

Experimental and Numerical Investigation of Deep Drawing Process for Carbon Fiber Reinforced High Density Polyethylene (CF-HDPE) Composites

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Abstract

This study investigates the deep drawing process of carbon fiber-reinforced high-density polyethylene (CF-HDPE) composites through experimental and numerical approaches. The experimental part involved fabricating CF-HDPE sheets and conducting deep drawing operations under controlled parameters (punch speed, temperature, and forming depth) to evaluate material behavior and mechanical properties. Numerically, finite element analysis (FEA) using ABAQUS simulated the forming process, analyzing stress distribution, strain development, and material deformation under varying conditions. Results revealed that increasing forming depth and decreasing forming temperature elevated the required forming force. Comparisons between experimental and numerical outcomes showed consistent trends, though some differences arose due to factors like friction and material nonlinearity. The findings contribute to optimizing deep drawing processes for composite materials, enhancing manufacturing precision, and minimizing material defects.

1. Introduction

Polymeric materials are widely used in industries because they are lightweight, corrosion resistant, excellent formability and moldability, recyclable, and can be manufactured after being combined with fibers [1]-[5].

With excellent mechanical properties, a high strength to weight ratio, excellent durability [6], and resistance to environmental factors like moisture and chemicals [7], fibres are widely used in industries. They show exceptional flexibility in design and can easily be incorporated into composite materials to improve the performance of the structure [8], [9]. They also impart better thermal and electrical properties, and so their application ranges to thousands of different fields, from aerospace to automobile and construction industries to sports equipment [10], [11]. The possibility of recyclability [12] and compatibility with various polymeric matrices offers an opportunity for elaborating sustainable, cost-effective composite solutions that might respond to the ever-growing demand for high-performance materials in the current applications of engineering [13].

The main forming methods of composite materials include Single point incremental forming-SPIF, vacuum forming, and compression molding [14].

Single point incremental forming, SPIF, is the process where localized pressure is applied to thermoplastic sheets to form a complex shape with great flexibility at low tooling cost.

This is one of the most common forming processes for making custom parts with complex geometries [15], [17].

In the vacuum forming process, the heated sheets are driven over forms by vacuum pressure. The method is particularly suitable for large lots of relatively simple components. Advantages of the process include minimum material waste and very repetitive manufacturing process [18], [19].

Compression molding refers to a technique where high-pressure application is implemented on composite materials that are in a heated condition inside a mold to generate tough and rigid parts. Some of the common techniques employed to manufacture high strength components with standard quality include sheet molding compound, SMC, and injection molding [20]-[22].

It provides precise predictions for research purposes since numerical methods and software programs allow simulating various composite forming techniques to a high level of precision. Among the commonly used numerical methods, Finite Element Analysis is highly used in the simulation of composite forming processes because of its ability to evaluate stress distribution, strain development, and material flow for different forming conditions. Numerical simulations identify possible defects like wrinkling, tearing, and thickness variations before the real manufacture is done, hence improving quality and reducing waste [14].

Several software generally used for the simulation and optimization of composite forming techniques include

ABAQUS, CAD CAM, CATIA V5, MasterCAM, and SolidWorks. ABAQUS is a powerful finite element analysis software used in the prediction of material behavior, optimizing process parameters, and refining tool design [23]. CAD CAM will be utilized for the modeling of forming operation, which allows modeling of composite structures and tool paths in exactly the same way [24]. CATIA V5 is one of the currently widely used design software that offers 3D modeling and analysis of composite parts which allow creating even complex geometries within the forming process [25]. MasterCAM is used to make tool paths and optimize machining strategies within the forming process operation of composites [26]. SolidWorks provides robust modeling capabilities and simulation tools to evaluate deformation and stress distribution during the forming process [27].

The deep drawing process of composite materials made of (CF-HDPE) is studied. These materials are characterized by excellent mechanical properties, such as a high strength to weight ratio, corrosion resistance, and recyclability. They combine the structural benefits of carbon fibers, such as high stiffness and thermal stability, with the flexibility and impact resistance of HDPE, making them suitable for various industrial applications.

The study employs two primary methodologies: theoretical analysis through numerical simulations using ABAQUS software and experimental analysis through composite material fabrication and deep drawing operations under different process parameters.

On the theoretical side, finite element analysis was carried out to predict the behavior of CF-HDPE sheets during the forming process. The simulations included key parameters such as forming depth, temperature, and punch speed to provide insights into stress and strain distributions, material deformation, and potential defects such as wrinkling and thinning.

The sheets were made using CF-HDPE and aluminum molds in a controlled experimental setup. Varying punch speeds, forming depths, and temperatures were applied in the forming process to understand their effect on the material's structural integrity.

The theoretical analysis as well as experimentally obtained data provide a more developed insight into process optimization for manufacturing composite materials deep drawing, thereby potentially widening both product performance improvement and industrial use.

