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Advanced Numerical Simulation of Hydromechanical Deep Drawing for Enhanced Formability of SUS304 Stainless Steel: Implications for Revolutionizing Biomedical Manufacturing

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ABSTRACT:

Deep drawing stands as a pivotal sheet metal forming technique extensively employed in contemporary industrial practices, with significant implications for future manufacturing advancements. This research delves into the formability and plastic deformation characteristics of SUS304 stainless steel under room temperature conditions, utilizing the innovative method of hydromechanical deep drawing. Advanced finite element simulations were meticulously conducted using the Dynaform software, encompassing a comprehensive modeling of the entire stamping die system. The study's findings reveal that the application of an optimal blank holding force markedly enhances the drawing ratio while concurrently mitigating material thinning, thus significantly improving the overall formability of the stainless steel. The fidelity of these numerical simulations was rigorously validated through experimental comparisons, affirming the critical role of blank holding force as a primary input parameter. This parameter exerts a profound influence on the deformation behavior of SUS304 stainless steel, directly impacting the structural integrity and quality of the final drawn component. This research presents a novel approach to predicting deep drawing processes, offering valuable insights into achieving superior formability and precision in sheet metal forming operations. The integration of hydromechanical techniques with advanced simulation tools marks a significant advancement in the field, promising enhanced efficiency and quality in Revolutionizing Biomedical Manufacturing applications.

Keywords: plastic deformation, hydromechanical deep drawing, process simulation, finite element method, sheet metal forming.

1. Introduction

Deep drawing is a critical sheet metal forming process, extensively applied across various industries such as automotive, aerospace, marine, and nuclear sectors. This process involves the plastic deformation of sheet metal blanks into specified shapes using a punch and die, effectively minimizing material waste. The mechanical and thermal properties of the sheet metal, along with the geometries of the punch and die, blank thickness, and frictional forces, all significantly contribute to the success of the forming process, with each factor being interdependent [1, 2]. A profound understanding of plastic deformation in sheet metal forming is imperative for optimizing production quality.

The increasing demand for high-performance mechanical products, including stainless steel cup-shaped components, necessitates continual advancements in forming technology [3]. Traditional deep drawing methods, which utilize rigid punches and dies, are being augmented with novel techniques aimed at reducing the number of processing steps, increasing drawing ratios, and enhancing product quality while avoiding common defects such as tearing, wrinkling, and thinning. Among these innovative techniques, hydromechanical deep drawing has gained prominence. This method employs a rigid punch and a die filled with high-pressure fluid to achieve superior forming results.

The rapid development of computer technology in mechanical engineering, particularly the finite element method (FEM), has revolutionized the simulation of mechanical processing. This advancement enables precise and accurate modeling of forming processes, facilitating optimized production. Numerical simulation using FEM represents a substantial leap from traditional, empirical methods, providing a more scientific and reliable approach to design and process optimization. FEM-based simulation in pressure processing assists in the quick and accurate design of molds, offering detailed analyses of stress and deformation distributions during forming [4]. This capability enables the swift optimization of process parameters, achieving high precision in product dimensions, shape, and mechanical properties [5].

Despite these advancements, the comprehensive study and practical application of hydromechanical deep drawing technology remain limited in Vietnam. To address this gap, this research focuses on the application of Dynaform software to simulate the hydromechanical deep drawing process for thin-walled, cup-shaped components. The primary objectives are to optimize the forming technology, reduce production costs, and save time in the preliminary stages before testing and application. This study represents a novel approach to leveraging advanced simulation tools for enhancing the efficiency and quality of sheet metal forming operations, thus contributing significantly to the field of mechanical engineering.

