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# Mechanical properties of carbon and glass fibre reinforced composites produced by additive manufacturing: A short review

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**Abstract.** Fibre reinforced composites are widely used in various sectors such as aerospace, wind energy and automotive. Due to its versatility and low cost for rapid prototyping and production applications, additive manufacturing technology has grown exponentially over the past few years. In this paper, performances of glass fibre and carbon fibre reinforced composites in additive manufacturing are reviewed from the perspective of mechanical properties. From the review, the reinforcements generally improve mechanical properties, in particular for tensile modulus and tensile strength. The paper presents a benchmark of additive manufacturing technologies for composite material as well as the spotlights of further research in the usage of carbon and glass fibres in rapid prototyping processes.

## 1. Introduction

The usage of fibre reinforced composites is well known on account of their outstanding mechanical properties, light weight and long-life span. These engineered materials are progressively used in construction and transportation sector for considerably low energy demand and impact to the environment [1, 2]. In the field of composite materials, low cost manufacturing technology have been an important topic of research. A wide variety of composite processing methods, such as hand lay-up [3] , injection moulding [4] and compression moulding [5] have been developed. However, most of these methods has long processing time and high energy intensity. The high cost of processing significantly restricted the application of composite material. Clearly, it is highly desirable to use new and more effective manufacturing technology such as additive manufacturing for composites. Additive manufacturing (AM) is described as a method of incorporating materials to fabricate objects from CAD models in successive layers [6]. AM technology has grown exponentially and continues to grow over the past few years because of its versatility and low manufacturing cost. Besides, the technology has customisability in manufacturing complex, geometries with micrometre solution and monolithic structures [7]. Most studies in fibre reinforced thermoplastic composites field only focused on conventional process, characterising the products and determining potential applications. Only a few studies were conducted on application of fibre reinforced composites in additive manufacturing. A thorough analysis or review on the mechanical properties of the studies needs to be conducted, in order to understand the correlation between type of reinforcement and manufacturing technique with the mechanical performance of the products. The focus of this review paper is on mechanical properties of carbon and glass fibre composites fabricated through AM techniques. Findings will provide a comprehensive perspective on fibre reinforced composite product performance in previous additive manufacturing studies, which will provide a useful reference for future studies.

## 2. Three-dimensional printing

3D printing uses 3D haptic physical models layer by layer based on CAD models [8]. Fibre reinforcement in 3D printed parts can significantly enhance the polymer matrix properties. The main concerns of these composites are the fibre orientation and void content of composites. To manufacture polymer composites, several printing techniques have been employed. Some of these methods are well established, such as laminated object manufacturing (LOM), stereolithography (SL), selective laser sintering (SLS), extrusion and fused deposition modelling (FDM). In the production of composite products, each technique has its own benefits and limitations. The choice of manufacturing process depends on the materials, processing speed and resolution, the costs and quality aspects of final products [8].

## 3. Mechanical properties of fibre reinforced composites

In literature, the performance of materials is usually represented by mechanical properties. Usually, the properties reported are tensile and flexural properties. These characteristics are important for determining material capacity, particularly under mechanical demanding conditions that are linked to engineering performance. Studies on the fibre content of carbon fibre reinforced polymer composites were conducted via 3D printing [9–11]. Carbon fibre was placed between layers of 3D printed polymer to improve strength as well as fatigue life. A study, showed that increasing the number of carbon fibre layers led to larger areas of void, which negatively affected the tensile strength [11]. Poor bonding between PLA and carbon fibre can significantly affect mechanical characteristics, however surface adhesion, tensile and flexural strength can be improved by surface treatment of carbon fibre bundles with methylene dichloride and PLA pellets [9].

Tensile properties of continuous glass fibre reinforced with PLA composite was also investigated [12]. Based on rule of mixture, by adding 4% of glass fibre, tensile strength of the composite should be 83 MPa. The findings of the tensile test showed the effectiveness of the method to achieve about 71 MPa of tensile strength. Mechanical properties of different weight percentages of pure polypropylene (PP) reinforced with glass fibre and addition of maleic anhydride polyolefin (POEg-MA) were also investigated [13]. Despite lowering its flexibility, the addition of glass fibre improved the tensile modulus and tensile strength of the composite. However, upon addition of POEg-MA, the composite exhibited decrease in modulus and strength while increased flexibility. Ning et al. [14] studied acrylonitrile butadiene styrene (ABS) composites with different fibre loading of carbon fibre in an FDM-based printer. The study reported improvement of tensile strength and modulus of the carbon fibre reinforced product. However, when compared to pure plastic samples, the modified material showed reduced ductility and yield strength.

Yang et al. [15] manufactured composite specimens using 10 wt% fibre content of continuous carbon fibre (CCF) and ABS thermoplastic via 3D printing technique. These specimens have improved their flexural strength and tensile strength to 127 MPa and 147 MPa, respectively. The results are close to the CCF/ABS composites fabricated from injection moulding with the same fibre content. Zhong et al. [16] investigated process-ability of ABS matrix composites strengthened by glass fibre with different glass fibre volume contents. The researchers noted that the filament tensile strength and surface rigidity could considerably enhanced by addition of glass fibres. A study on glass fibre reinforced polypropylene (PP) composites fabricated via FDM process showed some improvement of tensile modulus and strength, compared to pure PP [17]. Fabrication of carbon fibre reinforced ABS composites using compression moulding and FDM was compared by Tekinalp et al. [18]. At nearly all fibre content, results indicated that the tensile strength of parts manufacturing via FDM have lower tensile strength than the compression moulding. Both products showed notably increases in tensile strength as well as Young's modulus upon adding the carbon fibre. Table 1 presents the overview of changes in tensile properties of fibre reinforced products fabricated using additive manufacturing techniques compared to the control sample in each study. The negative value of percentage represents reduction in the properties.

