UDK 54-126:546.26:52-334.2
Original scientific article/Izvirni znanstveni članek

ISSN 1580-2949
MTAEC9, 58(5)587(2024)

# INTERFACIAL BONDING OF POLYAMIDE-REINFORCED CARBON FIBRE VIA ADDITIVE MANUFACTURING

## KOHEZIJA NA MEJAH MED OGLJIKOVIMI VLAKNI IN POLIAMIDNO MATRICO V KOMPOZITIH IZDELANIH Z DODAJALNO TEHNOLOGIJO

**Nisa Naima Khalid[1], Nabilah Afiqah Mohd Radzuan[1,2], Farhana Mohd Foudzi[1], Abu Bakar Sulong[1,2], Nurul Najwa Abd Rahman[3]**

[1]Advanced Manufacturing Research Group, Department of Mechanical & Manufacturing Engineering, Faculty of Engineering & Built Environment, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia
[2]Fuel Cell Institute, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia
[3]Division of Mechanical and Aerospace Technology, Science and Technology Research Institute for Defence (STRIDE), Ministry of Defence, Malaysia

*Prejem rokopisa – received: 2024-02-28; sprejem za objavo – accepted for publication: 2024-08-22*

doi:10.17222/mit.2024.1125

Printing orientation in polymer additive manufacturing (AM) is a crucial factor that affects both printing accuracy and the mechanical properties of the final products. Notably, printing orientation influences the interfacial bonding within printed lay-ups, thereby altering the mechanical properties to meet specific application requirements. This paper reviews studies on polyamide reinforced with carbon fibre, evaluating the impact of printing orientation, where interfacial bonding affects mechanical properties. The review shows that the common three printing orientations, 0°, 45°, and 90°, are often discussed in terms of tensile strength, fracture toughness, and electrical performance. Factors such as continuous-carbon-fibre raster angle, stacking sequence and loading direction are believed to be the main factors affecting mechanical properties. Among these, the 0° printing orientation is often associated with the highest tensile strength and stiffness due to the strong interfacial bonding between the polyamide and reinforcing carbon fibres in AM.

Keywords: polyamide-reinforced carbon fibre, mechanical properties, orientation, 3D printing, raster angle

Orientacija tiskanja je pri dodajalnih tehnologijah (AM; angl.: Additive Manufacturing) ključnega pomena, ker vpliva na natančnost izdelave in mehanske lastnosti končnega izdelka. Orientacija tiskanja pomembno vpliva tudi na kohezijo med posameznimi plastmi nanosa in s tem zagotavlja zahtevane mehanske lastnosti glede na vrsto uporabe izdelka. V članku avtorji opisujejo študijo polimernega kompozita ojačanega z ogljikovimi vlakni. V raziskavi so ocenjevali vpliv orientacije tiskanja na mehanske lastnosti s tehnologijo AM izdelanega poliamidnega kompozita. V pregledu literature avtorji ugotavljajo, da so v raziskavah vpliva natezne trdnosti, lomne žilavosti in električnih lastnosti kompozitov običajno izbrane tri orientacije vlaken 0°, 45° in 90°. Faktorji, kot so rasterski kot ogljikovih vlaken, sekvenca zlaganja in smer obremenitve kompozita, raziskovalci smatrajo kot glavne parametre, ki vplivajo na mehanske lastnosti. Med temi kot tiskanja 0° velja za tistega, ki daje največjo natezno trdnost in togost z AM tehnologijo izdelanih kompozitov s polimerno matrico zaradi zelo pomembnega vpliva trdnosti vezave med poliamidno matrico in ogljikovimi vlakni.

Ključne besede: z ogljikovimi vlakni ojačan poliamid, mehanske lastnosti, orientacija, 3D tiskanje, rasterski kot.

## 1 INTRODUCTION

Additive manufacturing (AM) technologies have significant potential in cost-saving, sustainable and complex component manufacturing. Consequently, AM is one of the most encouraging fields within component manufacturing, gaining significant attention. AM technologies encompass numerous methods. Usually referred to as 3D printing, AM or layer manufacturing is a progressive method that plays a key role in advancing manufacturing technology. The article presents potential outcomes of using 3D printing in the development of manufacturing technology. Carbon fibre-reinforced polymer composites (CFRPs) have a huge advantage over metals because they are lightweight, high in strength and stiffness, and resistant to corrosion and fatigue.[1] Using carbon fibre in AM can improve material properties, reduce the time required to manufacture functional parts compared to traditional subtractive technologies, and reduce warping, thereby enabling a larger possible build envelope. Thermosetting epoxy matrices are used in most CFRPs where a high strength and stiffness to weight ratio is necessary, for instance in aviation applications. Carbon fibre surface treatments and sizing technologies have been developed for aerospace thermosetting epoxy matrices over the years, achieving high interfacial bonding between fibres and the matrix and good mechanical properties.[2]

The advantages of continuous carbon fibres can be achieved using printing methods, such as 3D printing of continuous fibre-reinforced parts, which have caught attention from researchers. Like with traditional manufacturing techniques, a large number of printing parameters need to be carefully considered for the AM processes. The effects of printing parameters on mechanical proper-

*Corresponding author's e-mail:
afiqah@ukm.edu.my (Nabilah Afiqah Mohd Radzuan)

ties of 3D printed composites including continuous fibres have been only partly studied. In literature, the mechanical properties of 3D-printed polyamide (PA)-based composites reinforced with continuous carbon fibres were examined. The mechanical behaviours of 3D printed parts with different builds in horizontal and vertical orientations were also evaluated.[3] Fused deposition modelling (FDM) is one of the most regularly used low-cost 3D printing technology, which utilizes the hot-melt and adhesive properties of thermoplastic materials. As one of the main methods of designing thermoplastic polymer materials, PA possesses excellent comprehensive performance. The FDM technique used in 3D printing has significantly advanced manufacturing technology. By joining materials layer-by-layer based on 3D-model data, FDM has garnered considerable attention in recent years for its numerous advantages over traditional subtractive methods.[4]

