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Manufacturing of 3D Printed Laminated Carbon Fibre Reinforced Nylon Composites: Impact Mechanics

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Abstract

This paper presents the manufacturing development of laminated Carbon Fibre Reinforced Thermoplastics Polymer (CFRTP) specimens, which show significant improvement of mechanical properties in comparison with existing thermoplastic composites. There is a need to improve structural performance of thermoplastic composites by using a fully integrated chopped and continuous carbon fibre bundle into a thermoplastic resin matrix in a laminated shape with various stacking sequences. The developed manufacturing technique is capable to print components with various fibre orientations, which is spotted as the novelty of this research. The CFRTP specimens were tested under quasi-static tensile and low-velocity impact loading to proof the improvement of mechanical performance in both static and dynamic applications. Our results indicate a significant improvement in impact resistance and energy absorption capability of CFRTP composites in comparison with existing thermoplastic composites.

Keywords

Additive, Nylon, CFRTP, Thermoplastic, Impact

1. Introduction

Additive manufacturing is a growing manufacturing technique to produce prototypes for industrial applications in different domains like aerospace, automotive industry, space, civil and biomechanical engineering. The most common manufacturing methods in additive manufacturing are injected moulding and Fused Deposition Modelling (FDM); also called Fused Filament Fabrication (FFF). However, none of these existing methods can provide a fully integrated continuous carbon fibre integration to a thermoplastic matrix in laminated shape with various stacking sequences. Carbon Fibre Reinforced Thermoplastic Polymers (CFRTP) is a future solution for producing less waste using recyclable materials such as Nylon. Nylon, Polycarbonate and PEEK have the advantage of having long molecular materials in comparison with the most common materials such as PLA [1] [2], ABS [3] [4] and PETG [5] [6] [7]. Such materials can be recycled numerous times without losing any mechanical properties after the recycling process.

Thermoplastic resins have long and discrete molecules, which are processed once they reach their melting temperature. The fact that thermoplastics resins have long molecules makes them reliable to be reused after undergoing a recycling process. Moreover, recycled thermoplastics can be rapidly reprocessed [8]; when a thermoplastic is cured, its chemical composition is not affected by the curing process. The curing process is very simple, once the thermoplastic is heated at its melting temperature, the discrete molecules will melt to a viscous liquid. By simply reheating the thermoplastic to its melting temperature, the resin can form another shape if desired without any major effect on the mechanical properties of the resin [9]. Nylon or Polyamide Resins (PA) is very durable and commonly used in automotive, textile and sportswear [10]. Nylon 66, which is an engineered hexamethylene diamine and adipic acid PA shows remarkable properties suitable for gears and bearings. It is a semi-crystalline polyamide with high abrasion resistance, rigidity and thermal stability [11]. This PA has a high tensile strength and melting point making it suitable for piston guides, impact plates and friction strips [12]. Kuciel *et al.* [13] evaluated the combination of Nylon 66 and chopped Carbon Fibre. They showed that the new combination has higher tensile and compression values in comparison with pure Nylon 66 resin. It is known that the increase of fibre volume fraction significantly improves the mechanical properties of the composites. The reinforced Nylon 66 with chopped carbon fibre has enhanced mechanical properties compared to pure Nylon 66.

Despite the advantages of thermoplastics in comparison with thermosets, the development of continuous fibre reinforced thermoplastics composites is very limited compared to reinforced thermoset composites. The reason is due to the difficulty to integrate the continuous fibres to the matrix during the manufacturing process. This paper presents an advanced manufacturing technique of laminated CFRTP specimens, which show higher mechanical properties in comparison with other thermoplastic composites. Our manufacturing technique is capable to print components with various fibre orientations, which is a significant development in the field. The CFRTP specimens were tested under quasi-static tensile and low-velocity impact loading to proof the improvement of mechanical performance in both static and dynamic applications.

2. Manufacturing Methods

2.1. Development of 3D Printer

Printing Nylon requires high temperatures not just from the hot-end but also for the environments in which it is printed. If the environmental temperature is too cold the Nylon will come off or warp from the build platform. Integrating Carbon fibre to an unstable thermoplastic matrix is not feasible if a stable environmental temperature is not generated. Therefore, a containment chamber was developed here. The walls are made of blue foam (high density) was coated with 2 mm of concrete (high thermal mass) to provide optimal thermal isolation. The thermostat is mounted at the back of the chamber at the same height than the hot-end while it prints the first layers of a part. The reason for this configuration is for its simplicity and because heat rises in a closed room to perfectly have the best possible environmental conditions for the printing process.

