Jurnal Teknik Mesin
Mechanical Xplore (JTMMX)
Mechanical Engineering
Vol. 4 No. 2 (2024) pp. 98-108
p-ISSN: 2746-0045 e-ISSN: 2746-3672

A Comprehensive Investigation of Deep Drawing Processes for a 2-Inch Diameter Dop-pipe Cap: Numerical and Experimental Analysis

Ghazi Tikamori[1], Dhea Intan Patya[1*], Sukarman[1], Rizki Aulia Nanda[1], Dodi Mulyadi[1], Khoirudin[1], Muhamad Taufik Ulhakim[1], Amir[1], Taufiqur Rokhman[2], Safril[3]

[1]Department of Mechanical Engineering, Faculty of Engineering, Universitas Buana Perjuangan Karawang, Karawang, 41361, West Java, Indonesia

[2]Department of Mechanical Engineering, Faculty of Engineering, Universitas Islam 45, Bekasi 17113, West Java, Indonesia

[3]Department of Mechanical Engineering, Faculty of Mechanical and Automotive Engineering Technology, Universiti Malaysia Pahang, Pekan 26600, Pahang, Malaysia

ABSTRACT

The persistent challenges in material forming processes arise from recurrent issues encountered during the deep drawing process, particularly involving cracks and deviations from standard thickness dimensions. This article investigates the deep drawing process using both experimental and numerical methodologies. The experimental approach employs a 40-ton capacity power press machine, while the numerical method utilizes the ABAQUS student version software. SPCC-SD (JIS G3141) is the selected material for producing a Dop-pipe 2-inch diameter pipe cap in both approaches. Noteworthy findings include the highest positive and negative correlations observed in elements E 46 and E 48, with values of 0.715 and -0.933, respectively. Minimal disparities, averaging around 4.6% for all components, were evident between the experimental and numerical methodologies. The numerical approach yielded predictive results identifying potential issues in elements E 47 and E 48. This observation did not reveal instances of tearing failure but instead showcased an increase in thickness due to a higher axial force between the dies and punched-in components. The study successfully and accurately predicted product thickness for all components, presenting a contrast with outcomes obtained through the experimental method. Furthermore, this research advances the deep drawing process, extending its applicability to broader material forming applications and ultimately enhancing overall production process efficiency.

Keywords: *Deep drawing,* Dop-pipe cap, *Displacement. Numerical and experimental analysis*

Article information:
- Submitted: 06/01/2024
- Revised: 15/01/2024
- Accepted: 16/01/2024

Author correspondence:
*✉**:**
dhea.intan@ubpkarawang.ac.id

Type of article:
☑ Research papers
☐ Review papers

1. INTRODUCTIONS

Deep drawing techniques are crucial for producing metal components with intricate geometric complexity in the manufacturing industry. The primary innovation of this technique is evident in the production of pipe caps, a vital component in diverse industrial pipe applications. The high precision of deep drawing techniques in shaping metal has led to extensive research efforts to enhance product efficiency, quality, and durability. With the advancement of industry, there is a growing need for innovation to enhance and streamline production processes. A significant advancement is the press machine, which enables the shaping of components from sheet metal through molds or dies [1]. The stamping or press process, employing a die, utilizes the material-forming technique of deep drawing, which plays a crucial role in producing high-quality products within a reduced production timeframe [2]. The deep drawing -

process is crucial in producing various products made from sheet metal, including car and motorbike parts, household equipment, and pipe caps [3]. The deep drawing process entails applying both compressive and tensile forces to a metal sheet, resulting in the formation of a blank or component with the desired dimensions, while preserving the initial material thickness [4]. The single deep drawing method enables the completion of this process in a single stage of press work, commencing from a sheet metal material.

Multiple investigations on the deep drawing process have been conducted, including studies conducted by researchers [2, 5-9]. An experiment was conducted using a square cup drawing, where the angle was systematically altered [10]. In their study, Hkan et al. [11] investigated cup drawing by analyzing the parameters that affect friction factors. Kardan et al. [6] researched optimizing punch force in the cup deep drawing process using experimental and finite element methods. The study by [12] focused on investigating the square cup deep drawing technique and developing the tailor-welded blank process. In their study, Morishita et al. [13] examined the square cup drawing process in the trailer blank process for sheet steel of varying thicknesses, specifically thin and thick sheets. Park et al. [14] conducted additional research to examine the impact of punch loading on the elliptical deep drawing process, which is used for automotive components. Sen et al. [9] investigated square deep drawing using high-strength materials, specifically DP600 and DP80 steel. Studying cup deep drawing is crucial due to frequent occurrences of process failures. Figure 1 illustrates a process failure in the cup deep drawing process as documented by [15].