The 3D printing technology allows us to directly create objects with intricate geometrical features in a cost-effective way, requiring no moulding tool and providing near-net-shape manufacturing in a relatively short period of time[5] Likewise, 3D printing is generally helpful in fabricating customized parts and products with complex and tailored designs while being capable of harnessing digital information for the realization of a robust and decentralized 3D manufacturing system. So far, the latest studies on 3D printing of continuous fibre-reinforced thermoplastic composites have been based on polylactide acid (PLA),[6] thermoplastic polyimide (TPI),[7] and acrylonitrile butadiene styrene (ABS).[8] However, the mechanical properties of PLA, TPI and ABS could not meet the critical requirements in aviation.[9] To date, studies have utilized chopped carbon fibre and PLA as the reinforcing materials and a thermoplastic matrix, with different weight percentages of chopped carbon fibre of (12, 15, and 20) % to optimize the performance.[10] The results show that with a 15-% carbon fibre reinforcement, 32-% tensile strength and 22-% flexural strength enhancements were observed when compared to a pure PLA sample.[11] This indicates that increased mechanical properties can be achieved by adding a material as the filler instead of using a pure sample.[12] Additionally, the fibre arrangement hugely affects the mechanical properties of a 3D printed composite.[13] There are a few studies on the printer head design and printing path optimization, carried out with an endeavour to control the arrangement of short fibres.[14] The quality and success of the final print depends on various process parameters such as slicing, building orientation and temperature. All these parameters influence the mechanical properties of FDM products, especially end-use parts.[15] Thus, this paper reviews mechanical properties which include printing parameters, mechanical and electrical performance of printed samples and their effects on printing orientations and interfacial bonding when using carbon fibre-reinforced polyamide.

## 2 MATERIAL AND FABRICATION

The basic component of plastics and elastomers is a polymer. Since pure polymers often show poor resistance to external factors such as weathering, mechanical stress during their processing or end-use applications, they need an additional material to increase their mechanical properties including tensile and flexural strength.[16] This research is about using polymer composites as they allow the production of high-added-value products compared to pure polymer. Different kinds of additives present within a polymer result in different vulnerabilities and strengths. Thus, this research reviews additive fillers within a polymer that can influence the effectiveness of polymer production. A multi-phase polymer composite includes a reinforcing filler integrated into the polymer matrix, resulting in synergistic mechanical properties that cannot be achieved by either component alone.[17] A study of fibre-reinforced composites demonstrated that the amount of the filler material significantly affects the properties of the composites. The interaction with adhesion, dispersion in the matrix, and particle motion are significantly dependent on the amount of the filler. Their effectiveness is increased with a decrease in the filler size.[18]

For example, nanoscale fillers exhibit a very large surface-to-volume ratio. As properties like catalytic reactivity, electrical resistivity, adhesion, gas storage, and chemical reactivity depend on the nature of the interface, these properties change dramatically.[19] The effectiveness of nanoscale fillers was demonstrated by previous researchers, who observed that a unique microstructure depended on the simultaneous deposition of nanoscale carbon and nano-sized Cu particles on carbon fibres. This process shows great potential for tailoring the structural and functional performance of advanced fibre composites.[20] According to the results, carbon nanoscale reinforcements and nano-sized copper particles deposited on a carbon fabric through cathodic electrophoretic deposition (EPD) results in the enhancement of electrical and mechanical properties.[21] In another research, the tensile properties of multiwall carbon nanotube-filled PA6 composites were assessed and the impact of phenyl glycidyl ether (PGE) as an effective noncovalent functionalization agent was verified.[22] Recent studies investigated a nanoparticle polymer for medical applications, where researchers used thermally responsive and magnetic/polymer composite nanoparticles (MPCNPs). MPCNPs possess unique properties required for a combined simultaneous application of a magnetically induced, targeted delivery of drugs to tumours, hyperthermia, controlled drug discharge and magnetic resonance imaging (MRI). The results of an in-vitro drug release under magnetic hyperthermia conditions using MPCNPs show significant promise for a multi-modal mode of cancer treatment.[23] In conclusion, an increase in the strength of nanoparticles in composite materials has shown an improvement in mechanical, electrical and thermal properties, observed when reviewing multifunctional polymer composites.

In the scope of market requirements for engineering components, there is a huge demand for polyamide thermoplastic matrices reinforced with carbon fibres due to their versatile applications.[24] There are many methods of manufacturing composites using carbon fibre-reinforced polyamide such as 3D printing, resin transfer moulding (RTM), twin-screw extruder and injection moulding.[25,26] As a manufacturing process of engineering composites, advanced manufacturing technique such as 3D printing facilitates a layer-by-layer fabrication of customized products using a wide selection of materials. **Figure 1** illustrates the concept of multifunctionality, starting with a pure polymer and progressing through additive manufacturing polymers and conventional composites, finally leading to 3D-printed composites. Also, 3D printing is often referred to as solid freeform manufacturing for computer-assisted manufacturing (CAM) and layer-by-layer design.[27] 3D printing, depicted as AM, provides manageability, cost efficiency, good product design, and waste remediation including various material choices. Academics suggest that this technology potentially improves rapid prototyping, design production, sustainability and cost minimization compared to traditional methods. 3D printing is a broad area covering all processes that produce three-dimensional models by adding materials layer-by-layer, transitioning from liquid to solid, rather than by subtracting materials.[25,28,29]

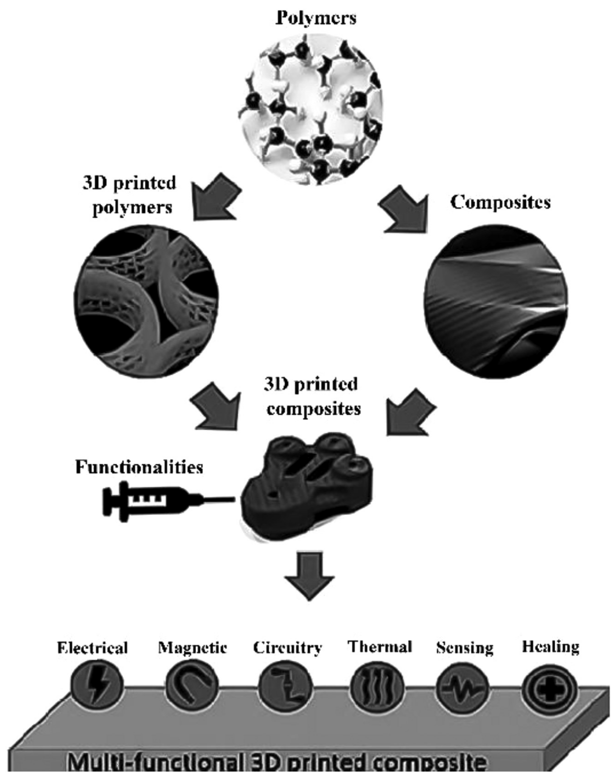


**Figure 1:** Graphical representation of the multifunctional concept, showing the progression from polymers to 3D-printed composites[30]

