



Coupled experimental, finite element and nanotechnology-based investigation of process parameters in conical cup deep drawing

Ahmed Abd Al Razzaq Khalaf, Jalil Jabbar Shukur, Mohammed Sattar Jabbar*

College of Production Engineering & Metallurgy, University of Technology- Iraq, Baghdad 10066, Iraq

*) Email: ahmedabdalrazzaq4@gmail.com

Received 1/5/2026, Received in revised form 25/7/2026, Accepted 2/9/2026, Published 15/10/2026

Deep drawing is one of the most widely used sheet metal forming processes for manufacturing axisymmetric components with high dimensional accuracy and structural integrity. The quality of deep-drawn products is strongly influenced by process parameters such as blank holder force (BHF), punch speed, and tooling geometry, particularly when forming conical cups with inclined walls. In this study, a coupled experimental and finite element investigation was conducted to evaluate the influence of key process parameters on the forming load during the deep drawing of conical cups. Circular blanks of 1008 AISI low-carbon steel with a thickness of 0.9 mm and a diameter of 110 mm were employed. Deep drawing experiments were performed using a conical punch with a wall angle of 70° and a conical die and blank holder having an inclination angle of 12°. Three punch speeds (25, 75, and 125 mm/min) and three spring stiffness values corresponding to different blank holder forces (0.053, 0.066, and 0.072 kN/mm) were investigated. Finite element simulations were carried out using ABAQUS/Explicit 2021, where the punch, die, and blank holder were modeled as rigid bodies and the sheet blank as a deformable body. The numerical predictions were validated through direct comparison with experimental results. The results demonstrated that increasing the blank holder force increased the ultimate forming load due to higher contact pressure and friction at the flange region. The maximum forming load of 36.5 kN was obtained at a spring stiffness of 0.072 kN/mm and a drawing speed of 75 mm/min, whereas the minimum load of 33.36 kN occurred at 125 mm/min and 0.053 kN/mm. Good agreement was achieved between experimental and numerical results, confirming the capability of the finite element model to accurately predict the deep drawing behavior of conical cups and assist in process optimization. From a nanotechnology perspective, the study contributes to understanding deformation mechanisms occurring at micro- and nano-scales during sheet metal forming. The finite element model provides insights into localized strain distribution and surface integrity, which are critical for the manufacturing of advanced metallic components used in nanotechnology-enabled engineering systems. The findings demonstrate the potential of combining experimental measurements

Keywords: Deep drawing; Conical cup; Blank holder force; Forming load; Finite element analysis.

1. INTRODUCTION

Deep drawing is one of the most important sheet metals forming processes employed in modern manufacturing industries for producing axisymmetric and non-axisymmetric components with high dimensional accuracy and excellent surface quality [1]. The process involves transforming a flat sheet blank into a hollow product by forcing the material into a die cavity using a punch [2]. Deep-drawn components are extensively used in automotive, aerospace, packaging, household appliances, and defense industries because of their ability to produce lightweight structures with minimal material waste and superior mechanical performance [3]. The increasing demand for complex geometries, including conical and tapered cups, has intensified the need to understand the influence of process parameters on formability, product quality, and manufacturing efficiency [4]. The successful execution of a deep drawing operation depends on the interaction among material properties, tooling geometry, friction conditions, and loading parameters. Among these factors, forming load plays a crucial role because it directly influences material flow, thickness distribution, energy consumption, and defect formation [5]. Excessive forming loads may lead to tearing and fracture, while insufficient loads may result in wrinkling and dimensional inaccuracies. Consequently, optimizing process parameters is essential for achieving defect-free products with improved structural integrity [6]. The quality and formability of deep-drawn products are strongly affected by several process parameters, including blank holder force (BHF), punch speed, die geometry, punch radius, die clearance, lubrication conditions, and material characteristics [7]. Blank holder force controls the flow of material from the flange region into the die cavity and is considered one of the most influential variables in preventing wrinkling and tearing. An insufficient blank holder force allows excessive material flow, causing wrinkles, whereas excessive force restricts material movement and increases the risk of fracture [8].

Punch speed also affects the deformation behavior and strain-rate sensitivity of sheet materials. Variations in drawing speed can alter frictional conditions, material flow characteristics, and energy dissipation during forming [9]. Furthermore, the geometry of conical dies, particularly the wall inclination angle, significantly influences the distribution of stresses and strains throughout the forming process. Appropriate combinations of these parameters can improve thickness uniformity, reduce defects, and minimize the required forming load [10]. Therefore, a comprehensive understanding of their combined effects is necessary for process optimization. Although deep drawing technology has been extensively studied for conventional cylindrical cups, the forming behavior of conical cups with inclined walls remains relatively complex [11]. The presence of wall inclination introduces additional variations in material flow patterns, contact pressure distribution, and stress concentrations compared with conventional geometries. These complexities often result in non-uniform deformation, thickness variations, wrinkling, and tearing during forming operations. In industrial applications, selecting appropriate blank holder forces and punch speeds for conical cup drawing is frequently based on trial-and-error approaches, leading to increased production costs and longer development times [12]. Moreover, inaccurate prediction of forming loads may result in improper equipment selection and reduced product quality. Therefore, there is a need for a systematic investigation capable of identifying the effects of key process parameters on the forming load and overall formability of conical cups. Previous studies have investigated the effects of blank holder force, die geometry, and drawing speed on conventional deep drawing processes. Several researchers have demonstrated that optimized blank holder force can improve thickness distribution and reduce

defect formation. Likewise, finite element analysis has been widely employed to predict forming loads and deformation behavior in cylindrical cup drawing [13].

However, limited studies have focused on the combined experimental and numerical evaluation of conical cup deep drawing involving inclined dies and blank holders. Furthermore, the interaction between blank holder force and drawing speed under inclined conical geometries has not been sufficiently explored. Existing investigations often concentrate on either experimental observations or numerical simulations without establishing a comprehensive validation between both approaches. This gap motivates the present work, which integrates experimental testing and finite element modeling to achieve a deeper understanding of the forming behavior of conical cups under various operating conditions. The primary objective of this study is to investigate the influence of blank holder force and drawing speed on the forming load during the deep drawing of conical cups manufactured from low-carbon steel sheets. Experimental investigations are conducted using specially designed tooling consisting of a conical punch with a wall angle of 70° and a conical die and blank holder with an inclination angle of 12° . Three levels of blank holder force, represented by different spring stiffness values, and three punch speeds are examined to evaluate their effects on formability. The scope of the study includes experimental deep drawing tests and finite element simulations using ABAQUS/Explicit to predict the deformation behavior and forming loads under different processing conditions. The numerical results are validated through direct comparison with experimental measurements. In recent years, nanotechnology has emerged as an important field in advanced manufacturing because many engineering products require precise control of surface quality, dimensional accuracy, and localized deformation behavior at micro- and nano-scales. Sheet metal forming processes are increasingly employed in the production of miniature metallic components, micro-electromechanical systems (MEMS), biomedical devices, micro-electronic enclosures, and nano-engineered structures. The understanding of strain localization, thickness variation, and surface integrity during deep drawing is therefore essential for achieving reliable performance in nano-enabled products. Finite element analysis provides an effective tool for investigating these deformation mechanisms and optimizing process parameters before manufacturing, thereby reducing cost and improving product quality.

The novelty of this work lies in the coupled experimental–numerical assessment of process parameters in inclined conical cup deep drawing. Unlike previous investigations focusing on conventional cup geometries, this study examines the combined effects of blank holder force and drawing speed on a conical configuration with inclined tooling. The main contribution of the research is the development of a validated finite element model capable of accurately predicting forming loads and supporting process optimization for industrial deep drawing applications. Several limitations are associated with the present investigation. The study is restricted to a single sheet material, namely 1008 AISI low-carbon steel, with a thickness of 0.9 mm. Only one die inclination angle (12°) and one punch wall angle (70°) are considered throughout the experimental and numerical analyses. Furthermore, the investigation focuses primarily on forming load behavior and does not include detailed analyses of residual stresses, spring back, microstructural evolution, or temperature-dependent effects. Friction conditions are assumed to remain constant during the simulations, and the influence of lubrication variations is not examined. Therefore, the conclusions are limited to the investigated material and processing conditions.

The remainder of this paper is organized as follows. Section 2 reviews previous research related to deep drawing processes, blank holder force optimization, and finite element modeling techniques. Section 3 describes the experimental materials, mechanical characterization, tooling design, and testing procedures. Section 4 presents the deep drawing experimental program and process parameters. Section 5 details the finite element modeling methodology implemented in ABAQUS/Explicit. Sections 6 and 7 discuss the effects of blank holder force and drawing speed on the forming load

through both experimental and numerical analyses. Finally, Section 8 summarizes the main findings and presents the conclusions and recommendations for future research.

2. EXPEREMENTAL WORK

3.1. Materials and mechanical properties

The experimental investigation was carried out using commercially available AISI 1008 low-carbon steel sheets with a nominal thickness of 0.9 mm. This material was selected because of its excellent formability, ductility, and widespread use in sheet-metal forming applications. Circular blanks with a diameter of 110 mm were prepared from the sheet material and utilized as workpieces for the deep drawing experiments. To ensure dimensional accuracy and minimize edge defects that could influence the forming behavior, all blanks and tensile specimens were fabricated using a precision laser-cutting machine. The mechanical properties of the sheet material were determined through uniaxial tensile testing performed in accordance with the ASTM E8M standard. Tensile specimens were prepared along three different orientations relative to the rolling direction of the sheet, namely 0°, 45°, and 90°, as illustrated in Figure 1. The geometric configuration and dimensions of the sheet-type tensile specimen employed in this study are presented in Figure 2, while the detailed dimensional specifications are listed in Table 1. Evaluating the material in multiple orientations allowed the assessment of anisotropic behavior induced by the rolling process and provided representative material data for the finite element simulations. The tensile tests were conducted at room temperature using a universal testing machine under displacement-controlled loading conditions. The obtained load–displacement data were converted into engineering stress–strain and true stress–true strain relationships. The resulting true stress–true strain curves corresponding to the three rolling directions are shown in Figure 3. These curves were subsequently used to determine the principal mechanical properties of the material, including yield strength, ultimate tensile strength, and strain-hardening characteristics. The measured mechanical properties are summarized in Table 2. As indicated in Table 2, the material exhibits slight anisotropic behavior, with the highest yield strength and ultimate tensile strength being observed in the 90° rolling direction, reaching 218 MPa and 411 MPa, respectively. The 45° orientation exhibited intermediate values of 211 MPa and 385 MPa, whereas the 0° orientation showed the lowest strength values of 205 MPa and 376 MPa. These experimentally determined properties were incorporated into the finite element model to accurately simulate the deformation behavior of the sheet during the deep drawing process.

