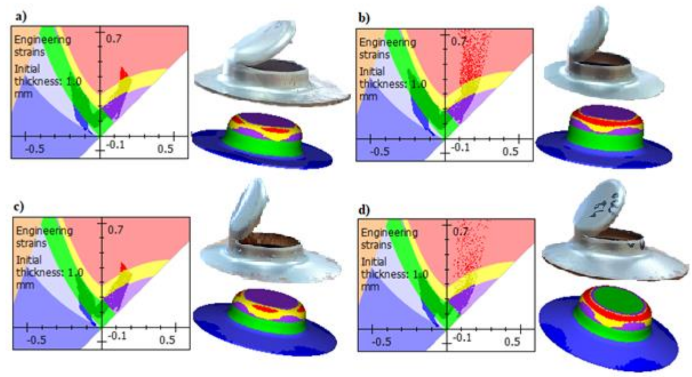


Fig. 12. The comparison of experimental and numerical deep drawing analysis for DP800 steel, a) 0º, b) 7.5º, c) 12.5º, d) 20º

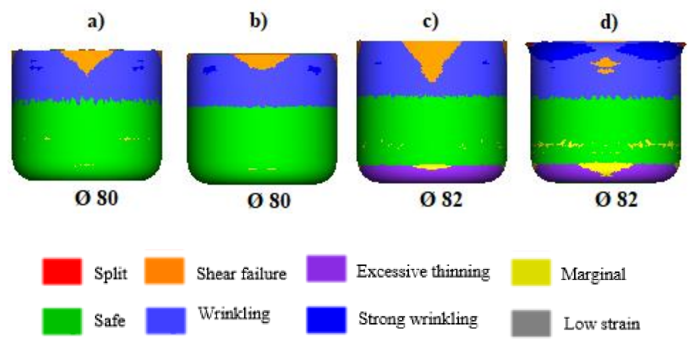


Fig. 13. Numerical deep drawing results for DP800 steel, a) 0º, b) 7.5º, c) 12.5º, d) 20º, dimensions are in mm

### *3.3 Effect of conical die deep drawing method on the wall thickness variation*

One of the key parameters of a successful forming operation is to obtain a uniform thickness variation in the formed products. In deep drawing forming process the regions near to cup nose are the most susceptible regions to excessive thinning. Hence, in most deep drawing processes failures occur around the cup nose. Cup flange regions, on the other hand, are susceptible to thickness increase due to the formation of compressive stresses around the circumference of the sheet flange during the deep drawing process. The variation of thickness along the deep drawn DP800 and MART1400 cups formed at different die angles have been shown in Figures 14 and 15, respectively. In both steels, the highest thickness reduction have occurred around the punch nose region (15 mm – 30 mm). The lowest thicknesses observed for DP800 steel have been 0.88, 0.99, 0.87 and 0.92 mm for 0º, 7.5º, 12.5º, and 20º die angles, respectively. The lowest thicknesses observed for MART1400 steel have been 1.33, 1.39, 1.43 and 1.43 mm for 0º, 7.5º, 12.5º, and 20º die angles, respectively. A monotonic increase in the thickness for both types of steels has been observed in the sidewall region for each die angles. Thus, no significant difference have been noticed in the thickness variations of both types deep drawn at different die angles. The small variations may have been caused due to the experimental errors like correct aligning of the sheet metal on the die surface.

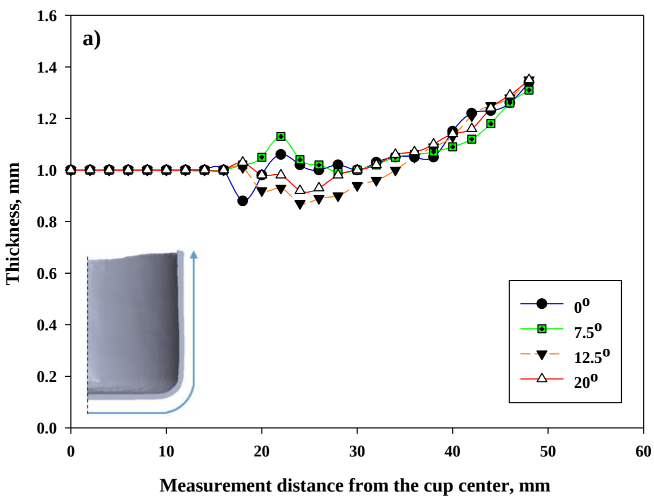


Fig. 14. Thickness variation along the deep drawn DP800 cups formed at different die angles

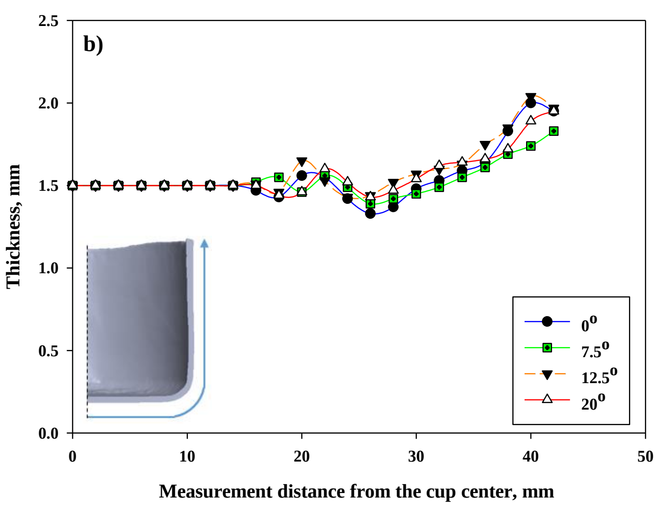


Fig. 15. Thickness variation along the deep drawn MART1400 cups formed at different die angles

## 4. Conclusions

In this study, experimental and numerical deep drawing tests have been conducted in different die angles ($0^o$, $7.5^o$, $12.5^o$, and $20^o$) for DP800 and MART1400 AHSSs to improve their DDRs. The main conclusions that can be drawn from the study have been listed below:

- In deep drawing tests of MART1400 steel in different die angles, no improvement has been observed in terms of DDR. Maximum achieved DDR has been 1.98 in each die angle setup.

- In deep drawing tests of DP800 steel in different die angles, only a slight increase has been observed in the DDR around 2.46% in $20^o$ die angle setup as compared to any other die angle setups. The maximum achieved DDR in $0^o$, $7.5^o$, $12.5^o$ die angles has been 2.12, while it has been 2.18 in $20^o$ die angle.

- FEA model diagnosed with Keeler FLD criteria has been able to correctly capture the location of fracture (cup nose region) and closely estimated the DDRs for each types of steels.

- A similar thickness variation have been observed in each die angle setups for DP800 and MART1400 steels.

- It has been postulated that the amount of work hardening decrease on the cup sidewalls by the use of a conical die for low die angle ranges ($0^o$ - $20^o$) has been diminutive to cause an improvement on the DDRs of MART1400 and DP800 steels.

## Acknowledgment

For this work, the authors gratefully acknowledge the financial support provided by the Duzce University Research Fund [Project No: 2020.06.05.1113].

## Conflict of Interest Statement

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

## CRediT Author Statement

**Nuri ŞEN:** Conceptualization, Supervision,
**Tolgahan CİVEK:** Conceptualization, Writing-original draft,
**Ezgi TONGÜ:** Data curation, Formal analysis

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