2. Experimental part

The selection of woven carbon fibers (WCFs), high-density polyethylene (HDPE), and aluminum alloys is based on their complementary properties. The high tensile strength, stiffness, and low weight of WCFs make them ideal materials for applications where weight reduction and durability are crucial. Additionally, WCFs offer excellent thermal stability, making them suitable for high-performance applications. HDPE is chosen for its outstanding processability, chemical resistance, and impact strength, as demonstrated in Table 1 [28]-[30] and Fig. 1. These properties ensure HDPE's suitability for composite applications that require resilience and ease of processing. Aluminum alloys are selected for mold fabrication in the forming process due to their lightweight nature, ease of machining, and high thermal conductivity [31], which facilitates uniform and rapid heat distribution. These

characteristics contribute to achieving consistent forming conditions and improved material performance.

Aluminum molds are manufactured for the purpose of producing composite materials accurately and easily. Two molds are created: composite sheet forming mold and forming die, each with different functions in the production process. The composite sheet fabrication mold is designed to manufacture composite sheets made of HDPE and woven carbon fiber WCF.

Table 1 Mechanical properties of T300 WCFs and HDPE

Property	T300 Woven Carbon Fiber	HDPE
Density	1.6 g/cm ³	954 kg/m ³
Elastic Modulus	240 GPa	750 MPa
Tensile Strength	3400 MPa	23 MPa (Yield) 12 MPa (Break)
Elongation at Break	1.7 %	200 %
Poisson's Ratio	0.25	-
Shear Strength	40 MPa	-
Flexural Modulus	-	800 MPa
Izod Impact Strength	-	28 J/m
Vicat Softening Point	-	121 °C
Brittleness Temperature	-	< -75 °C

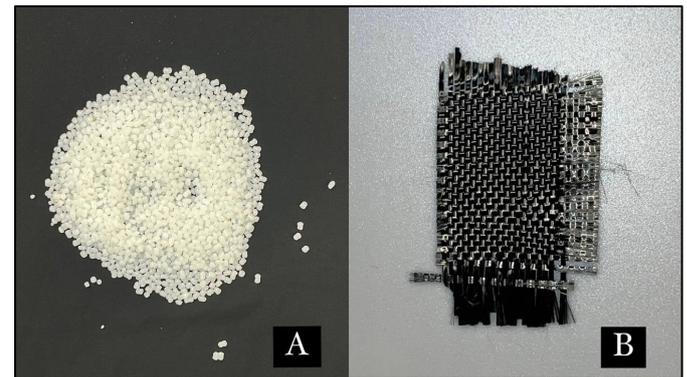


Fig. 1 (A) HDPE granules, (B) WCFs.

It consists of a main cavity into which the layers are placed in the following order, polymer, fiber, polymer, an inner piece that sits on top of the layers to help compress them into the cavity, from which air can escape freely, and a top cover that seals everything. This multipart die is designed to withstand the heat and pressure required to melt the polymer and bond them to the fiber, see Fig. 2 and 3.

The forming die is designed and manufactured for deep drawing of CF-HDPE sheets under controlled conditions. The die consists of a main die unit, a sheet blank holder equipped with a set of spacer spring-loaded screws to provide adequate pressure on the sheets so that they do not tear or slide quickly into the die gap, and a punch that applies force during forming. The die features a specific gap equal to the punch capacity, which helps to meet the optimum forming conditions to the maximum extent, see Fig. 4.

The initial manufacturing process begins with the preparation of high-density polyethylene (HDPE) sheets, where HDPE granules are placed inside a preheated aluminum mold and subjected to heat, pressure, and time as follows: a temperature of 130 °C, pressure of 7.5 MPa, and a duration of 30 seconds. Once the sheets cool and solidify, they are

extracted from the mold, followed by precise cutting and trimming to meet the required dimensions.

Composite sheets are manufactured by placing a layer of WCFs between two HDPE sheets.

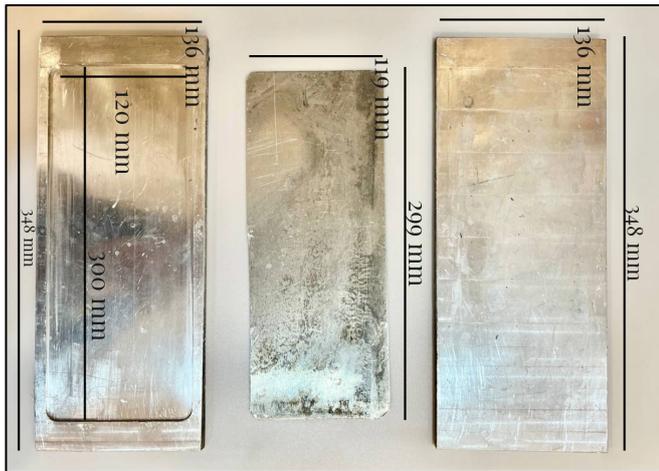


Fig. 2 Sheet fabrication mold.

