Experimental Study Of Deep Drawing Of High-Strength Carbon Fiber-HDPE Composites

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Deep drawing of high-density polyethylene (HDPE) reinforced with woven carbon fibers (WCFs) demonstrates excellent resilience under stress, making it a promising material for applications demanding high strength and durability. This study investigated the influence of forming parameters, including temperature, forming depth, and punch velocity, on the deep drawability of HDPE-WCF composites. A dedicated experimental rig was designed and constructed for this purpose. Results indicate that increasing the forming temperature enhances the material's flexibility, thereby reducing the required forming force. However, careful temperature control is crucial to prevent melting and potential degradation of material properties. The optimal forming temperature range was determined to be between 80°C and 90°C, significantly improving material formability. Conversely, at temperatures below 80°C, increasing the forming depth and velocity can increase the risk of material tearing and significantly elevate the required forming force.

Keywords: Composites; Carbon Fiber; Forming Force; Forming Temperature; Deep Drawing.

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1. Introduction

Composites comprising high-density polyethylene (HDPE) reinforced with woven carbon fibers (WCFs) have lighter weight alongside high mechanical strength. Reinforcement with WCFs improves strength, impact resistance and thermal properties of HDPE at relatively lower weight. These advantages make the composites appropriate for use in the automotive, aerospace, prosthetics, and sporting equipment applications [1–4]. It is also worth mentioning that WCFs generate less friction and have higher wear resistance than other types of fillers. Distribution and most importantly concentration of WCFs in the matrix of the composite HDPE has been proved to be very effective on the performance of the composite material hence a prudent balance has to be struck for best performance [5–7]. A deep drawing, which is applied in metal forming, has also been identified as one of the ways of processing the composites. It possesses the advantage of enabling efficiency in the production of complex shapes while also controlling the flow of materials thereby causing less wastage of materials. Deep drawing technology is undergoing modifications to utilize composite materials, such as WCFs-reinforced HDPE, for manufacturing high-performance components [8, 9]. Forming parameters management forming depth, temperature, punch velocity, and holder force is important to prevent defects like wrinkling, earring, and tearing. Research indicates that while elevated temperatures can improve material flexibility, temperature must be managed to prevent excessive heat damage [10]. Defects like wrinkling, tearing, and thickness variations often occur because of the composite's anisotropic properties and the particular arrangement of its fibers [11]. Laminated composites often have uneven thickness and inconsistent stress-strain distribution, making them susceptible to wrinkling during the forming process. Properly controlling the blank-holder force is crucial to avoid issues like tearing and wrinkling, especially when working with complex shapes, as insufficient force can lead to these defects [12]. High temperatures in thermal deep drawing enhance the flexibility of the composite material, making it easier to shape, but can also risk fiber damage, leading to surface defects [10]. Balancing the parameters' blank-holder force, temperature, and forming speed is essential to minimize these issues and ensure the integrity and uniformity of the final product [13–17].

Coating carbon fibers with carbon nanotubes (CNTs) has been shown to improve bonding and wear resistance capabilities. The strength of this approach is countered by the costs and complexities of industrialization of the process [7, 8].

This research aims to study how HDPE-WCFs composites behave during the deep drawing process, looking closely at how main parameters affect forming and the forces involved. It also focuses on understanding the common defects that can occur, with the goal of improving composite performance and making production more efficient.

2. Materials and methods

2.1. Material Selection

The selection of carbon fibers WCFs, HDPE, and aluminum alloys is based on their complementary properties [18]. Aluminum alloys are used for the molds in the forming process because they are lightweight, easy to machine, and have good thermal conductivity, which helps in quickly and evenly distributing heat. The high tensile strength, stiffness, and low weight of WCFs make them materials of choice for applications where weight and durability are both required, and WCFs exhibit high thermal stability (see Fig. 1). HDPE exhibits excellent processability, chemical resistance, and impact strength (Table 1) [19, 20].