A dual cyclops hot-end was used for dual colour prints, which was modified in a way to print simultaneously two different materials. A novel method to cool down the hot-end was developed using high-speed radial fans integrated into the hot-end structure. A cooling structure design was introduced to the hot-end for a more efficient airflow around the heatsinks of the hot-end. Moreover, a probing sensor was programmed into the motherboard of the printer to use an advanced probing system to optimise the hot-end before the printing process gets started (see **Figure 1**).

Experimental extrusion systems, which are similar to the Cyclops hot-end, can extrude two materials at the same time. Also, these extrusion systems are built to extrude simultaneously materials, which have the same mechanical and thermal properties. In order to integrate continuous Carbon fibre, a homogeneous integration system is used to avoid any clogging while extruding the material. Homogeneous heat distribution is required along the passage of the fibre through the throat of the hot-end to embed the fibre into the thermoplastic matrix. To prevent any curling of the fibre, the hot-end needs to be cleared from any disruptions in the internal structure of the hot-end. A constant and undisturbed flow of the fibre through the throat of the hot-end is crucial to achieving a successful deposition of the material as presented in **Figure 2**.

The long heater cartridge represents a significant advantage over any other hot-end on the market. It offers a constant and stable heat propagation throughout the throat of the hot-end. This system is ideal to combine two similar materials and extrude them simultaneously. Due to its right angel at the transition area, which is located between the throat and the heat block, the fibre is curled by the feed of the incoming material from the first input throat. The dual extrusion

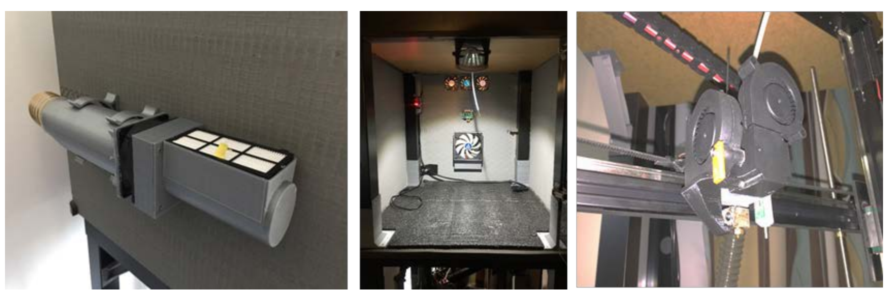

Figure 1. Final design dual extrusion system with radial fans.

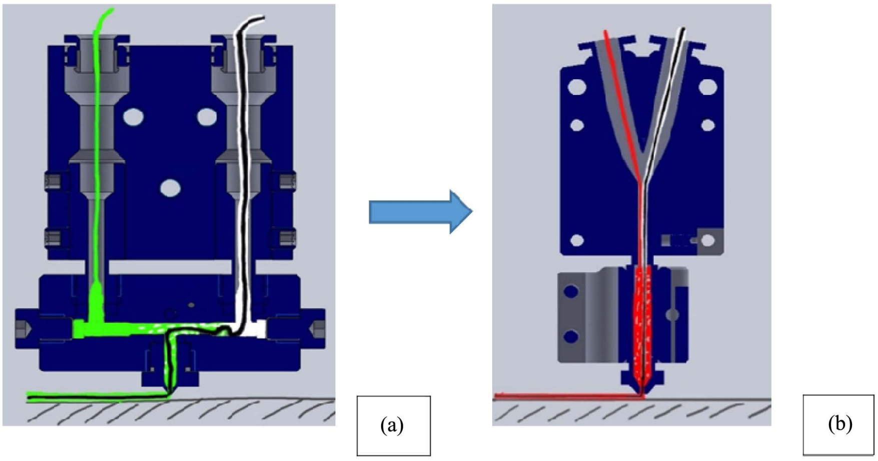

Figure 2. (a) Extrusion systems Cyclops vs (b) Dual extrusion hot end.

hot-end has shown more promising results than the cyclops hot-end (see Figure 3(b)). The thermostat is mounted in the back of the chamber at the same height while it prints the first layers of a part. To avoid any environmental contamination, a particle filter is implemented to filter any burned Nylon from the hot-end filling the containment chamber with toxic gases. A novel design was introduced using charcoals as a particle filter and two high-speed fans to suck the air out of the containment chamber. A relay and a temperature sensor automatically trigger the fans as soon as the temperature reaches 40˚C. This is the optimal environmental temperature to print Nylon 910.