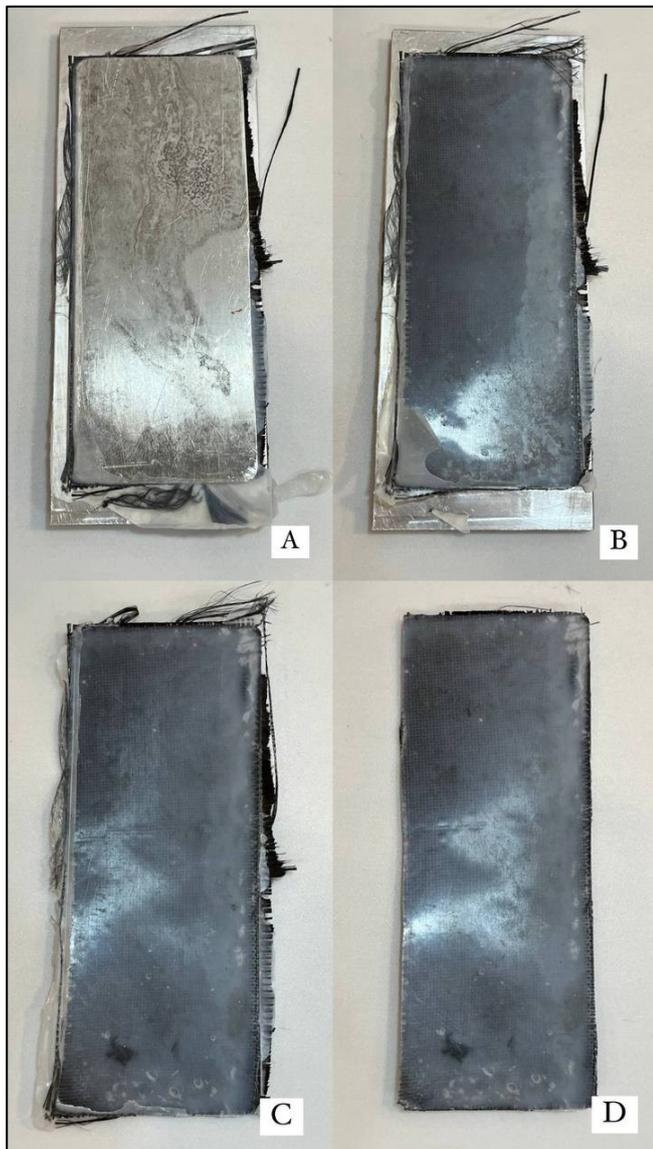


Fig. 3 Production stages of WCFs and HDPE composite sheet, (A) Remove the mold from the oven and open the outer cover of the mold, (B) Lift the inner piece of the mold, (C) Extract the sample from the mold, (D) Perform trimming.

The layered structure is then repositioned inside the mold and subjected to the same conditions used for manufacturing HDPE sheets, ensuring complete bonding of the materials. The mold is then allowed to cool gradually before extracting the composite sheets.

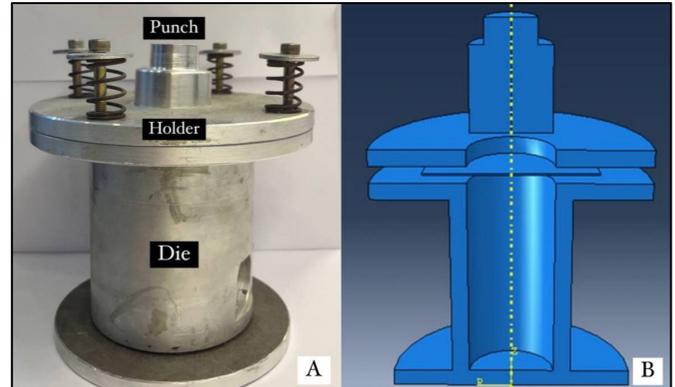


Fig. 4 (A) Forming die, (B) Cross-section of a forming die with a CF-HDPE sheet sample.

The deep drawing process of composite materials begins with preparing uniformly cut CF-HDPE specimens with dimensions of 100 mm × 100 mm. The prepared sample is placed inside an aluminum mold, where a sheet holder equipped with spring-loaded screws is used. The screws are evenly distributed to secure the sample and ensure uniform pressure distribution. To facilitate smooth material flow and reduce friction, a thin layer of oil is applied to both sides of the sample.

The mold and composite sheet are preheated to the required forming temperature to enhance material flexibility and prevent defects such as tearing or wrinkling during forming. Once the desired temperature (70, 80, or 90 °C) is reached, the punch applies a controlled force to shape the composite according to the mold cavity.

After the forming process is completed, the mold is gradually cooled to ensure material stability and prevent internal stresses and to avoid the spring back phenomenon. The formed composite sample is then carefully extracted and prepared for further inspection and analysis, see Fig. 6 and 7.

