COMPOSITE 3D PRINTING: AN EMERGING TECHNOLOGY

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1. Introduction

Composites typically comprise matrix material and a reinforcing material. The composite material offers higher strength and stiffness compared to non-reinforced polymers. Here are a few different forms of composites including: particle composites; fiber composites (short fiber, long fiber, continuous fiber); layered composites; and impregnated composites. 3D printing, on the other hand, enables the manufacturing process to be automated, since the entire process is driven by software and requires manual input only at the post-processing stage. There are two forms of 3D printing: first is a chopped fiber 3D printing filament, and second is a continuous strand of carbon fiber.

1.1 Chopped Fiber 3D Printing

Chopped fiber filled plastics are the most common type of composite 3D printed plastics. The most widely used chopped composite 3D printing material is chopped carbon fiber - where carbon fiber pieces are mixed with traditional 3D printing plastics like nylon, ABS, or PLA. These fibers are chopped up into fine pieces and mixed into the plastic before it gets extruded into a spool for use with material deposition-based 3D printers. In this case, the 3D printing process remains the same, because the fibers are just suspended in the thermoplastic - so it gets heated, extruded, and cooled into the part just like any other FFF style 3D printed. Chopped composite 3D printing materials take normal plastic that may be lacking in certain properties and boost it. In the case of carbon fiber, the fibers boost the strength, stiffness, and dimensional stability of the part to make it higher-performing than its base plastic.

Figure 1: Chopped carbon fibers used in 3D printing.

Most 3D printers capable of processing composite materials are based on the polymer-extrusion process, known as Fused Filament Fabrication (FFF). In FFF, a nozzle is moving above the build platform, extruding a melted thread of plastic, called a filament, and creating an object layer-by-layer. 3D printing of filaments containing chopped fibres is straightforward, only requiring a hardened steel nozzle to resist abrasive fibre strands. However, when it comes to continuous fibre printing, the FFF process will require a second nozzle to separately deposit a single, uninterrupted strand of fibre.

1.2 Continuous Fiber 3D Printing

Continuous fiber 3D printing adds continuous strands of fiber reinforcement to the part (think back to fiber strands), to achieve metal-strength properties at a fraction of the weight. Using two print nozzles, the printer builds the matrix material out of a thermoplastic, and irons down continuous strands of continuous fibers into the part. This process is called continuous fiber fabrication (CFF). The CFF 3D printing process consists of two steps per layer - first, a thermoplastic is extruded to form the infill and shells of the part - this serves as the “matrix” material of the composite. Next, the continuous fiber is ironed into that matrix, fusing with the thermoplastic by use of a compatible resin coating. This process repeats layer by layer, forming the fibers into the backbone of the 3D printed part, while the thermoplastic acts as a skin.

2. Types of fibers

There are diverse fibers that can be used to reinforce a polymer, here a short list:

Carbon fibers (graphitic or amorphous carbon): thermally and electrically conductive, provide high mechanical resistance at high temperature. Lightweight and low density, expensive.

Glass fibers: thermally and electrically insulative, provide high stability, high tensile stiffness and strength, small bending stiffness. Medium density, medium weight, low cost.

Ceramic fibers (e.g., silicon carbide or alumina): highly thermally conductive, grant thermal stability, mechanical strength, high-temperature creep resistivity, low density, and stability against oxidation.

Aramid fibers (such as Kevlar): high impact resistance, high strength, high modulus, toughness, and thermal stability. Kevlar fibers are highly crystalline, their surface is chemically inert. Kevlar is used in a wide range of applications due to its high strength-to-weight ratio, and it is five times stronger than steel on an equal weight basis.

Basalt fibers: brittle, high modulus of elasticity, excellent heat resistance, significant capability of heat and acoustic resistance and outstanding vibration isolators.

Wood fibers: environmentally friendly material, strong in tension and flexible.

3. Types of Resins

Polyamide / nylon (PA):

Acrylonitrile butadiene styrene (ABS)

Polylactic acid (PLA)

Polycarbonate (PC)

Polyetherimide (PE)

Polyphenylene sulfide (PPS)

Polyether ether ketone (PEEK)

Polyaryletherketone (PAEK)

4. Mechanisms of 3D printing

Co-extrusion, dual extrusion, and compaction roller methods are three popular approaches for 3D printing CFRC.

