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Advanced Analysis of Deep Drawing Processes for 1-Inch Diameter Dop-Pipe Caps: Simulation and Experimental Insights

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ABSTRACT

This article investigates the challenges and solutions within the deep drawing process, focusing on issues like cracks and deviations from standard thickness dimensions. Utilizing both experimental methods with a 40-ton power press machine and numerical simulations via ABAQUS software, the study uses SPCC-SD steel to produce a Dop-pipe 1-inch diameter pipe cap. Key findings reveal significant correlations in elements E-90 and E-91, with minimal disparities of around 4.5% between experimental and numerical approaches, showcasing the accuracy of numerical predictions. Notably, the numerical simulations identify potential issues such as increased thickness due to higher axial forces, providing valuable insights for process optimization and defect reduction. By advancing the deep drawing process and extending its applicability to broader material-forming applications, this research contributes significantly to enhancing production efficiency and improving manufacturing practices, emphasizing the importance of simulation-driven approaches in achieving precision and quality enhancement in complex manufacturing processes.

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

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1. INTRODUCTIONS

Advanced industry requires efficiency and effectiveness in production, including deep drawing. Along with the rapid development of the manufacturing industry, sheet metal transportation technology continues to progress. Deep drawing, as a simple but effective process, is the main focus in achieving optimal product quality. This process is widely used in various industries, such as automotive, electronics, and household appliance manufacturing. Deep drawing can transform products and assemblies and enable mass production in a relatively short time, thereby significantly increasing productivity. However, deep drawing also has common problems related to cracks (tear) and wrinkles during the process. Figure 1 illustrates a process failure in the cup deep drawing process as documented by [1].

Deep drawing, an important process in the manufacturing industry, has become a major focus in forming 3-D components from thin metal sheets for automotive components with good strength and quality [1]. Deep drawing is very important in creating various geometric shapes and sizes, ranging from simple to complex, and is used in products such as car bodies, aircraft panels, kitchen utensils, and beverage cans [2]. The deep drawing process produces changes in the dimensions and mechanical properties of the material, with dimensional changes directly proportional to the hardness of the material [3]. Parameters in the deep drawing process include die radius, blank holder force, and performance coefficient, where the die radius greatly influences the process [4]. Research has considered blank holder pressure, punch radius, die radius, and lubrication, which influence the product's stress distribution and the possibility of wrinkling [5, 6].

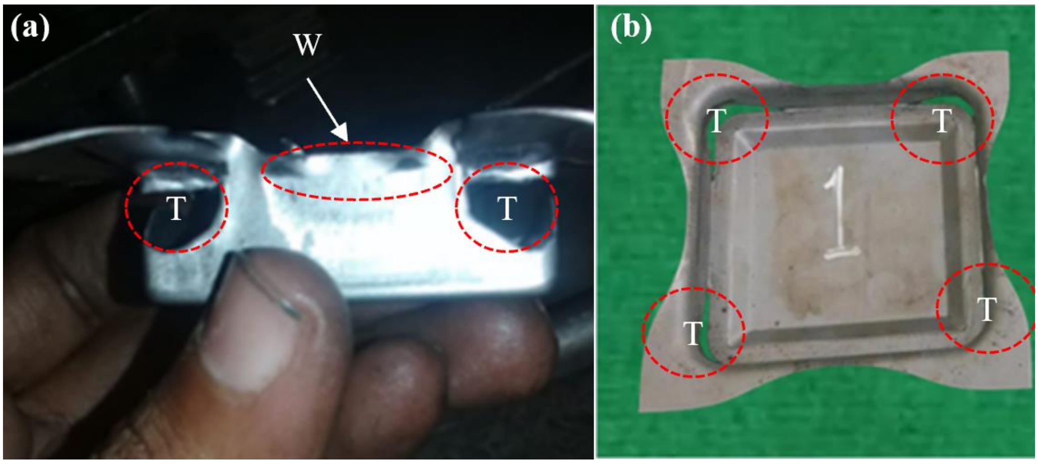

Figure 1. Failures of Deep Drawing reported by: (a) T= tear and W= wrinkles (b) T= Tear

Various investigations have explored the intricacies of deep drawing processes, covering both round and square cup drawing methodologies. A study involving square cup drawing included systematic modifications to the angle [7]. H Kalkan et al. [8] analyzed cup drawing parameters affecting friction factors. Kardan et al. [9] worked on optimizing punch force in cup deep drawing using experimental and finite element approaches. K. Mori et al. [10] investigate deep drawing focused on square cup deep drawing techniques and advancing tailor-welded blank processes. Morishita et al. [11] examined square cup drawing in trailer blank processes, studying varying thicknesses of sheet steel. Park et al. [12] investigated the effects of punch-loading on elliptical deep drawing, particularly in automotive component production. Sen et al. [13] explored square deep drawing using high-strength materials like DP600 and DP80 steel. Karyadi et al. [14] developed the blank dimension using square dies to optimize the square cup component.