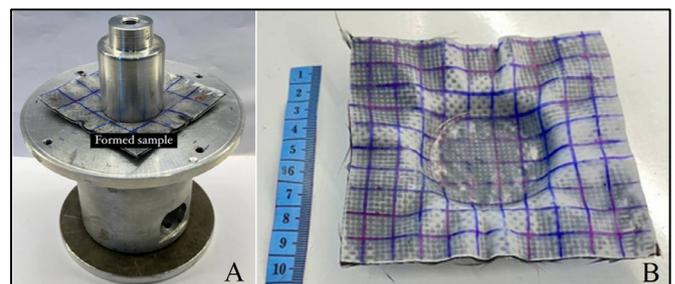


Fig. 5 (A) Formed sample on forming die, (B) Sample shape after forming.

The forming parameters, including punch speed, forming depth, and temperature, are carefully monitored to achieve optimal results.

2.1. The effect of forming depth on forming force

The forming depth significantly affects the forming force, as demonstrated in Figs. 6, 7, and 8. With increasing forming depth, the material requires higher force to overcome the resistance to deformation and flow within the mold. At a depth of 10 mm, the force required is relatively low due to the short

distance the material needs to travel. However, at greater depths of 20 and 30 mm, the required forming force increases significantly due to material resistance.

2.2. The effect of forming temperature on forming force

Figures 6, 7, and 8 indicate that increasing the forming temperature from 70 °C to 90 °C results in a decrease in the required forming force across all depths. Higher temperatures reduce material stiffness, making it more pliable and easier to shape, whereas lower temperatures lead to increased force requirements due to higher resistance to flow. The behavior of the curves in Figs. 6 and 8 is for the most part logical and reasonable, but the overlapping regions of the curves are problematic to explain due to the nonlinear behavior of the material and the combined effects of temperature, forming depth, and punch speed.

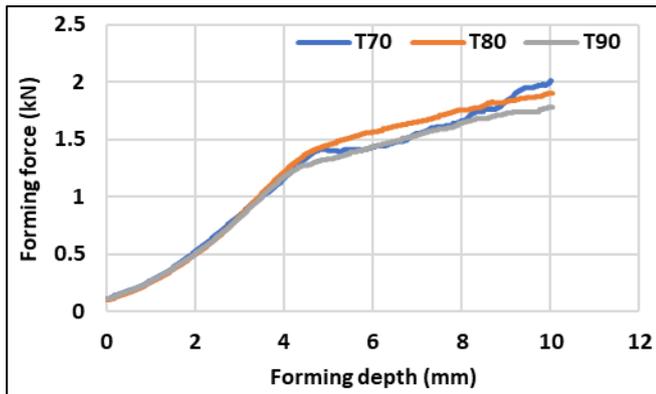


Fig. 6 Relationship between forming depth (up to 10 mm) and forming force at various temperatures.

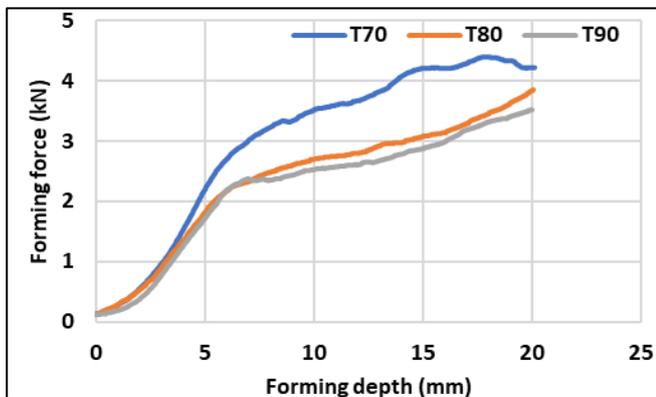


Fig. 7 Relationship between forming depth (up to 20 mm) and forming force at various temperatures.

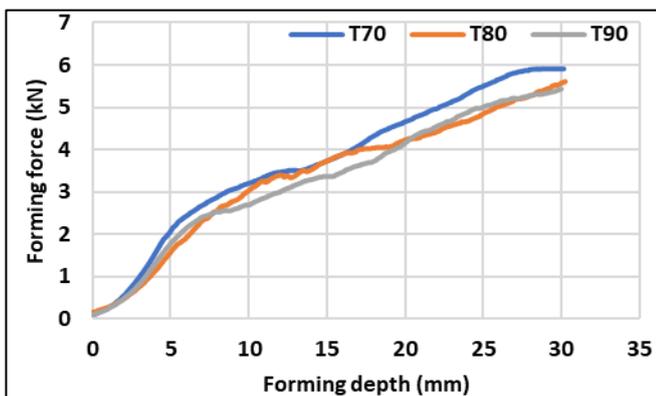


Fig. 8 Relationship between forming depth (up to 30 mm) and forming force at various temperatures.

2.3. Effect of punch speed on forming force

The data reveal that punch speed plays a crucial role in determining the maximum forming force required. As the punch speed increases from 0.25 mm/s to 0.75 mm/s, a significant rise in the maximum forming force is observed across the studied temperatures (70 °C, 80 °C, 90 °C). This is attributed to the direct impact of punch speed on the material deformation rate, as higher speed results in increased resistance to material flow, thereby requiring greater force to achieve the desired forming process.