Figure 1. Failures of Deep Drawing reported by [15]

This study innovatively examines the deep drawing process of manufacturing a 2-inch diameter pipe cap made from an SPCC-SD steel plate. The study thoroughly examines the complex relationship between process parameters and material properties in producing a dop-pipe 2-inch diameter pipe cap. The methodology involves combining experimentation and simulation using ABAQUS software to collect empirical data on the behavior of materials, deformation, and process parameters in the deep drawing process. The gathered data confirms the accuracy of the ABAQUS simulation model in representing the deep-drawing phenomenon. This validation process guarantees the precision of the simulation results, thereby establishing simulation as a dependable tool for optimizing manufacturing processes. The study investigates the crucial determinants that impact the quality and efficiency of the deep drawing process. It is achieved by employing experimental and simulation techniques, which contribute to improving precision and effectiveness in metal forming methods. Furthermore, it aims to enhance the comprehension of deep drawing in producing a 2-inch diameter pipe cap while investigating the possibility of integrating experimentation and simulation to optimize future processes.

2. METHOD

2.1. Material

The experiments conducted in this research form the cornerstone for understanding the properties of SPCC-SD material with a thickness of 0.8 mm. Various tests were performed, including tensile strength tests to assess the material's pressure resistance and ductility tests to evaluate its deformation tolerance without fracturing. Additionally, hardness testing provided valuable insights into the material's ability to withstand penetration and deformation. This data is crucial for determining optimal process parameters during the subsequent deep drawing process.

Die and punch examination is crucial for evaluating the tool's suitability with the designated material. The die and punch's dimensional accuracy, strength, and abrasion resistance significantly impact the results of the deep drawing process. As a result, the experimental deep drawing process utilized the SPCC-SD material, which had a thickness of 0.8 mm, to produce a dop-pipe 2-inch diameter pipe cap. Detailed records of the applied pressure, deformations, and process parameter settings were meticulously maintained for future analysis.

Low-carbon steel is the most prevalent and cost-effective type, with a carbon content of up to 0.3%. Its exceptional malleability makes it highly suitable for various structural applications [16] . In contrast, medium carbon steel, positioned between low and high carbon steel, features carbon content ranging from 0.31% to 0.6% and magnesium content ranging from 0.31% to 1.60% [17]. High carbon steel, with a carbon content exceeding 0.6%, offers superior strength and hardness but exhibits relatively lower malleability than other steel varieties. It contains a magnesium content ranging from 0.31% to 0.9% [18]. The carbon and magnesium composition variations impact each steel variant's mechanical characteristics, influencing their applicability across diverse industrial sectors. The specifications for various subclasses of carbon steel are based on their carbon content [16, 19]. Low-carbon steel is characterized by a carbon content of less than 0.30% [20]. Medium carbon steel falls from 0.30% to 0.60% carbon. High-carbon steel contains more than 0.60% up to 1.00% carbon [21]. Finally, ultra-high carbon steel is defined by a carbon content ranging from 1.0% to 2.1%. These specifications assist in classifying carbon steel into different subclasses, each with distinct carbon percentage ranges.

2.2. Blank Diameter and Drawing Ratio

The determination of the blank diameter is adjusted according to the specific shape of the desired end product to be created [10]. This study emphasizes the significance of accurately determining the diameter of the blank, acknowledging it as a crucial element in attaining the intended dimensions and qualities of the end product. Precision in determining the diameter of the blank not only impacts the shape and final dimensions of the product but also substantially impacts process efficiency and the most effective use of materials. Hence, the precise measurement of the diameter of the blank is a critical step in guaranteeing the effectiveness of the material-forming process. Figure 2 show the geometric of dop-pipe 2-inch diameter pipe cap will be use in this study. Equation 1 is employed to calculate the diameter of the blank accurately by the specific shape requirements of the product [22].

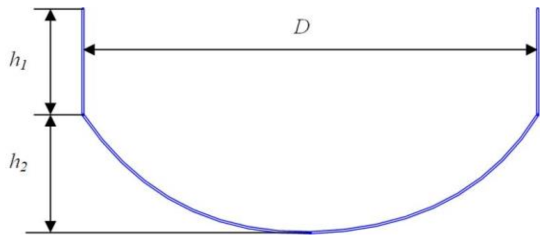

Figure 2. The geometric illustration of dop-pipe 2-inch diameter pipe cap

$$D = \sqrt{d^2 + 4\,.\,(h_{1^2} + d\,.\,h_2} \quad (1)$$

Where d represents the diameter within the workpiece (in millimeters), h_1 denotes the depth of the workpiece radius (in millimeters), and h_2 signifies the depth of the workpiece before the drawing radius (in millimeters). These parameters play a crucial role in the calculations and analysis related to the material-forming processes, contributing to the overall understanding of the shaping and dimensioning aspects involved in the study.