2. Key Factors in the Deep Drawing Process

In the hydromechanical deep drawing process, the sheet metal blank is subjected to various stress states, as illustrated in Figure 1. The key factors influencing this process include:

2.1. Blank Holder Region

In both hydromechanical and conventional deep drawing, the blank holder region experiences a biaxial compressive and uniaxial tensile stress state, which results in biaxial tensile and uniaxial compressive deformation. This stress configuration causes the blank in the flange area to thicken, potentially leading to instability and wrinkling. To counteract these issues, a blank holder is crucial for maintaining the stability of the blank and preventing wrinkling. The force applied by the blank holder and the method of holding must be precisely controlled, as these factors directly impact the quality of the final product. An optimal blank holding force ensures that the blank remains stable, enhancing the overall formability and surface finish of the drawn component.

2.2. Transition Zone between Blank and Tools

The transition zone, where the blank interfaces with the punch and die, undergoes complex biaxial stress and deformation. Unlike conventional deep drawing, the presence of high-pressure fluid in hydromechanical drawing introduces a compressive stress component that significantly enhances the stability and plastic deformation capacity of the blank. This added stability reduces the adverse effects of friction, which are more pronounced in conventional methods. In traditional deep drawing, the radius of curvature is prone to thinning, increasing the risk of blank rupture. Hydromechanical drawing, however, mitigates this risk by maintaining a more uniform stress distribution across the blank.

2.3. Cylindrical Wall

The cylindrical wall region in hydromechanical deep drawing is subjected to biaxial stress, with one axis experiencing tensile stress and the other compressive stress. This is in contrast to conventional deep drawing, where the cylindrical wall predominantly experiences uniaxial compressive stress. Experimental observations indicate that, in hydromechanical drawing, the blank undergoes minimal deformation in this region, which helps in maintaining the original thickness and enhancing the surface quality of the product. The lack of direct contact with the die surface in hydromechanical drawing further contributes to the superior surface finish of the drawn component.

2.4. Punch Corner Radius

The punch corner radius is a critical area in both conventional and hydromechanical deep drawing. In conventional deep drawing, this region experiences significant thinning and biaxial tensile stress, which diminishes the ductility of the material and increases the risk of rupture. In hydromechanical deep drawing, however, the application of fluid pressure ensures a more favorable uniaxial stress state. This reduces the deformation extent and enhances the ductility of the material, thereby preventing blank failure and ensuring a more consistent wall thickness around the punch corner.

2.5. Punch Face

The punch face region is primarily subjected to uniaxial stress, with other stress components being negligible. This results in minimal deformation in this area. In conventional deep drawing, the punch face experiences biaxial tensile stress and volumetric strain, which can lead to significant thinning of the blank. Hydromechanical deep drawing, by contrast, maintains the integrity of the blank by ensuring that the stress state remains uniaxial, thus minimizing the risk of thinning and ensuring a uniform material distribution.

The key factors in the deep drawing process—ranging from the blank holder region to the punch face—highlight the intricate interplay of stresses and deformations that determine the quality and integrity of the final product. The hydromechanical deep drawing process, with its introduction of high-pressure fluid, offers significant advantages over conventional methods by enhancing stability, reducing thinning, and improving surface quality. Understanding and optimizing these factors are crucial for advancing the technology and achieving superior formability in sheet metal forming operations. This research contributes to the field by providing a comprehensive analysis of these factors and demonstrating the potential of hydromechanical deep drawing to meet the growing demand for high-quality, precisely formed components.

3. Research Methodology

3.1. Materials

In mechanical engineering, the properties of materials are paramount for ensuring the accuracy and reliability of any manufacturing process. This is especially true in numerical simulations, where material models must accurately represent the material's response to external mechanical forces. The blank material used in deep drawing undergoes significant deformation during the process. When the deformation exceeds 3%, it is considered large deformation, necessitating precise material models to ensure reliable simulation, experimentation, and practical application.

$$\bar{\sigma} = K(\varepsilon_0 + \bar{\varepsilon})^n = 864.2(0.000177 + \bar{\varepsilon})^{0.195} \quad (1)$$