### *2.1 Background of polymer composites*

Polymer composites, also known as polymer matrix composites (PMCs), are composite materials containing various short or continuous fibres bound together by an organic polymer matrix. The shape of the fibre can be spherical, cubic, platelet, having regular or irregular geometries.[31] The reason of adding fibres to a material is an improvement of a product that can be found in its creep, wear, fracture toughness, and thermal stability.[32] For example, an application of polymer composites in aircraft and other products improves their quality and service life. The overall ductility of all composites can be increased by adding polymer reinforcement and curing them in dry air.[33] Ductility enhancement is achieved by adding polymer reinforcement; ductility of composites can be shown using a visco-plastic material model to capture the complex behaviour of the composites. The capability of a visco-plastic model includes capturing measured anisotropic properties, such as tension/compression asymmetry and material rate dependence.[34] In this study, PMC is used as a raw material in 3D printing that facilitates layer-by-layer customized fabrication using different materials such as polymers, metals, ceramics and composites. Using 3D printing in fabricating polymer composites is subjected to an extensive review in this paper.[35] During the design, the sustainability of a polymer composite is ensured by choosing the appropri-

**Table 1:** Recent applications of polymer composites

| Matrix material | Reinforcement | Findings | Application |
|---|---|---|---|
| Acrylonitrile butadiene styrene | Modified tapioca starch | Reduction in mechanical strength, improved features | Food packaging industry[38] |
| Thermoplastic composites | Carbon fibre | Increased tensile strength and stiffness, improved printing versatility | Bio-medical industry[39] |
| Polyactic matrix composites | Carbon fibre | Higher mechanical strength, improved extrusion of materials | Automotive industry[40] |
| Polycarbonate/ acrylonitrile butadiene styrene | Carbon fibre | Minimum wear rate, higher mechanical strength | Additive manufacturing industry[41] |
| Acrylonitrile butadiene styrene | Plastic fibre | Increased tensile strength | Aerospace industry[42] |
| Polyactic acid | Carbon fibre with plastic as The matrix | Increased flexural strength and flexural modulus | Light structures in aviation and aerospace industry[43] |

ate raw material.[36] Raw polymer materials widely used for 3D printing have to provide for various properties of the final product according to the specified requirements.[37] Various applications of polymer matrix composites can be seen in **Table 1**.

### *2.2 Polyamide and carbon fibre*

In this work, the use of carbon fibre-reinforced polyamide (PA)-based composites in 3D printing was studied. Polyamide-6 (PA6), as a promising engineering thermoplastic, is used in electronic components, mechanical parts and automotive industry due to its excellent abrasion resistance, heat resistance, and high mechanical strength. In a few recent studies, the crystalline PA6 was modified by introducing an amorphous polymer to prevent severe warpage so that it could be applied in FDM technology. PA-6 or polycaprolactam is a biodegradable and synthetic polymeric substance with good physical and mechanical properties.[44] Continuous carbon fibre (CCF)-reinforced polyamide was chosen in this study as the effective matrix with reinforcement due to superior mechanical properties of both materials. According to previous studies, CCF tows are not pure clusters of continuous carbon fibres. Specifically, it was found that CCF tows include continuous carbon fibre-reinforced polyamide, containing 48 *w*/% of pure continuous carbon fibres. As an outcome of a previous study, a composite was produced, where the matrix phase provided higher toughness values.[45] In general, carbon fibre-reinforced polyamide containing 30 *w*/% of carbon fibres achieved a tensile strength of 250 MPa in high-performance parts.[46]

### *2.3 Processing parameter*

In recent years, additive manufacturing has become a well-known method. The method, which involves 3D printing, provides possibilities for the creation of innovative prototypes and technologies in manufacturing. As several other significant parameters rely on the content in 3D printing the content is the most critical parameter.[47] There are several different methods of 3D printing, but the most widely used is the process known as fused deposition modelling (FDM). Using this technology, a wide range of polymeric materials can be processed. Nowadays, fibre-reinforced thermoplastic composites are becoming more and more important for this technique. With this technology, low-melting-point polymers are transformed into a semi-liquid and extruded in a controlled way through a nozzle, until the desired layers are deposited. So far, different printing parameters including temperature control, deposition pattern and layer thickness have been found to influence the final properties of FDM-printed parts. The extrusion of 1.75 mm carbon fibre/polyamide 6 filaments from prepared pellets through a desktop single-screw filament extruder, using 3D printing is depicted in **Figure 2** below.[48] Different printing parameters such as nozzle diameter, placement of the part in the build plate, height of the layer, printing pattern and infill density can be set to vary the appearance, quality and mechanical behaviour of a sample.[49]

Rectangular plates were built in the xy plane, using three printing architectures, shown in **Figure 3**, with different bead orientations within the stacked layers. All samples were fabricated in accordance with the printing parameters.[51] The specimens were FDM-printed with infill support, and the overlap area was 12.5 × 25 $mm^2$. In addition, the re-entrant honeycomb structure was subsequently manufactured, and the in-plane compression test was conducted at a constant strain rate of 2 mm/min.[50] Previous research showed that the mechanical properties were influenced by process parameters such as type of the infill pattern, shell thickness, type of the material, printing temperature and infill density.