2.2. Aluminum Mold Design and Specimen Preparation

The aluminum molds have been used to cast and mold the composite materials. They provide accuracy and efficiency in production [18, 21]. The sheet fabrication mold is a custom-designed tool used to create composite sheets

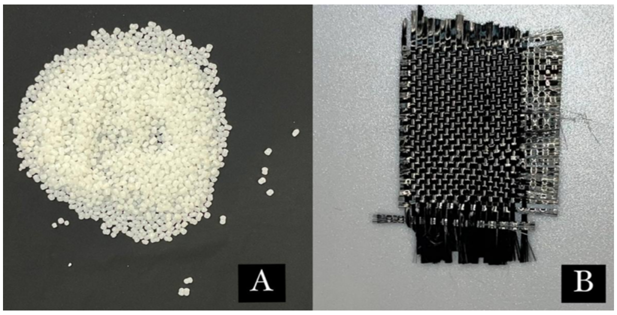


Fig. 1. A) HDPE granules; B) WCFs.

from HDPE and WCFs. It consists of three primary components; a base cavity where the raw materials are placed, an internal piece designed to allow air to escape from all sides, and a top cover that secures the entire setup tightly (Fig. 2a). This multi-part mold withstands the heat and pressure needed for even melting and bonding of materials. Careful consideration is given to the design to prevent air pockets and ensure the composite sheet's integrity. This setup guarantees that each sheet is uniform, structurally stable, and free of common manufacturing defects. The process for making composite samples begins with the shaping of (HDPE) sheets. First, HDPE granules (see Fig. 1, A) are loaded into a sheet fabrication mold and then placed in a heat press at 130 degrees Celsius with pressure equivalent to 7.5 MPa applied for two minutes (Fig. 2a). Once the granules have softened and taken the shape of the mold, the mold is removed from the heat press and allowed to cool. The formed sheets are then extracted from the mold, followed by cutting and trimming processes. This ensures that the sheets produced are smooth, evenly thick, and free from defects.

For the composite samples, a layer of WCFs is sandwiched between two HDPE sheets (see Fig. 2b). The layers are placed back in the heat press under the same controlled conditions. The applied heat melts the HDPE, allowing it to bond securely to the WCFs, creating a cohesive and durable composite. Achieving even pressure and consistent heat distribution is essential to maintain strong bonding and uniform properties. After cooling, the samples are cut precisely to the required dimensions (see Fig. 2c, d). This meticulous approach ensures the production of high-quality, defect-free specimens.

2.3. Forming Die

The forming die is a specialized mold designed to form WCFs and HDPE composite sheets under controlled conditions. It includes the main mold body, a sheet blank holder with evenly spaced screws to keep the sheet secure, and a

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	23MPa(Yield), 12MPa(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 Temp.	-	< -75°C