For this study, SUS304 stainless steel, known for its anisotropic properties when produced by rolling, was chosen. This material's behavior under mechanical stress is best represented using the Material Model (Eq. 1): 3-Parameter Barlat Plasticity. This model effectively simulates anisotropic cold-deformation under plane stress conditions by employing the Lankford parameter to define the anisotropic yield surface. The yield surface is mathematically expressed as:

$$\bar{\sigma} = \sqrt{H(\sigma_{11} - \sigma_{22})^2 + F\sigma_{22}^2 + G\sigma_{11}^2 + 2N\sigma_{12}^2} \quad (2)$$

Where:

- $\bar{\sigma}$ is the stress,
- σ_{11}, σ_{22}, σ_{12} are the stresses components,
- $\bar{\varepsilon}$ is the plastic strain.

Where E is Young's modulus. The material parameters K, n, H, F, G, N, and N are derived from the Lankford parameters, providing a comprehensive description of the material's anisotropic behavior.

3.2. Research Method

The research aims to examine the impact of blank holding force on the formability of SUS304 stainless steel during the hydromechanical deep drawing process using finite element simulation. This investigation was conducted using Eta/Dynaform software integrated with the powerful LS-DYNA solver. The research methodology involved several key steps:

Establishing the 3D Model: The first step involved creating a detailed 3D model of the deep drawing problem, which included the punch, die, blank holder, and the blank itself. This model served as the basis for subsequent simulation steps (Fig. 1).

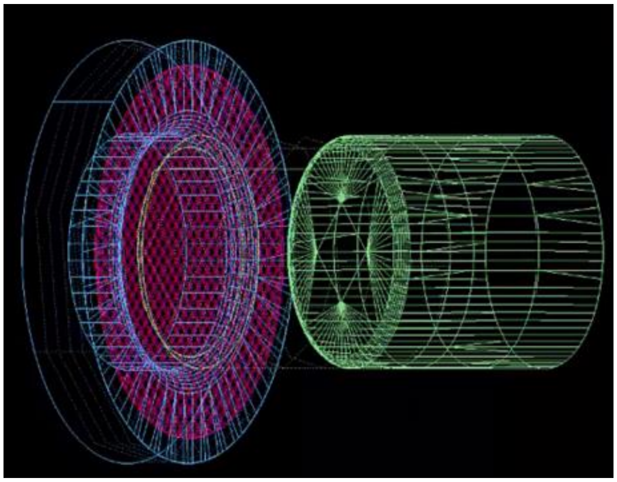

Fig 1. 3D FEM modeling.

Meshing: The blank and tools were meshed using appropriate techniques. The Blank Generator was used for meshing the blank, ensuring a fine mesh to capture the significant deformations accurately. The tools were meshed using Surface Mesh to ensure an accurate representation of their geometry and interaction with the blank.

Defining Material Properties: Material properties were defined using the Blank Material and Property Definition in Dynaform. This step included specifying the anisotropic properties of SUS304 stainless steel, incorporating the parameters from the 3-Parameter Barlat Plasticity model to simulate the material behavior accurately (Fig. 2).