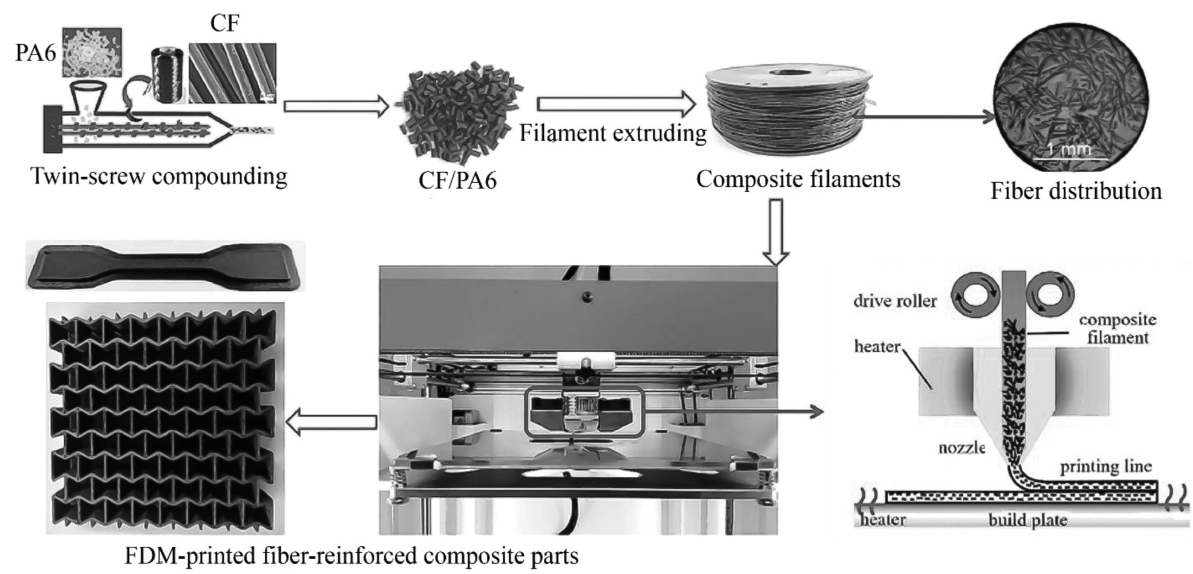


**Figure 2:** Schematic illustration of 3D-printed CF/PA6 composite filament fabrication[50]

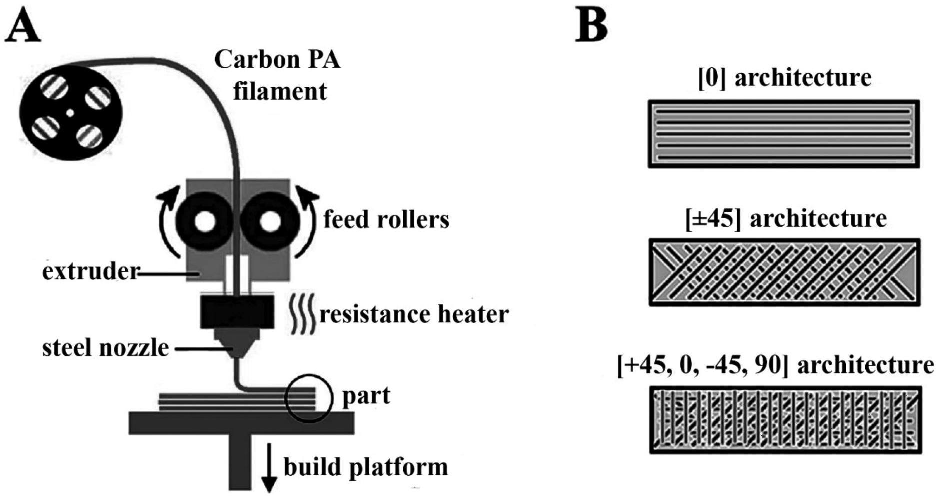


**Figure 3:** (A) Conceptual sketch of the FDM manufacturing process and (B) schematic representation of 3D-printed specimens with different printing architectures[51]

Other results showed that an object had to be both lightweight and durable so the best set of parameters was used with the honeycomb pattern with a fill density of about 40–50 %, and a shell thickness of 2–3 layers/lines.[52] In addition, there are other parameters that govern the properties of a printed product. Studies have demonstrated that anisotropy and orientation of print layers are two additional factors affecting 3D-printed products as they cause significant variations in the electrochemical activity.[53]

Due to the uniqueness of 3D printing, this paper reviews the process parameters, which influence orientation. During a previous study, specimens were produced in accordance with the 3D-printing parameters from **Table 2**, with the highest build-plate temperature of 105 °C. The influence of the build-plate temperature on the FDM-printed carbon fibre-reinforced polyamide specimens was investigated. The result shows that with an increase in the built-plate temperature, the tensile strength was also increased. The experiment was conducted on specimens with a 0° raster angle, while the other printing parameters were taken from **Table 2**.[50]

**Table 2:** FDM printing parameters for PACF specimens[50]

| Parameter | Value |
|---|---|
| Printing speed | 30 mm/s |
| Infill density | 100 % |
| Nozzle diameter | 0.4 mm |
| Printing raster angle | 0°, 45°/-45°, 90° |
| Layer thickness | 0.15 mm |
| Nozzle temperature | 260 °C |
| Environment temperature | 22 °C |
| Built-plate temperature | (30, 55, 80, 105) °C |

Other studies focusing on an increased printing speed and layer thickness found that mechanical properties were also affected. The layer thickness and printing speed were crucial printing parameters, affecting the impact strength. The optimal mechanical properties were achieved when the printing speed and layer thickness were 5 mm/s and 0.1 mm, respectively.[54] According to previous results, nozzle temperature ($T_n$), platform temperature ($T_p$), printing speed ($v$), and layer thickness ($d$) were selected as the main FDM 3D-printing parameters to be investigated.[55]

## 3 EFFECTS OF FIBRE ORIENTATIONS

A printing parameter can directly or indirectly affect mechanical properties of printed parts during fused deposition modelling (FDM). Thus, this building and orientation of 3D-FDM were studied. A previous study showed that with an increase in the nozzle temperature, the density of the produced parts was improved as air pores were partially expelled. In addition, the interlayer gap between the two materials weakened the bending resistance.[56] AM or 3D printing is economical because it neither requires rotary tools nor produces wasted raw materials; AM also enables a simultaneous manufacture of multiple products. Besides that, AM improves reproducibility with the development of related technology. Printing layer thickness, angle, orientation, laser intensity and speed are critical factors in AM, along with proper parameter setting, to achieve optimal results in 3D printing. Printing orientation is crucial because it can affect the mechanical properties such as tensile and flexural strength.[57,58] Previous research showed that a reduction in the UTS of 3D-printing materials become smaller with the printing angle decreasing from 90° to 0°, as can be seen in Table 3.[59] The reduction was calculated using the UTSRC Equation (1) shown below:

$$UTS_{RC} = UTS / UTS\ (90°) \qquad (1)$$

UTS – 3D printing materials at all printing angles
UTS (90°) – 3D printing materials at a 90° printing angle
$UTS_{RC}$ – UTS reduction coefficient