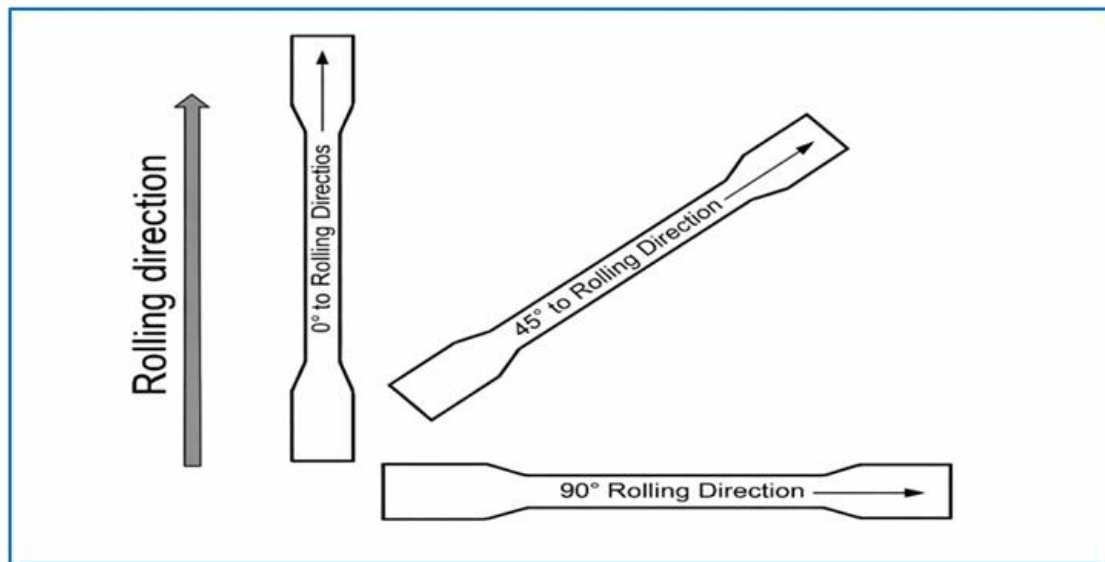


Figure 1 Orientation of ASTM E8M tensile test specimens prepared at 0°, 45°, and 90° relative to the rolling direction of the low-carbon steel sheet.

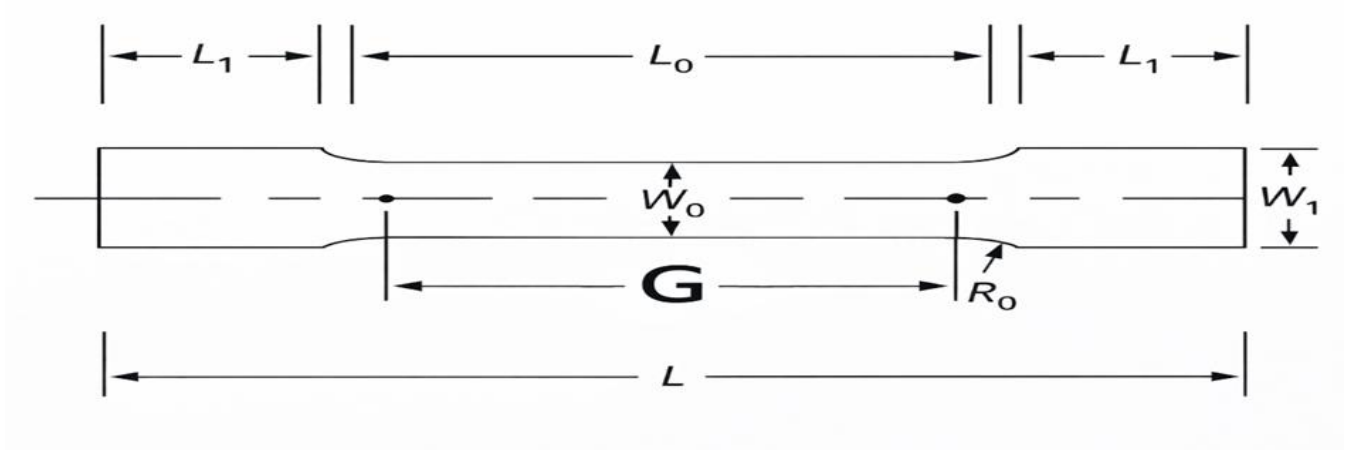


Figure 2 Geometry and dimensions of the ASTM E8M standard tensile specimen used for mechanical characterization of the low-carbon steel sheet.

Table 1 Geometrical dimensions and specifications of the ASTM E8M sheet-type tensile specimen used for the mechanical characterization of AISI 1008 low-carbon steel.

Symbol	Description	Sheet-type specimen (mm)
G	Gauge Length	50.0 ± 0.1
W ₀	Gauge width	12.5 ± 0.2
R ₀	Radius of fillet	12.5
L	overall length	200
L ₀	Length of Radius section	57
L ₁	Length of grip section	50
W ₁	Width of grip section	20

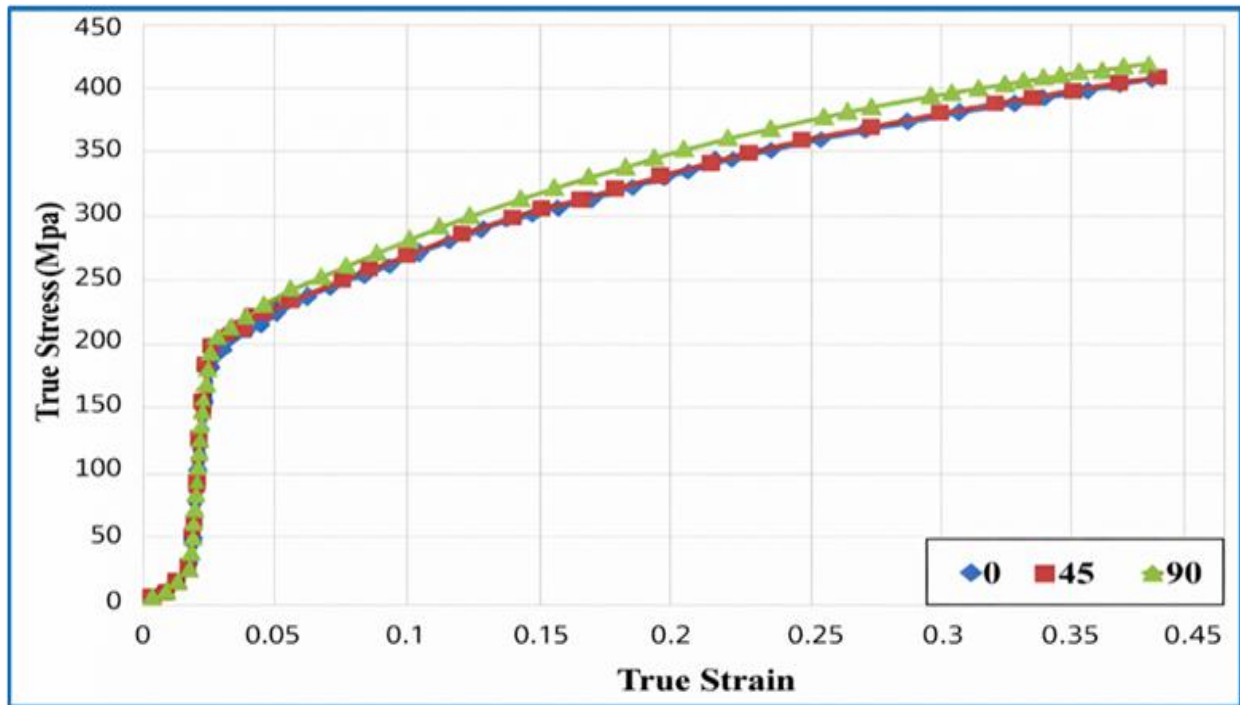


Figure 3 True stress–true strain curves of AISI 1008 low-carbon steel measured at different orientations (0°, 45°, and 90°) relative to the rolling direction.

Table 2 Mechanical properties of AISI 1008 low-carbon steel obtained from tensile tests conducted at different orientations relative to the rolling direction.

Material	Rolling Direction	Yield Strength (MPa)	Tensile Strength (MPa)
Low Carbon Steel	90°	218	411
	45°	211	385
	0°	205	376

3.2. Experimental tooling

A specially designed tooling system was developed to investigate the deep drawing behavior of conical cups under different processing conditions. The tooling assembly consisted of a conical punch, a conical die, an inclined blank holder, guiding components, and interchangeable spring assemblies for controlling the blank holder force. A schematic representation of the complete deep drawing setup is shown in Figure 4. The arrangement was designed to ensure accurate alignment between the punch, die, and blank holder throughout the forming process while maintaining consistent loading conditions during all experiments.