2.2. Carbon Fibre Reinforced Thermoplastic (CFRTP) Composites

Depending on the material density, a 750 g filament spool is combined with PLA and Nylon for the total length of 169 m and 193.5 m, respectively. In this research, a 450 g filament was used for Nylon, which represents 77.76 m. In some cases, filament quality can clog the nozzle of the hot-end because of the contained particles in the material. This can also happen when the filament is recycled, therefore it is very important to have objects cleaned and cleared of debris to get recycled and extruded on a spool. The storage of Nylon is crucial as the material is extremely hygroscopic. Right after the purchase, the material should be processed in an oven at 100˚C for 60 min. Nylon can absorb humidity up to 4% from its total mass and once it is printed the material will have poor mechanical properties. In order to keep the matrix filament, as well as the continuous fibre (CF), coated dry, an efficient storage box had to be manufactured. A 370 × 310 × 280 mm^3 storage box was chosen for this research. It is recommended to add 1 Kg of silica gel to the bottom of the box to absorb any infiltrating moisture. A 370 mm long PVC rod was added along the length of the box to carry the filament spool. To prevent any humidity to build up inside the box a heater had to be incorporated. The heater used for this purpose is a reptile/vivarium heater as it produces a gradual heat increase along the surface of the heater, which can reach 35˚C. This heater was chosen as it doesn't produce a

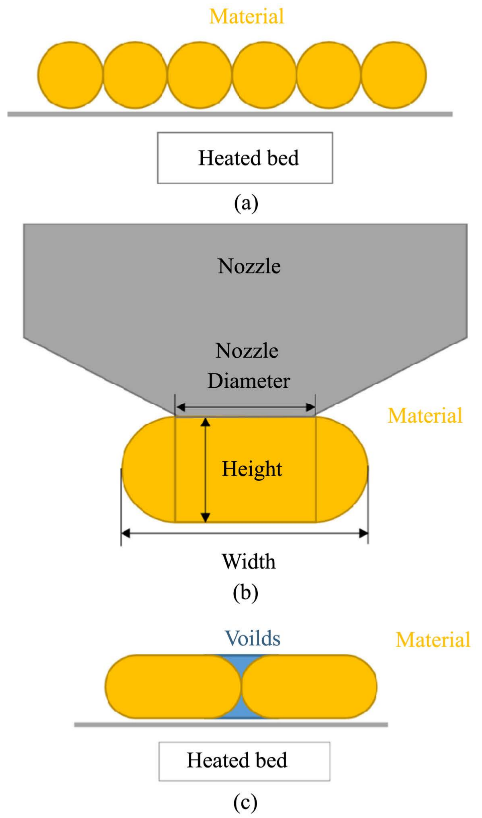

Figure 3. (a) Material deposition on a heated bed; (b) Effect of nozzle height on the material deposition and (c) Voids between material paths along the plane.

high heat on a certain area of the heating surface when it is in contact with the silica gel. A temperature and humidity-monitoring unit were incorporated to the box to monitor and control a trigger switch, which triggers the heater until the humidity levels drop down to 20% and turn it off once the target humidity level is reached.

2.3. Material Flow

The flow is the amount of material, which is pushed through the hot-end over a certain period. The flow is a crucial parameter as if two adjacent deposited material paths are too close, they will overlap and if they are too distant, the gaps will be visible which leads to delamination and de-bonding of the layers (see Figure 3). Thicker paths will have a better bonding with the lower layer, which is ideal for mechanical parts. However, the paths are not able to approximate the object shape and fill small gaps or narrow curves. Thinner paths compromise the bonding but provide better shape accuracy. Also, the extrusion width can be controlled only when extruding over an existing surface. The shape will be always round and unequal to the nozzle diameter if it is extruded in free air.

2.4. Printing a Laminated CFRTP

The key parameter to manufacture CFRTP laminates entirely depends on the process and toolpath control of the FDM printer. With a 0.8 mm nozzle printing at a layer height of 0.35 mm and phenol dissolved Nylon mixture as a coating for the heated bed, the CFRTP samples are printed. The start and end-point and printing direction of a single layer printing path have been optimised in the slicing software to avoid any fibre crossing. By simplifying the toolpath pattern the continuous fibre (CF) cutter actuation is reduced allowing the printer to layup the layer one by one in the simplest way. This reduces the processing power of the motherboard (see Figure 4).