**Table 3:** $UTS_{RC}$ (TAD) for 3D printing materials[59]

| Layer thickness (mm) | 0° | 15° | 30° | 45° | 60° | 75° | 90° |
|---|---|---|---|---|---|---|---|
| 0.1 | 47.71% | 51.36% | 56.36% | 57.73% | 63.71% | 76.67% | 100.00% |
| 0.2 | 48.15% | 53.01% | 54.71% | 57.80% | 70.55% | 84.50% | 100.00% |
| 0.3 | 52.54% | 59.83% | 61.80% | 64.43% | 76.54% | 85.22% | 100.00% |

**Table 4:** Tensile strength, Young's modulus and Poison's ratio for different 3D-printed composite specimens[63]

| Test type | Property | Mean value | Standard error |
|---|---|---|---|
| Zero-degree orientation tensile samples | TS1 | 524.66 MPa | 1.80 |
| | E1 | 73.20 GPa | 1.41 |
| | υ12 | 0.33 | 0.01 |
| Ninety-degree orientation tensile samples | TS2 | 38.66 MPa | 2.77 |
| | E2 | 4.1 GPa | 0.17 |
| | υ21 | 0.19 | 0.02 |
| Quasi-isotropic orientation tensile samples | TS | 273.6 MPa | 12.46 |
| | E | 50.83 GPa | 1.13 |

### *3.1 Tensile strength*

Excellent mechanical properties of PACF composites can be acquired by controlling the effect of deposition path during 3D printing on the tensile strength.[60] Since the fibre orientation is directly related to the molten polymer of polyamide fluid during printing, three-directional angles of 0°, 45°/–45° and 90° were adopted as illustrated in **Figure 4**. The interface adhesion between the carbon fibre and polyamide was improved, which was beneficial for the stress transfer from the matrix to the fibre. In addition, the tensile strength of discontinuous fibre-reinforced thermoplastics is also linked with the distribution of fibre orientations.[61] When the tensile loading direction is parallel to the deposition direction, fibres can bear more loading, achieving a higher tensile strength and modulus. When the printing direction is at 90°, fibres are still oriented along the printing direction but are perpendicular to the tensile loading direction, thus failing at load carrying and resulting in decreased tensile strength.

Tensile strength, stiffness and Poisson's ratio of continuous carbon fibre-reinforced thermoplastic polyamide with longitudinal and transverse directions can be measured using tensile testing. Effects on the mechanical properties of 3D-printed polymer composites filled with continuous carbon fibres with different orientations can be seen in **Table 4**.[62] The maximum tensile strength and stiffness achieved for the fibres in the loading direction were 524.66 MPa and 73 GPa. These results can be strongly supported with those of the other studies, which show that specimens with a 0° printing direction aligned with the tensile stress exhibit the maximal Young's modulus and tensile strength, followed by 45°/–45° and 90° orientations, as shown in **Figure 5**.[50]

However, the parameters used in the FDM process present a conflicting effect on the tensile properties. The air gap, raster angle, contour width, raster width, and contour number are the five process parameters used in the FDM process.[64] Among these parameters, the raster angle has the highest influence. It is important and has the strongest effect on the tensile strength as seen in **Figure 6**. The sample with an angle of 0° is stronger than that with a 90` raster angle. The sample with the 0° raster angle is oriented in the longitudinal direction, which is parallel to the tensile load direction. This results in an increase in the applied tensile load, thus improving the tensile strength of the material.[65] Previous research shows how limitations are overcome when using other materials, such as polyetheretherketone (PEEK), owing to the