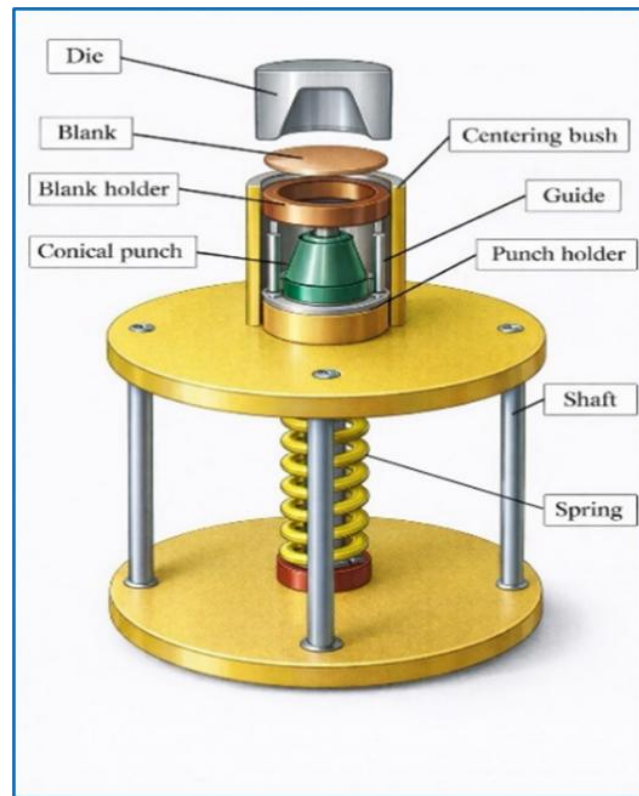


Figure 4 Schematic illustration of the experimental deep drawing setup showing the arrangement of the punch, blank holder, die, springs, guide system, and sheet blank.

To study the influence of inclined geometries on the deep drawing process, a conical die with an inclination angle of 12° was employed. A corresponding blank holder having the same inclination angle was fabricated to ensure proper contact and material restraint during deformation. The manufactured die and blank holder are presented in Figure 5. In addition, the tooling system was equipped with a spring-loaded guiding mechanism to provide stable operation, minimize misalignment, and maintain uniform pressure distribution over the blank during forming.



Figure 5 Photograph of the fabricated conical die and inclined blank holder with an inclination angle of 12° used in the deep drawing experiments.

The punch and die components were manufactured from CK45 steel because of its high strength, wear resistance, and dimensional stability under repeated loading conditions. The guide components were fabricated from ST50 steel to provide adequate structural rigidity and support throughout the deep drawing operation. The conical punch, shown in Figure 6, was designed with a height of 55 mm, an upper diameter of 80 mm, and a lower diameter of 40 mm. The punch nose radius was maintained at $R_p = 10$ mm, while the die profile radius was $R_d = 6$ mm. The punch wall angle was fixed at 70° , corresponding to the geometry of the conical cup investigated in this study.



Figure 6 Photograph of the conical punch with a wall angle of 70° employed for the fabrication of conical cups.

All deep drawing experiments were conducted using circular AISI 1008 low-carbon steel blanks with a diameter of 110 mm and a thickness of 0.9 mm. A constant forming clearance of 1.3 mm was maintained between the punch and die throughout the experimental program to ensure consistent material flow conditions. To investigate the influence of blank holder force on the forming load, three spring assemblies designated as A, B, and C were employed. The spring stiffness values were determined experimentally using compression tests performed at a constant loading rate of 10 mm min⁻¹. The spring constant was calculated from the slope of the linear elastic region of the load–displacement curve. The measured stiffness values were 0.053 kN mm⁻¹, 0.066 kN mm⁻¹, and 0.072 kN mm⁻¹ for springs A, B, and C, respectively. These spring assemblies provided different blank holder force levels and enabled a systematic evaluation of their effect on the deep drawing behavior of the conical cups.

3.3. Nanotechnology perspective

Although the present investigation focuses on conventional sheet thicknesses, the obtained results provide valuable information for future nano-manufacturing and micro-forming applications. The deep drawing process involves localized plastic deformation, material flow, and surface interactions that directly influence surface morphology and structural integrity at micro- and nano-scales. The finite element simulations enable detailed analysis of stress and strain concentrations that are closely associated with nano-scale deformation mechanisms and surface engineering processes. Therefore, the experimental and numerical methodologies employed in this study can serve as a basis for future investigations involving nano-structured metallic sheets and precision micro-forming technologies.

4. DEEP DRAWING TESTS

The deep drawing experiments were conducted using a WDW-200E universal testing machine equipped with a computer-controlled data acquisition and control system. The machine has a maximum load capacity of 200 kN, enabling accurate measurement and monitoring of the forming load throughout the deep drawing process. The experimental setup was configured to manufacture conical cups under controlled forming conditions while ensuring repeatability and consistency among all test runs. To investigate the influence of process parameters on the forming load, three punch drawing speeds of 25, 75 and 125 mm min⁻¹ were selected. In addition, three spring assemblies designated as A, B, and C, corresponding to different blank holder force levels, were employed. The spring stiffness values were previously determined through compression testing and used to regulate the blank holder force during the deep drawing operation. All experiments were performed using the conical punch and die configuration described in Section 3, with a fixed die inclination angle of 12° and a constant forming clearance of 1.3 mm. The experimental program was designed to systematically evaluate the combined effects of drawing speed and blank holder force on the forming behavior of the conical cups. A total of nine experimental conditions were investigated, representing all possible combinations of the three drawing speeds and the three spring assemblies. During each test, the forming load and punch displacement were continuously recorded to assess the deformation behavior and formability of the sheet material. The experimental parameters employed in the present investigation are summarized in Table 3, while the complete test matrix is presented in Table 4.

Table 3 Summary of the process parameters used in the deep drawing experiments.

No	Variables	Values
1	Drawing speed (mm/min)	25-75-125
2	Springs	(A-B-C)
3	Die inclination angle	12 ⁰

Table 4 Experimental matrix showing the combinations of die inclination angle, drawing speed, and spring assembly used during the deep drawing tests.

Test No.	Die Inclination Angle (°)	Drawing Speed (mm min ⁻¹)	Spring Assembly
1	12	25	A
2		75	
3		125	
4		25	B
5		75	
6		125	
7		25	C
8		75	
9		125	

5. NUMERICAL SIMULATION

Finite element simulations were performed using ABAQUS/CAE 2021 to analyze the deep drawing process and predict the forming load behavior of the conical cups under different processing conditions. The numerical model was developed to replicate the experimental setup as closely as possible and to provide a comprehensive understanding of material deformation during the forming operation. The material properties used in the simulations were obtained from the experimentally measured tensile data presented in Section 3. The true stress–true strain curves derived from the tensile tests were incorporated into the material model to accurately represent the elastoplastic behavior of the AISI 1008 low-carbon steel sheet. The mechanical properties employed in the finite element analysis are summarized in Table 5. The finite element model consisted of four principal components: the punch, die, blank holder, and sheet blank. To reduce computational cost while maintaining simulation accuracy, the punch, die, and blank holder were modeled as rigid bodies, whereas the sheet blank was modeled as a deformable body capable of undergoing large plastic deformation. The assembled finite element model used in the simulation is shown in Figure 7.

The punch, die, and blank holder geometries were created in ABAQUS/CAE using three-dimensional rigid-body elements (R3D3 and R3D4). These rigid components were meshed using a global element size of 3 mm to ensure sufficient geometric representation while minimizing computational requirements. The deformable sheet blank was discretized using three-dimensional reduced-integration solid elements (C3D8R and C3D6), which are suitable for simulating large deformation and contact problems encountered in sheet metal forming processes. To generate a structured mesh with improved element quality, the sweep meshing technique was employed for both shell and solid model configurations. The deep drawing process was simulated using the Dynamic Explicit Solver available in ABAQUS/Explicit. This solver was selected because of its robustness in handling highly nonlinear contact interactions, large plastic deformations, and complex material flow behavior associated with sheet metal forming operations. Appropriate contact interactions were defined between the punch, blank, die, and blank holder surfaces to accurately capture frictional effects and material flow during

deformation. The numerical results obtained from the simulations were subsequently compared with the experimental measurements to validate the finite element model and assess its capability to predict the forming load behavior of the conical deep drawing process.

Table 5 Mechanical properties of AISI 1008 low-carbon steel used in the finite element simulation.

Material	Property	Value
AISI 1008 Low Carbon Steel	Young’s modulus	200 GPa
	Density	7.8 g.cm ⁻³
	Poisson ratio	0.30
	Yield strength	205 MPa

The finite element model developed in this study consisted of four main components: the punch, die, blank holder, and sheet blank. To improve computational efficiency while maintaining simulation accuracy, the punch, die, and blank holder were modeled as rigid bodies, whereas the sheet blank was modeled as a deformable body capable of undergoing large plastic deformation during the deep drawing process. The assembled geometry of the conical cup used in the finite element simulation is illustrated in Figure 7. The punch, die, and blank holder were generated in ABAQUS/CAE 2021 using three-dimensional rigid-body elements (R3D3 and R3D4), while the deformable sheet blank was discretized using reduced-integration solid elements (C3D8R and C3D6). To ensure accurate representation of the geometry and deformation behavior, the sweep meshing technique was employed for generating a structured mesh throughout the model. The resulting finite element mesh and numerical representation of the conical cup are presented in Figure 8, demonstrating the discretization strategy adopted for the deep drawing simulations. This modeling approach enabled accurate prediction of material flow, strain distribution, thickness variation, and forming load during the deep drawing operation.