The drawing ratio (β) is a critical numerical parameter in the cylinder drawing process, as it determines the number of drawing steps needed. The drawing ratio is the quotient of the initial blank diameter divided by the diameter of the drawn part [4, 9, 23]. The drawing ratio determines the maximum allowable deformation limit in deep drawing. Equation 2 is derived from the drawing ratio β, used in the initial drawing process involving a single drawing operation [24].

$$\beta = \frac{blank{-}\emptyset\, D}{punch{-}\ \emptyset\, d} \tag{2}$$

2.3. Dies and Punch

The deep drawing dies and punch is essential in transforming sheet metal into the desired shape. The die functions as a mold, converting sheet metal into precise shapes, such as cups, with the assistance of the punch that applies pressure to the metal sheet [25]. The purpose of the blank holders used in the forming process is not only to shape the sheet but also to minimize wrinkles and ensure stability by securing the sheet's outer edge [10]. Comprehending the concepts of elastic and plastic deformation is essential when considering deep drawing. Elastic deformation is when a metal changes shape when subjected to a load but returns to its original form once removed, indicating its ability to reverse the deformation [26].

In contrast, the punch exerts a downward force originating from the power source, exerting pressure on the metal blank [20] . The object's shape corresponds to the desired final product shape, and its position on top of the metal blank can be modified depending on the drawing die employed [25]. The accuracy and configuration of the deep drawing die and punch substantially impact the ultimate result of the process[21]. Plastic deformation becomes apparent during the deep drawing process as the metal undergoes shaping within a mold, resulting in a permanent change in its shape and size, which persists even after the load is removed. The irreversibility of this change is crucial for attaining the intended shape of the product in metal-forming processes such as deep drawing. The components of dies and punches consist of the die, which shapes the work material; the punch, which applies pressure; the guide post, which supports the movement of the punch; the die spring, which provides back pressure; the guide spring, which ensures stability, the upper plate, which supports the movement of the punch and dies, and the lower plate, which aids movement during forming processes [27].

2.4. 3D-design Preparations

Student versions of SolidWorks software are employed to create an accurate 3D model that accurately represents the geometry of the pipe hub. This model is specifically designed for production using the deep drawing method. Ensuring precise geometric design at this stage is crucial, as it forms the basis for subsequent complex simulations. Precise focus is given to the geometric details, including the thickness of the material, the shape, and the resulting dimensions, to ensure an accurate representation. Figure 3 depicts the dies and punches employed for modeling in SolidWorks.

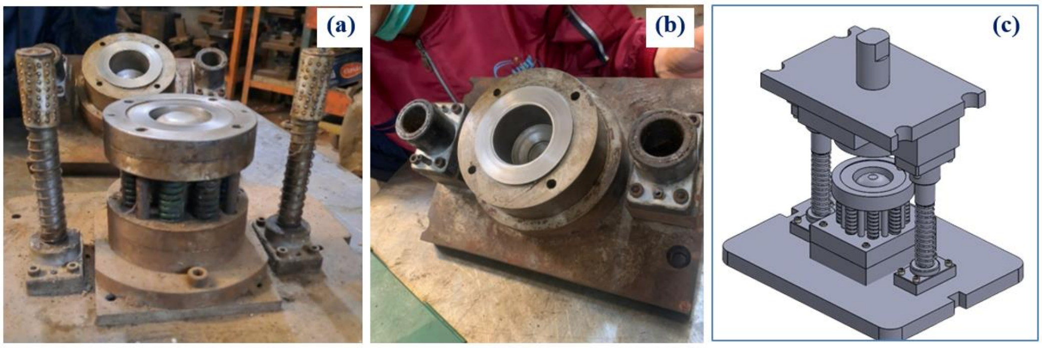

Figure 3. The Dies and Punch of Cup drawing: (a) Dies, (b) Punch, and (d) SolidWork Design.

2.5. Deep Drawing Simulations

The utilization of ABAQUS simulation is an essential and crucial stage in this research undertaking. SolidWorks's pipe hub geometry model was successfully imported into ABAQUS [28]. The simulation in ABAQUS incorporated process parameters such as pressure, rolling speed, temperature, and the material properties of SPCC-SD with a thickness of 0.8 mm. This simulation aims to reproduce the deep drawing process using the established model accurately. The data obtained from these simulations will enable a comprehensive analysis of material behavior, cooling kinetics, and inherent process characteristics associated with the deep drawing procedure [16]. This experimentation, modeling, and simulation combination aims to thoroughly understand how process parameters, material properties, and geometry interact when creating a dop-pipe 2-inch diameter pipe cap using 0.8 mm thick SPCC-SD material [26]. The results obtained from this three-part approach will establish a firm basis, facilitating the future advancement of metal-forming techniques that are more efficient and accurate.