This innovative study explores the deep drawing process for manufacturing a 1-inch diameter pipe cap using an SPCC-SD steel plate. The research thoroughly investigates the interplay between process parameters and material properties in producing a dop-pipe 1-inch diameter pipe cap. The methodology integrates experimentation and simulation through ABAQUS software to gather empirical data on material behaviour, deformation, and process parameters during deep drawing. The collected data validates the accuracy of the ABAQUS simulation model in representing deep-drawing phenomena, ensuring precise simulation results and establishing simulation as a reliable tool for process optimization. The study delves into critical factors impacting the quality and efficiency of deep drawing, utilizing experimental and simulation techniques to enhance precision and effectiveness in metal forming methods. Additionally, it seeks to improve understanding of deep drawing in manufacturing a 1-inch diameter pipe cap while exploring the potential for integrating experimentation and simulation to optimize future processes.

2. METHOD

2.1. Material

The experiments in this study use SPCC-SD material, particularly when it's 0.8 mm thick and meets the JIS 3141 standard [14]. A range of tests was conducted, from tensile strength assessments for pressure resilience to ductility tests for deformation tolerance without fracturing. The material's hardness and tensile strength provided important properties for its ability to withstand penetration and deformation, which is crucial for determining optimal parameters during subsequent deep drawing processes.

Evaluating the die and punch in the deep drawing is critical for assessing their compatibility with the designated material. Dimensional accuracy, strength, and abrasion resistance significantly influence deep drawing process outcomes. Consequently, the experimental deep drawing process utilized 0.8 mm thick SPCC-SD material to create a 1-inch diameter pipe cap, with detailed records on applied pressure, deformations, and process parameter settings for future analysis.

The low-carbon steel has a carbon content of up to 0.3% and stands out as the most prevalent and cost-effective option, offering exceptional malleability suitable for various structural applications [15]. Medium carbon steel, ranging from 0.31% to 0.6% carbon and 0.31% to 1.60% magnesium, occupies a middle ground [16]. In contrast, high-carbon steel, exceeding 0.6% carbon and 0.31% to 0.9% magnesium, offers superior strength and hardness but lower malleability [17]. These composition variations impact mechanical characteristics, guiding their applicability across different industrial sectors. Carbon steel subclasses are classified based on carbon content, with low-carbon steel under 0.30%, medium carbon steel from 0.30% to 0.60%, high-carbon steel from over 0.60% to 1.00%, and ultra-high carbon steel from 1.0% to 2.1%. Such specifications aid in categorizing carbon steel into distinct subclasses with varying carbon percentage ranges [15, 18-20].

2.2. Blank diameter and drawing ratio

Determining the blank diameter is tailored to match the specific shape of the desired end product [7]. This study underlines the importance of accurately establishing the blank's diameter, recognizing it as a pivotal factor in achieving the intended dimensions and characteristics of the final product. The precision in determining the blank's diameter not only affects the shape and ultimate dimensions of the product but also significantly influences process efficiency and the optimal utilization of materials. Therefore, the precise measurement of the blank's diameter is a critical step in ensuring the effectiveness of the deep drawing process. Figure 2 illustrates the geometry of this study's 1-inch diameter pipe cap. Equation 1 is utilized to precisely calculate the blank's diameter based on the specific shape requirements of the product [21].