At lower velocities, such as 0.25 mm/s, the material has more time to distribute stresses evenly, reducing the required force. In contrast, at higher velocities, such as 0.75 mm/s, the loading rate increases rapidly, leading to non-uniform flow and increased internal resistance, consequently raising the forming force.

The results also illustrate the effect of temperature on the relationship between punch speed and maximum forming force. At lower temperatures (70 °C), the material is stiffer, which increases the required force as punch speed rises. Conversely, at higher temperatures (90 °C), the material becomes more flexible, reducing the resistance to flow and thus decreasing the required force. However, the forming force continues to increase with rising punch speed, highlighting the need for careful adjustment of punch speed to achieve an optimal balance between material flow and forming quality, see Fig. 9.

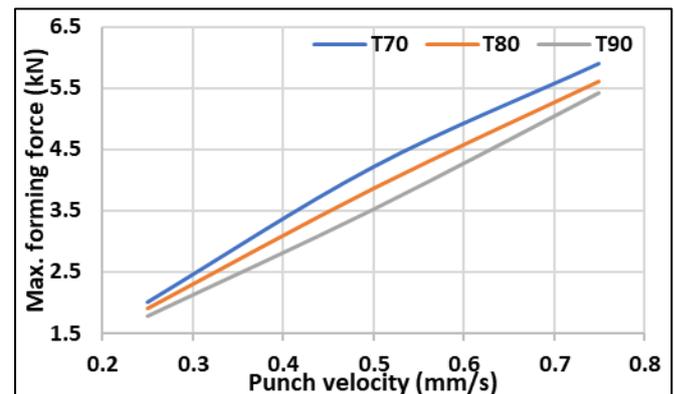


Fig. 9 Effect of punch speed on Max. forming force at various forming temperatures

3. Numerical part

The deep drawing modeling process is based on finite element analysis (FEA) using ABAQUS/CAE software. This method allows studying the stress and strain distribution across CF-HDPE sheets and identifying weak points. The numerical modeling approach consists of several modules.

Part module: This model creates the engineering design parts, the properties of the CF-HDPE composite material are defined in the Property module, which includes assigning the mechanical properties of the material to be analyzed.

The model components are assembled in the Assembly module, and the analysis steps are created in the Steps module, where the appropriate type of analysis is defined for each step. In the Interaction module, the contact and friction between the composite sheet and each component (die, punch, and blank holder) are analyzed individually to determine how these interactions affect the material flow during forming. In the Load module, loads are applied to the simulation model

components under conditions that reflect the real forming process. This involves simulating the forces exerted by the punch and the pressure from the blank holder on the CF-HDPE sheets. The loads are applied incrementally to replicate the actual forming process, while boundary conditions are set for each part and step in the model. In the mesh module, the CF-HDPE sheet is divided into small elements through meshing, allowing for accurate analysis of the forming process. In the Job module, the computational job is prepared and executed to analyze the forming process using the generated model.

3.1. Analysis of 3D images of Von Mises stress distribution in the deep drawing of CF-HDPE sheets at different depths and temperatures

The 3D images show the distribution of stresses according to the Von Mises theory resulting from the simulation of deep drawing processes at different depths (10, 20, and 30 mm) and varying temperatures (T70, T80, T90). It is observed that the stress distribution is primarily concentrated around the central area, which is the point where the punch is directly inserted into the die. As the forming depth increases from 10 to 30 mm, the stresses generally increase due to the force required to subject or conform the CF-HDPE sheets.

The analysis of the 3D images helps in identifying stress concentration points in some areas of the die and punch, contributing to design improvements to ensure the final product quality, see Figs. 10, 11, and 12.