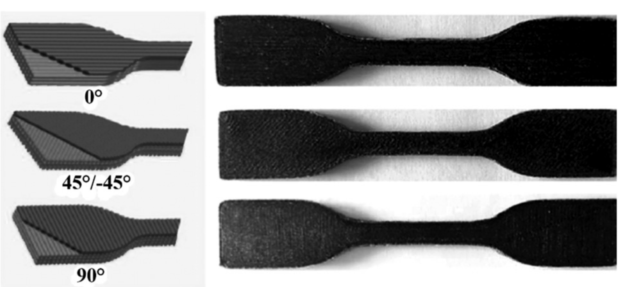


**Figure 4:** PACF specimen with different directional angles[50]

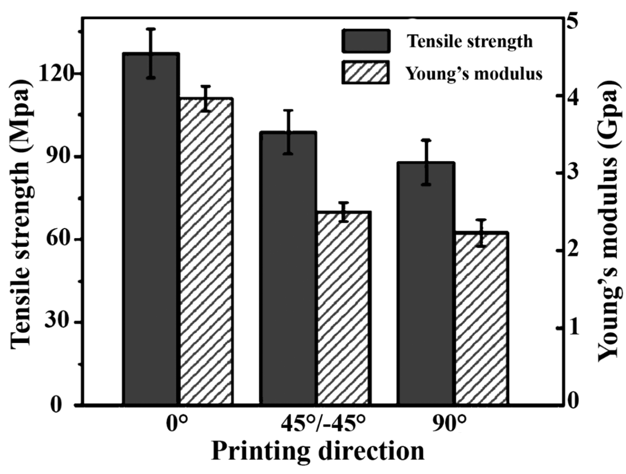


**Figure 5:** Tensile properties and Young's modulus at different printing directions[50]

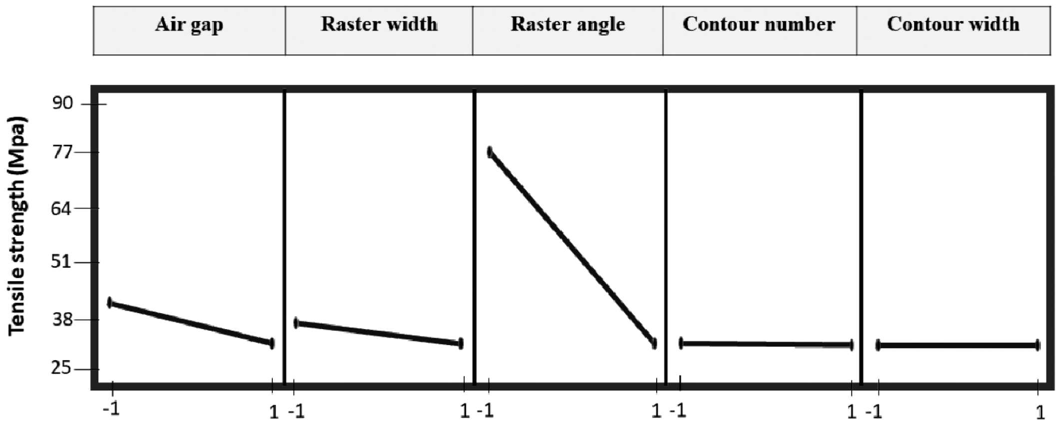


**Figure 6:** Plot of the main effects showing the influence of process parameters on the tensile strength[69]

difficulty of preparing composites with a high melting temperature and high viscosity in the FDM process.[66] Tensile strength, tensile modulus and flexural strength of the carbon fibre-reinforced PA6 composites increase as the carbon fibre content is increased. However, the use of continuous carbon fibres provides for a higher mechanical strength than that of short carbon fibre-reinforced PA6.[67] The melting temperature ($T_m$) and thermal degradation temperature are affected by the addition of carbon fibres.[68] Thus, this paper reviews the mechanical properties related to the orientation and the use of parameters in processing carbon fibre-reinforced polyamide.

### *3.2 Fracture and toughness*

Fracture is one of the most widely recognized reasons of failure in engineering structures. Consequently, studying the behaviour of materials with cracks and defects has always been of utmost importance.[70] To improve the inter-line interfacial bonding performance of 3D-printed continuous fibre-reinforced composites, enhancing fracture and toughness strength was proposed. Delamination failure is the most significant and detrimental type of damage in carbon fibre- reinforced composites because the load-bearing capability of the composite may be severely decreased without showing visible damage.[71] Numerical methods such as finite element analyses have been extensively employed to capture the fracture properties of carbon fibre-reinforced polyamide.[72,73]

The effect of orientation during 3D printing results in fracture toughness. Composites printed at 0° and 90° raster angle allow similar fracture toughness, while the weakest composite is the one with the 45° direction. This is because 3D printing induces anisotropy.[74] For 0° and 90° samples, the 90° layers are pulled along their strong axes. However, the 0° layers depend on inter-filament fusion for their strength.[75] Anisotropy is the property of substances that exhibit variations in physical properties along various molecular axes. Besides, the material strength is highly anisotropic, generally much weaker along the printing direction.[69] Previous studies found that the toughness, stiffness, and strength of unidirectional lay-ups are higher when fibres are parallel or aligned with the loading direction. For lay-ups with the layer orientation shifted by 90°, which is the standard in FDM printing, we found that the material is quite isotropic in terms of stiffness and strength, but not in terms of toughness.[76] Some studies show that the arrangement of fibres can force cracks to turn into the direction of the fibre path. As the deflection of a crack occurs under the force of continuous fibres, specimens exhibit a longer plateau before failing completely and can absorb more fracture energy.[77]

### *3.3 Electrical properties*

There are two fundamental strategies for FDM 3D printing of functional devices. The first method allows us to fabricate a structural component using 3D printing, while the second one allows for the prefabrication of electronic functional devices with conventional manufacturing and their integration into structural components, such as electrical components or electrical conducting fluid.[78–81] If a reduced mass of a part becomes important in most areas, then carbon fibre-reinforced composites (CFRPs) are the best choice. Besides its structural role, carbon fibre can be used, based on its electrical properties, for several secondary functions such as welding, sensing, crosslinking and facilitating self-healing. Carbon fibres can be used for different tasks based on their electrical properties. Long carbon fibre-reinforced epoxy-matrix composites are used, however, to improve the efficiency of their electrical properties, nanosized carbon fibres, for example, carbon black or carbon nanotubes, are added to composites.[82] New nano-engineered applications such as multi-scale and multi-functional carbon nanotube composites can be used for system health monitoring, with changes in thermal resistance and fire resistance induced by damage, along with other multi-functional attributes.[83]

Previous studies focused on the electrical properties related to the raster angle in 3D printing. The electrical conductivity of samples was measured with a Keithley

2400 SourceMeter, used at four different points during a tensile test with different point-to-point spaces. The samples were prepared at different loading percentages and different raster angles. The results showed that samples with raster angles of 0° and 90° exhibit conductive properties at a lower reinforcement ratio compared to those with a raster angle of –45°/45°. This is because the traces in the raster angle of –45°/+45° are discontinuous due to the cross-layer pattern. As printing continuity is provided by raster angles of 0° and 90°, electrical conductivity is provided at a lower reinforcement rate.[84] Significantly higher electrical properties have been demonstrated in polymeric composite materials with higher filler loadings.[85] Using carbon fibres in 3D printing is a good option when studying the effects of different variables on the anisotropic electrical properties of the carbon fibre content. At a carbon fibre content of 0.3 *w*/%, the sensors exhibited the maximal anisotropy.[59] Additionally, an increase in the electrical conductivity of PA6/carbon nanotube (PA6/CNT) microparts is firmly related to CNT loading concentrations and the development of internal microstructure. The formation of three-dimensional (3D) conductive pathways is found to be essential for the improvement of electrical conductivity of as-moulded microparts.[54]

## 4 CONCLUSIONS

In our study, the printing orientation at different raster angles including 0°, 45° and 90° is investigated as it affects the 3D printing of additively manufactured polyamide reinforced with carbon fibres. The major findings are listed below:

At a printing orientation of 0°, the tensile strength increased to its maximum, showing an improvement by ≈72 %. Notably, the 0° printing orientation resulted in an increased resistance to applied tensile loadings, thus improving the tensile strength of the material.

Investigation of the printing parameters for 3D printing showed that the raster angle influences most of mechanical properties compared to air gap, raster width, contour number and contour width. By adjusting the raster angle, better interfacial bonding within the lay-ups is achieved, improving the load transfer through the printed samples.