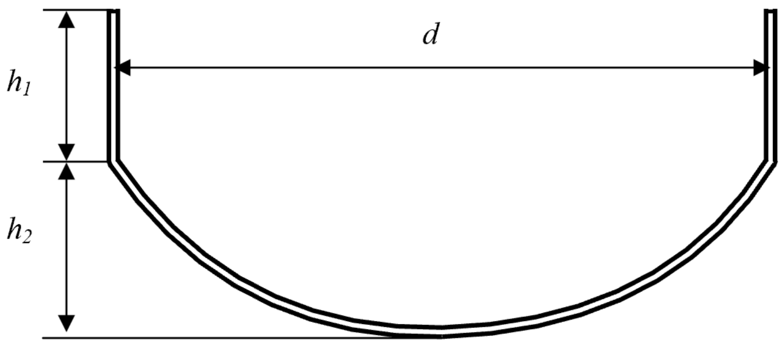

Figure 2. The geometric of dop-pipe 1-inch diameter

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

Where d donated for punch diameter (mm), h_1 and h_2 denote part depth for deep drawing processing. The drawing ratio (β) a critical parameter in the deep drawing process because it dictates the number of deep drawing steps required. The drawing ratio is calculated by dividing the initial blank diameter by the diameter of the drawn part [6, 13, 22]. This ratio determines the maximum allowable deformation limit during deep drawing. Equation 2 is is used to determine the drawing ratio [23].

$$\beta = \frac{D_{blank}}{D_{punch}} = \frac{D}{d} \qquad (2)$$

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 [24]. 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 [7]. 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 [25].

In contrast, the punch exerts a downward force originating from the power source, exerting pressure on the metal blank [19] . 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 [24]. The accuracy and configuration of the deep drawing die and punch substantially impact the ultimate result of the process [20]. 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 [26].

2.4. 3D design preparations

The geometry of the pipe hub is accurately represented in a 3D model made using student versions of SolidWorks software. The deep drawing method was specifically used to design this model for production. This stage is important to ensure accurate geometric design because it is paid to the geometric details, such as the material's thickness, shape, and resulting dimensions, to guarantee an accurate depiction. The dies and punches used in SolidWorks modeling are shown in Figure 3.

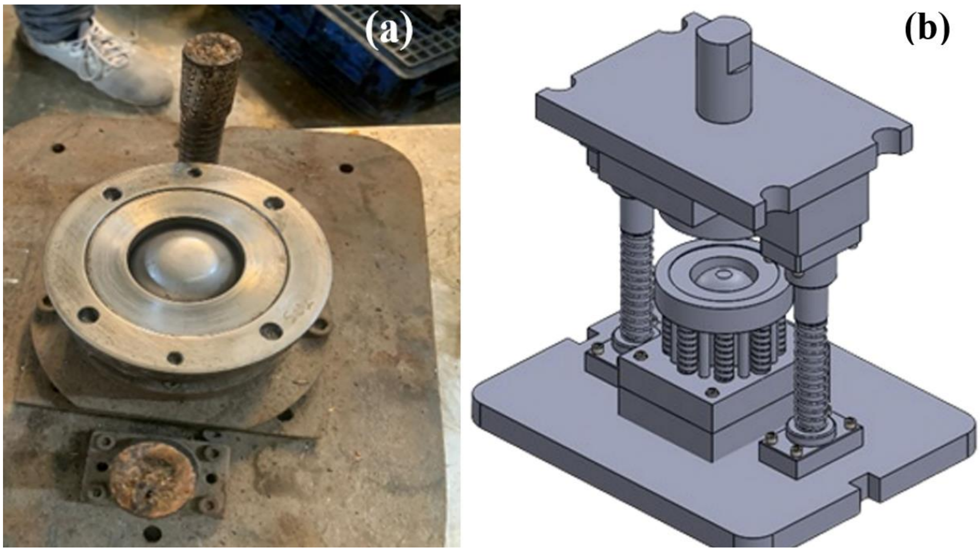

Figure 3. The 1-inch-deep drawing: (a) dies and punch (b) SolidWork Design.

2.5. Deep drawing simulations

The deep drawing simulations in ABAQUS are conducted systematically, commencing with creating geometry followed by meshing for discretization and determining material properties such as elasticity and yield strength [27]. Subsequently, contact interactions and boundary conditions are precisely defined, and loads and constraints are applied to replicate the deep drawing process accurately. Solver settings are