In the co-extrusion technique (figure 2), the thermoplastic filament and the reinforcing fiber are added separately to the head of the printing machine.

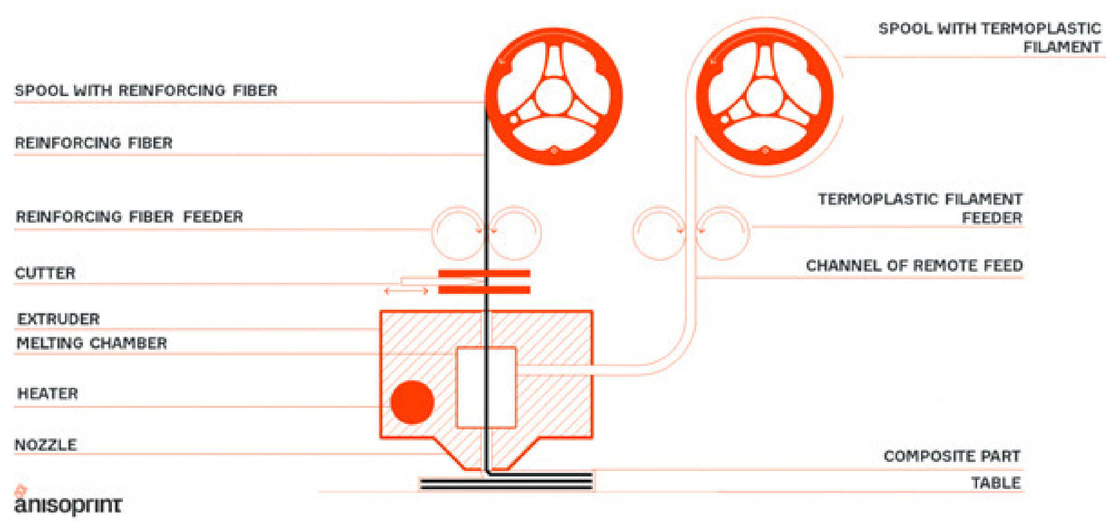
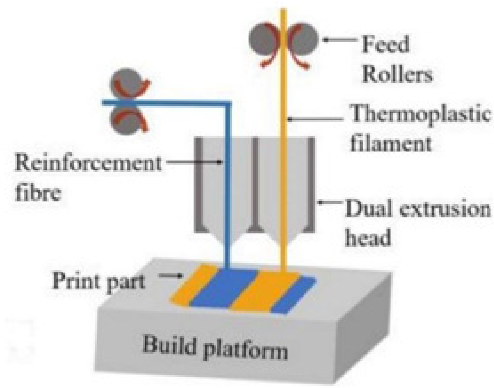


Figure 2: Composite fiber co-extrusion process.

In the dual extrusion method (figure 3), the thermoplastic filament and the fiber-reinforced are extruded separately through two nozzles on the build platform.

In the compaction roller technique (figure 4), a cartridge heater was secured to the nozzle body and used as a fixed shaft to support the compaction roller. The compaction roller has internal bearings to allow it to rotate freely around the cartridge heater.



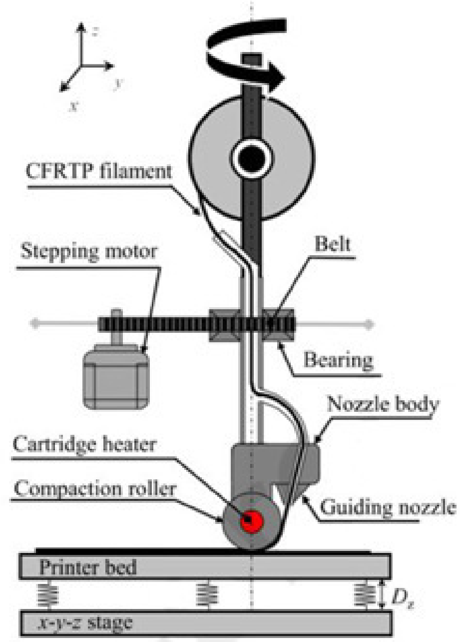


Figure 3: Dual-extrusion FDM printing. **Figure 4:** Compaction roller FDM printing.