In contrast to the excellent mechanical properties at the 0° printing orientation, electrical conductivity is higher at the 45° raster angle. This is due to the discontinuous traces in the raster angle of –45°/45° at the printing layers. Therefore, it is strongly recommended that the printing process is tailored to the printing orientation based on the targeted performance.

## Acknowledgment

The authors acknowledge the support by Geran Universiti Penyelidikan (GUP), grant number GUP-2022-012, funded by the Centre for Research and Instrumentation Management (CRIM), Universiti Kebangsaan Malaysia. A part of this research is supported by the Faculty of Engineering and Build Environment, Dana Pecutan Penerbitan.

## 5 REFERENCES

[1] Y. S. Chang, Z. Yan, K. H. Wang, Y. Yao, J Taiwan Inst Chem Eng, 61 (**2016**), 54–63

[2] Y. Peng, Y. Wu, S. Li, K. Wang, S. Yao, Z. Liu, Compos Sci Technol, 199 (**2020**), 108337

[3] K. Raney, E. Lani, D. K. Kalla, Mater Today Proc, 4 (**2017**), 7956–7961

[4] X. Zhang, W. Fan, T. Liu, Composites Communications, (**2020**), 100413

[5] S. C. Daminabo, S. Goel, S. A. Grammatikos, H. Y. Nezhad, V. K. Thakur, Mater Today Chem, 16 (**2020**), 100248

[6] K. Balamurugan, M. V. Pavan, S. K. A. Ali, G. Kalusuraman, Mater Today Proc, (**2021**), 1687–1691

[7] W. Ye, G. Lin, W. Wu, P. Geng, X. Hu, Z. Gao, J. Zhao, Compos Part A Appl Sci Manuf, 121 (**2019**), 457–464

[8] L. G. Blok, M. L. Longana, H. Yu, B. K. S. Woods, Addit Manuf, 22 (**2018**), 176–186

[9] B. Chang, X. Li, P. Parandoush, S. Ruan, C. Shen, D. Lin, Polym Test, 88 (**2020**), 106563

[10] S. Chang, L. Li, L. Lu, J. Y. H. Fuh, Materials, 10 (**2017**), 1–11

[11] V. C. Gavali, P. R. Kubade, H. B. Kulkarni, Mater Today Proc, 22 (**2019**), 1786–1795

[12] J. Wang, S. Mubarak, D. Dhamodharan, N. Divakaran, L. Wu, X. Zhang, Composites Communications, 19 (**2020**), 142–146

[13] A. Anwer, H. E. Naguib, Addit Manuf, 22 (**2018**), 360–367

[14] H. L. Tekinalp, V. Kunc, G. M. Velez-Garcia, C. E. Duty, L. J. Love, A. K. Naskar, C. A. Blue, S. Ozcan, Compos Sci Technol, 105 (**2014**), 144–150

[15] D. Popescu, A. Zapciu, C. Amza, F. Baciu, R. Marinescu, Polym Test, 69 (**2018**), 157–166

[16] F. Yilan, İ. B. Şahin, F. Koç, L. Urtekin, El-Cezeri Journal of Science and Engineering, 10 (**2023**), 160–173

[17] R. K. Mishra, S. Thomas, N. Kalarikkal, Woodhead Publishing Series in Composites Science and Engineering, (**2017**), 97–111

[18] M. Ajorloo, M. Fasihi, H. Khoramishad, J Taiwan Inst Chem Eng, 108 (**2020**), 82–91

[19] Synthesis, Properties, and Applications Micro and Nano Technologies, (**2019**), 47–83

[20] R. K. Thines, N. M. Mubarak, S. Nizamuddin, J. N. Sahu, E. C. Abdullah, P. Ganesan, J Taiwan Inst Chem Eng, 72 (**2017**), 116–133

[21] S. B. Lee, O. Choi, W. Lee, J. W. Yi, B. S. Kim, J. H. Byun, M. K. Yoon, H. Fong, E. T. Thostenson, T. W. Chou, Compos Part A Appl Sci Manuf, 42 (**2011**), 337–344

[22] M. Park, H. Lee, J. un Jang, J. H. Park, C. H. Kim, S. Y. Kim, J. Kim, Compos Sci Technol, 177 (**2019**), 96–102

[23] S. Kayal, Mater Today Proc, (2021), 1116–1119

[24] M. Silva, A. M. Pereira, N. Alves, A. Mateus, C. Malça, Procedia Manuf, 12 (**2017**), 195–202

[25] M. Iragi, C. Pascual-González, A. Esnaola, C. S. Lopes, L. Aretxabaleta, Addit Manuf, 30 (**2019**), 100884

[26] T. N. A. T. Rahim, A. M. Abdullah, H. M. Akil, D. Mohamad, AIP Conference Proceedings, American Institute of Physics Inc., 1791 (2016), 02007

[27] S. Chakraborty, M. C. Biswas, Compos Struct, 248 (**2020**), 112562

[29] S. M. F. Kabir, K. Mathur, A. F. M. Seyam, Compos Struct, 232 (2020)

[30] D. G. Bekas, Y. Hou, Y. Liu, A. Panesar, Compos B Eng, 179 (**2019**), 107540

[31] K. Joseph, S. K. Malhotra, K. Goda, M. S. Sreekala, 1 (**2012**), 1–16

[32] P. M. Hinton, A. S. Kaddour, P. D. Soden, NAFEMS World Congress, (2011)

[33] A. Lin, Y. K. Tan, C. Wang, H. W. Kua, H. Taylor, Compos Struct, (**2020**), 112764

[34] S. Kazemahvazi, C. Schneider, V. S. Deshpande, Compos Part A Appl Sci Manuf, 71 (**2015**), 32–39

[35] B. Singh, R. Kumar, J. Singh Chohan, Mater Today Proc, 33 (**2020**), 1562–1567

[36] S. Shahinur, M. Hasan, Advances in Sustainable Polymer Composites, (**2021**), 209–229

[37] K. S. Boparai, R. Singh, Encyclopedia of Materials: Composites, 1 (**2018**), 774–784

[38] R. Singh, I. Singh, R. Kumar, Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, (**2019**), 5919–5932

[39] M. L. Longana, H. Yu, Additive Manufacturing, 22 (**2018**), 176–186

[40] J. S. Dai, Mechanisms and Machine Science, (**2019**), 2611–2620

[41] O. A. Mohamed, S. H. Masood, J. L. Bhowmik, A. E. Somers, J Manuf Process, 29 (**2017**), 149–159