In this research, the laminate design of [+45/−45/0/90/0/90/0/90]s was chosen as one of the most used laminates in aircraft structural design. The angle change for the Z-axes with the hot-end moves upwards to the next layer the stepper motors, which are slowed down to ease the integration of the fibre for the next layer. Also, the retraction speed is augmented the layer change, which prevents the fibre to ooze out of the nozzle and stick to the bottom layer before the stepper motors set the hot-end in motion to its starting point. When the path reaches the start point of the first printing path, the nozzle changes direction to the second path and the printing process circulates until reaching the end-point of the single layer. The material stacking along the thickness direction of each composite part follows the printing path of the single layer. By taking these printing path control methods, the 3D printer efficiently showed the aim of rapid prototyping of continuous carbon fibre reinforced Nylon composite part. Every single fibre path is uniformly compacted by employing an appropriate space between the nozzle and heating panel.

3. Experimental Impact Studies

3.1. Tensile Test Samples

In order to determine the manufacturing process and analysis of CFRTP composite materials, it is necessary to perform a tensile test on individual phase

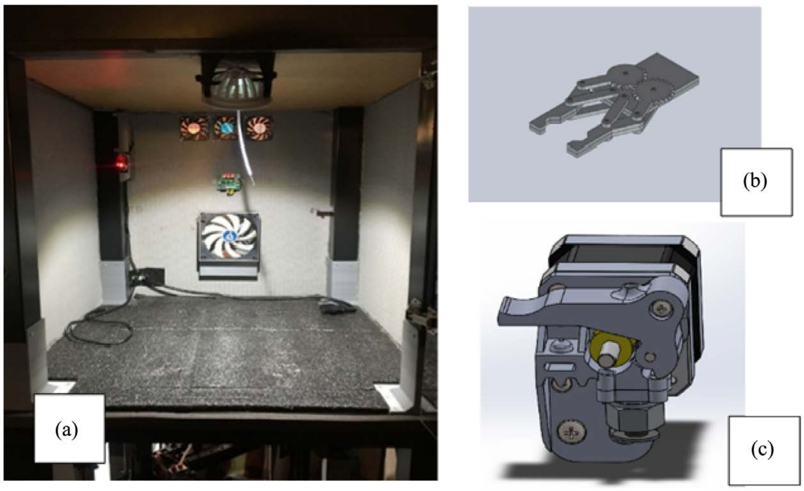

Figure 4. (a) Containment chamber with extraction fans and temperature regulator; (b) Cutter clamping design and (c) Cutter 2 Bowden design.

components. Tensile bone samples were manufactured according to BSI standards ISO 527-2.1A.50 with a thickness of 7.2 mm as shown in Figure 5. Two different types of short fibre and pure Nylon 910 samples have been tested in this work. For the Nylon 910, the tensile strength reached 0.056 GPa; however the short fibre samples showed a tensile strength of 110 GPa.

To measure the mechanical performance of developed materials, the Digital Imaging Correlation (DIC) method was applied to the Nylon, chopped CF and continuous CF bone samples. The Instron machine was set for each sample to acquire measurement over 300 seconds at a speed of 5 mm/min. The maximum tensile force was set at 5 kN. Once the machine is set up and the cameras of the DIC calibrated the sample can be clamped in position in the machine clamps and the test get started (see Figure 6).

3.2. Effect of Temperature on Layer Adhesion

The effect of temperature on the tensile test samples and their effect on the layer adhesion was investigated in this section. According to the manufacturers' recommendation, the Nylon 910 should be printed in a temperature range between 250˚C - 275˚C. However, if the temperature rises higher than the limit for the CF the polyamide coating will dissolve before it reaches the heating chamber of the hot-end and the fibres will curl inside the nozzle, which can cause a clog. In Figure 7, the graph represents the values of the ultimate tensile strength (UTS) against samples printed in the Z direction, which are perpendicular to the heated bed and an XY direction parallel to the heated bed at various temperatures.

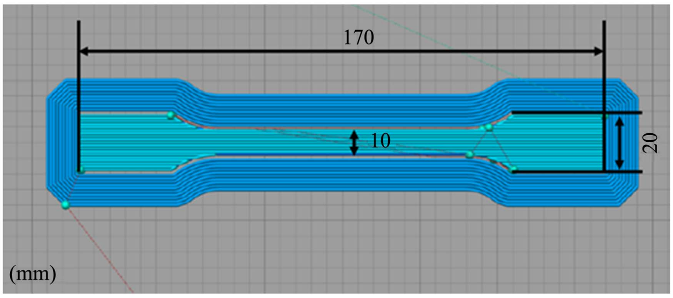

Figure 5. A tensile test sample of pure Nylon 910.