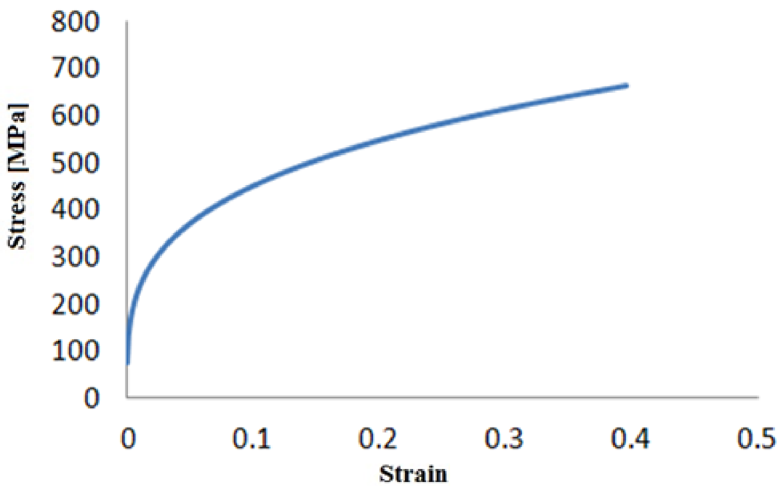

Fig. 2 The flow stress

Setting Boundary Conditions: Boundary conditions were established in LS-DYNA, including the displacement of tools, the blank holding force, and the die cavity pressure. These conditions were crucial for simulating the actual deep drawing process. The simulation was initiated to calculate the stress and strain distributions, deformation patterns, and potential defects.

By following these steps, the study effectively simulates the hydromechanical deep drawing process, providing insights into the impact of blank holding force on the formability of SUS304 stainless steel. This methodology highlights the innovative application of finite element analysis in optimizing the deep drawing process, reducing production costs, and saving time in the testing and application phases.

4. Results and Discussion

The numerical simulation conducted with LS-DYNA has provided a comprehensive analysis of the plastic deformation and formability characteristics of SUS304 stainless steel during the hydromechanical deep drawing process. The simulation results are presented through various analytical outputs, including the Forming Limit Diagram (FLD), stress distribution along the Z-axis, stress distribution in the XY-plane, strain distributions along the X, Y, and Z axes, and thickness distribution. The simulation parameters were carefully chosen to reflect realistic manufacturing conditions: SUS304 stainless steel was used at room temperature, with a blank diameter of 100 mm and thickness of 2 mm, aiming to form a final cup with a diameter of 50 mm and a height of 40 mm.

4.1. Forming Limit Diagram (FLD)

The FLD is a crucial tool in evaluating the formability of sheet metal during the deep drawing process (Fig. 3). It maps the limits of strain that the material can withstand before failure. In this study, the FLD for SUS304 stainless steel revealed the critical strain paths and the forming limits under different conditions of blank holding force and die cavity pressure. The diagram demonstrated that with an optimal blank holding force, the drawing ratio could be significantly increased without encountering defects such as tearing or wrinkling (Fig. 4).