[42] G. C. Onwubolu, F. Rayegani, International Journal of Manufacturing Engineering, 2014 (2014), 1–13

[43] X. Tian, T. Liu, C. Yang, Q. Wang, D. Li, Compos Part A Appl Sci Manuf, 88 (**2016**), 198–205

[44] X. Zhang, W. Fan, T. Liu, Fused deposition modelling 3D printing of polyamide-based composites and its applications, Composites Communications, 21 (**2020**), 100413

[45] E. C. Botelho, L. Figiel, M. C. Rezende, B. Lauke, Compos Sci Technol, 63 (**2003**), 1843–1855

[46] K. Saeed, A. McIlhagger, E. Harkin-Jones, J. Kelly, E. Archer, Compos Struct, 259, (**2021**), 113226

[47] R. N. Chikkangoudar, T. G. Sachidananda, N. Pattar, Mater Today Proc, 26 (2020)

[48] V. Tambrallimath, R. Keshavamurthy, P. Koppad, G. S. P. Kumar, Composites Communications, 15 (**2019**), 129–134

[49] E. Verdejo, D. Toro, J. Coello, A. Matínez, E. Técnica, S. De Ingenieros, Procedia Manuf, 41 (**2020**), 731–738

[50] X. Peng, M. Zhang, Z. Guo, L. Sang, W. Hou, Composites Communications, 22 (**2020**), 100478

[51] F. Lupone, E. Padovano, A. Veca, L. Franceschetti, C. Badini, Mater Des, 193 (**2020**), 108869

[52] G. Ćwikła, C. Grabowik, K. Kalinowski, I. Paprocka, P. Ociepka, IOP Conf Ser Mater Sci Eng, 227 (**2017**), 012033

[53] H. H. Bin Hamzah, O. Keattch, D. Covill, B. A. Patel, Sci Rep, 8 (**2018**), 1–8

[54] S. Zhou, A. N. Hrymak, M. R. Kamal, Compos Part A Appl Sci Manuf, 103 (**2017**), 84–95

[55] P. Wang, B. Zou, H. Xiao, S. Ding, C. Huang, J Mater Process Technol, 271 (**2019**), 62–74

[56] S. Ding, B. Zou, P. Wang, H. Ding, Polym Test, 78 (**2019**), 105948

[57] T. Letcher, Proceedings of the ASME 2014 International Mechanical Engineering Congress and Exposition, 2016, 1–8

[58] B. M. Tymrak, M. Kreiger, J. M. Pearce, Mater Des, 58 (**2014**), 242–246

[59] T. Yao, Z. Deng, K. Zhang, S. Li, Compos B Eng, 163 (**2019**), 393–402

[60] G. Ehrmann, A. Ehrmann, Polymers (Basel), 13 (**2021**), 1275

[61] J. M. O'Rourke and V. D. Scott, Composites Science and Technology, 56 (**1996**), 957–965

[62] K. Saeed, A. McIlhagger, E. Harkin-Jones, J. Kelly, E. Archer, Compos Struct, (2020), 113226

[63] N. Forintos, T. Czigány, Composites Part B, 162, (**2019**), 331–343

[64] A. Dadashi, M. Azadi, Heliyon, 162, (**2019**), 331–343

[65] A. Zanin, Procedia Manuf, 30 (**2019**), 331–338

[66] X. Han, D. Yang, C. Yang, S. Spintzyk, L. Scheideler, P. Li, D. Li, J. Geis-Gerstorfer, F. Rupp, J Clin Med, 8 (**2019**), 240

[67] C. K. Kundu, L. Song, Y. Hu, J Taiwan Inst Chem Eng, 112 (**2020**), 15–19

[68] H. J. An, J. S. Kim, K. Y. Kim, D. Y. Lim, D. H. Kim, Fibers and Polymers, 15 (**2014**), 2355–2359

[69] A. Zanin, Procedia Manuf, 30 (**2019**), 331–338

[70] B. Bahrami, M. R. Ayatollahi, I. Sedighi, M. A. Pérez, A. A. Garcia-Granada, Eng Fract Mech, 231 (**2020**), 107018

[71] K. L. White, H. J. Sue, Polymer (Guildf), 53 (**2012**), 37–42

[72] M. R. Khosravani, P. Frohn-Sörensen, J. Reuter, B. Engel, T. Reinicke, Theoretical and Applied Fracture Mechanics, 119 (**2022**), 103317

[73] T. Li, Y. Chen, L. Wang, Compos Sci Technol, 167 (**2018**), 251–259

[74] P. Zhang, A. C. To, Int J Plast, 80 (**2016**), 56–74

[75] T. D. McLouth, J. V. Severino, P. M. Adams, D. N. Patel, R. J. Zaldivar, Addit Manuf, 18 (**2017**), 103–109

[76] J. Kiendl, C. Gao, Composites Part B, 180 (**2020**), 107562

[77] J. Shang, X. Tian, M. Luo, W. Zhu, D. Li, Y. Qin, Z. Shan, Compos Sci Technol, 192 (**2020**), 108096

[78] Y. Z. Yu, J. R. Lu, J. Liu, Mater Des, 122 (**2017**), 80–89

[79] K. Kadimisetty, I. M. Mosa, S. Malla, J. E. Satterwhite-Warden, T. M. Kuhns, R. C. Faria, N. H. Lee, J. F. Rusling, Biosens Bioelectron, 77 (**2016**), 188–193

[80] D. C. Zuluaga, A. Menges, Materials Research Society Symposium Proceedings, 1800 (**2015**), 24–31

[81] H. Ota, S. Emaminejad, Y. Gao, A. Zhao, E. Wu, S. Challa, K. Chen, H. M. Fahad, A. K. Jha, D. Kiriya, W. Gao, H. Shiraki, K. Morioka, A. R. Ferguson, K. E. Healy, R. W. Davis, A. Javey, Adv Mater. Technol., 1 (**2016**), 1–8

[82] H. K. Sezer, O. Eren, J Manuf Process, 37 (**2019**), 339–347

[83] Q. Mu, L. Wang, C. K. Dunn, X. Kuang, F. Duan, Z. Zhang, H. J. Qi, T. Wang, Addit Manuf, 18 (**2017**), 74–83