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meticulously configured, and the simulation is executed with a thorough analysis of the results. ABAQUS, being a potent finite element analysis platform, enables engineers to predict material behavior during deep drawing operations with a high degree of accuracy. The validation process, which involves comparison against experimental data or analytical solutions, is crucial in ensuring the accuracy of the simulation results, providing valuable insights into the deformation, stress, strain, and overall mechanical performance of the simulated material. Incorporating ABAQUS simulation is a pivotal and indispensable stage in this research project. The successful importation of SolidWorks' pipe hub geometry model into ABAQUS has been achieved. The simulation in ABAQUS encompasses process parameters such as pressure, rolling speed, temperature, and material properties specific to SPCC-SD with a thickness of 0.8 mm. This simulation aims to faithfully reproduce the deep drawing process using the established model, with the overarching goal of comprehensively understanding how process parameters, material properties, and geometry synergize while fabricating a 1-inch diameter pipe cap from 0.8 mm thick SPCC-SD material [25]. The results derived from this three-part approach are anticipated to lay a robust foundation for advancing more efficient and precise metal-forming techniques. **Figure 4** provided the numerical simulation.

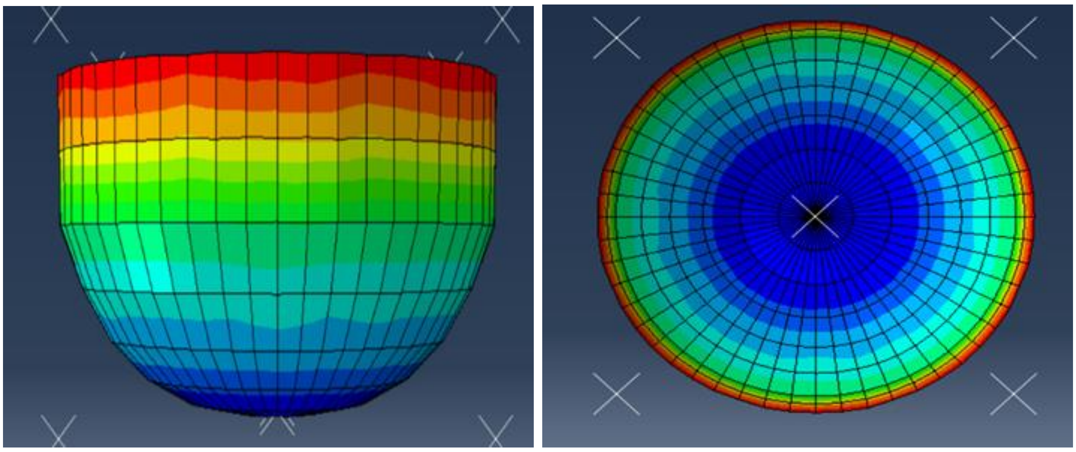

Figure 4. The numerical simulation and messing elements.

The simulation evidence encompasses critical parameters related to the 1-inch diameter Dop-pipe cap, including the dimensions of the initial blank material and the tooling components listed in Table 1.

Table 1. Parameter of ABAQUS simulations

Parameters simulations	**Symbol**	**Unit**	**Value**
Blank diameter	D	mm	78.10
Blank thickness	s	mm	0.80
Punch diameter	d	mm	49.89
Die diameter	D_o	mm	51.93
Die-punch clearance	C	mm	1.02
Die friction coefficient	f_d	-	0.05
Holder friction coefficient	f_h	-	0.08
Punch friction coefficient	f_p	-	0.125

3. RESULTS AND DISCUSSION

3.1. Numerical analysis

The results derived from the ABAQUS simulation serve as crucial reference points for understanding the deep drawing process [28]. This simulation data is compared against the experimental results obtained from actual workpiece measurements. Figure 5 presents a graph illustrating the relationship between displacement and thickness for specific elements, including E-85, E-86, E-87, E-88, E-89, E-90, E-91, and E-04. The graph visually depicts how the thickness of the material varies as the punch displacement ranges from 0 mm to -30 mm. The punch y-axis movement starts at the zero point, and it denotes the beginning of the simulation's deep drawing process. On the other hand, negative displacement values represent a y-axis descent, which reflects the punch movement during the deep drawing operation. This graphical representation makes comparing simulation and experimental results easier and offers insightful information about the material's deformation behavior during the deep drawing.

Figure 5 shows that as the punch displacement increased, several elements experienced thickness variations ranging from 2.0% to 17.5%. Comparing the experimental and numerical results at different pipe hub wall locations revealed the thickness congruency. On the other hand, irregularities arise from a smaller die radius and too much distance between the fixed die and the moved punch. Additionally, comparing experimental and numerical results depends on the displacement ratio.