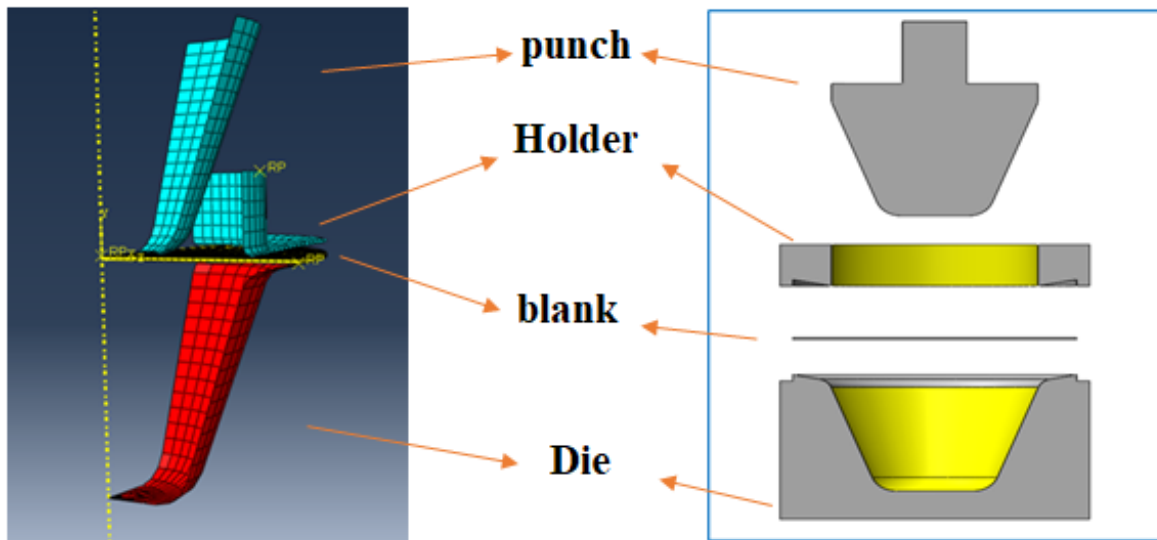


Figure 7 Three-dimensional assembled geometry of the conical cup deep drawing model developed in ABAQUS/CAE 2021.

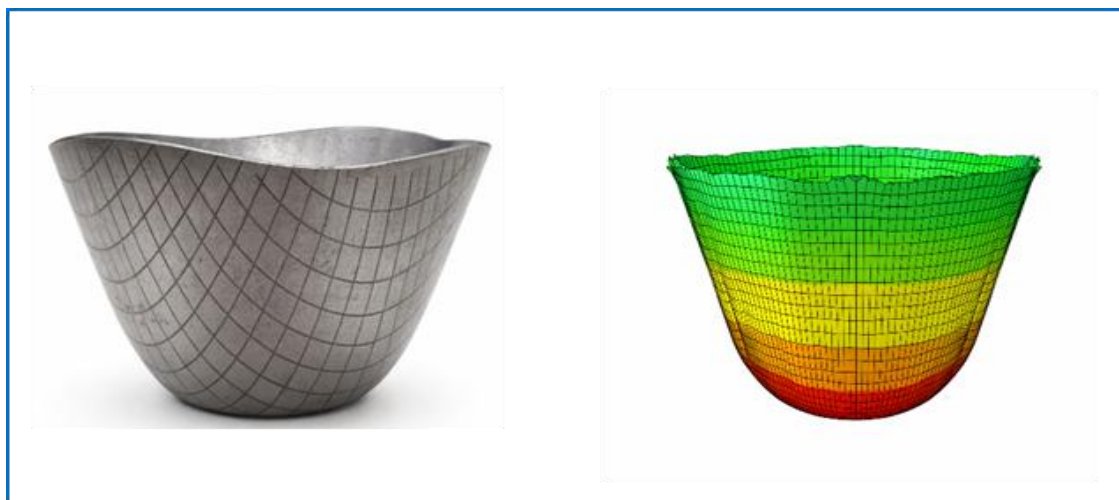


Figure 8 Finite element mesh of the conical cup model showing the discretization scheme employed for the numerical simulation of the deep drawing process.

5.1. Effect of blank holder force at a drawing speed of 25 mm min^{-1} and a die inclination angle of 12°

The influence of blank holder force (BHF) on the forming load was investigated at a constant drawing speed of 25 mm.min^{-1} and a die inclination angle of 12° . Three spring assemblies with different stiffness values were employed to generate different levels of blank holder force. The corresponding forming load–punch travel curves are presented in Figure 9, while the ultimate forming load (UFL) values obtained under each condition are summarized in Table 6. As shown in Figure 9, the forming load increased progressively with punch travel for all spring configurations until reaching a maximum value, after which a slight fluctuation was observed before the final stage of drawing. The overall trend indicates that the blank holder force significantly influences the material flow behavior and the resistance encountered during deformation. According to Table 6, increasing the spring stiffness from

0.053 kN.mm⁻¹ (Spring A) to 0.066 kN.mm⁻¹ (Spring B) resulted in an increase in the ultimate forming load from 34 kN to 36 kN, corresponding to an increase of approximately 5.9%. This behavior can be attributed to the higher blank holder force, which restricts material flow from the flange region into the die cavity and consequently increases the tensile stresses developed within the cup wall. The increased resistance to material movement requires a higher punch force to complete the drawing operation. When the spring stiffness was further increased to 0.072 kN.mm⁻¹ (Spring C), the ultimate forming load reached 35 kN, representing only a marginal increase compared with Spring A and a slight decrease relative to Spring B. This observation suggests the existence of an optimum blank holder force beyond which further increases in stiffness provide limited improvement in process stability while increasing resistance to material flow. The results demonstrate that the forming load is sensitive to changes in blank holder force, particularly at moderate stiffness levels. The highest ultimate forming load of 36 kN was obtained using Spring B (0.066 kN.mm⁻¹), indicating that this condition provides the greatest resistance to material deformation under the investigated processing parameters.

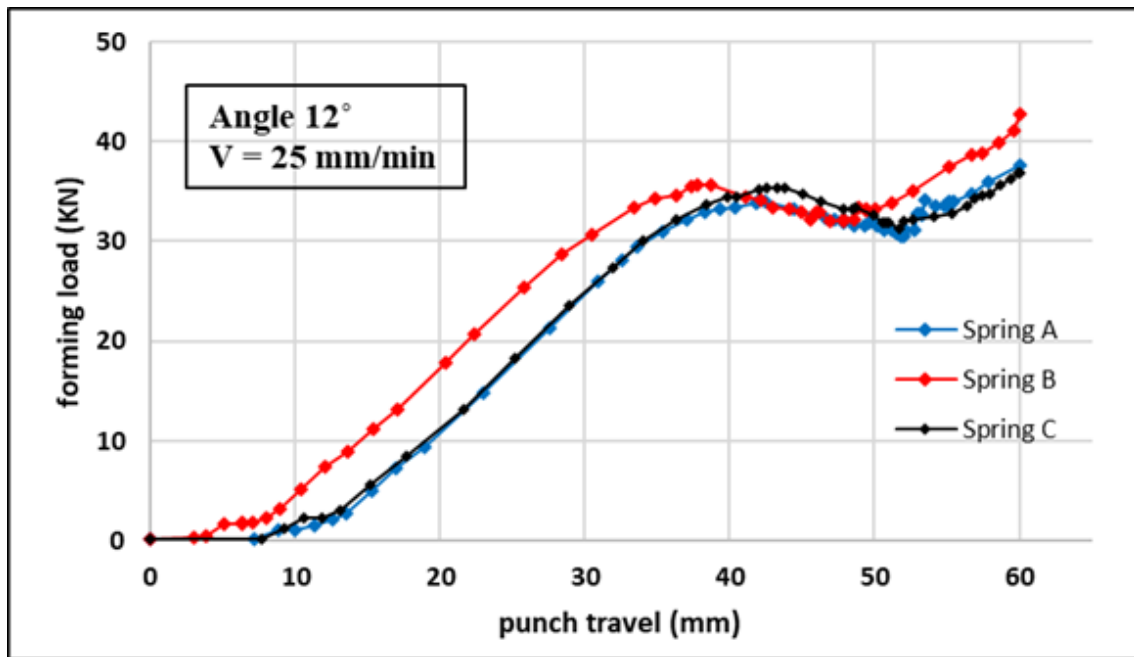


Figure 9 Effect of blank holder force, represented by different spring stiffness values, on the forming load–punch travel behavior at a drawing speed of 25 mm.min⁻¹ and a die inclination angle of 12°.

Table 6 Effect of spring stiffness (blank holder force) on the ultimate forming load at a drawing speed of 25 mm.min⁻¹ and a die inclination angle of 12°.

Springs	Stiffness (KN/mm)	Drawing speed (mm/min)	Ultimate Forming Load (KN)	Punch travel (mm)	Increase (KN)
A	0.053	25	34.00	36.20	—
B	0.066		36.00	37.00	+2.00
C	0.072		35.00	36.80	+1.00

5.2. Effect of blank holder force at a drawing speed of $25 \text{ mm} \cdot \text{min}^{-1}$ and a die inclination angle of 12°

The effect of blank holder force on the forming load was further evaluated at a drawing speed of $75 \text{ mm} \cdot \text{min}^{-1}$ while maintaining a constant die inclination angle of 12° . Three spring assemblies with stiffness values of 0.053 , 0.066 , and $0.072 \text{ kN} \cdot \text{mm}^{-1}$ were employed to generate different levels of blank holder force. The corresponding forming load–punch travel curves are illustrated in Figure 10, whereas the ultimate forming load values are summarized in Table 7. As shown in Figure 10, all spring configurations exhibit a similar trend, where the forming load increases progressively with punch travel until reaching a peak value, followed by a slight decrease and a subsequent increase toward the end of the drawing process. This behavior is attributed to the continuous evolution of contact conditions and material flow during deformation. However, the magnitude of the forming load varies according to the spring stiffness, indicating a significant influence of blank holder force on the drawing process. According to Table 7, increasing the spring stiffness from $0.053 \text{ kN} \cdot \text{mm}^{-1}$ (Spring A) to $0.066 \text{ kN} \cdot \text{mm}^{-1}$ (Spring B) increased the ultimate forming load from 34.0 kN to 36.0 kN , corresponding to an increase of 2.0 kN . This increase is associated with the higher blank holder force, which restricts the flow of material from the flange region and increases the tensile stresses developed in the cup wall. Consequently, a greater punch force is required to overcome the increased resistance to deformation. When the spring stiffness was further increased to $0.072 \text{ kN} \cdot \text{mm}^{-1}$ (Spring C), the ultimate forming load reached 35.5 kN , representing an increase of 1.5 kN compared with Spring A. Although the forming load remained higher than that obtained using Spring A, the increase was less pronounced than that observed for Spring B. This behavior suggests that the influence of blank holder force becomes less significant at higher stiffness levels, indicating a nonlinear relationship between spring stiffness and forming load. The results demonstrate that the deep drawing process at a die inclination angle of 12° remains sensitive to variations in blank holder force. Among the investigated conditions, Spring B ($0.066 \text{ kN} \cdot \text{mm}^{-1}$) produced the highest ultimate forming load of 36.0 kN , indicating the greatest restriction of material flow and resistance to deformation during the drawing operation.