5. 3D printing Process Parameters

The bulk of CFRC 3D printing research has focused on printing (processing) parameters rather than pre- and post-processing conditions (figure 5). The process factors can have a significant influence on mechanical properties, according to the literature. Figure 5 depicts the process variables.

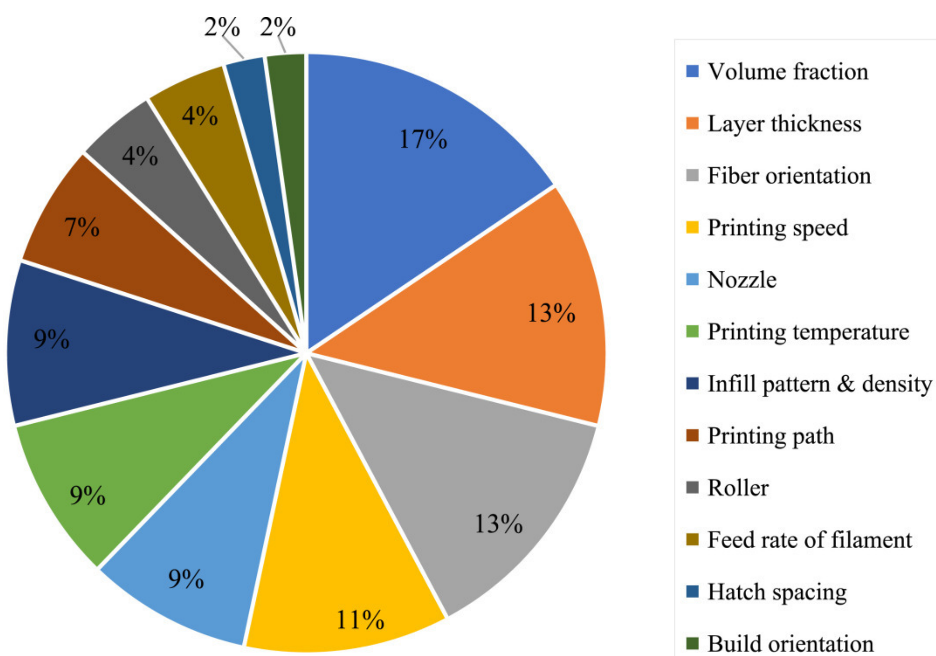


Figure 5: 3Dprinting Processing parameters.

Fiber volume fraction - As demonstrated in figure 6, raising the FVF improves the mechanical characteristics. FVF is a very effective factor that may boost tensile and flexural strength up to 1000 MPa. Furthermore, the minimum FVF necessary to achieve a tensile strength greater than 600 MPa is 25%.