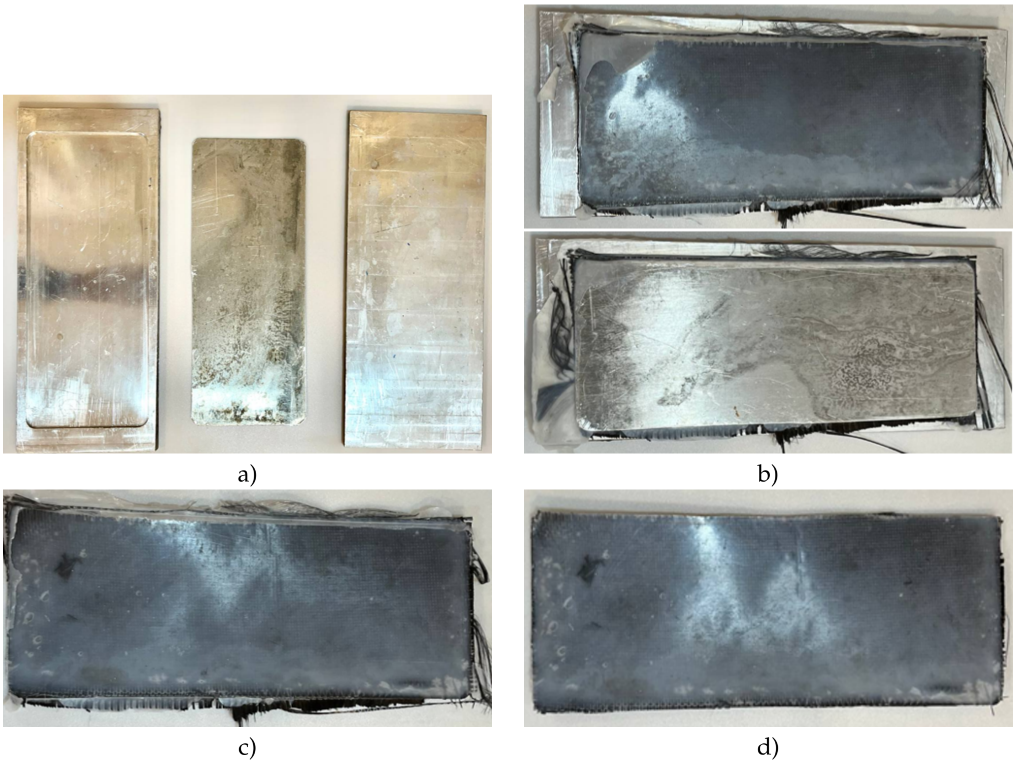


Fig. 2. Production stages of WCFs and HDPE composite sheet: a) aluminum mold parts; b) composite materials inside the mold; c) and d) removal of the composite materials and trimming the edges of the pieces.

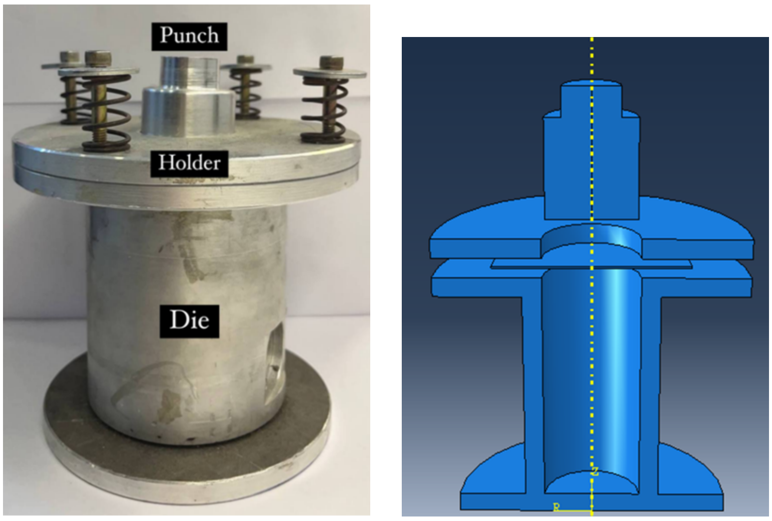
punch that applies the forming force.

The holder ensures the sheet remains in place, distributing pressure evenly to avoid unfair slippage and ensure consistent deformation. The die is designed with a precisely calibrated gap that matches the punch's capacity, ensuring optimal forming conditions. The mold is manufactured with precisely calculated dimensions, mold hole diameter, composite material sample thickness, and punch diameter to ensure proper forming without large voids. The punch diameter is 48 mm, the sample thickness is 2 mm, and the die hole diameter is 54 mm, resulting in 1 mm tolerances on each side. These tolerances allow for proper movement of the sample during the forming process and prevent tearing or damage to the sample. This gap is neither too narrow, which would risk tearing the sheet blank, nor too wide, which could lead to wrinkling. The punch velocity, force, and hold time are managed to ensure best results (see Fig. 3a, and b).