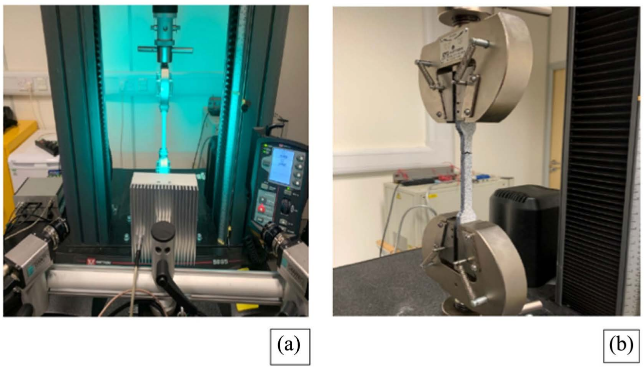

Figure 6. Digital Imaging Correlation (DIC) tensile test.

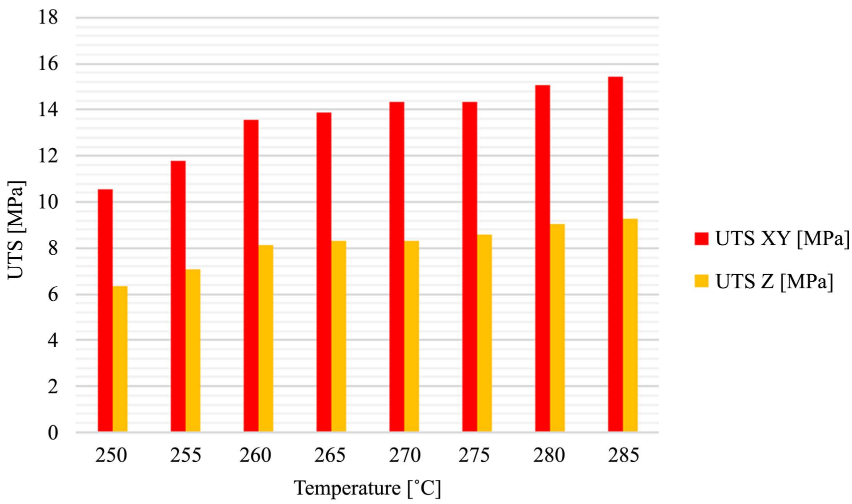

Figure 7. Effect of temperature on UTS with samples printed on XY plane and Z plane.

Both categories of samples were tested and it was shown that by increasing the temperature in the hot-end the molecules inside the heating chamber of the nozzle have more time to bond. The result is similar to an injection moulding part. The downside of an increase in temperature is the crystallisation of the material, which results in a brittle final part. In our case, if Nylon becomes brittle the impact properties of the material will disappear. Moreover, the polyamide coating of the fibre will decay before the fibre reaches the heating chamber of the hot-end.

3.3. Low-Velocity Impact

In order to determine the energy absorption capabilities of CFRTP composite samples under low-velocity impact loading conditions, the test samples were manufactured with the laminate design of [45/−45/0/90/0/90/0/90]s. The samples were manufactured according to ASTM standard for low-velocity impact testing of thermoplastics (see **Figure 8**). Three different types of samples of pure Nylon 910, chopped fibre and continuous CF were tested under impact energy of 10 J and impactor mass of 4.1 kg in terms of comparison with their energy absorption capabilities (see **Table 1**).

The impactor shape can affect the impact response of the composite and damage mechanism of the CFRTP composite with a diameter of 12 mm and a length of 6 mm for the impactor tip. The total weight of the impactor + gantry is 4.185 kg. The clamping system is 4-point rubber clamping mounts and the sample is aligned on top of the out cut of the base plate. The speed at which the impactor hits the surface of the test sample is set at 2.21 m/s. In order to compare all these printed samples total kinetic energy of 10 J was applied to all tested samples.

The continuous CF samples have shown a significant increase in energy absorption compared to pure Nylon and chopped fibres. It can be deducted that continuous fibre prevents the fibre pulling during a loading condition whereas the short fibre is dependent on the matrix, which holds them on the place. Moreover, the fibre content of the chopped fibre (SC) filament is at 20% and the continuous (CF) sample is at 30%. As shown in Figure 9 the impact resistance and energy absorption of the Nylon 910 is the poorest in comparison with chopped and continuous fibre composites.