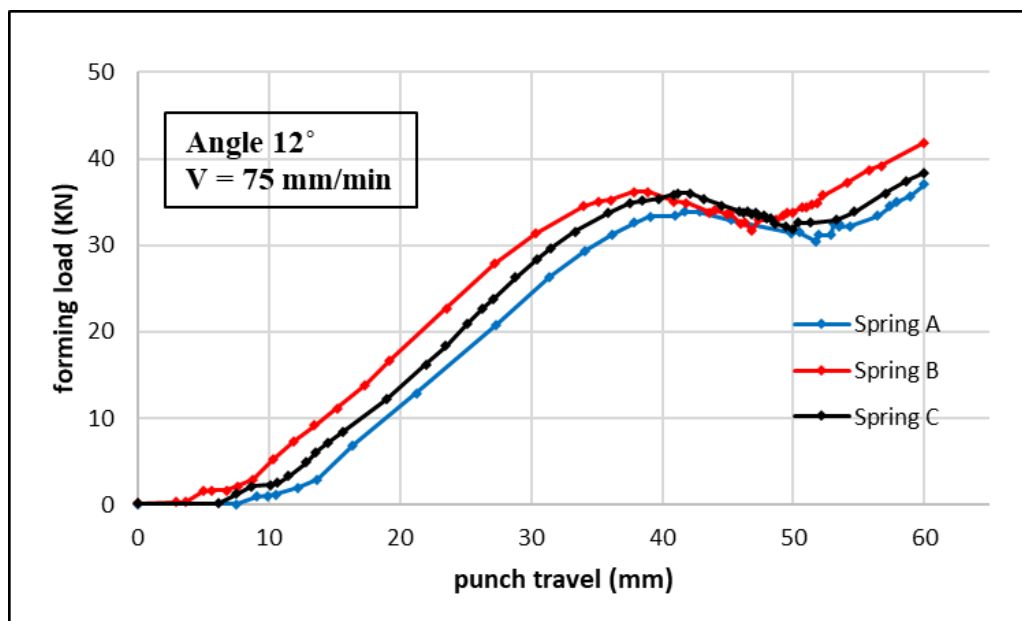


Figure 10 Effect of blank holder force, represented by different spring stiffness values, on the forming load–punch travel curves at a drawing speed of $75 \text{ mm} \cdot \text{min}^{-1}$ and a die inclination angle of 12° .

Table 7 Influence of spring stiffness (blank holder force) on the ultimate forming load at a drawing speed of 75 mm min⁻¹ and a die inclination angle of 12°.

Springs	Stiffness (KN/mm)	Drawing speed (mm/min)	Ultimate Forming Load (KN)	Punch travel (mm)	Increase (KN)
A	0.053	75	34.00	40.00	—
B	0.066		36.00	38.00	+2.00
C	0.072		35.50	40.00	+1.50

5.3. Effect of blank holder force at a drawing speed of 125 mm.min⁻¹ and a die inclination angle of 12°

The influence of blank holder force on the forming load was also examined at a drawing speed of 125 mm.min⁻¹ while maintaining a constant die inclination angle of 12°. Three spring assemblies with stiffness values of 0.053, 0.066, and 0.072 kN.mm⁻¹ were used to provide different levels of blank holder force. The resulting forming load–punch travel curves are presented in Figure 11, and the corresponding ultimate forming load values are summarized in Table 8. As illustrated in Figure 11, the forming load increased progressively with punch travel for all spring configurations until reaching the first peak load, followed by slight fluctuations during the intermediate stage of deformation. Differences in the load–displacement response among the three springs indicate the influence of blank holder force on material flow resistance and deformation behavior. Higher spring stiffness values generally produced higher forming loads due to increased contact pressure between the blank holder and the sheet. According to Table 8, the ultimate forming load increased from 33.36 kN for Spring A (0.053 kN.mm⁻¹) to 34.36 kN for Spring B (0.066 kN.mm⁻¹), representing an increase of 1.00 kN. When the spring stiffness was further increased to 0.072 kN mm⁻¹ (Spring C), the ultimate forming load reached 35.21 kN, corresponding to an increase of 1.85 kN relative to Spring A. This gradual increase in forming load can be attributed to the higher blank holder force, which increases frictional resistance and contact pressure in the flange region, thereby restricting material flow into the die cavity. The results indicate that increasing blank holder force enhances the resistance to deformation and consequently increases the required punch load. However, the increase in forming load is not directly proportional to the increase in spring stiffness. The reduced rate of load increase at higher stiffness values suggests the existence of a nonlinear relationship between blank holder force and forming load. This behavior indicates that beyond a certain blank holder force level, additional increases in stiffness provide only marginal changes in forming load while potentially increasing energy consumption and tool loading.

The results demonstrate that the deep drawing process remains sensitive to blank holder force at a drawing speed of 125 mm.min⁻¹, with Spring C (0.072 kN.mm⁻¹) producing the highest ultimate forming load of 35.21 kN among the investigated conditions.

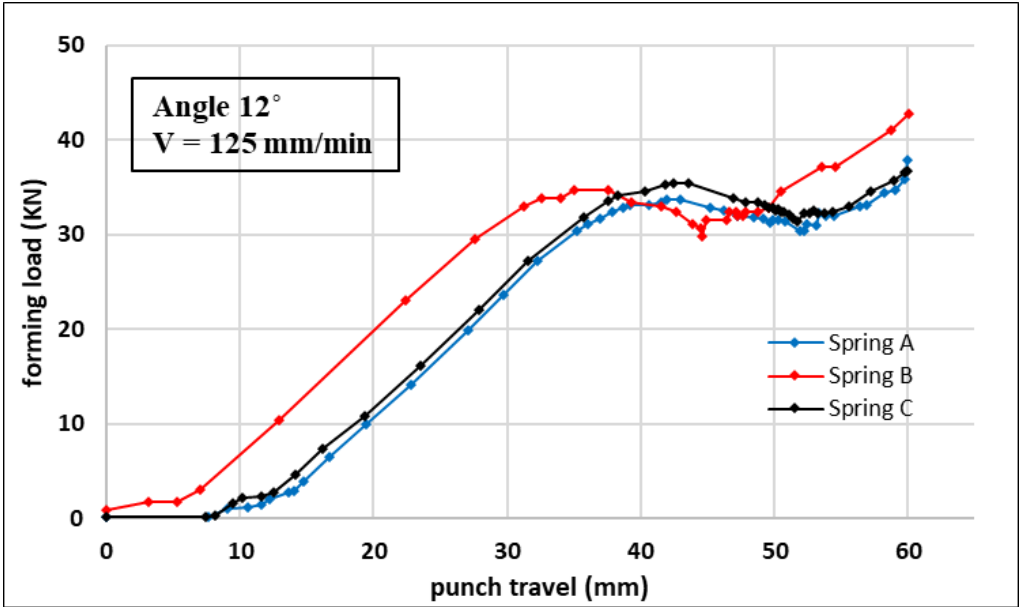


Figure 11 Effect of blank holder force, represented by different spring stiffness values, on the forming load–punch travel curves at a drawing speed of 125 mm min⁻¹ and a die inclination angle of 12°.

Table 8 Influence of spring stiffness (blank holder force) on the ultimate forming load at a drawing speed of 125 mm min⁻¹ and a die inclination angle of 12°.

Springs	Stiffness (KN/mm)	Drawing speed (mm/min)	Ultimate Forming Load (KN)	Punch travel (mm)	Increase (KN)
A	0.053	125	33.36	41.49	—
B	0.066		34.36	35.39	+1.00
C	0.072		35.21	42.41	+1.85

5.4. Effect of drawing speed at a spring stiffness of 0.053 kn.mm⁻¹ and a die inclination angle of 12°

The influence of drawing speed on the forming load was investigated using Spring A with a stiffness of 0.053 kN.mm⁻¹ while maintaining a constant die inclination angle of 12°. Three drawing speeds, namely 25, 75, and 125 mm.min⁻¹, were employed to evaluate their effect on the load–displacement behavior during the deep drawing process. The corresponding forming load–punch travel curves are presented in Figure 12, while the ultimate forming load values are summarized in Table 9. As shown in Figure 12, the forming load–punch travel curves obtained at the three drawing speeds exhibit very similar trends throughout the deformation process. The load increases gradually with punch travel until reaching the first peak load, followed by a slight reduction and a subsequent increase toward the final stage of drawing. The close overlap of the curves indicates that drawing speed has a relatively limited influence on the forming load under the investigated conditions. The results presented in Table 9 reveal that the ultimate forming load remained almost unchanged when the drawing speed increased from 25 mm.min⁻¹ to 75 mm.min⁻¹, with both conditions producing a peak load of 34.0 kN. Further increasing the drawing speed to 125 mm.min⁻¹ resulted in a slight reduction in the ultimate forming load to 33.5 kN, corresponding to a decrease of 0.5 kN. This minor reduction may be attributed to changes in frictional conditions and material flow characteristics at higher drawing speeds, which slightly reduce the resistance to deformation. The results indicate that drawing speed has a negligible effect on the ultimate forming load when a spring stiffness of 0.053 kN.mm⁻¹ is used. The similarity of

the load–displacement curves suggests that the deformation behavior is primarily governed by the blank holder force and die geometry rather than the punch speed within the investigated speed range. Consequently, variations in drawing speed between 25 and 125 mm.min⁻¹ do not significantly affect the forming load under these processing conditions.