2.4. Deep Drawing Process

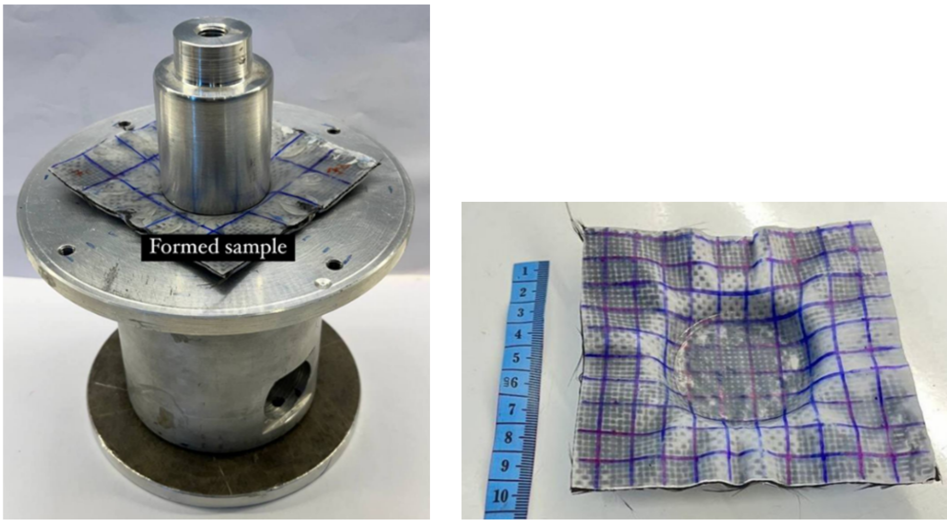
The deep drawing process of composite materials begins with ensuring consistency in cutting the specimens into equal pieces. Composed of (HDPE) and WCFs, are cut into uniform 100 mm x 100 mm squares, and 2 mm thickness.

The sample is placed inside the mold, and a holding



a) b)

Fig. 3. a) Forming die; b) Cross-section of a forming die with a sheet sample.



a) b)

Fig. 4. a) Die and punch; b) Formed shape specimen.

piece with screws is used to secure it evenly, ensuring balanced pressure distribution (Fig. 4a). Oil is applied to both surfaces of the sample to minimize friction and facilitate smooth material flow. The forming mold and blank sheet is preheated to achieve the ideal temperature, which enhances material pliability and reduces the risk of defects.

When the mold is ready, the punch descends at a controlled velocity to press the composite into the desired shape. Parameters such as punch velocity, forming depth, and forming temperature are carefully regulated to prevent defects like tearing or wrinkling. The forming pressure is maintained for 40 seconds. The forming time remains constant throughout the drawing process. This is due to the machine settings, where the minimum time was selected to maintain the stability of the mold temperature during forming. Additionally, it was kept fixed because no temperature change occurs during this period (i.e., no temperature gradient is present). Experimental findings showed that when the initial forming temperature was set to 70, 80, and 90 degrees Celsius, the temperature remained unchanged at the same values at the end of the specified 40-second forming period. This prevents the influence of temperature gradients and eliminates the need to consider them as additional variables or parameters in the experiment, thereby improving the accuracy of the results. The mold is gradually cooled to stabilize the material and avoid inter-

Fig. 5. Equipment and machines: a) Heat press; b) Thermometer; c) Tensile testing machine; d) Forming process.

nal stresses. The formed sample is then removed, ready for inspection and analysis (see Fig. 4b).

2.5. Equipments

The equipment employed in this research includes a heat press, tensile testing machine, thermal heater, and thermometer, each serving a specific role in the preparation and forming of composite samples. Fig. 5a shows the heat press, which is used to produce composite sheets made of HDPE and WCFs using a sheet fabrication mold (see Fig. 2a, b). It controls the pressure, temperature, and time to ensure the sheets are uniform in thickness and smooth, free from surface imperfections.

A thermal heater is used to maintain the required temperature of the composite samples and mold during the forming time. Accurate control over temperature and time settings is vital for achieving optimal forming conditions, ensuring that the material is sufficiently pliable for shaping. Thermometer is used at various locations on the mold and the sample to monitor the temperature. Thermometer helps ensure that heat distribution is even across the mold, reducing the chance of localized overheating or under heating and contributes to monitoring the quality of production of formed samples (Fig. 5b).

The tensile testing machine serves two main purposes in this research. First, it is used to determine the mechanical properties of the composite sheets, such as tensile strength, elasticity, and elongation at break (Fig. 5c). These measurements are crucial for understanding how the material will perform under stress. Second, the tensile testing machine is used as a press in the forming process, where it precisely regulates critical parameters, including punch velocity, forming depth (Fig. 5d). This level of control ensures that the composite material is shaped accurately while minimizing the risk of defects, such as tearing or wrinkling.