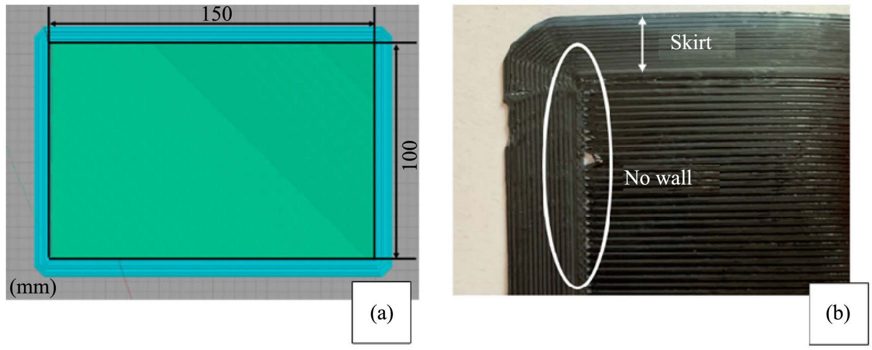

Figure 8. CFRTP plate with a total dimension of 150 mm × 100 mm, (a) Dimensions and (b) Produced a sample with a skirt before trimming.

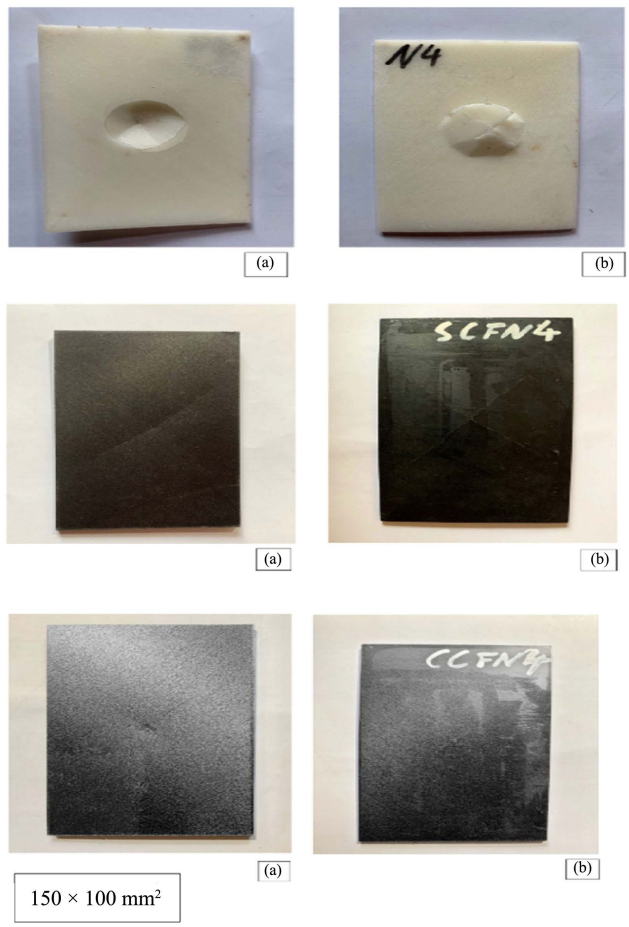

Figure 9. Low-velocity impact test on Nylon (N), Chopped Carbon Fibre Nylon (SC) and Continuous Carbon Fibre Nylon (CF), (a) Front face and (b) Back face (Dimensions 150 × 100 mm²).

Table 1. Comparison between impact test results of pure Nylon, chopped fibre (SC) and continuous fibre (CF) Nylon composites.

	Nylon 910	Chopped SC	Continuous CF
Max load [kN]	1.8	2.5	3.2
Absorbed Energy [J]	4.4	8.2	8.5
Velocity [m/s]	2.2	2.2	2.2

It was observed that the CF samples showed slightly higher energy absorption capability in comparison with SC samples, which concludes the following observation. Because of the random orientation of the short carbon fibres in the SC samples, the fibre does not redistribute the same amount of energy to the matrix. Finally, the CF samples showed the difference between the efficiency of having continuous fibre in the matrix, which redistributes the energy from the impact to the matrix. In Table 1 the comparison of the test results between the Nylon, SC and CF samples are presented in terms of maximum load and absorbed energy. Our results showed that reinforcement improves energy absorption capabilities of thermoplastic composites in comparison with pure thermoplastic composites. However, energy absorption capabilities of chopped and continuous thermoplastic composites are very close to each other compared to Nylon 910.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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