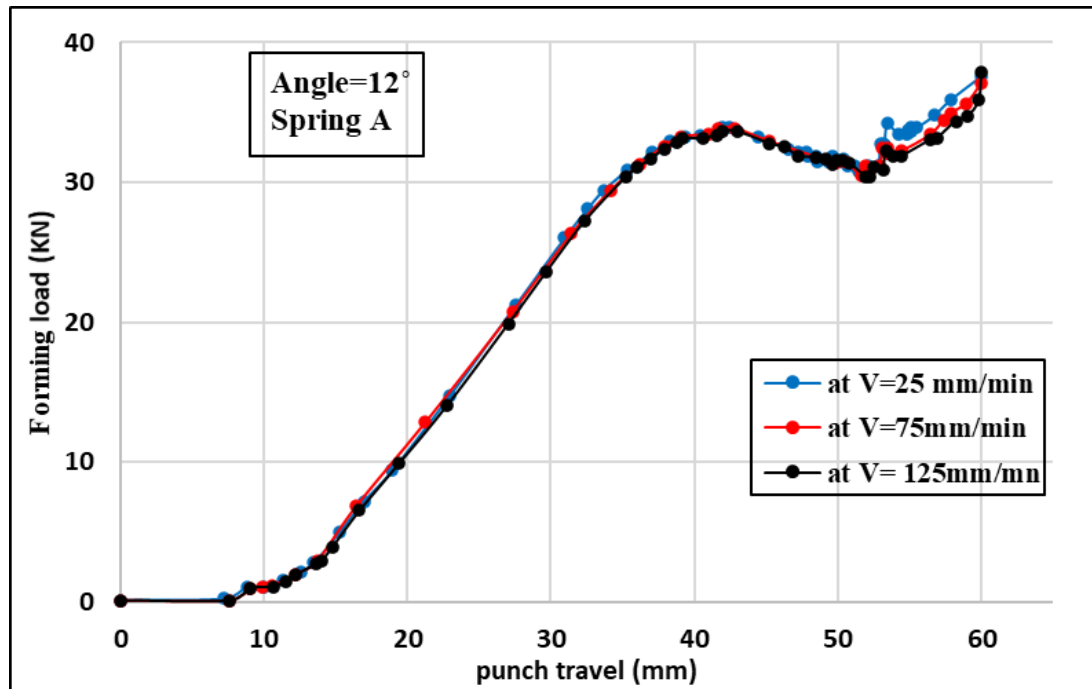


Figure 12 Effect of drawing speed on the forming load–punch travel behavior at a spring stiffness of 0.053 kN.mm⁻¹ (Spring A) and a die inclination angle of 12°

Table 9 Effect of drawing speed on the ultimate forming load at a die inclination angle of 12° and a spring stiffness of 0.053 kN.mm⁻¹ (Spring A).

Springs	Stiffness (KN/mm)	Drawing Speed (mm/min)	Ultimate Forming Load (KN)	Increase (KN)
A	0.053	25	34.0	—
		75	34.0	0.00
		125	33.5	−0.50

5.5. Effect of drawing speed at a spring stiffness of 0.066 kN.mm⁻¹ and a die inclination angle of 12°

The effect of drawing speed on the forming load was investigated using Spring B with a stiffness of 0.066 kN.mm⁻¹ while maintaining a constant die inclination angle of 12°. Drawing speeds of 25, 75, and 125 mm.min⁻¹ were applied to evaluate their influence on the forming behavior of the conical cup. The resulting forming load–punch travel curves are presented in Figure 13, and the corresponding ultimate forming load values are summarized in Table 10. As illustrated in Figure 13, the forming load increases progressively with punch travel for all drawing speeds until reaching the first peak load, followed by a slight reduction before increasing again during the final stage of deformation. The load–displacement curves exhibit very similar profiles, indicating that the overall deformation behavior is only marginally affected by the variation in drawing speed. According to Table 10, increasing the drawing speed from 25 mm.min⁻¹ to 75 mm min⁻¹ increased the ultimate forming load from 35.0 kN to

36.0 kN, corresponding to an increase of 1.0 kN. This increase may be attributed to the higher strain rate and the resulting increase in deformation resistance during the forming process. However, when the drawing speed was further increased to 125 mm.min⁻¹, the ultimate forming load decreased slightly to 34.5 kN, representing a reduction of 0.5 kN relative to the value obtained at 25 mm.min⁻¹. The slight reduction in forming load at 125 mm.min⁻¹ may be associated with changes in frictional conditions and improved material draw-in at higher punch speeds. Increased drawing speed can reduce the effective contact time between the tooling and the sheet, resulting in a marginal decrease in frictional resistance. Nevertheless, the observed differences remain relatively small, confirming that drawing speed has a limited influence on the first peak forming load under the investigated conditions. Tufts indicate that the forming load is only slightly affected by variations in drawing speed when using Spring B (0.066 kN.mm⁻¹). The maximum ultimate forming load of 36.0 kN was obtained at a drawing speed of 75 mm.min⁻¹, whereas the lowest value of 34.5 kN was recorded at 125 mm.min⁻¹. These findings suggest that blank holder force plays a more dominant role than drawing speed in determining the forming load during the deep drawing process.

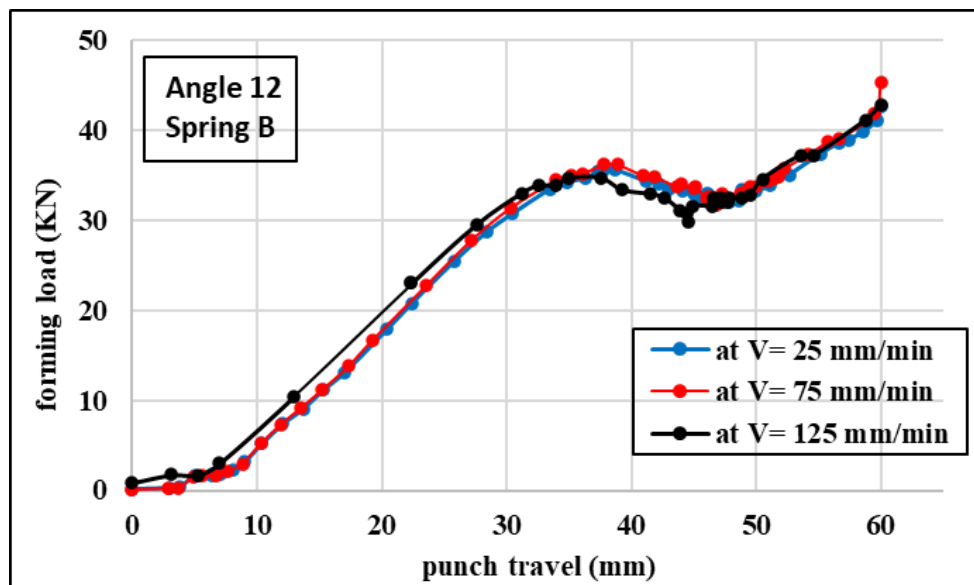


Figure 13 Effect of drawing speed on the forming load–punch travel curves at a spring stiffness of 0.066 kN.mm⁻¹ (Spring B) and a die inclination angle of 12°.

Table 10 Effect of drawing speed on the ultimate forming load at a die inclination angle of 12° and a spring stiffness of 0.066 kN.mm⁻¹ (Spring B).

Springs	Stiffness (kN/mm)	Drawing Speed (mm/min)	Ultimate Forming Load (kN)	Increase (kN)
B	0.066	25	35.0	—
		75	36.0	+1.0
		125	34.5	−0.5

5.6. Effect of drawing speed at a spring stiffness of 0.072 kN.mm⁻¹ and a die inclination angle of 12°

The influence of drawing speed on the forming load was investigated using Spring C with a stiffness of 0.072 kN.mm⁻¹ while maintaining a constant die inclination angle of 12°. Three drawing speeds of 25,

75, and 125 mm.min⁻¹ were employed to evaluate their effect on the load–displacement response during the deep drawing process. The corresponding forming load–punch travel curves are presented in Figure 14, while the ultimate forming load values are summarized in Table 11. As shown in Figure 14, the forming load increased progressively with punch travel for all drawing speeds until reaching the first peak load, followed by a slight reduction and a subsequent increase during the final stage of drawing. Although the overall shape of the load–displacement curves remains similar, slight differences can be observed in the peak load values, indicating the influence of drawing speed on the deformation behavior. According to Table 11, increasing the drawing speed from 25 mm.min⁻¹ to 75 mm.min⁻¹ increased the ultimate forming load from 35.5 kN to 36.5 kN, corresponding to an increase of 1.0 kN. This increase can be attributed to the strain-rate effect, where higher deformation rates enhance the material resistance to plastic flow and consequently require a greater punch force. When the drawing speed was further increased to 125 mm min⁻¹, the ultimate forming load decreased slightly to 36.0 kN, representing an increase of only 0.5 kN relative to the value obtained at 25 mm.min⁻¹. The slight reduction in forming load at the highest drawing speed may be associated with changes in frictional behavior and material flow conditions during deformation. Increased punch speed can promote smoother material draw-in and reduce the effective resistance at the flange region, partially compensating for the strain-rate strengthening effect. As a result, the increase in forming load becomes less pronounced at higher drawing speeds. The results indicate that the effect of drawing speed on the forming load remains relatively limited compared with the influence of blank holder force. The highest ultimate forming load of 36.5 kN was obtained at a drawing speed of 75 mm.min⁻¹, suggesting that this condition provides the greatest resistance to deformation under the investigated processing parameters. The observed variations confirm that the forming load is governed by a combination of material strain-rate sensitivity, frictional conditions, and blank holder force during the deep drawing process.