The simulation data pertains to the 2-inch diameter Dop-pipe cap and encompasses several crucial parameters. The initial material, denoted as the blank, possesses a diameter of 85.21 mm and a thickness of 0.8 mm. The punch, responsible for shaping the material, has a diameter of 50.48 mm. Conversely, the die, instrumental in producing the final product, features a diameter of 52.52 mm. The clearance, defined as the distance between the die and the punch, measures 1.02 mm. Additionally, distinct interfaces within the procedure have been assigned friction factors: 0.125 for the die sheet, 0.125 for the holder sheet, and 0.25 for the punch sheet. These values represent critical input parameters that exert a significant impact on the outcome of the deep drawing procedure for the 2-inch diameter dop-pipe cap.

3. RESULTS AND DISCUSSION

3.1. Numerical Analysis

The results obtained from the ABAQUS simulation are crucial reference points for the deep drawing process [8]. The simulation data is a benchmark for comparing the experimental results obtained from workpiece measurements. Figure 3 displays a graph that depicts the relationship between displacement and thickness for specific elements (E 110, E 41, E 42, E 43, E 44, E 45, E 46, E 47, and E 48). The graph illustrates how the thickness varies as the punch displacement ranges from 0 mm to -35 mm. The punch movement begins at the starting point, indicated by zero displacement, and signifies the commencement of the deep drawing process in the simulation. In contrast, negative displacement indicates a descent along the y-axis.

Figure 4 demonstrates that multiple elements underwent a thickness variation ranging from 2.5% to 17.5% as the punch displacement advanced. The simulation results are compared to the experimental outcomes, as shown in Figure 3. The comparison reveals the congruity in thickness between the experimental and numerical findings at specific locations on the pipe hub wall. Nevertheless, inconsistencies occur due to reduced die radius and excessive space between the punch and die. Furthermore, the displacement ratio is vital for comparing experimental and numerical findings.

Figure 4 depicts a significant disparity in thickness observed from elements E46 to E47. Element E46 surpasses the material's 8.0 mm thickness threshold when it reaches a displacement of approximately 23 mm. Subsequently, the thickness experiences a rapid decline, reaching approximately 0.72 mm. In elements E47 and E48, there is a noticeable phenomenon of material density consistently increasing during the punch displacement process. This results in final thicknesses ranging between 0.88 mm and 0.95 mm. Figure 4 illustrates explicitly the pattern observed in elements E47 and E48. This phenomenon is consistent with prior reported by [9] , which suggests that the thickness in this area increases due to the axial force applied to the material. However, the simulation results demonstrate greater accuracy and precision as the observed fluctuations in thickness are confined to a narrower range of variation. The precision of the thickness ratio in this study exceeds that reported by [13]. Figure 5 shows that the estimated thickness ratio ranges from approximately 8.75% to 1.25%, based on the observed maximum thickness of 0.87 and minimum thickness of 0.79. However, the thickness ratio reported in [13] reached a value of 20%.

