A review of the mechanical properties of additively manufactured fiber reinforced composites

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Abstract. Recent developments in additive manufacturing technologies have made it possible to print fiber reinforced composite materials that have reasonable mechanical performance. In this paper, a brief review of the additive manufacturing technologies for composites are presented. The focus is the mechanical properties of both discontinuous and continuous fiber reinforced composites fabricated by state-of-the-art additive manufacturing technologies. The deformation mechanisms are also briefly discussed. In addition, recommendations for future work are made.

Keywords: additive manufacturing; fiber reinforced composites; mechanical properties; deformation mechanism; review.

1. Introduction
Additive manufacturing (AM) technology has advantages in rapid prototyping and ability to produce customized and complex geometries [1] compared with traditional manufacturing technologies (such as Injection Molding and Compression Molding). Therefore, AM has applications in some industrial fields, such as aerospace, automotive, biological and medical [2]. However, AM cannot replace traditional manufacturing methods in the past decades due to the poor mechanical properties of pure materials it produced [3, 4]. For example, automotive industry requires metals with ultimate strengths between 200 MPa and 1600 MPa to bear load and improve crash resistance [5]. However, the tested average tensile strengths of previously 3D printed pure polymers were relatively low with tensile strengths of 28.5 MPa for ABS and 56.6 MPa for PLA as reported by Tymrak et al. [6]. The low strength of additively manufactured pure polymers does not meet the requirement of industrial applications for load bearing. Such drawback restricts the wide applications of AM technologies in various industrial sectors [4].

The mechanical properties of printed polymer materials can be improved significantly by adding fibers into pure polymers. The most popular reinforced fibers employed by AM technologies are carbon fibers (CF), glass fibers (GF) and Kevlar fibers (KF). Fibers can be either discontinuous or continuous. There are mainly five AM technologies to produce fiber reinforced composites (FRCs), namely Fused Deposition Modeling (FDM) using thermoplastic filaments, Laminated Object Manufacturing (LOM) using laminated sheets, Stereolithography (SLA) using photopolymer resin, Selective Laser Sintering (SLS) using plastic powder, and Direct Ink Writing (DIW) using thermoset epoxy resin. Please note SLS can only be used to print discontinuous fiber reinforced composites. FDM, LOM, SLA and DIW can be used to print both discontinuous and continuous fiber reinforced composites. Figure 1 is a flowchart shows the relation of raw material, AM process and component property. As for FDM, the most commonly used filament materials are polylactic acid (PLA), acrylonitrile butadiene styrene (ABS) and Nylon. With the recent development of 3D printers, some leading 3D printing companies can print...
using advanced polymers, such as polyether ether ketone (PEEK), which have much better mechanical performance than previously mentioned polymers [7]. For LOM, prepreg carbon fiber reinforced polymer sheets are required instead of filaments. In terms of SLS method, pertinent 3D printers can use a variety of powdery materials (the most common one is polyamide such as Nylon PA12 and PA11). DIW and SLA are able to print products with high precision and smooth visual appearance, but they are less frequently used to print fiber reinforced composites due to their limitations of using thermoset materials (resins) and difficulties to control fiber orientations. Among all these methods, FDM and LOM are the two desired methods to print FRCs because they can print composites with relatively high strength [8]. Comprehensive review of the AM technologies for fiber reinforced composites can be found in [9, 10].

**Figure 1.** Flowchart to identify the most suitable AM technologies based on required materials and performances.

The aim of the current study is to review the mechanical properties of the fiber reinforced composites produced by AM technologies. Section 1 presents the background information. Sections 2 and 3 will discuss discontinuous and continuous fiber reinforced composites, respectively. Conclusions and recommendations for future work will be presented in Section 4.

2. Mechanical properties of 3D printed composites with discontinuous fibers
The mechanical performance of discontinuous fiber reinforced composites printed by different AM technologies, FDM, SLS, DIW and SLA in published papers will be summarized and compared in the following sub-sections.

2.1. Fused Deposition Modeling
Fused Deposition Modeling (FDM) technology is the most mature and developed AM technology. It is simple and cost effective [11]. Currently, the fiber length suitable for FDM is from 5 to 300 μm. The
Impregnated fiber filaments that suitable for FDM can be manufactured by plastic extruding machines. Regarding the filament preparation process, carbon fiber and plastic resin pellets are compounded in a blender/mixer to produce a mixture of carbon fiber and plastic resin. Subsequently, the mixture is fed into an extruder to produce the filament. The fibers tend to orient automatically along with the printing direction due to shear forces acting on the nozzle during extrusion. Therefore, mechanical properties of the printed materials are better along the printing direction and weaker in other directions.