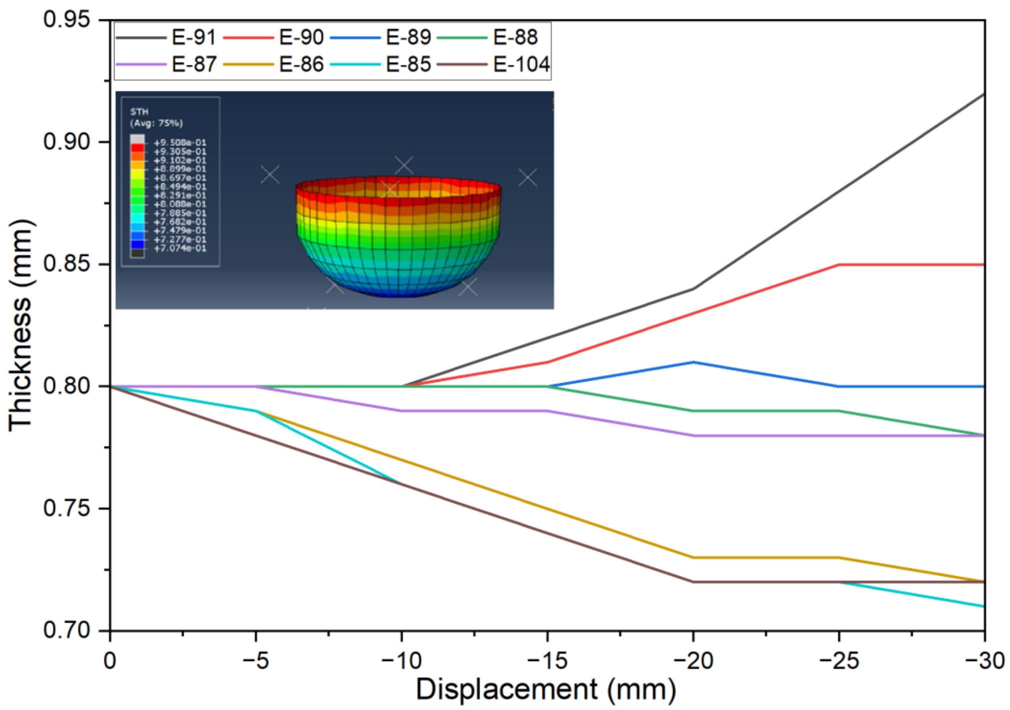

Figure 5. Displacement vs thickness at all elements

Figure 6 depicts a significant disparity in thickness observed from elements E-91 to E-85. Element E-91 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 E-91 and E-90, there is a noticeable phenomenon of material thickness consistently increasing during the punch displacement process. This results in final thicknesses ranging between 0.85 mm and 0.92 mm. This phenomenon is consistent with prior reports by [13], which suggest that the thickness in this area increases due to the axial force applied to the material. However, the simulation results demonstrate superior 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 [11]. Figure 6 shows that the estimated thickness ratio ranges from approximately 11.25% to 15.0%, based on the observed maximum thickness of 0.92 and minimum thickness of 0.71. However, the thickness ratio reported in [11] reached a value of 20%.

3.2. Experimental 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 [23]. 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 mild steel. Figure 5 illustrates the relationship between the measured thickness results and the computational results for all elements, as explained in Figure 7.