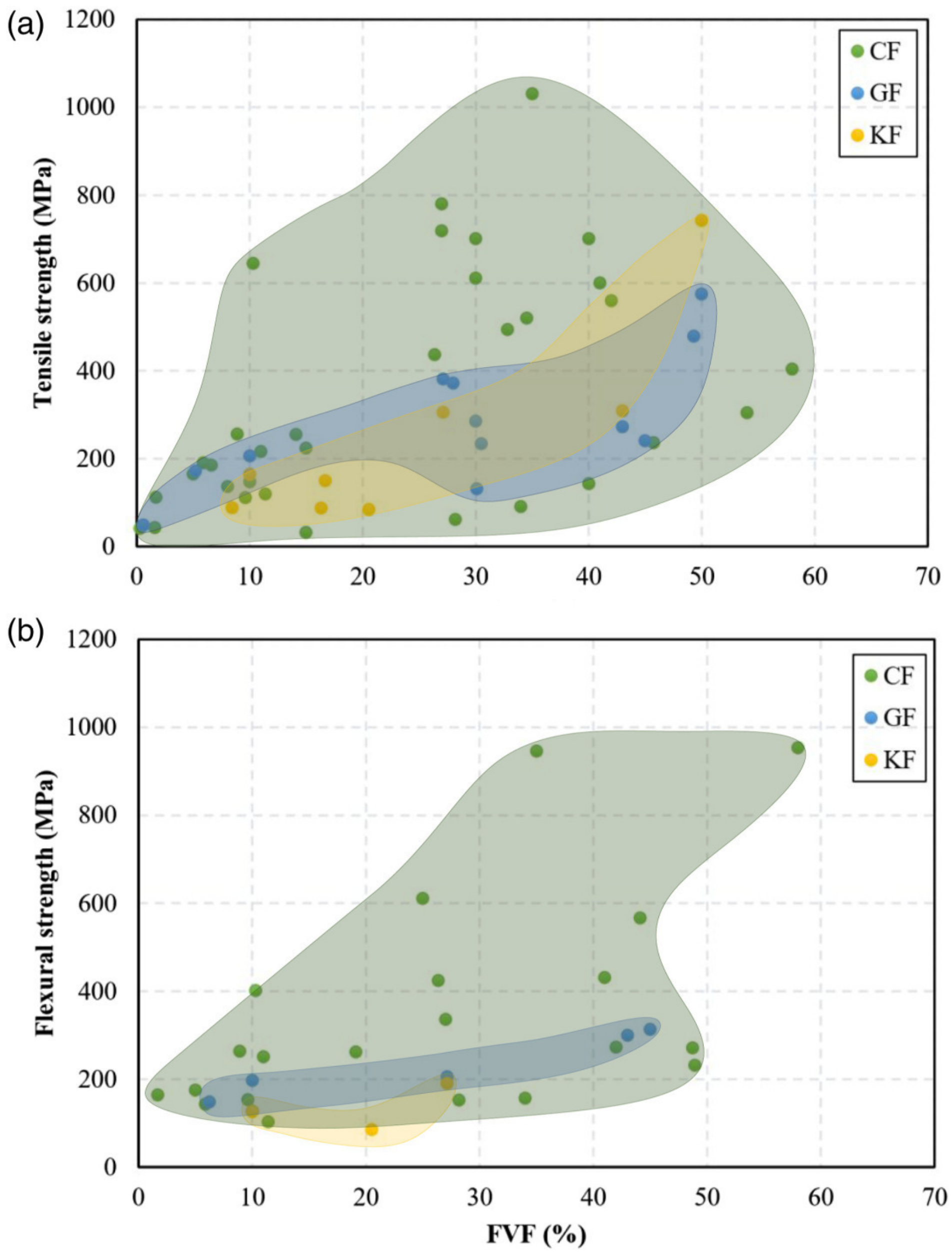


Figure 6: Relation between fiber volume fraction and tensile (a) and flexural strength (b) of continuous fiber reinforced composites.

Printing parameters - Layer thickness, printing speed and temperature, hatch spacing, and filament feedrate (figure 7) are five critical printing parameters that highly influence the mechanical properties.

