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Influence of Punch Radius on Forming Depth in Deep Drawing of SPCC Sheet Materials: A Simulation-Based Study Using ABAQUS

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Abstract: In the deep drawing process of SPCC sheet materials, multiple technological factors such as workpiece temperature, blank holder force, and forming level significantly influence both the processing performance and the final product quality. Among these factors, the radius of curvature of the punch plays a critical role in determining the forming depth of the formed components. This study aims to investigate and evaluate the impact of varying punch radii on the forming depth during the deep drawing of cup-shaped parts from SPCC material. Utilizing advanced simulation methods, this research employs ABAQUS, a commercial finite element analysis (FEA) software, to model and analyze the stamping process. ABAQUS's robust capabilities allow for precise simulation of the complex interactions and deformation behaviors inherent in metal forming operations. The simulations are designed to systematically vary the punch radius and observe its effects on the forming depth, capturing detailed stress-strain distributions and identifying potential defect regions. By comparing simulation results with experimental data, the study aims to validate the accuracy of the simulations and ensure their reliability in predicting real-world outcomes. Key findings reveal that smaller punch radii tend to increase localized stresses, leading to deeper forming depths but also a higher risk of material failure. Conversely, larger punch radii distribute stresses more evenly, resulting in shallower forming depths and improved structural integrity of the formed parts. These insights are critical for optimizing punch design and process parameters in industrial applications. This research contributes to the field of sheet metal forming by providing a comprehensive understanding of the relationship between punch geometry and forming performance. The findings offer practical guidelines for manufacturing engineers to enhance product quality and reduce defects in stamped components. Furthermore, the methodology established in this study can be extended to investigate other material types and forming processes, paving the way for broader applications and innovations in metal forming technology.

Keywords: Deep Drawing, SPCC Sheet Materials ,Punch Radius, Finite Element Analysis (FEA), ABAQUS Simulation

1. Introduction

In the current industrial age, the field of manufacturing mechanical spare parts for automobiles, motorcycles, airplanes, and other applications is pivotal to advancing industrialization, modernization, and economic growth. A significant portion of these components, such as shell and frame details, are produced using the plate stamping method [1-4]. Among these, the fuel filter cup for automobiles, typically made from SPCC sheet material (as per JIS G3141 standard), is a prominent example. This component has been the focus of extensive research and production by both domestic and international enterprises. However, large-scale manufacturing of these filter cups often encounters issues such as wrinkles, tears, and inconsistencies in product dimensions and height, primarily due to the stamping process [5-9] (see Figure 1). These defects can significantly impact the final product's quality and dimensional accuracy [12-13].

To mitigate these issues and enhance the quality of stamped products, it is imperative to explore new technological solutions that support the stamping process. This includes optimizing technological parameters, geometric configurations, and material properties. One promising approach is the application of numerical simulation to predict the formability of the product before actual manufacturing. By adjusting the punch's radius of curvature when stamping high-hardness materials, it is possible to control the material's shapeability and address the aforementioned defects.

Previous studies have extensively examined the influence of various technological and geometrical parameters on the shaping parameters post-stamping [10-13]. However, there is a need for more detailed research focusing specifically on controlling the forming height by varying the punch radius. Our research group aims to fill this gap by conducting an "Investigation and Evaluation of the Influence of Punch Radius on the Forming Height During the Stamping of Cup-Shaped Parts from SPCC Material Using Simulation Methods." This study seeks to contribute to the advancement of the mechanical industry in general and the sheet metal processing sector in particular by providing a deeper understanding of how punch geometry affects forming performance.

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2. Research Materials and Methods

2.1 Materials

The material utilized in this simulation study is SPCC steel, adhering to the JIS-G3134 standard. SPCC steel plates are predominantly employed in the production of automotive parts, but their versatility extends to various construction applications such as construction mechanics, steel structures, and solar power installations. SPCC cold-rolled steel coils are also integral in the manufacturing of galvanized products, including GI coils and color sheets. Additionally, SPCC material finds extensive use in the fabrication of electrical equipment, containers, and the production of tubes and boxes. Other common applications include fan blades, frying pans, wall mounts, metal stampings, and ceiling mounts.