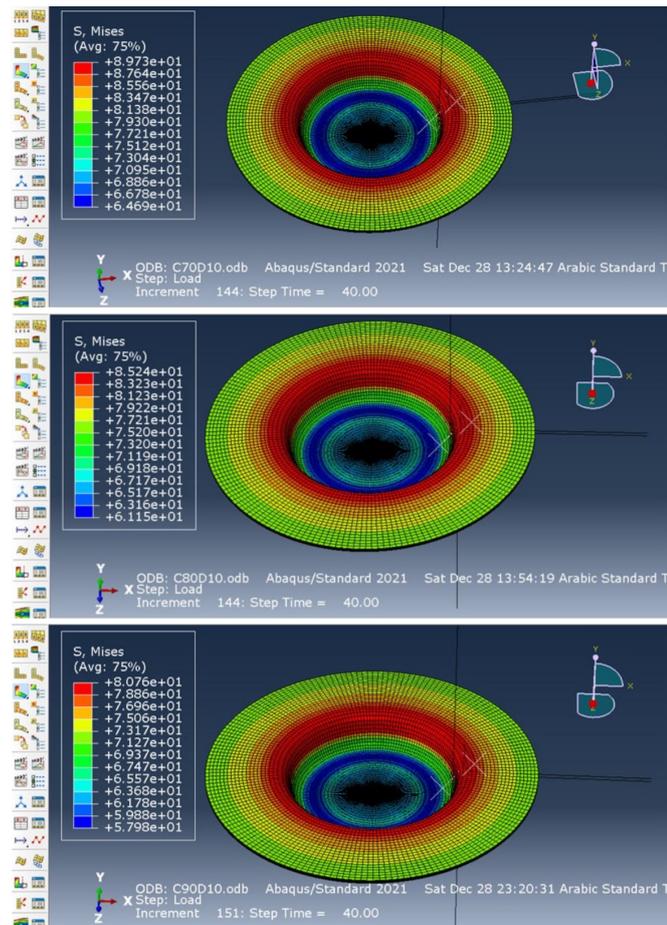


Fig. 10 3D image analysis of Von Mises stress distribution at 10 mm forming depth and various temperatures 70, 80, and 90 °C.

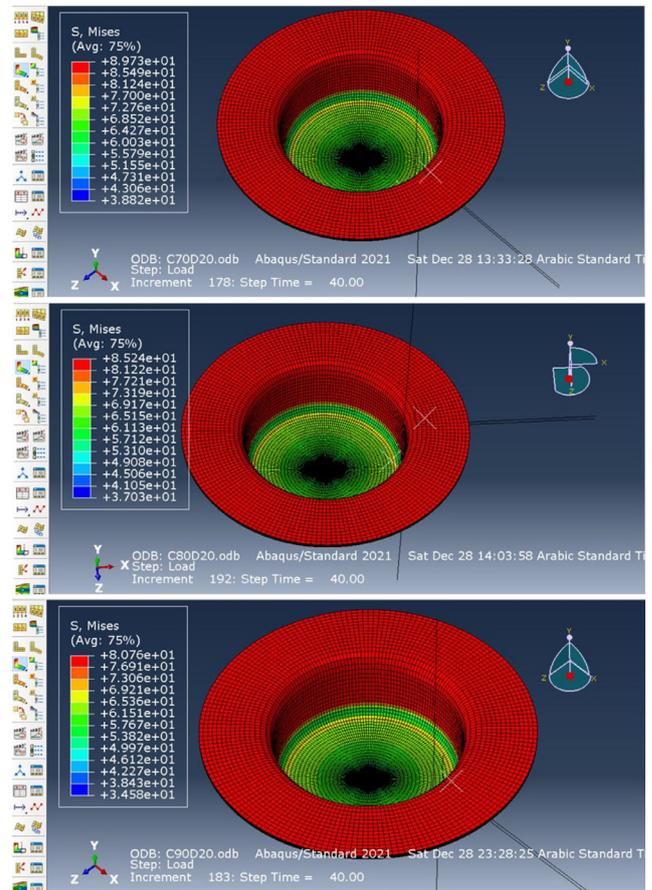


Fig. 11 3D image analysis of Von Mises stress distribution at 20 mm forming depth and various temperatures 70, 80, and 90 °C.

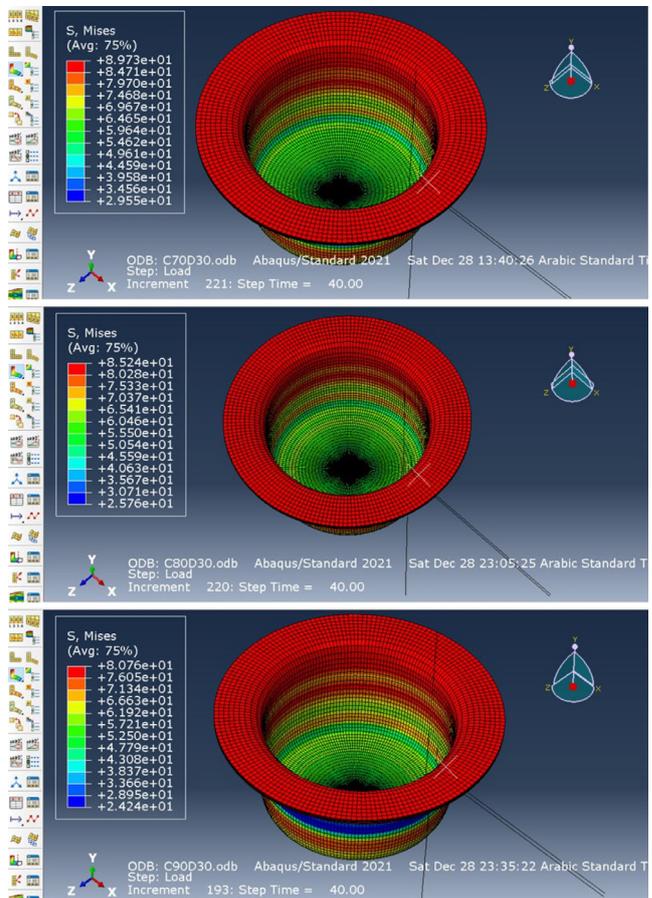


Fig. 12 3D image analysis of Von Mises stress distribution at 30 mm forming depth and various temperatures 70, 80, and 90 °C.