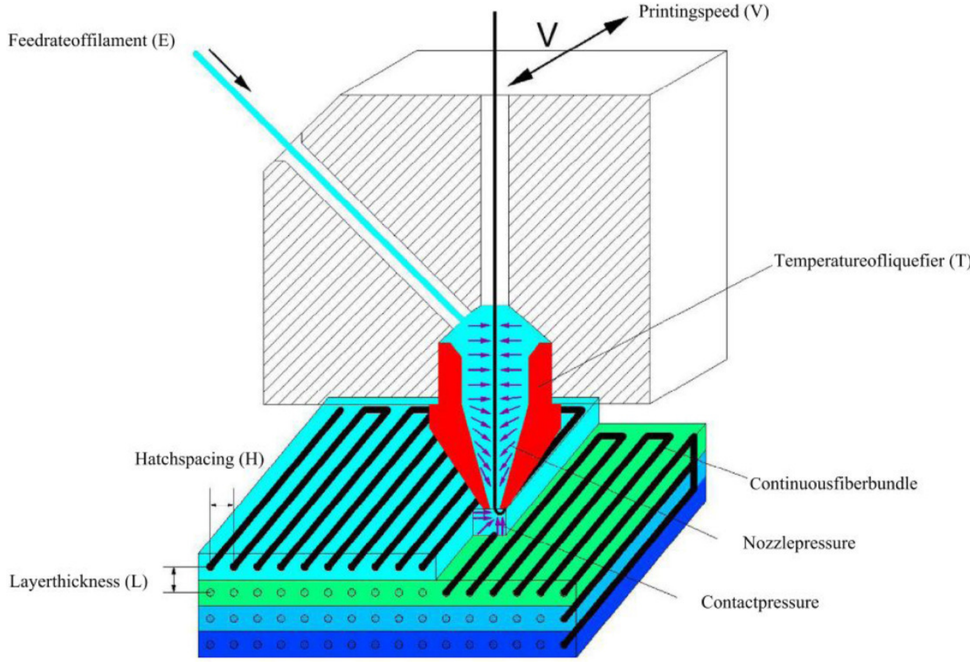


Figure 7: Schematic of process parameters for 3D printing of continuous fiber reinforced composites.

Layer thickness - The number of layers required to print the item is directly connected to the layer thickness, which in turn directly affects the printing time. Layer thickness influences manufacturing accuracy, interfacial bonding, performance, and mechanical characteristics of the samples. The mechanical characteristics of a sample with a smaller layer thickness are superior. However, decreasing the layer's thickness lengthens the printing time. As a result, an optimal thickness value must be determined that gives acceptable mechanical characteristics and a reasonable printing time.

Printing speed - The printing speed can impact the filament retention time in the extruder head as well as the resin melting rate, and if the printing speed is low, the bond between the filament and the continuous reinforcing fiber will be better. As printing speed rises, the time that filament stays in the nozzle decreases, reducing pressure and impregnation time. In most studies, increasing printing speed resulted in a loss in mechanical characteristics, whereas in others, the influence of print speed on mechanical properties was shown to be insignificant.

Printing temperature - Temperature is a significant factor in CFRC 3D printing because it influences the impregnation quality of reinforcing fibers. When the printing temperature rises, so do the mechanical characteristics because the molten filament forms a stronger connection with the produced composite. However, printed composites lose their aesthetic characteristics and dimensional precision at extremely high temperatures. As a result, a temperature should be chosen that preserves the part's appearance and dimensional accuracy while still providing acceptable mechanical characteristics. In some situations, the temperature did not influence mechanical characteristics, which might be due to the printing temperature's restricted range.

Hatch spacing - Smaller hatch spacing results in improved mechanical characteristics. The hatch spacing may be ranging from 0.5 to 2.0 mm. The average flexural strength may increase from 130 to 335 MPa and the flexural modulus may improve from 6.26 to 30 GB when hatch spacing was reduced from 2.0 to 0.5 mm.

Filament feed rate - The filament feed rate specifies the volume of material fed into the printing head per unit time. It controls the inner pressure of the printing head and the extrusion speed of the melt material. Increased feed rates resulted in a drop in fiber content while increasing the internal pressure of the liquefier and the contact pressure between the nozzle and the deposited layer. A feed rate of 80–100 mm/min may be used to balance these opposing effects. Using a small feed rate (without adjusting other parameter values) leads to deposition of an insufficient amount of material, which results in low forming pressure and poor interfacial performance.

Fiber orientation - As shown in figure 8, the fibers can be printed in two ways: concentric and isotropic. In the isotropic form, they can be printed at varied angles (0, ±45, 90°).