The chemical composition and physical properties of SPCC steel are crucial to its performance in these applications. The composition parameters of chemical elements in SPCC material, according to the JIS G3141 standard, are as follows:

Table 1. Chemical composition and physical properties of SPCC steel

Element	**Carbon (C)**	**Manganese (Mn)**	**Phosphorus (P)**	**Sulfur (S)**	**Iron (Fe)**
Quantification	≤ 0.15 %	≤ 0.60 %	≤ 0.05 %	≤ 0.05 %	Remaining

The tensile strength of SPCC steel plate is specified to be at least 270 N/mm² (MPa). The elongation properties of SPCC steel vary with thickness, with a minimum elongation range from 27% to 31%, applicable for thicknesses ranging from 0.25 mm to 2.5 mm or more [1].
The physical properties of SPCC material, as per the JIS G3141 standard, are as follows:

- **Material density (ρ kg/mm³)**: 7.8e-06
- **Elastic modulus (E, N/mm²)**: 210,000
- **Poisson's coefficient**: 0.33

2.2 Research Methods

This study employs a combination of theoretical analysis and simulation using ABAQUS software to investigate the influence of punch radius (R_P) on forming depth (H_r) during the deep drawing process. ABAQUS is a commercial finite element analysis (FEA) software renowned for its robust capabilities in simulating complex interactions and deformation behaviors in metal forming operations.
The research methodology involves the following steps:
Theoretical Analysis: Establishing the theoretical framework for understanding how punch radius affects material flow, stress distribution, and deformation during the stamping process.
Simulation Setup: Developing detailed finite element models in ABAQUS to simulate the deep drawing process. The models incorporate various punch radii to systematically study their impact on forming depth.
Parameter Variation: Conducting a series of simulations where the punch radius is varied incrementally. Each simulation captures detailed stress-strain distributions, deformation patterns, and potential defect regions.
Data Analysis: Analyzing the simulation results to identify trends and correlations between punch radius and forming depth. The simulations aim to replicate real-world conditions as closely as possible.
Experimental Validation: Comparing the simulation results with experimental data to validate the accuracy of the simulations. This step ensures that the findings are reliable and applicable to practical scenarios.
Conclusion and Recommendations: Drawing conclusions from the simulation and experimental results to provide practical guidelines for optimizing punch design and process parameters in industrial applications.
By integrating theoretical insights with advanced simulation techniques, this research aims to provide a comprehensive understanding of how punch geometry influences forming performance, thereby offering valuable contributions to the field of sheet metal forming.

3. Theoretical Basis

3.1 Theoretical Basis of the Drawing Process

The drawing process is a mechanical forming technique used to alter the shape of a material by applying force through a punch and die. Depending on the relative height of the part, multiple deep drawing operations may be necessary to achieve the desired shape. Initially, a flat blank with diameter D is stamped to form a hollow blank with diameter d_1 and height h_1. Subsequent operations continue to draw the hollow blank, increasing its height while reducing its diameter. Typically, these operations are performed with the blank in a cold state, without the need to heat the workpiece.

However, for stamping parts from thick metal sheets (thickness t>20 mm), heating the workpiece can reduce deformation resistance.

During the cold stamping process, the metal often undergoes stabilization, which reduces its ductility. Excessive hardening can lead to a loss of ductility and eventual failure. To mitigate this, parts with a relatively large height (height-to-diameter ratio h/d>1) often require recrystallization between stamping operations to remove destabilization and restore the plasticity of the metal.

3.2 Theoretical Basis of Material Destruction

Plastic Deformation of Materials

Plastic deformation refers to the irreversible change in shape that occurs when a material is subjected to an external force. For instance, bending or beating a sheet of metal or plastic into a new shape causes a permanent change within the material. In engineering terms, the transition from an elastic state to a plastic flow state is known as plastic flow.

Tresca Criterion [9] The Tresca criterion is based on the assumption that material failure is primarily due to shear stress, which is particularly relevant for metals. Using the Mohr's circle for the principal stress state, the maximum shear stress the material can withstand is calculated. According to this criterion, material failure occurs if: $\sigma_1 - \sigma_3 \geq \sigma_0$, where σ_1 is the maximum normal stress, σ_3 is the minimum normal stress, and σ_0 is the uniaxial yield stress. The yield surface can be visualized, with elastic deformation occurring inside the surface and plastic deformation outside.

Von Mises Criterion [10] The Von Mises criterion, building on the Tresca criterion, posits that static stress does not cause material damage. Von Mises calculated the effective stress under uniaxial loading and assumed that any effective stress greater than this would lead to plastic deformation. The yield surface is represented by an ellipse, with elastic deformation inside and plastic deformation outside.