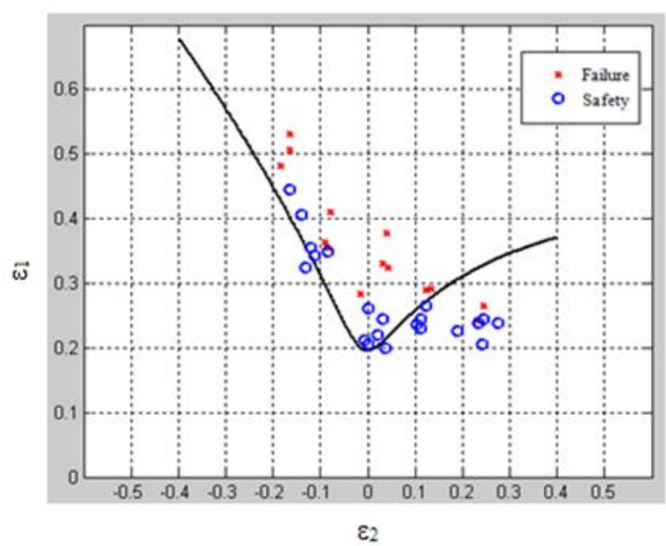

Fig. 3. The forming limit curve

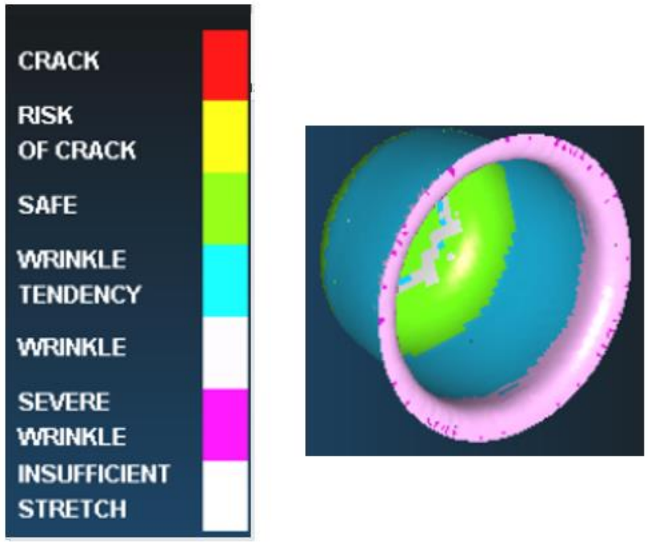

Fig. 4. Critical position

4.2. Stress and Strain Distributions

The stress distribution along the Z-axis provided insights into the material's response to the applied forces during the deep drawing process (Fig. 5). The simulation indicated that the stress was uniformly distributed along the punch, ensuring consistent deformation and reducing the risk of localized thinning or rupture. The XY-plane stress distribution further confirmed the material's isotropic behavior under plane stress conditions, crucial for achieving uniform wall thickness in the final cup-shaped component.

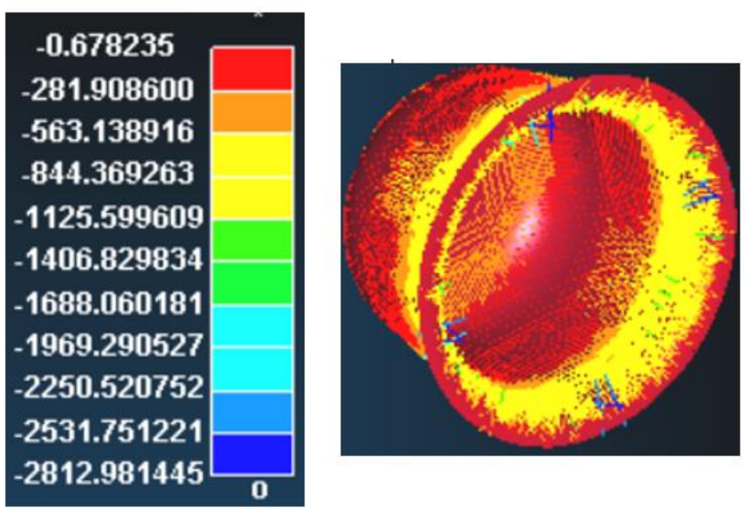

Fig. 5. Stress distribution along the Z-axis

Strain distributions along the X, Y, and Z axes were analyzed to understand the deformation behavior more thoroughly. The results showed that the material exhibited significant plastic deformation in the regions subjected to high-pressure fluid, enhancing its formability. The strain distribution analysis highlighted the areas of maximum elongation and compression, providing valuable data for optimizing the process parameters to minimize defects and ensure dimensional accuracy.

4.3. Thickness Distribution

Thickness distribution is a critical factor in assessing the quality of the formed part (Fig. 6). The simulation results indicated that the appropriate blank holding force contributed to maintaining a uniform thickness distribution throughout the cup's walls. This uniformity is essential for ensuring the structural integrity and performance of the final product. The study demonstrated that by adjusting the blank holding force and die cavity pressure, it was possible to control the material flow and achieve the desired thickness profile.