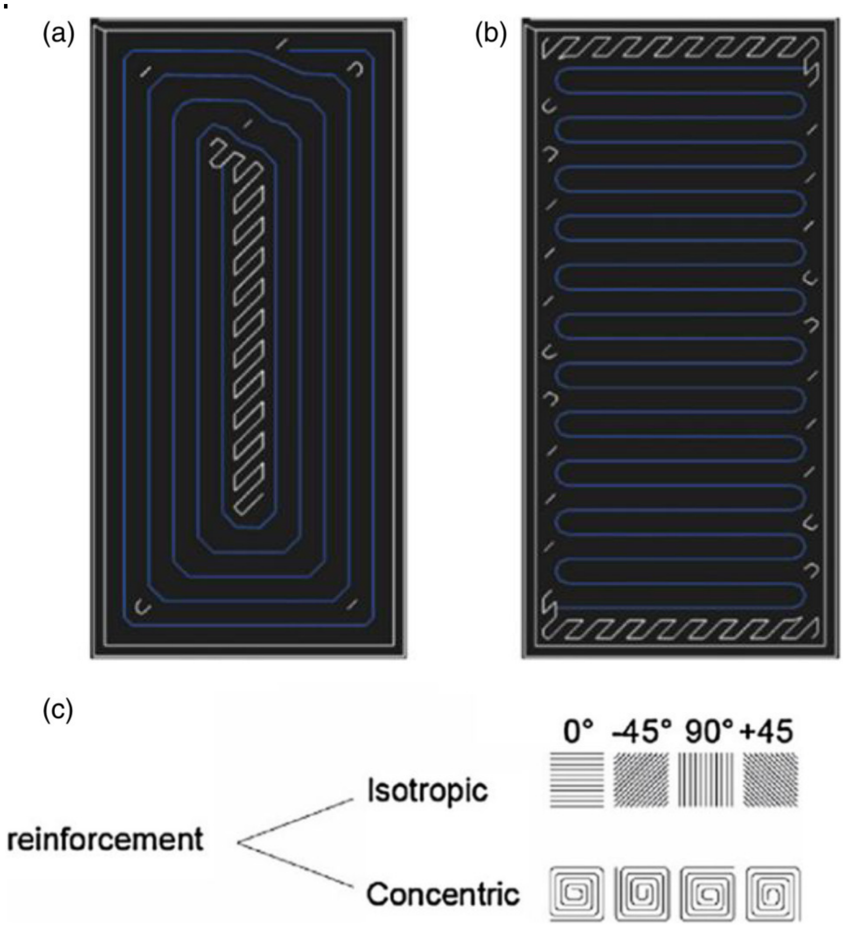


Figure 8: Fiber reinforcement configuration, (A) concentric, and (B) isotropic – 0°, and (C) fiber orientations in a single layer.

Build orientation - Three potential orientations for 3D printing composites are flat, on-edge, and upright. The on-edge composites can give higher impact strength, according to the results of Charpy tests performed on them.

Infill pattern and density - Composites of Onyx/CF composites with a triangle design performed better in tensile tests than those with a rectangular pattern. The modulus of elasticity improved when the infill density of the specimens was increased from 10% to 70%, but the tensile strength of these two composites was nearly identical.

Compaction during 3D printing - Applying pressure during the printing process substantially enhances the mechanical characteristics of CFRCs. The mechanical characteristics of composites compacted during printing are even superior to those of hot-pressed composites (figure 9).

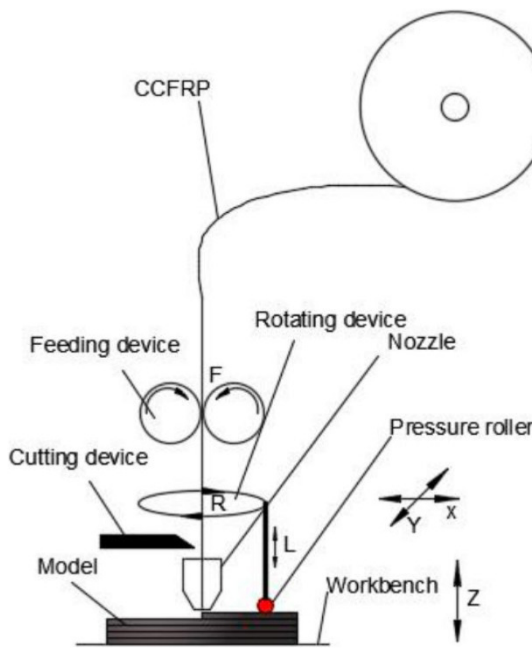


Figure 9: Schematic of the 3D-printing machine with pressure roller.

6. Properties of 3D printed composites

The reinforcing fibers (short or continuous) have excellent properties including high strength, lightweight, and anti-corrosion. The use of these reinforcing fibers in the common 3D printing process results in a fiber-reinforced composite with improved properties. The mechanical characteristics of continuous fiber reinforced composites (CFRC), such as Young's modulus, tensile strength, and flexural strength, are significantly higher than those of short fiber reinforced or neat components (figure 10).

7. Major Applications

3D printing applications in aerospace - NASA and SpaceX have been heavily investing and using 3D printing technology to manufacture their rocket SpaceX chambers etc.