Comparison of Tresca and Von Mises Criteria [7] The primary difference between the two criteria lies in their respective yield surfaces: the Tresca yield surface is hexagonal, while the Von Mises yield surface is elliptical. This distinction affects their application to different materials and loading conditions.

3.3 Selecting the Radius of Curvature of the Punch

The radius of curvature of the punch (R_p) is a critical parameter determined by the forming height, stamping level, and the drawing material. The recommended dimensions for the die and punch radius of curvature are often based on the punch diameter (d_p). Below is a table suggesting basic dimensions Table 2.

Table 2: Basic dimensions

Punch Diameter (d_p)	**Radius of Curvature (R_p)**
Small	Proportional to d_p
Medium	Slightly larger than d_p
Large	Significantly larger than d_p

These guidelines ensure optimal forming conditions, balancing material flow and minimizing the risk of defects such as wrinkles and tears. Proper selection of Rp enhances the precision and quality of stamped components, contributing to the overall efficiency and effectiveness of the manufacturing process.

By integrating these theoretical principles, the study aims to deepen the understanding of the deep drawing process and provide practical insights for optimizing punch design and stamping operations.

4. Simulation and Evaluation

4.1 Simulation Model

The simulation process was conducted using the commercial software Abaqus. The technological parameters for the simulation are presented in Table 3:

Table 3: Technological parameters for the simulation

Parameter	**Value**
Plate diameter (D_0)	150 mm
Sheet thickness (t)	0.5 mm
Diameter of punch (d_p)	67 mm
Punch and die clearance (w_c)	1 mm

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Parameter	**Value**
Mill turning radius (R_d)	6 mm
Punch radius (R_p)	2, 4, 6, 8, 10 mm
Elastic modulus (E)	210,000 N/mm²
Material density	7.8e-6 kg/mm³
Poisson's coefficient	0.3
Execution time	1 s
Friction coefficient (μ)	
Punch-workpiece (μ_p)	0.25
Workpiece stop plate-workpiece (μ_h)	0.125
Die-workpiece (μ_d)	0.125

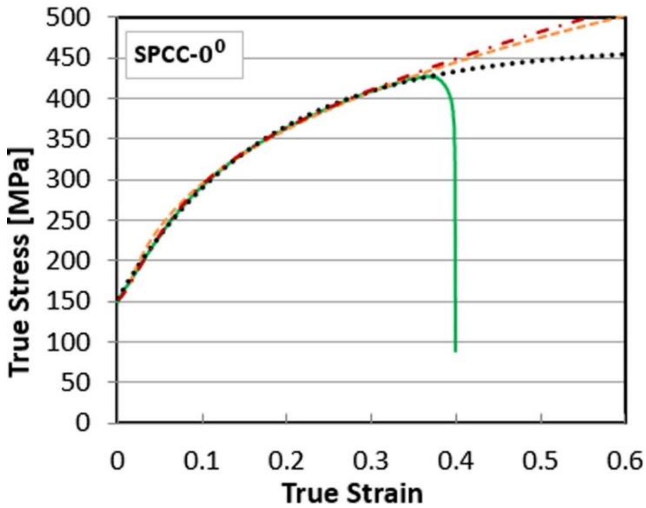


Figure 1: Stress-Strain Curve

The stress-strain parameters for SPCC panels were derived from hardening models proposed by [4], [5], and [6]. Figure 1 compares the stress-strain curves of these models. This simulation utilizes the Kim-Tuan stress-strain equation with the hardening model parameters shown in Table 4:

Table 4: Hardening Modeling Parameters

Parameter	**Value**
σ_0	152.1 MPa
K	460.2 MPa
t	25.86
h	0.48

The Forming Limit Curve (FLC) data for the SPCC material was also derived from the hardening model. The FLC curves were built based on models from [4], [5], and [3]. The simulation employs model results as input data (Table 5).

Table 6: Major-Minor strain of SPCC Material Model

Mode	ε_1	ε_2
Plane strain deformation	0.668	-0.334
Uniaxial tensile deformation	0.282	0
Biaxial deformation	0.445	0.445

Abaqus was used to simulate the deep drawing process for a cup and die set. The blank holder and die were fixed, while the punch moved vertically to achieve the part size through the forming deformation state. The absolute stiffness model was applied to the drawing punch, blank holder, and die, represented by the motion of a predetermined reference node (Figure 2). The metal blank was modeled as a circular flat sheet of SPCC material and meshed accordingly.