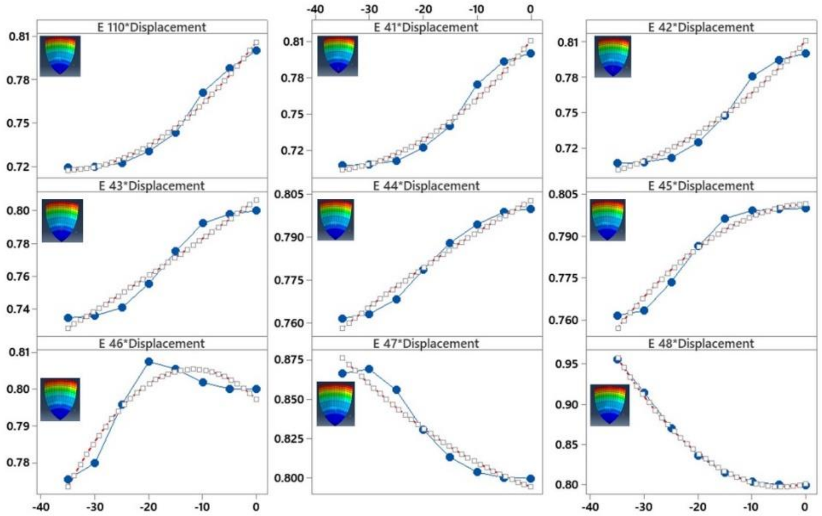

Figure 4. Displacement vs thickness at all elements

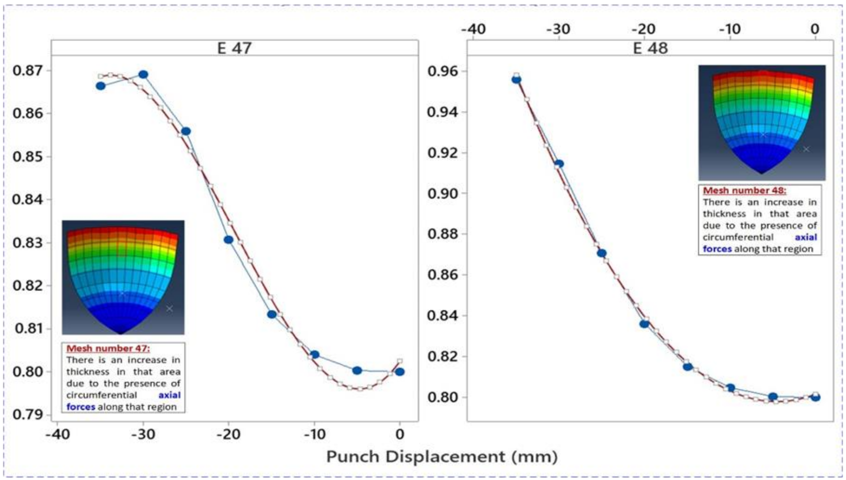

Figure 5. The phenomenon of thickness vs displacement at E 47 and E 48 element

3.2. Expetimental Validations

The primary goal of the analysis and comparison was to evaluate the consistency of the outcomes of the deep drawing process obtained from numerical simulation results and experimental data. This study primarily aims to assess the variation in metal thickness in the formed pipe hub. This assessment is crucial for evaluating the accuracy and relevance of numerical predictions compared to actual experimental results in metal forming using deep drawing techniques [24]. The experimental results were acquired utilizing a micrometer possessing a precision of 0.01 mm. This study seeks to thoroughly understand the differences and similarities between numerical and experimental results. Its main objective is to offer comprehensive insights into the effectiveness of numerical simulation techniques in predicting metal forming processes, specifically in manufacturing 2-inch diameter pipe caps using low-carbon steel. Figure 5 illustrates the relationship between the measured thickness results and the computational results for all elements, as explained in Figure 6.

The evaluation obtained by comparing empirical data and computational simulations reveals crucial insights into the deep drawing process. The changes in the thickness of the workpiece provide insight into the effect of the displacement of the punch movement. As illustrated in Figure 5, the observed variations in thickness range from 2.5% to 17.5% compared to the initial thickness, with an average overall change of approximately 4%. In this study, the maximum thickness exhibited an increase of approximately 8.8% and a decrease of 1.3%. In contrast, a study by [9] found a 20-40% increase and a 10% decrease, while another study by [29] documented a 21.3% reduction in thickness. The results suggest that numerical simulations closely match experimental results despite some observed differences. These variations may arise due to a reduced die radius and excessive clearance between the punch and die. Moreover, comparing displacement in experimental and numerical data plays a crucial role in evaluating the precision of the deep drawing process. In order to improve the agreement between experimental and numerical results, it is crucial to conduct a thorough evaluation of critical parameters. This improvement can enhance the precision of numerical simulations, making them more applicable in industrial settings and large-scale manufacturing.

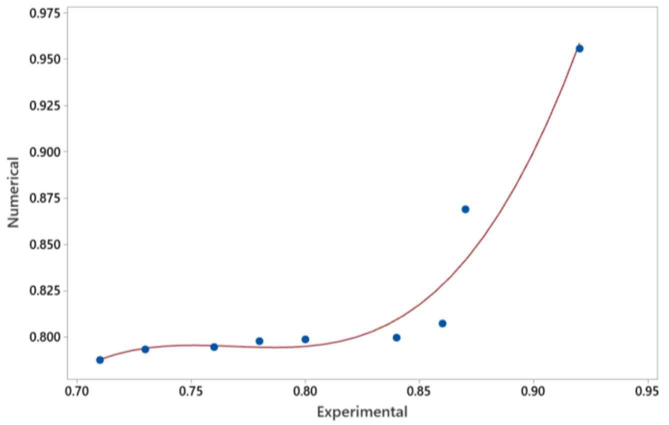

Figure 6. Experimental Vs Numerical thickness

Figure 7 illustrates the comparison of material thickness using experimental and numerical approaches. The comparison of experimental and numerical data is presented to assess the accuracy of numerical predictions against experimental results. The accuracy of numerical data indicates satisfactory outcomes, with the lowest and highest deviations being approximately 0.1% and 10.9%, respectively, and an average around 4.6%. This data confirms that the numerical approach can predict well during the production process of a dop-pipe 2-inch diameter.