3.2. Analysis of the influence of temperature and forming depth on forming force using ABAQUS

The results obtained from ABAQUS software indicate that the forming force increases with the increase in forming depth, which is an expected trend. Greater depths require higher forces to deform the material, reflecting the additional energy needed to overcome the material's resistance and complete the forming process.

For samples with a forming depth of 10 mm, the required forming forces are relatively low and gradually increase. At a depth of 20 mm, a significant rise in forming forces is observed, with a widening gap between the forces required at different temperatures. At a depth of 30 mm, the forming forces reach their highest values, with samples formed at T70 requiring the highest force, while those at T90 require the least. Numerical analysis reveals an inverse relationship between forming force and temperature, where increasing the temperature of the samples leads to a reduction in the required forming force.

This effect improves energy efficiency and reduces tool wear compared to forming at lower temperatures (T70), which demand higher forces. This reduction is attributed to the decrease in material strength and the increase in ductility at elevated temperatures, making deformation easier.

The curves may appear overly smooth as a result of neglecting friction between the holder and the die on one side and the CF-HDPE sheet on the other side, and simplifying the material behavior in ABAQUS. Factors such as nonlinear material behavior, progressive hardening, anisotropic properties, and microstructural imperfections might not be fully represented in the simulation. Additionally, neglecting some effects such as slip/adhesion can result in smoother and less representative outcomes.

The graphs obtained from ABAQUS software, Figs. 13, 14, and 15 illustrate the relationship between forming depth in (mm) and forming force in (kN) at three different temperatures (T70, T80, T90), providing deeper insights into the influence of temperature on the forming process.

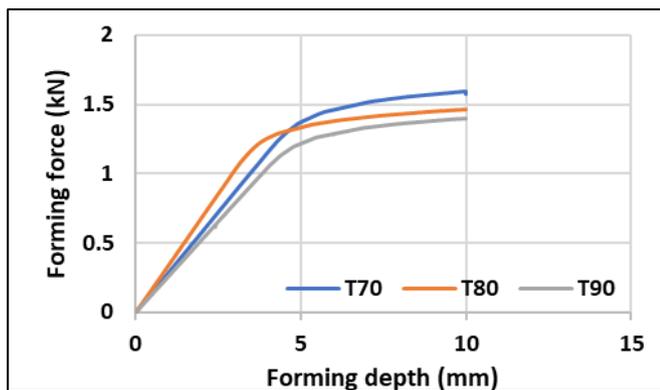


Fig. 13 Effect of forming depth on forming force at different temperatures for a maximum depth of 10 mm.

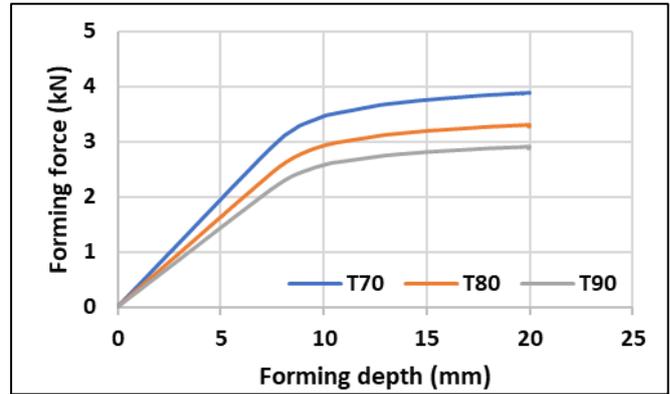


Fig. 14 Effect of forming depth on forming force at different temperatures for a maximum depth of 20 mm.

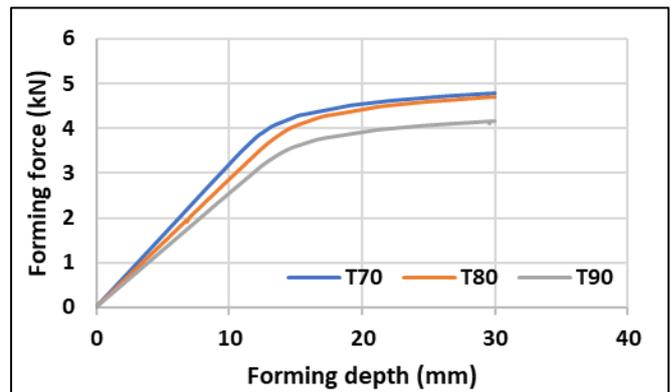


Fig. 15 Effect of forming depth on forming force at different temperatures for a maximum depth of 30 mm.

4. Experimental vs. theoretical analysis of deep drawing process in CF-HDPE composites

The comparison between the experimental results and the theoretical results obtained using the ABAQUS program, as shown in the graphs, Figs. 16, 17, and 18, reveals a general similarity in trends between the two sets of results, especially in the early stages of the forming process. However, the differences become more apparent as the forming depth increases.