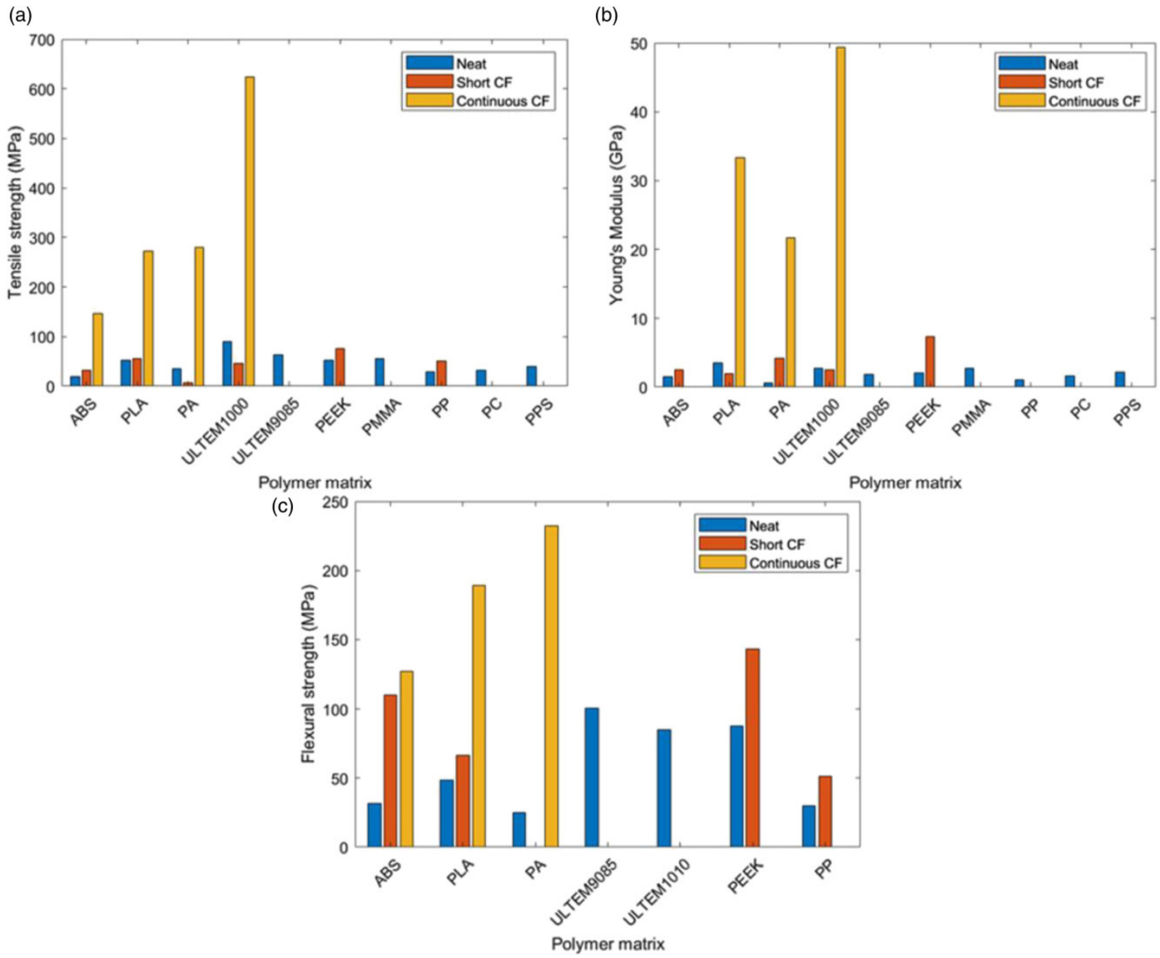


Figure 10: Overall mechanical performance for fused filament fabrication-produced specimens. Average (a) tensile strength, (b) Young's modulus, and (c) flexural strength values for neat, short, and continuous carbon fiber reinforced specimens.

3D printing applications in the medical industry - 3D printing technology is a boon for the health sector, where biomaterials can be printed in desired shape and size. For the first time in history, it is witnessed that synthetic human body parts are printed accurately. Lifesaving surgeries like heart transplants or tissue transplants are being achieved without donors and in a very short period.

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