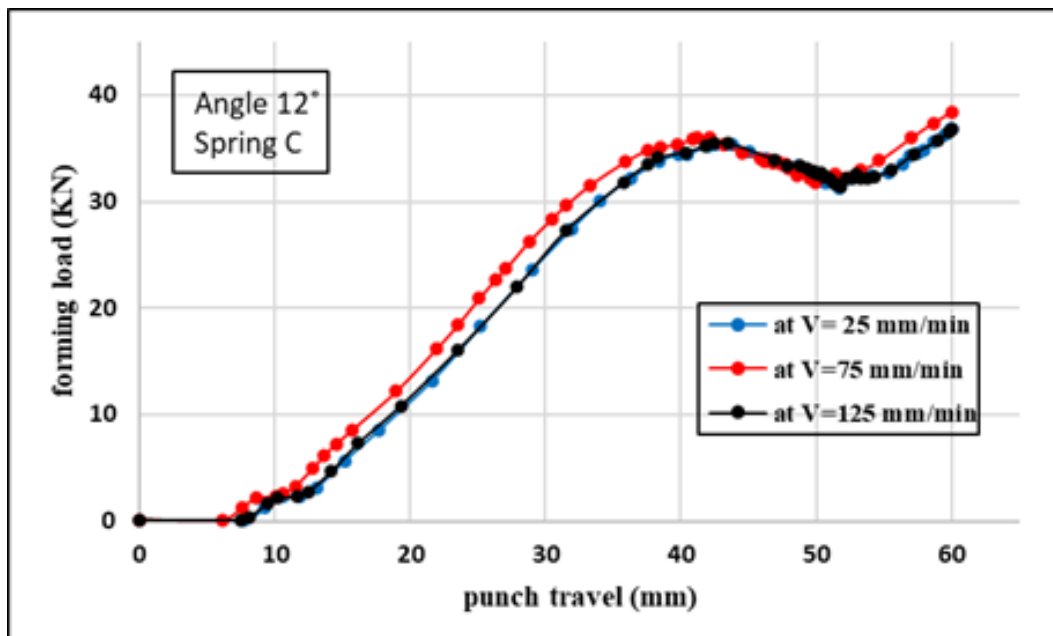


Figure 14 Effect of drawing speed on the forming load–punch travel curves at a spring stiffness of 0.072 kN.mm⁻¹ (Spring C) and a die inclination angle of 12°.

Table 11 Effect of drawing speed on the ultimate forming load at a die inclination angle of 12° and a spring stiffness of 0.072 kN.mm⁻¹ (Spring C).

Springs	Stiffness (KN/mm)	Drawing Speed (mm/min)	Ultimate Forming Load (KN)	Increase (KN)
C	0.072	25	35.5	—
		75	36.5	+1.0
		125	36.0	+0.5

5.7. Nanotechnology implications of the deep drawing process

The present results have important implications for nanotechnology-assisted manufacturing. The increase in forming load with increasing blank holder force indicates greater resistance to material flow, which influences the development of localized strain gradients and surface morphology. Such deformation characteristics become increasingly significant in micro-forming and nano-manufacturing applications where even small variations in stress distribution can affect component performance. The finite element simulations revealed localized regions of high stress concentration near the punch radius and flange regions. These areas are potential sites for grain refinement, microstructural evolution, and nano-scale surface modification during forming operations. Furthermore, the accurate prediction of forming loads contributes to the development of precision forming technologies used for manufacturing miniaturized metallic components in biomedical, electronic, and aerospace applications. The coupled experimental–numerical approach demonstrated in this study provides a framework for future investigations involving nano-coated sheets, nano-reinforced metals, and advanced surface-engineered materials subjected to deep drawing operations.

Table 12 Relevance of deep drawing parameters to nanotechnology-based manufacturing.

Process Parameter	Nano-scale Influence	Engineering Significance
Blank Holder Force	Controls local strain gradients	Surface integrity
Drawing Speed	Influences deformation rate	Microstructural evolution
Die Angle	Alters stress concentration	Thickness uniformity
Friction Condition	Affects surface morphology	Nano-scale wear behavior
Forming Load	Determines deformation resistance	Precision manufacturing

Figure 15 illustrates various deformation mechanisms, defect formation phenomena, and stress distribution characteristics associated with the deep drawing process from both macroscopic and microstructural perspectives. Figure 15(a) schematically illustrates the stress–strain states that develop in the sheet material during deep drawing, particularly around the die corner region. As the punch forces the blank into the die cavity, the material undergoes simultaneous bending and stretching.

Tensile stresses are generated on the outer surface of the sheet, while compressive stresses develop on the inner surface adjacent to the die radius. The neutral axis separates these two regions and shifts during deformation due to non-uniform strain distribution. The figure also highlights the transition from plane stress conditions in the flange region to more complex biaxial stress states near the punch and die radii. These localized stress concentrations strongly influence material flow, thickness variation, and the onset of defects such as tearing or excessive thinning. Figure 15(b) presents the “orange peel” surface defect commonly observed in deep-drawn components. This phenomenon appears as a rough, uneven surface texture resembling the skin of an orange and is primarily associated with coarse grain structures within the sheet material. During plastic deformation, grains deform non-uniformly, leading to localized surface protrusions and depressions. The severity of orange peel

increases with larger grain sizes and higher deformation levels. The defect negatively affects surface quality, dimensional accuracy, and aesthetic appearance. Refinement of grain structure through appropriate material processing and heat treatment is an effective method for minimizing this defect during deep drawing operations. Figure 15(c) shows the finite element stress distribution across the conical cup during the deep drawing process. The color contours indicate regions of varying stress intensity on both the outer and inner surfaces of the formed component. Higher stress concentrations are observed near the punch radius and die corner regions where severe plastic deformation occurs.

The stress gradients reveal non-uniform deformation behavior throughout the cup wall, with the maximum stresses located in regions experiencing significant stretching and bending. Such stress distributions are important for predicting thickness reduction, localized strain accumulation, and potential failure zones. The finite element results provide valuable insight into process optimization and tool design. Figure 15(d) illustrates the material flow mechanism occurring during deep drawing. As the punch moves downward, material from the flange region is drawn inward and subjected to tensile stresses along the cup wall. Simultaneously, the material experiences bending over the die radius followed by unbending as it enters the wall section. This repeated bending–unbending process contributes significantly to plastic deformation and strain hardening. The figure demonstrates how tensile forces promote material flow while maintaining the continuity of the formed component. Understanding this deformation mechanism is essential for controlling wrinkling, tearing, and thickness variations during the deep drawing operation.

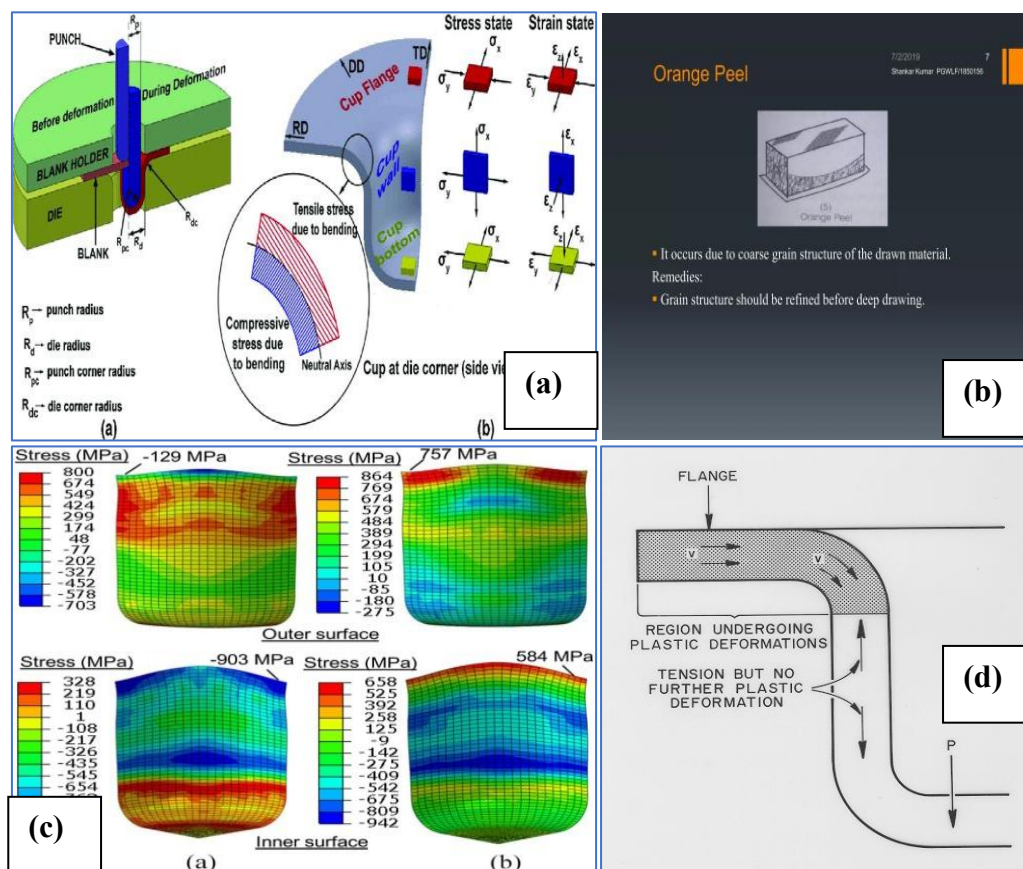


Figure 15 Deep drawing deformation mechanisms and defect formation: (a) stress and strain states developed during bending and drawing around the die corner region, (b) orange peel surface defect caused by coarse grain structure, (c) finite element stress distribution showing localized stress concentrations on the formed cup, and (d) schematic representation of material flow and plastic deformation during deep drawing.