2.6. Experimental Forming Parameters

The forming parameters punch velocity, temperature, and forming depth significantly impact the maximum force required in the deep drawing process of composite materials. Higher punch velocities and greater forming depths generally lead to increased forming force, as the material faces more resistance. Temperature adjustments also play a critical role; elevated temperatures tend to reduce the necessary force by making the material more pliable, allowing for smoother shaping (see Table 2).

3. Results and discussion

The experimental results reveal how different forming parameters significantly affect the maximum forming force needed in the deep drawing process of HDPE-WCFs. The stress-strain behavior, and the influence of main parameters, such as temperature, forming depth, and punch velocity, on the forming force have been presented.

3.1. Stress-Strain Curve

The stress-strain curve represents the forming process efficiency, i.e. formability. Therefore, the highest observed stress corresponds to the maximum forming force. This curve illustrates the material's strength and flexibility, which are critical for ensuring structural integrity and resilience in real-world applications. Achieving an optimal balance of temperature, forming depth, and punch velocity is crucial to reduce defects and enhance energy efficiency during the forming process, see Fig. 6.

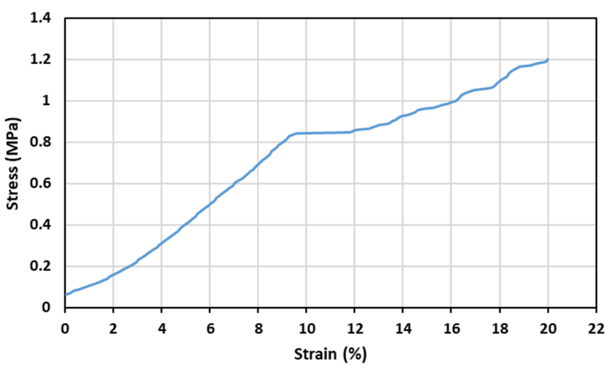


Fig. 6. The stress-strain curve.

3.2. Effect of Temperature and Forming Depth on Forming Force

Increasing the forming temperature from 70°C to 90°C significantly reduces the required forming force at each depth level (Fig. 7a). This reduction occurs because higher temperatures make the material more pliable, allowing it to flow and shape more easily under pressure, thereby reducing the load on both the punch and the material.

The forming depth has a substantial impact on the required force; greater depths demand more force to achieve the desired shape. This emphasizes the importance of balancing temperature and depth in the deep drawing process to optimize energy efficiency and reduce material stress, see Fig. 7. The forming depth directly correlates with the forming force, with deeper draws requiring higher forces. This observation suggests that as the punch descends.

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3.3. Effect of Punch Velocity

Higher punch velocities increase the forming force, possibly due to the material's response rate under quick deformation. At a punch velocity of 0.75 mm/s, the forming forces are consistently higher compared to lower velocities, indicating that slower forming speeds may allow the material more time to adapt to the shape, reducing the necessary force (see Table 2).

3.4. Forming Defects

There are some defects, primarily tearing, wrinkling, and melting have been noticed. When the blank holder force is inadequate, it fails to secure the composite sheet against the die tightly, allowing excess material movement, which leads to wrinkles [22], see Fig. 8a. Effective force control can mitigate these issues and enhance product quality.

At elevated temperatures, especially above the material's softening point, HDPE may lose structural integrity and blend with the reinforcing fibers, leading to visible melting spots (see Fig. 8b). Zhang et al. [10] found similar results in their study on thermal deep drawing of WCFs

Table 2. The forming parameters.

Test No.	Forming depth (mm)	Temp. (°C)	Punch velocity (mm/s)	Max. forming force (kN)
1	10	70	0.25	2.01
2	20	70	0.5	4.22
3	30	70	0.75	5.91
4	10	80	0.25	1.9
5	20	80	0.5	3.86
6	30	80	0.75	5.61
7	10	90	0.25	1.78
8	20	90	0.5	3.52
9	30	90	0.75	5.42