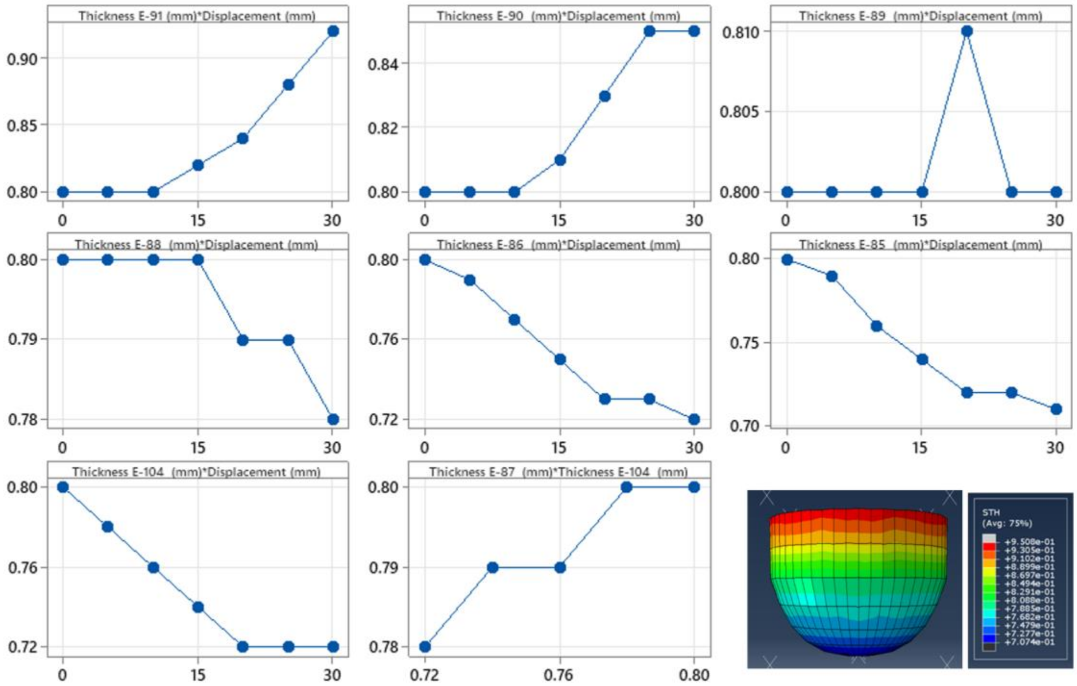

Figure 6. The phenomenon of thickness vs displacement at all element

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 7, 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 [13] 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.

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Figure 8 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.

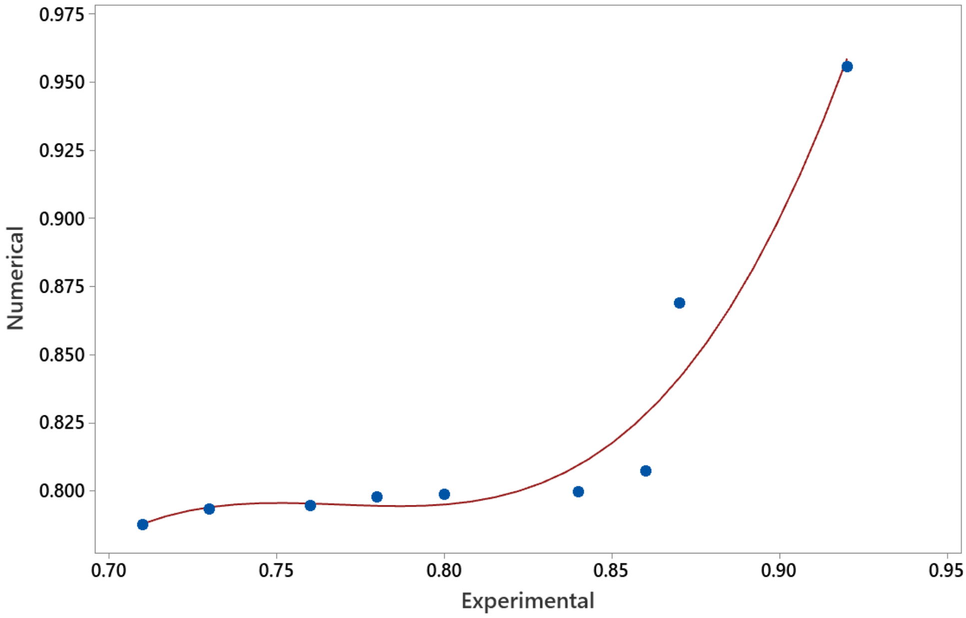

Figure 7. Experimental Vs numerical thickness.