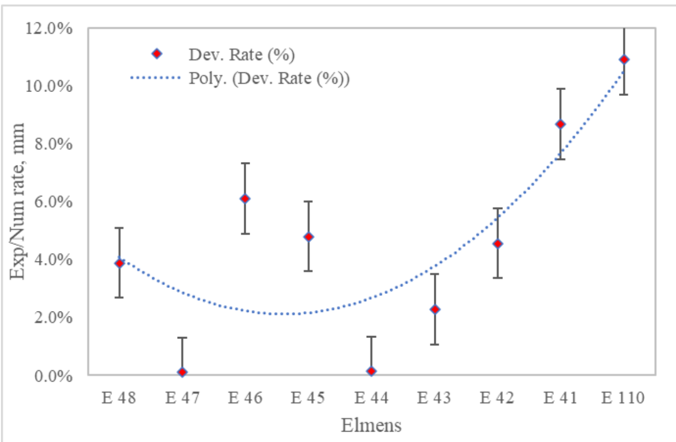

Figure 7. Experimental vs Numerical deviations rates

3.3. Statistical Pearson Correlations

The Pearson correlation analysis is utilized to evaluate the extent of the linear association between numerical and experimental results in these deep drawing investigations. A robust correlation, with a value approaching 1, indicates a substantial concurrence between numerical predictions and experimental data [30]. This analysis aids in identifying patterns within the data, where positive correlation values nearing 1 indicate a positive association between numerical and experimental outcomes. In contrast, values close to -1 indicate a negative association [31]. Figure 8 displays the Pearson correlation data, which examines each element's association between displacement and thickness. The elements E 110, E 41, E 42, E 43, E 44, E 45, and E 46 display positive correlations of 0.953, 0.956, 0.963, 0.973, 0.982, 0.946, and 0.715, respectively. In contrast, elements E 47 and E 48 exhibit negative correlations of -0.957 and -0.933, respectively.

The presence of a positive correlation among elements E 110, E 41, E 42, E 43, E 44, E 45, and E 46 suggests a direct connection between the metal's thickness and the punch's displacement. Nevertheless, more significant punch displacement reduces wall thickness when the punch moves in the negative direction along the y-axis [30, 32]. Elements E 47 and E 48 positively correlate, indicating an inverse association between thickness and displacement. Interestingly, when the punch moves deeper within elements E 47 and E 48, the walls become thicker because of the punch's negative movement direction. The strong Pearson correlation values confirm the dependability of the numerical model in forecasting experimental results. It affirms the reliability and precision of the numerical model in representing the deep drawing process for 2-inch diameter pipes using low-carbon steel.

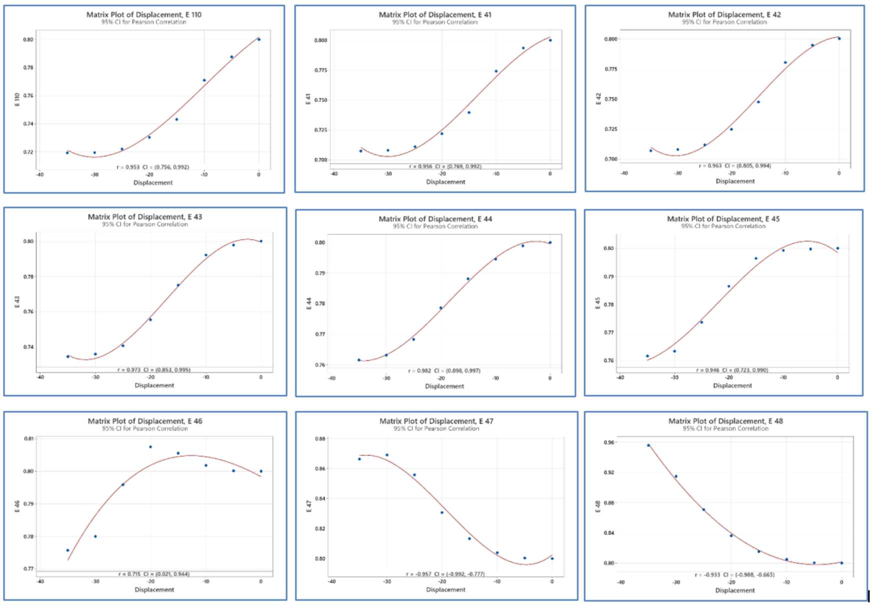

Figure 8. Pearson correlations: Displacement vs Thickness

4. CONCLUSIONS

The numerical simulations accurately reproduce the distribution of wall thickness and pressure, effectively reflecting the experimental measurements. The difference between the observed results for experimental and numerical models is very small, highlighting the effective design, production, and testing of the deep drawing mould, guaranteeing its optimal performance. The research findings demonstrate strong correlations between the two methodologies. Strong positive correlations were found among elements with the following numbers: E 110, E 41, E 42, E 43, E 44, E 45, and E 46. Nevertheless, there were negative correlations observed in E 47 and E 48. The elements E 43 and E 47 displayed the most significant positive and negative correlations, with correlation coefficients of 0.982 and -0.957, respectively. The comparison of experimental and numerical data is presented to assess the accuracy of numerical predictions against experimental results. The numerical data exhibits a high level of accuracy, with deviations ranging from approximately 0.1% to 10.9%. On average, the deviations amount to around 4.6%. There is a significant difference of around 17.5% between the ABAQUS and experimental simulation results. Nevertheless, this distinction remains relatively insignificant when compared to the wide array of discrepancies documented in the references, which ranged from 21.3% to 40%. Moreover, the experimental results demonstrate a higher thickness ratio in comparison to previously documented data from earlier studies.