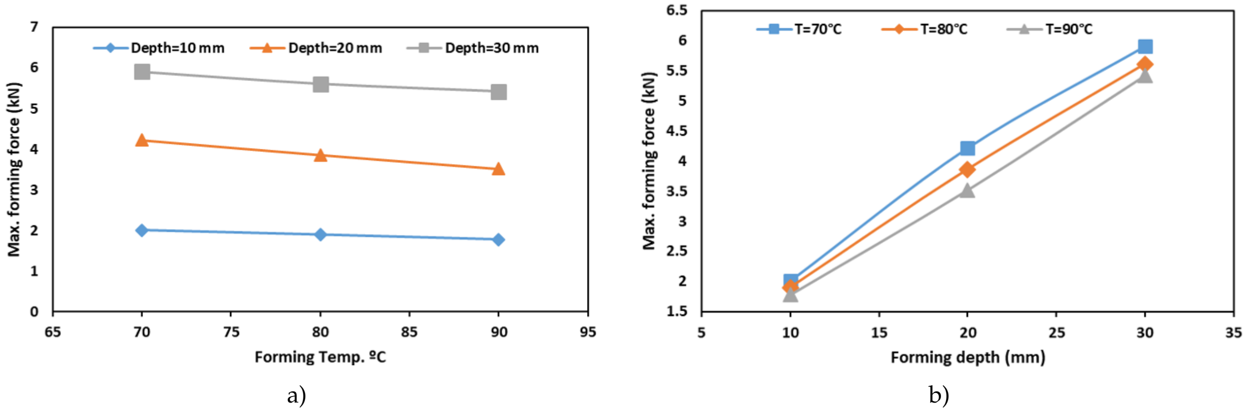

Fig. 7. a), and b) Effect of temperature and depth on forming force, respectively.

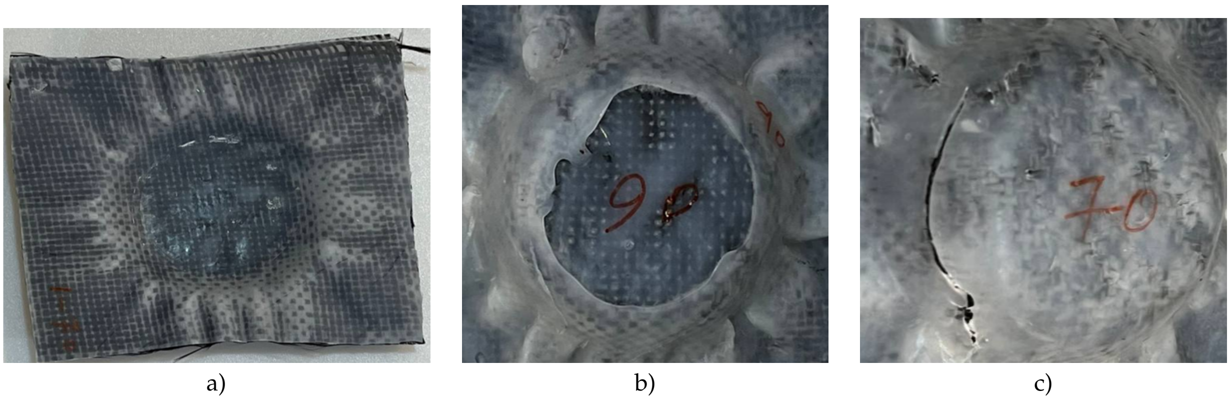

Fig. 8. a) Wrinkling defects (top view); b) Melting defect in composite material at 90°C forming temperature (back view); c) Tearing defect in composite material at 70°C forming temperature (back view).

composites. They noted that high temperatures can damage the fibers and weaken the bond with the resin. Tearing occurs in regions of high stress concentration, especially at sharp geometries, low temperatures, and high punch speeds, where the material lacks sufficient pliability. Under these conditions, rapid deformation generates concentrated stresses, particularly in the bending zones at the contact points between the sheet and the punch, which can exceed the material's tensile strength, resulting in tearing (see Fig. 8c). The tearing in the deep drawing process mainly happens in areas with high stress, like near punch strokes or sharp corners [23, 24]. Proper control of the blank-holder force, good tool design, and better lubrication can help reduce tearing (Fig. 8c). These observations underscore the need for careful control over blank-holder force, temperature, and punch velocity to optimize composite forming outcomes and minimize defect occurrences.