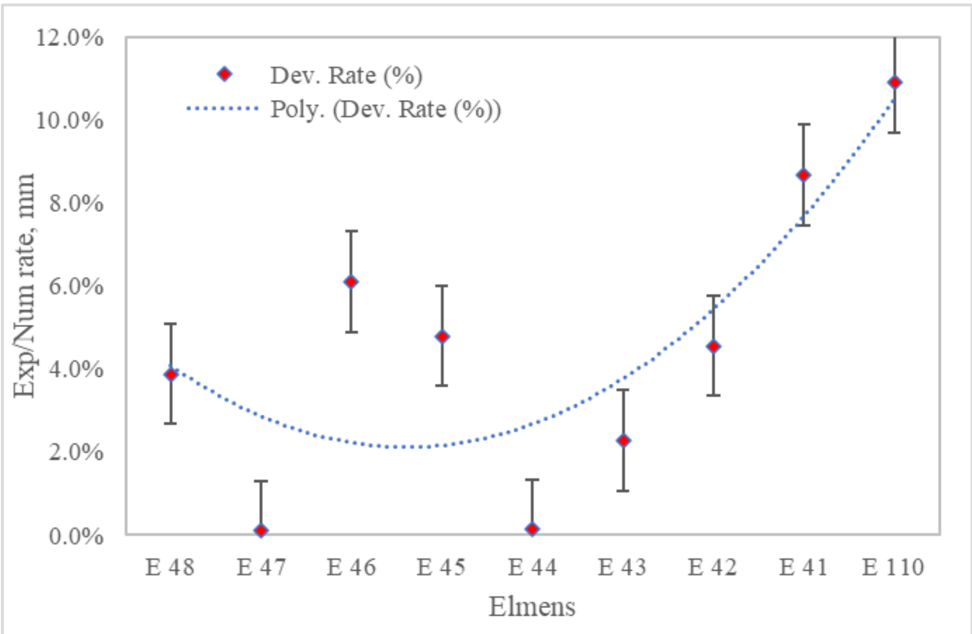

Figure 8. Experimental vs numerical deviations rates.

3.3. *Statistical validation*

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 9 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.

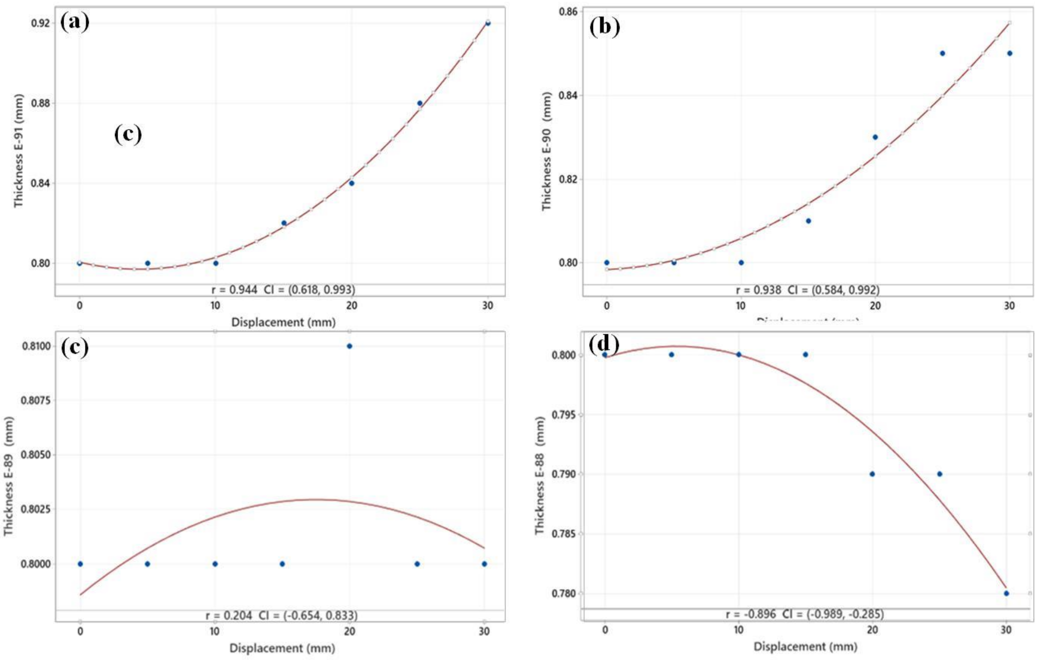

Figure 9. Spearman correlations: displacement (mm) vs thickness (mm): (a) element E-91, (b) element E-90, (c) element E-89, and (d) element E-88.

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 mild steel material.

4. CONCLUSIONS

The numerical simulations yield outcomes that closely replicate the distribution of wall thickness and pressure, effectively mirroring 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-85, E-86, E-87, E-88, E-89, E-90, E-91, and E-104. Nevertheless, there were negative correlations observed in E 99 and E-91. The elements E-90 and E-90 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.

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Availability of data and materials

All data from this study are accessible through the authors.

Competing interests

The authors declare no competing interest.

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