**Table 1.** Percentage of changes in tensile properties in fibre reinforced products.

| Source | Matrix | Reinforcement | Additive manufacturing Techniques | Changes (%) Tensile strength (MPa) | Changes (%) Tensile modulus (MPa) |
|---|---|---|---|---|---|
| Ning et al. [14] | ABS | Carbon fibre powder (100 μm, 150 μm) | FDM | 23.53 | 25 |
| Tekinalp et al. [18] | ABS | Short carbon fibre (3.2 mm, after mixing: 0.26 mm) | FDM | 94.44 | 550 |
| Li et al. [9] | PLA | Continuous carbon fibre | FDM | 225 | - |
| Ferreira et al. [19] | PLA | Short carbon fibre (60 μm) | FFF | -2.38 | 97.37 |
| Chabaud et al. [20] | Polyamide | Continuous glass fibre | FFF | 3400 | - |
| Liao et.al [21] | Polyamide | Continuous carbon fibre (6-7 μm) | FDM | 87.50 | 240 |
| Sano et al. [22] | Resin | Glass fibre powder | SLA | 150 | 426.32 |
| Li et.al [23] | PF | Glass fibre powder | SLS | 11.34 | - |
| Kleijnen et al. [24] | PP | E-glass | SLS | -2.56 | 11.43 |
| Kleijnen et al. [24] | PP | E-glass | SLS | -18.97 | 60 |
| Matsuzaki et.al [25] | PLA | Carbon fibre powder | FDM | 350 | 375 |
| Blok et al. [26] | Nylon | Continuous carbon fibre | FFF | 33.33 | 33.26 |
| Blok et al. [26] | Nylon | Short carbon fibre | FFF | 150.15 | 148.65 |
| Shofner et al. [27] | ABS | Carbon nanofibres (100 μm) | FDM | 39.03 | - |
| Ning et al. [28] | ABS | Carbon fibre powders | FDM | 23.53 | 31.58 |
| Akhoundi et al. [12] | PLA | Continuous glass fibre | FDM | 66.67 | - |
| Yang et al. [15] | ABS | Continuous carbon fibre | FDM | 390 | 99.95 |

FDM: fused deposition modelling, SLS: selective laser sintering, SLA: stereolithography, FFF: fused filament fabrication, PP: Polyproplyene, PF: Phenol formaldehyde

## 4. Discussion

Additive manufacturing (AM) of polymer fibre composites is a robust manufacturing paradigm where it is possible to produce customised components with considerably enhanced mechanical characteristics compared to unreinforced polymers. From the review, the most common technique for fabricating polymer composites is fused deposition modelling (FDM). In general, the thermoplastics used for FDM are currently limited to amorphous polymers or the ones with low crystallinity levels, such as acrylonitrile butadiene styrene (ABS) or polylactic acid (PLA) [2, 29]. It was reported that, laminated object manufacturing (LOM) is superior in terms of dimensional accuracy, speed and cost efficiency [30]. Stereolithography (SLA) offers superior dimensional precision and surface finish. In terms of material usage, selective laser melting (SLM) is only suitable for metals such as steel and aluminium. Various polymers, metals and allow powders can be fabricated using selective laser sintering (SLS). These method is commonly used for advanced applications in various industries, including tissue scaffolds, lattices, aerospace and electronics [30]. As depicted in Table 1, a review of the studies carried out on printing of reinforced composites shows the different matrix, the size of the reinforcement and the resulting tensile properties. While prior studies use various properties to characterise the product, tensile properties are the main focused in this paper, as the properties are commonly reported in the literature. This is done for a fair comparison. It is presented in Table 1 that most of the published works on application 3D printer process was using carbon fibre, in comparison with glass fibre. This is despite the fact that in the supply chain, the quantity glass fibre is considerably greater compared to carbon fibre [31]. The usage of carbon fibre can be due to its high strength to weight ratio and lightweight. Significant work in carbon fibre composites is motivated by the higher price and embodied energy of carbon fibre compared to glass fibre composites [32].

Several studies reported on the use of mixed thermoplastic polymer and very short carbon fibre (~0.1 mm). The matrix and the reinforcement are usually screw extruded to form the filament used in 3D printing processes. The use of short fibre can improve the strength of the printed product. However, the high shear mixing leads to fibre breakage therefore further reduces the fibre length in the filaments. As a result, the strength in the printed parts is weaker. The strength remains low in comparison with CFRP products fabricated by conventional composite manufacturing methods such as resin infusion and autoclave [33, 34]. From Table 1, it can be clearly seen that the addition of fibre mostly improved tensile properties. The improvement can be related to parameters such as manufacturing technique, type of reinforcement and fibre loading. The material and energy consumption of AM processes, particularly involving fibre reinforced composite are rarely reported in literature. These facets are important ensure resource efficient additive manufacturing processes.

## 5. Conclusions

From literature, it is clear that the addition of carbon and glass fibre in additive manufacturing of thermoplastics could improve mechanical properties of the product. Studies should be expanded on using recycled fibres, which have less embodied energy and cheaper. The use of recycled fibres could reduce the environmental and financial impact of virgin fibre production. Studies required to fully characterise physical and mechanical behaviour of fibre reinforced 3D printed structures from aspects other than tensile and flexural properties. Such studies will open a new market for application of the structures in various sectors. Besides, material and energy consumption associated with the products should be considered, ideally from life cycle assessment perspective.

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