6. CONCLUSION

This study presented a coupled experimental and finite element investigation of the deep drawing behavior of conical cups manufactured from AISI 1008 low-carbon steel sheets. The influence of key process parameters, namely blank holder force (BHF) and drawing speed, on the forming load was systematically evaluated using a specially designed conical die with an inclination angle of 12° and a conical punch with a wall angle of 70° . Experimental deep drawing tests were conducted using three spring stiffness values and three drawing speeds, while finite element simulations were performed using ABAQUS/Explicit to predict the deformation behavior and forming load response. The results demonstrated that the forming load increased with increasing blank holder force due to the higher contact pressure and frictional resistance developed in the flange region, which restricted material flow into the die cavity. Among the investigated conditions, the maximum forming load of 36.5 kN was obtained at a drawing speed of 75 mm min^{-1} using a spring stiffness of 0.072 kN mm^{-1} and a die inclination angle of 12° . The findings also revealed that increasing the drawing speed from 25 mm min^{-1} to 75 mm min^{-1} slightly increased the forming load because of strain-rate effects and enhanced deformation resistance. However, further increasing the drawing speed to 125 mm min^{-1} produced only a marginal increase or slight reduction in the forming load, which was attributed to changes in frictional conditions and improved material flow characteristics during deformation. Furthermore, the numerical simulations showed good agreement with the experimental measurements, with a maximum discrepancy of approximately 13%, confirming the capability of the developed finite element model to accurately predict the forming behavior of conical cups. From a nanotechnology perspective, the present work demonstrates that deep drawing parameters significantly influence deformation behavior and surface integrity, which are critical factors in advanced manufacturing applications. The validated finite element model provides a useful platform for future studies involving nano-structured materials, micro-forming technologies, and precision manufacturing processes. The integration of experimental measurements with numerical simulation offers an effective methodology for optimizing forming conditions in emerging nano-engineered metallic components. Therefore, the validated numerical model can serve as an effective tool for process optimization and design of deep drawing operations involving inclined conical geometries.

References

- [1] A. Taşkın, M. Karaağaç, A. Gürünlü, The International Journal of Advanced Manufacturing Technology 132 (2024) 39 <https://doi.org/10.1007/s00170-024-13477-z>
- [2] W. M. Shewakh, M. M. El-Sebaie, Processes 12 (2024) 525 <https://doi.org/10.3390/pr12030525>
- [3] Z. H. Mohsein, A. M. Al-Sultani, Technology & Applied Science Research 14 (2024) 14500 <https://doi.org/10.48084/etasr.70731>
- [4] J. Leelaseat, P. Uthaisangsuk, S. Mahabunphachai, Metals 15 (2025) 68 <https://doi.org/10.3390/met15010068>
- [5] C. Klaynil, S. Mahabunphachai, P. Uthaisangsuk, Discover Mechanical Engineering 5 (2025) 99 <https://doi.org/10.1007/s44245-025-00135-1>
- [6] E. Hedayati, A. Hedayati, M. Vahedi, S. Faroughi, American Journal of Engineering and Applied Sciences 18 (2025) 39 <https://doi.org/10.3844/ajeassp.2025.39.46>
- [7] A. Abd-Eltwab, M. El-Sebaie, M. El-Hadek, Journal of Engineering Sciences 53 (2025) 137 <https://doi.org/10.21608/jesaun.2025.453723>
- [8] E. Abdullah, H. Al-Azzawi, S. Hamza, Journal of Machine Engineering 25 (2025) 11 <https://doi.org/10.36897/jme/202922>
- [9] E. Shamso, M. Salem, H. Ahmed, Scientific Reports 16 (2026) 77 <https://doi.org/10.1038/s41598-026-43324-w>

- [10] V. D. Quang, N. H. Nguyen, T. M. Le, *European Journal of Engineering Research and Science* 11 (2026) 345 <https://doi.org/10.24018/ejers.2026.11.2.4089>
- [11] W. M. Shewakh, M. M. El-Sebaie, *Processes* 12 (2024) 1 <https://doi.org/10.3390/pr12030525>
- [12] A. Kaimkuriya, A. A. Hassan, M. El-Sebaie, *MATEC Web of Conferences* 398 (2024) 79 <https://doi.org/10.1051/mateconf/202439801017>
- [13] A. Taşkın and M. Karaağaç, *The International Journal of Advanced Manufacturing Technology* 132 (2024) 973 <https://doi.org/10.1007/s00170-024-13477-z>
- [14] J. Leelaseat, P. Uthaisangsuk, S. Mahabunphachai, *Metals* 15 (2025) 55 <https://doi.org/10.3390/met15010068>
- [15] A. Parveen, *J. Cond. Matter*, 3 (2025) 124. <https://doi.org/10.61343/jcm.v3i02.70>
- [16] D. S. Silversmit et al., *J. Sol–Gel Sci. Technol.*, 61 (2012) 61. <https://doi.org/10.1016/j.ceramint.2020.06.185>
- [17] M. Sadeldine, *Experimental and Theoretical NANOTECHNOLOGY*, 9 (2025) 1 <https://doi.org/10.56053/9.1.1>
- [18] N. M. Slaber, J. S. Kith, *Experimental and Theoretical NANOTECHNOLOGY*, 9 (2025) 9 <https://doi.org/10.56053/9.1.9>
- [19] Nabaa Abbas Zubaidi, Mustafa Kareem AL-Azzawi, Marwan Saleh Mahdi, Murtadha Hadi Ajmi, *Experimental and Theoretical NANOTECHNOLOGY*, 9 (2025) 15 <https://doi.org/10.56053/9.S.15>
- [20] H. I. Ahmed, *AIP Conference Proceedings*, 2235 (2020) 020038. <https://doi.org/10.1063/5.0008913>
- [21] H. I. Ahmed, *AIP Conference Proceedings*, 2235 (2020) 020038. <https://doi.org/10.1063/5.0008913>
- [22] A. Abd-Eltwab, M. El-Sebaie, M. El-Hadek, *Journal of Engineering Sciences* 53 (2025) 25 <https://doi.org/10.21608/jesaun.2025.453755>
- [23] V. D. Quang, N. H. Nguyen, T. M. Le, *European Journal of Engineering Research and Science* 11 (2026) 77 <https://doi.org/10.24018/ejers.2026.11.2.4089>
- [24] E. Shamso, M. Salem, H. Ahmed, *Scientific Reports* 16 (2026) 91 <https://doi.org/10.1038/s41598-026-43323-w>
- [25] C. Klaynil, P. Uthaisangsuk, S. Mahabunphachai, *Discover Mechanical Engineering* 5 (2025) 133 <https://doi.org/10.1007/s44245-025-00135-1>
- [26] E. Abdullah, H. Al-Azzawi, S. Hamza, *Journal of Machine Engineering* 25 (2025) 99 <https://doi.org/10.36897/jme/202911>
- [27] Hussein Shundi Alhaji Al-Gharbawi, Marwan Saleh Mahdi, Mustafa Naeem Nuhair Al-sarray, Sajjad Jawad Kadhi Al-sarray, *Experimental and Theoretical NANOTECHNOLOGY*, 9 (2025) 27 <https://doi.org/10.56053/9.S.27>
- [28] Hajir Maher Abdullah, Mojahid M. Najim, Ban A. Yousif, *Experimental and Theoretical NANOTECHNOLOGY*, 9 (2025) 39 <https://doi.org/10.56053/9.S.39>
- [29] K. M. Parida, S. Singha, *Appl. Surf. Sci.* 256 (2025) 2670. <https://doi.org/10.1016/j.apsusc.2024.162088>
- [30] I. Sondi, B. Salopek-Sondi, *J. Colloid Interface Sci.*, 275 (2004) 177. <https://doi.org/10.1016/j.jcis.2004.03.013>
- [31] R. S. Mahmood, et al., *Journal of the Mechanical Behavior of Materials*, 34 (2025) 1. <https://doi.org/10.1515/jmbm-2025-0040>
- [32] A. K. Geim, K. S. Novoselov, *Nat. Mater.*, 6 (2021) 183 <https://doi.org/10.32350/bsr.0303.01>
- [33] Alaa M. Theban, Falah H. Ali, *Experimental and Theoretical NANOTECHNOLOGY*, 9 (2025) 51 <https://doi.org/10.56053/9.S.51>
- [34] Hajir Maher Abdullah, Mojahid M. Najim, Ban A. Yousif, *Experimental and Theoretical NANOTECHNOLOGY*, 9 (2025) 67 <https://doi.org/10.56053/9.S.67>
- [35] H. Hasan, A. Nooruldeen, H. I. Ahmed, and M. J. Jaafer, *Periodicals of Engineering and Natural Sciences (PEN)*, 8 (2020) 2 727. <https://doi.org/10.21533/pen.v8.i2.1100>

- [36] M. Rai, A. Yadav, A. Gade, *Biotechnol. Adv.*, 27 (2009) 76.
<https://doi.org/10.1016/j.biotechadv.2008.09.002>
- [37] S. P. Dubey, M. Lahtinen, M. Sillanpää, *Collo. Sur. A: Phys. Eng. Asp.*, 364 (2010) 34.
<https://doi.org/10.1016/j.colsurfa.2010.05.033>
- [38] Y. K. Shin, H. Kwak, A. V. Vasenkov, D. Sengupta, A. C. T. van Duin, *ACS Catal.* 5 (2015) 7226. <https://doi.org/10.1021/acscatal.5b01766>
- [39] Zainab R.Muslim, Ali Q . Kadhum, Zina A. Al Shadidi, Smah A.Kadhum, *Experimental and Theoretical NANOTECHNOLOGY*, 9 (2025) 79 <https://doi.org/10.56053/9.S.79>
- [40] A. Ahmed, M. A. Salam, A. A. El-Sayed, *J. Inorg. Organomet. Polym.*, 28 (2018) 2418.
<https://doi.org/10.62441/nano-ntp.v20is7.33>
- [41] M. A. Valenzuela, P. Bosch, T. López, *J. Mol. Catal. A Chem.*, 167 (2017) 103.
<https://doi.org/10.1016/j.matchemphys.2017.09.047>
- [42] Ali Q. Kadhum, Zainab R.Muslim, Zina A. Al Shadidi, Asmaa S.Khaleel, *Experimental and Theoretical NANOTECHNOLOGY*, 9 (2025) 87 <https://doi.org/10.56053/9.S.87>
- [43] Fadhaa Bader Hadi, Ahmed Jadah Farhan, *Experimental and Theoretical NANOTECHNOLOGY*, 9 (2025) 93 <https://doi.org/10.56053/9.S.93>
- [44] Z. H. Mohsein and A. M. Al-Sultani, *Engineering, Technology & Applied Science Research* 14 (2024) 55 <https://doi.org/10.48084/etasr.7072>