These differences are primarily due to the neglect or lack of representation of certain behaviors in the theoretical simulation. Friction between the blank holder and the composite sheet, as well as between the die and the sheet, was ignored. Conversely, friction was only accounted for between the punch and the sheet, leading to smoother theoretical curves. This simplification reduces the complexity of calculating or representing some material behaviors in the simulation program.

Another source of divergence lies in the lack of representation of some nonlinear properties of the composite material in the simulation. These include the interactions between fibers and the matrix within the composite material, the defects present in the CF-HDPE sheets, and variations in thickness across different regions. The theoretical models rely on idealized assumptions of the material, which neglect these factors that play a significant role during the experimental forming process.

As the forming depth increases, the effect of friction becomes more pronounced, further widening the gap between the theoretical and experimental results. In practical

experiments, friction and the non-linear behavior of the material increase the resistance to material flow, requiring higher forming forces. This is particularly evident at depths exceeding 20 mm, where the differences between theoretical and experimental results become more noticeable. Consequently, experimental results are typically higher than the theoretical ones.

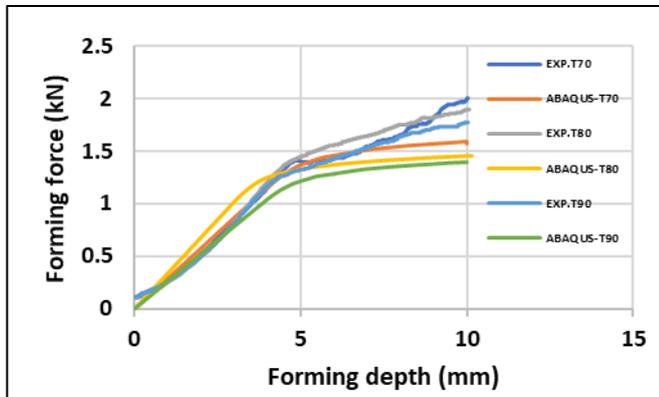


Fig. 16 Comparison of forming force vs. forming depth for ABAQUS and experimental results at forming temperatures 70 °C, 80 °C, 90 °C and forming depth 10 mm.

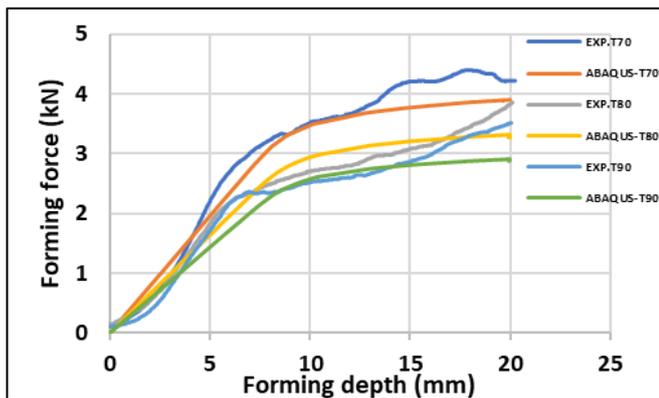


Fig. 17 Comparison of forming force vs. forming depth for ABAQUS and experimental results at forming temperatures 70 °C, 80 °C, 90 °C and forming depth 20 mm.

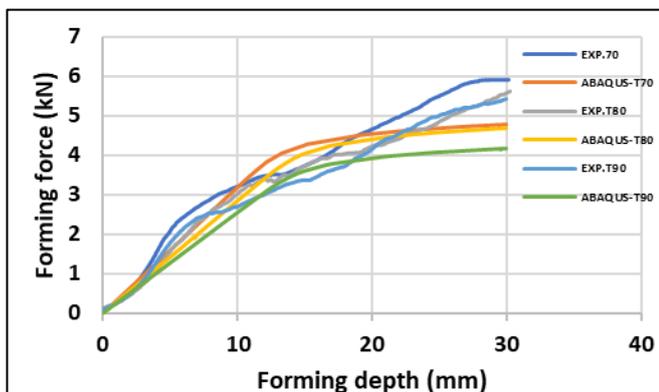


Fig. 18 Comparison of forming force vs. forming depth for ABAQUS and experimental results at forming temperatures 70 °C, 80 °C, 90 °C and forming depth 30 mm.

5. Conclusions

The research provides comprehensive insights into the deep drawing process of CF-HDPE composites, integrating experimental and numerical methodologies. The findings include the significant influence of forming parameters (depth, temperature, and punch speed) on forming force. Higher forming depths and lower temperatures increased forming force, while elevated temperatures reduced material resistance, enhancing formability and reducing the force required for forming. Numerical simulations via ABAQUS aligned with experimental trends but exhibited some differences due to neglecting some nonlinear behavior of the material and not representing it in the ABAQUS simulation as well as neglecting friction effects between some surfaces. These results underscore the importance of parameter optimization in composite forming to balance material flow, energy efficiency, and product quality. Future recommendations include studying additional parameters and refining simulation models to incorporate advanced material behaviors, as well as exploring alternative forming techniques to further enhance composite manufacturability.

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