AUTHOR’S DECLARATION

Authors’ contributions and responsibilities

The authors have played crucial roles in conceiving and designing the study. They actively engaged in data analysis, interpretation, and discussions of the results. All authors have thoroughly reviewed and approved the final manuscript, underscoring their collective and individual contributions to the research endeavor.

Acknowledgment

The author expresses gratitude to Buana Perjuangan University Karawang for providing funding for this research. Additionally, the author extends appreciation to all parties, particularly PT Isalindo Nusantara, for providing the opportunity to collect experimental data..

Availability of data and materials

All data from this study are accessible through the authors.

Competing interests

The authors declare no competing interest.

REFERENCES

[1] B. Vukota, "Sheet Metal Forming Fundamentals," *Industrial Press Inc.*, pp. 450-450, 2004.
[2] O. M. Badr, B. Rolfe, P. Hodgson, and M. Weiss, "Forming of high strength titanium sheet at room temperature," *Materials and Design*, vol. 66, no. PB, pp. 618-626, 2015.
[3] B. Chongthairungruang, V. Uthaisangsuk, S. Suranuntchai, and S. Jirathearanat, "Springback prediction in sheet metal forming of high strength steels," *Materials and Design*, vol. 50, pp. 253-266, 2013.
[4] C. Özek and M. Bal, "The effect of die/blank holder and punch radiuses on limit drawing ratio in angular deep-drawing dies," *The International Journal of Advanced Manufacturing Technology*, vol. 40, no. 11-12, pp. 1077-1083, 2008.
[5] S. Candra, I. M. L. Batan, W. Berata, and A. S. Pramono, "Analytical Study and FEM Simulation of the Maximum Varying Blank Holder Force to Prevent Cracking on Cylindrical Cup Deep Drawing," *Procedia CIRP*, vol. 26, pp. 548-553, 2015.
[6] M. Kardan, A. Parvizi, and A. Askari, "Experimental and Finite Element Results for Optimization of Punch Force and Thickness Distribution in Deep Drawing Process," *Arabian Journal for Science and Engineering*, vol. 43, no. 3, pp. 1165-1175, 2017.
[7] V. Gautam, V. M. Raut, and D. R. Kumar, "Analytical prediction of springback in bending of tailor-welded blanks incorporating effect of anisotropy and weld zone properties," *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications*, vol. 232, no. 4, pp. 294-306, 2018.
[8] A. Badrish, A. Morchhale, N. Kotkunde, and S. K. Singh, "Influence of material modeling on warm forming behavior of nickel based super alloy," *International Journal of Material Forming*, vol. 13, no. 3, pp. 445-465, 2020.
[9] N. Şen, İ. ÇOlakoĞLu, and V. TaŞDemİR, "Investigation of deep drawing of square cups using

high-strength DP600 and DP800 sheets," *International Journal of Automotive Science And Technology*, vol. 5, pp. 378-385, 2021.

[10] M. Hassan, L. Hezam, M. El-Sebaie, and J. Purbolaksono, "Deep Drawing Characteristics of Square Cups through Conical Dies," *Procedia Engineering*, vol. 81, pp. 873-880, 2014.

[11] H. Kalkan, T. Hacaloglu, and B. Kaftanoglu, "Experimental investigation of friction in deep drawing," *The International Journal of Advanced Manufacturing Technology*, vol. 92, no. 9-12, pp. 3311-3318, 2017.

[12] K. Mori, Y. Abe, K. Osakada, and S. Hiramatsu, "Plate forging of tailored blanks having local thickening for deep drawing of square cups," *Journal of Materials Processing Technology*, vol. 211, no. 10, pp. 1569-1574, 2011.

[13] Y. Morishita, T. Kado, S. Abe, Y. Sakamoto, and F. Yoshida, "Role of counterpunch for square-cup drawing of tailored blank composed of thick/thin sheets," *Journal of Materials Processing Technology*, vol. 212, no. 10, pp. 2102-2108, 2012.

[14] D. H. Park and P. K. D. V. Yarlagadda, "Effects of punch load for elliptical deep drawing product of automotive parts," *The International Journal of Advanced Manufacturing Technology*, vol. 35, no. 7-8, pp. 814-820, 2006.