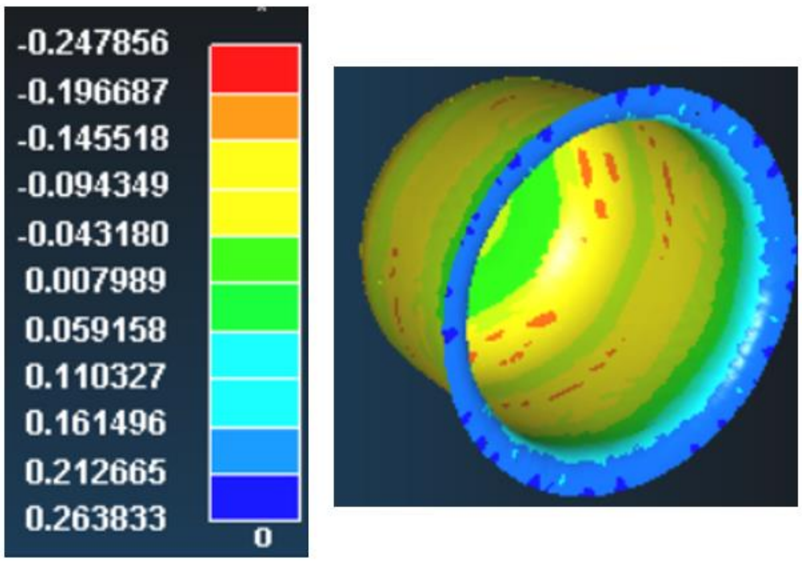

Fig. 6. Thickness distribution

4.4. Impact of Blank Holding Force

One of the key findings of this study is the impact of blank holding force on the formability of SUS304 stainless steel. By adjusting the boundary conditions in the numerical model, the formability was evaluated for varying cup heights (10 mm, 20 mm, 30 mm, and 40 mm) while maintaining a constant blank thickness. The correlation between tool displacement, blank holding force, and die cavity pressure was established. This correlation is crucial for ensuring the desired part quality.

The results clearly indicate that an appropriate blank holding force increases the drawing ratio, making it a critical parameter for controlling the hydromechanical deep drawing process. This finding is particularly relevant for high-pressure forming equipment, such as 200-ton hydraulic presses, commonly used in the Vietnamese manufacturing industry. The ability to optimize blank holding force to enhance formability and product quality represents a significant advancement in stainless steel forming technology.

4.5. Novelty and Practical Implications

This research demonstrates the novel application of finite element analysis in optimizing the hydromechanical deep drawing process for SUS304 stainless steel. The comprehensive

simulation approach allows for precise control of process parameters, leading to improved formability, reduced production costs, and shorter development times. The practical implications of this study are significant for industries such as automotive, aerospace, and marine, where high-quality stainless steel components are essential.
In conclusion, the findings underscore the importance of blank holding force as a key technological parameter in the hydromechanical deep drawing process. The ability to fine-tune this parameter to achieve optimal formability and product quality opens new avenues for advanced manufacturing techniques in stainless steel forming, providing a valuable reference for future research and industrial applications.

5. Conclusion

This research has demonstrated the efficacy of numerical simulation using Eta/Dynaform for investigating the plastic deformation and formability of SUS304 stainless steel at room temperature during the hydromechanical deep drawing process. The use of finite element analysis (FEA) has provided valuable insights into the material's response under various stress states, facilitating a deeper understanding of the critical factors that influence the deep drawing process.
The comprehensive simulation results, including the Forming Limit Diagram (FLD), stress and strain distributions, and thickness variation, have highlighted the pivotal role of blank holding force in determining the quality of the final product. By meticulously adjusting the blank holding force and die cavity pressure, the simulations have shown that it is possible to optimize the drawing ratio and minimize common defects such as tearing, wrinkling, and thinning. This capability is crucial for ensuring the dimensional accuracy and mechanical integrity of the final stainless steel components.
The ability to simulate and test various technological parameters and configurations before actual production is a significant advancement. It allows for the optimization of input parameters, leading to improved formability and quality of stainless steel parts. This research has underscored the importance of blank holding force as a critical input parameter that directly impacts the material formability and the final product's shape and mechanical properties in the deep drawing process.
In practical terms, the findings of this study provide a robust framework for optimizing hydromechanical deep drawing processes in industrial applications. The methodology and results can be applied to high-pressure forming equipment, such as 200-ton hydraulic presses, commonly used in the automotive, aerospace, marine, and nuclear sectors. This research not only contributes to the theoretical understanding of deep drawing processes but also offers practical guidelines for enhancing production efficiency and product quality in the manufacturing industry.

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