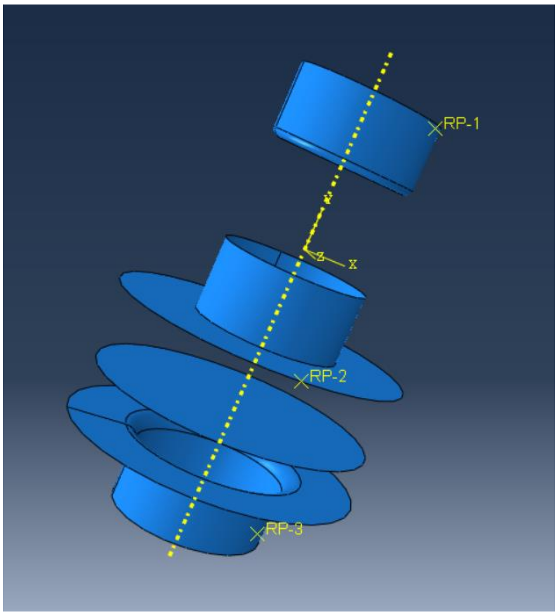
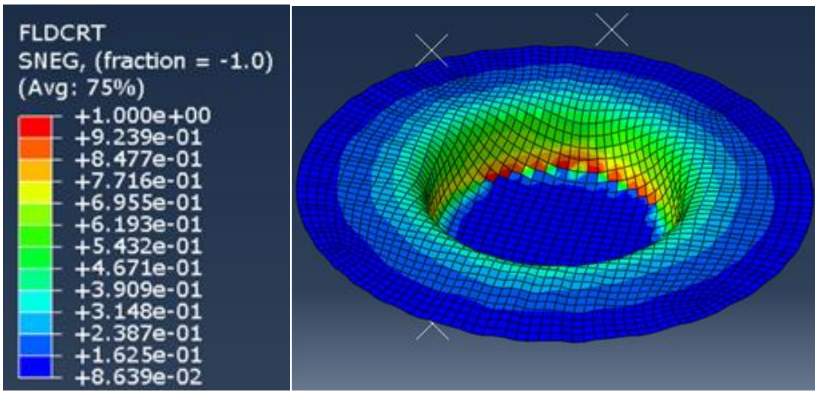


Figure 2: Simulation Model in Abaqus

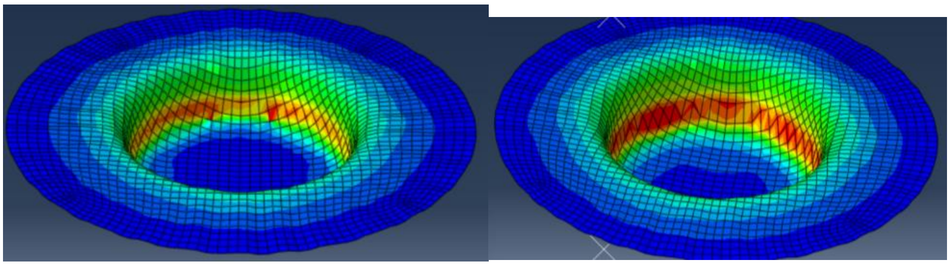
4.2 Results and Discussion

4.2.1 Results

The simulation of the SPCC material drawing process demonstrated that tearing occurred at mesh positions where the FLC destruction standard value reached 1.0. The punch moved vertically by 50 mm from the plate surface to the end of the stamping process. The process was divided into steps, with each drawing step being 0.25 mm down, allowing for detailed visualization of the simulation. The punch radius (R_p) was varied from 2 mm to 10 mm in increments (2 mm, 4 mm, 6 mm, 8 mm, 10 mm), as illustrated in Figures 3.



R_P = 6 (mm)



$R_P = 8(mm)$ $R_P = 10(mm)$

Figures 3 Simulations of Punching with Various Punch Radii (R_p)

4.2.2 Discussion

The simulation results provided data on the forming height H and the number of steps taken for different punch radii R_p, as shown in Table 7.