4. Conclusions

The mechanical behavior of HDPE-WCF composites under deep drawing has been studied, and the optimum parameters to obtain a suitable product have been determined. The following conclusions have been summarized:

1. Increasing the forming temperature reduces the required forming force, making the material more flexible and easier to shape. However, very high temperatures can lead to material melting, especially in areas with high stress concentration.

2. Optimal temperature parameters for deep drawing range between 80°C and 90°C, where material pliability is achieved without risking melting.

3. Greater forming depths require higher forming forces, which increases the chances of tearing and wrinkling if not controlled carefully.

4. Punch velocity also impacts the forming process, with high speeds increasing the likelihood of tearing due to sudden stress.

5. Proper control of temperature, forming depth, and punch velocity is essential for minimizing defects and ensuring energy efficiency.

6. The findings suggest that HDPE-WCFs composites are resilient and capable of withstanding the stresses involved in deep drawing when processed within the identified optimal conditions, which makes them ideal for applications requiring durability under stress.

References

[1] E. K. Njim, F. A. Hadi, M. N. Hamzah, N. A. Alhilo, and M. H. Al-Maamori, (2024) *"Numerical and Experimental Investigation of Nano zinc Oxide's Effect on the Mechanical Properties of Chloroprene and Natural Rubber (CR/NR) Composites"* **Physics and Chemistry of Solid State** ***25***(1): 14–25. DOI: 10.15330/pcss.25.1.14-25.

[2] A. Al-Mukhtar, (2020) *"Aircraft fuselage cracking and simulation"* **Procedia Structural Integrity** ***28***: 124–131. DOI: 10.1016/j.prostr.2020.10.016.

[3] H. K. Talla, A. K. F. Hassan, and J. K. Oleiwi, (2022) *"Study the effect of reinforcing kevlar fibers with carbon fibers and glass fibers on the performance of the athletic prosthetic foot"* **Basrah J Eng Sci** **22**: 41–48. DOI: 10.33971/bjes.22.2.7.

[4] O. A. Abdullah and A. K. F. Hassan, (2016) *"Effect of prestress level on the strength of CFRP composite laminate"* **Journal of Mechanical Science and Technology** ***30***: 5115–5123. DOI: 10.1007/s12206-016-1029-1.

[5] Y. Guo, D. Liu, Y. Chen, T. Zhang, and S. Zhu, (2019) *"Preparation and properties of carbon-fiber-and pine-cone-fiber-reinforced high-density polyethylene composites"* **Journal of Applied Polymer Science** ***136***(14): 47304. DOI: 10.1002/app.47304.

[6] X. Zhao, Z. Gui, X. Chen, W. Zhang, P. Yang, J. Zheng, and A. Liu, (2021) *"Finite element analysis and experiment study on the elastic properties of randomly and controllably distributed carbon fiber-reinforced hydroxyapatite composites"* **Ceramics International** ***47***(9): 12613–12622. DOI: 10.1016/j.ceramint.2021.01.120.

[7] C. Hu, X. Liao, Q.-H. Qin, and G. Wang, (2019) *"The fabrication and characterization of high density polyethylene composites reinforced by carbon nanotube coated carbon fibers"* **Composites Part A: Applied Science and Manufacturing** ***121***: 149–156. DOI: 10.1016/j.compositesa.2019.03.027.

[8] M. J. Ziedan, A. F. Hassan, N. A. Saad, and A. Al-Mukhtar, (2024) *"A Comprehensive Review of Forming Methods for Composite Materials and Cracking"* **Procedia Structural Integrity** ***66***: 229–246. DOI: 10.1016/j.prostr.2024.11.074.

[9] W. K. Jawad and A. Jaafar, (2018) *"The influence of punch profile radius on deep drawing process in case of a low carbon steel cylindrical cup"* **Engineering and Technology Journal** ***36***(10A): 1048–1058. DOI: 10.30684/etj.36.10A.5.