[15] R. Dwivedi and G. Agnihotri, "Study of Deep Drawing Process Parameters," *Materials Today: Proceedings*, vol. 4, no. 2, pp. 820-826, 2017.

[16] I. B. Rahardja, N. Rahdiana, D. Mulyadi, S. Sumanto, A. I. Ramadhan, and S. Sukarman, "ANALISIS PENGARUH RADIUS BENDING PADA PROSES BENDING MENGGUNAKAN PELAT SPCC-SD TERHADAP PERUBAHAN STRUKTUR MIKRO," vol. 01, no. 01, pp. 1-10, 2020.

[17] P. Muthu, "Optimization of the Process Parameters of Resistance Spot Welding of AISI 316l Sheets Using Taguchi Method," *Mechanics and Mechanical Engineering*, vol. 23, no. 1, pp. 64-69, 2019.

[18] A. Wübbeke *et al.*, "Investigation of residual stresses in polypropylene using hot plate welding," *Welding in the World*, vol. 64, no. 10, pp. 1671-1680, 2020.

[19] A. Abdurahman, S. Sukarman, A. Djafar Shieddieque, S. Safril, D. Setiawan, and N. Rahdiana, "EVALUASI KEKUATAN UJI TARIK PADA PROSES PENGELASAN BUSUR LISTRIK BEDA MATERIAL SPHC DAN S30-C," *Jurnal Teknik Mesin Mechanical Xplore*, vol. 1, no. 2, pp. 29-37, 2021.

[20] S. Sukarman *et al.*, "OPTIMAL TENSILE-SHEAR STRENGTH OF GALVANIZED/MILD STEEL (SPCC-SD) DISSIMILAR RESISTANCE SPOT WELDING USING TAGUCHI DOE," *Jurnal Teknologi*, vol. 4, pp. 167-177, 2023.

[21] F. Mucharom *et al.*, "Tensile shear load in resistance spot welding of dissimilar metals: An optimization study using response surface methodology," *Mechanical Engineering for Society and Industry*, vol. 3, no. 2, pp. 66-77, 2023.

[22] T. Altan, *Metal Forming Handbook*. Springer Verlag Berlin, 1998.

[23] R. LeSar and R. LeSar, "Materials selection and design," *Introduction to Computational Materials Science*, pp. 269-278, 2013.

[24] S. K. Ghosh, "Handbook of metal forming," vol. 16, ed, 1988, pp. 353-356.

[25] Sukarman, C. Anwar, N. Rahdiana, and A. I. Ramadhan, "ANALISIS PENGARUH RADIUS DIES TERHADAP SPRINGBACK LOGAM LEMBARAN STAINLESS-STEEL PADA PROSES BENDING HIDROLIK V-DIE," *Junal Teknologi*, vol. 12, no. 2, 2020.

[26] K. Khoirudin, S. Sukarman, N. Rahdiana, and A. Fauzi, "ANALISIS FENOMENA SPRING-BACK / SPRING-GO FACTOR PADA LEMBARAN BAJA KARBON RENDAH MENGGUNAKAN PENDEKATAN EKSPERIMENTAL," *Jurnal Teknologi*, vol. 14, no. 1, 2022.

[27] K. Khoirudin, S. Sukarman, S. Siswanto, N. Rahdiana, and A. Suhara, "Analysis of Spring-back and Spring-go on Variation of V-Dies Bending Angle Using Galvanized SGCC Steel Sheet," *Jurnal Teknik Mesin Mechanical Xplore (JTMMX)*, vol. 3, no. 1, pp. 17-25, 2022.

[28] S. Sukarman, K. Khoirudin, M. Murtalim, D. Mulyadi, and N. Rahdiana, "Evaluasi Desain Bejana Bertekanan pada Radiator Cooling System Menggunakan Material SPCC-SD," *Rekayasa: Journal of Science adn Technology*, vol. 14, no. 1, pp. 10-16, 2021.

[29] B.-S. Kang, W.-J. Song, and T.-W. Ku, "Study on process parameters and its analytic application for nonaxisymmetric rectangular cup of multistage deep drawing process using low carbon thin steel sheet," *The International Journal of Advanced Manufacturing Technology*, vol. 49, no. 9-12, pp. 925-940, 2009.
[30] D. Nettleton, "Selection of Variables and Factor Derivation," in *Commercial Data Mining*, 2014, pp. 79-104.
[31] S. Kalpakjian and S. R. Schmid, *Manufacturing Engineering and Technology*, Six ed. New York: Pearson Prentice Hall, 2010, pp. 399-400.
[32] V. Kotu and B. Deshpande, "Classification," in *Data Science*, 2019, pp. 65-163.