Table 7: Simulation Results

R_p (mm)	**2**	**4**	**6**	**8**	**10**
Steps	54	59	75	76	90
Critical Height H(mm)	13.5	14.75	18.75	19	22.5

The data was processed using Microsoft Excel to produce a diagram showing the forming height H when tearing begins, depending on the punch radius R_p.

The results (Figure 4) indicated that the forming height H changed most significantly by 4 mm when the punch radius R_p was increased from 4 mm to 6 mm. This change was followed by increases of 3.5 mm and 1.25 mm when R_p was increased from 8 mm to 10 mm and 2 mm to 4 mm, respectively. The least change, 0.25 mm, occurred when R_p was increased from 6 mm to 8 mm.

The analysis demonstrates that smaller punch radii result in higher localized stresses, leading to deeper forming depths but also an increased risk of material failure. Conversely, larger punch radii distribute stresses more evenly, resulting in shallower forming depths and improved structural integrity of the formed parts. These insights are crucial for optimizing punch design and process parameters in industrial applications, ultimately enhancing product quality and reducing defects in stamped components.

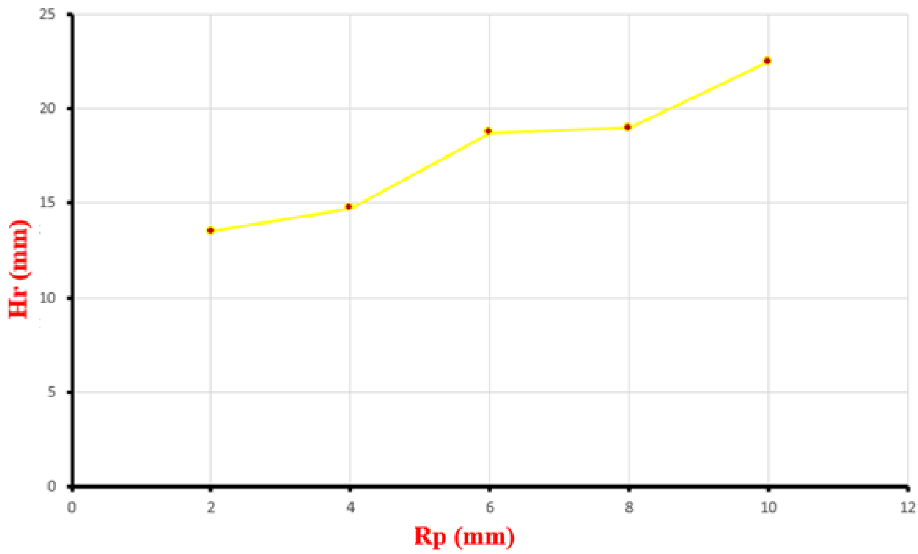


Figure 4: Dependence of H_r on Punch Radius R_p

5. Conclusion

This study has provided valuable findings regarding the impact of punch radius R_p on the forming height H_r in the deep drawing process. Through extensive simulations using Abaqus software and validation against experimental data, several key conclusions can be drawn:

Effect of Punch Radius on Forming Depth: The research confirms that varying the punch radius RpR_pRp directly affects the forming height H_r during the deep drawing of SPCC material. It was observed that smaller R_p values tend to deepen the forming depth, albeit with increased risks of material failure due to localized stresses. Conversely, larger R_p values distribute stresses more evenly, resulting in shallower forming depths but improved structural integrity.

Non-Uniform Influence of R_p: The study highlights that the influence of R_p on H_r is not uniform. There exist critical ranges of R_p where small changes lead to significant alterations in H_r, while in other ranges, variations in R_p result in minimal changes in H_r. This nuanced understanding underscores the importance of precise punch design in optimizing the deep drawing process for SPCC parts.

Practical Implications for Industrial Applications: The findings provide practical guidelines for manufacturing engineers aiming to enhance product quality and reduce defects in stamped components. By leveraging simulation-driven insights into punch radius optimization, industrial practitioners can achieve better control over the forming process, thereby improving efficiency and product reliability.

This research contributes to the advancement of knowledge in sheet metal forming technology by elucidating the intricate relationship between punch geometry and forming performance. The methodologies developed here can serve as a robust foundation for future studies exploring similar phenomena in other materials and forming processes. By integrating theoretical frameworks with advanced simulation techniques, this study exemplifies a systematic approach to enhancing manufacturing processes in the modern industrial landscape.

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