[10] Q. Zhang, J. Cai, and Q. Gao, (2014) *"Simulation and experimental study on thermal deep drawing of carbon fiber woven composites"* **Journal of Materials Processing Technology** ***214***(4): 802–810. DOI: 10.1016/j.jmatprotec.2013.11.024.

[11] T. Naik and Z. Hu. "Computer Simulation of Deep Drawing Process for a Laminated Composite Cup". In: *ASME International Mechanical Engineering Congress and Exposition*. ***42975***. 2007, 567–572. DOI: 10.1115/IMECE2007-41593.

[12] A. Wifi and A. Mosallam, (2007) *"Some aspects of blank-holder force schemes in deep drawing process"* **Journal of Achievements in Materials and Manufacturing Engineering** ***24***(1): 315–323.

[13] F. Qayyum, M. Shah, A. Muqeet, and J. Afzal. "The effect of anisotropy on the intermediate and final form in deep drawing of SS304L, with high draw ratios: Experimentation and numerical simulation". In: *IOP Conference Series: Materials Science and Engineering*. ***146***. 1. IOP Publishing. 2016, 012031. DOI: 10.1088/1757-899X/146/1/012031.

[14] R. K. Saxena and P. Dixit, (2009) *"Finite element simulation of earing defect in deep drawing"* **The International Journal of Advanced Manufacturing Technology *45***: 219–233. DOI: 10.1007/s00170-009-1963-5.

[15] A. Rajabi, M. Kadkhodayan, M. Manoochehri, and R. Farjadfar, (2015) *"Deep-drawing of thermoplastic metal-composite structures: Experimental investigations, statistical analyses and finite element modeling"* **Journal of Materials Processing Technology *215***: 159–170. DOI: 10.1016/j.jmatprotec.2014.08.012.

[16] A. P. Anaraki, M. Shahabizadeh, and B. Babaee, (2012) *"Finite element simulation of multi-stage deep drawing processes & comparison with experimental results"* **World Academy of Science, Engineering and Technology *61***: 670–674.

[17] C. Sguazzo, M. Harhash, M. Grafenhorst, H. Palkowski, and S. Hartmann, (2014) *"Deep drawing of a layered composite: material characterization and finite-element simulation"* **PAMM *14***(1): 245–246. DOI: 10.1002/pamm.201410110.

[18] E. K. Njim, H. R. Hasan, M. J. Jweeg, M. Al-Waily, A. A. Hameed, A. M. Youssef, and F. M. Elsayed, (2024) *"Mechanical properties of sandwiched construction with composite and hybrid core structure"* **Advances in Polymer Technology *2024***(1): 3803199. DOI: 10.1155/2024/3803199.

[19] B. Muralidhara, S. K. Babu, and B. Suresha, (2020) *"The effect of fiber architecture on the mechanical properties of carbon/epoxy composites"* **Materials Today: Proceedings *22***: 1755–1764. DOI: 10.1016/j.matpr.2020.03.008.

[20] A. Elduque, D. Elduque, C. Javierre, Á. Fernández, and J. Santolaria, (2015) *"Environmental impact analysis of the injection molding process: analysis of the processing of high-density polyethylene parts"* **Journal of Cleaner Production *108***: 80–89. DOI: 10.1016/j.jclepro.2015.07.119.

[21] A. K. F. Hassan and A. S. Hashim, (2015) *"Three dimensional finite element analysis of wire drawing process"* **Universal Journal of Mechanical Engineering *3***(3): 71–82. DOI: 10.13189/ujme.2015.030302.

[22] J. Fan, C. Y. Tang, C. P. Tsui, L. C. Chan, and T. Lee, (2006) *"3D finite element simulation of deep drawing with damage development"* **International Journal of Machine Tools and Manufacture *46***(9): 1035–1044. DOI: 10.1016/j.ijmachtools.2005.07.044.

[23] C. P. Singh and G. Agnihotri, (2015) *"Study of deep drawing process parameters: a review"* **International Journal of Scientific and Research Publications *5***(2): 1–15.

[24] A. Al-Mukhtar12, (2012) *"The Effected Parameters For Designing The Single Layer Composite Materials"* **International Journal of Mechanical Engineering and Robotics Research**: DOI: 10.18178/ijmerr.