Table 1 shows a summary of the mechanical properties of 3D printed composites with different fibers and matrix combinations. The mechanical properties of FRCs are affected by various factors. Firstly, Blok et al. [12] pointed out that the increased fiber volume fractions (Vf) contributed to the improvement in tensile properties of carbon FRCs. For example, a discontinuous carbon fiber reinforced Nylon material had tensile strengths of 33.5 MPa and 83.8 MPa when Vf of fibers were 6% and 18%, respectively. Secondly, Blok et al. [12] modified the standard FDM process by adding a consolidation step when preparing the reinforced filaments to further increase the processability and enhance the performances of CFRs. For instance, the tensile strength of a carbon fiber reinforced Nylon material was 250 MPa with 12% Vf fibers, which was two times larger than that tensile strength of standard FDM manufactured Nylon FRCs (15% Vf fibers). Thirdly, Blok et al. [12] showed the processing temperature could also affect the performances of FRCs. In general, higher processing temperature leads to the increase in tensile properties of the PLA and ABS materials, while for Nylon materials decrease in tensile strengths is observed when temperature increases. The overall low performance of carbon fiber reinforced Nylon materials may be attributed to the low modulus of pure Nylon. ABS materials have the highest tensile strength of 320 MPa and modulus of 25 GPa.

In addition to the commonly used polymers, new polymers such as PEEK (whose tensile strengths are higher than that of pure ABS and PLA) have also been employed in FDM technologies. Wang et al. [13] examined the tensile and flexural properties of carbon and glass fiber reinforced PEEK materials and found out that the printed composites were stronger than pure PEEK. The largest tensile and flexural strengths are 94 MPa for CF/PEEK and 165 MPa for GF/PEEK (165 MPa) with 5 wt% fibers, indicating the increase of 19% and 17% compared with that of the printed pure PEEK respectively. However, there were no significant discrepancies in both tensile and flexural properties between GF/PEEK and CF/PEEK. Moreover, different from previously mentioned trend that the mechanical properties of FRCs increased with fiber volume fractions, both the tensile and flexural strengths of GF/PEEK and CF/PEEK decreased with the increase of fiber weight percentage in the range of 5 wt% to 15 wt%. In order to understand the reasons, the tensile fracture surfaces of 3D printed fiber reinforced PEEK were examined using SEM (Scanning Electron Microscope) [13]. The observed microstructure showed more visible gaps and fiber pull-out phenomenon in composites with high fiber percentage, which led to the decrease in strengths.
Table 1. Mechanical properties of fiber reinforced composites manufactured by FDM.

| Source          | Material (Reinforcement/Matrix) | Tensile Strength (MPa) | Tensile Modulus (GPa) | Flexural Strength (MPa) | Flexural Modulus (GPa) |
|-----------------|---------------------------------|------------------------|-----------------------|-------------------------|------------------------|
| Blok et al.1 [12] | 6% Vf CF/Nylon                  | 33.5                   | 1.8                   | 55.3                    | 3.0                    |
|                 | 15% Vf CF/Nylon                 | 83.8                   | 4.6                   | 138.3                   | 7.5                    |
| Blok et al.2 [12] | 12.5% Vf CF/Nylon T= 200 degrees | 250.0*                 | 17.5*                 |                         |                        |
|                 | 12.5% Vf CF/Nylon T= 260 degrees | 200.0*                 | 17.5*                 |                         |                        |
|                 | 12.5% Vf CF/PLA T= 170 degrees  | 220.0*                 | 20.5*                 |                         |                        |
|                 | 12.5% Vf CF/PLA T= 210 degrees  | 300.0*                 | 24.5*                 |                         |                        |
|                 | 12.5% Vf CF/ABS T= 177 degrees  | 90.0*                  | 13.5*                 |                         |                        |
|                 | 12.5% Vf CF/ABS T= 260 degrees  | 320.0*                 | 25.0*                 |                         |                        |
| Wang et al. [13] | 5 wt% GF/PEEK                   | 94.0±3.0               | -                     | 165.0±3.0               |                        |
|                 | 10 wt% GF/PEEK                  | 82.8±3.9               | -                     | 151.7±4.2               |                        |
|                 | 15 wt% GF/PEEK                  | 79.1±2.3               | -                     | 150.9±1.6               |                        |
|                 | 5 wt% CF/PEEK                   | 94.0±2.0               | -                     | 156.1±4.5               |                        |
|                 | 10 wt% CF/PEEK                  | 84.7±3.5               | -                     | 150.8±3.1               |                        |
|                 | 15 wt% CF/PEEK                  | 83.4±1.3               | -                     | 147.2±2.2               |                        |

*Numbers are extracted from the graph.
1Standard FDM process without consolidation steps.
2Modified FDM process with consolidation steps and printing at different temperatures.

2.2. Selective Laser Sintering

Selective laser sintering (SLS) uses CO₂ laser as a heat source, composite powder (with a combination of reinforced fibers and polymers) as raw materials to fabricate FRCs. The ideal fibers size is between 20 and 80 μm. Carbon fibers and plastic resins are firstly dissolved in an organic solvent to make a homogeneous mixture. This solvent is then removed to precipitate out the powder, which is composed of carbon fiber and plastics. The powder is further crushed and milled. Since the fibers are in a form of fine powder as the raw material, the printed materials have nearly isotropic mechanical properties.

The mechanical properties of the composites fabricated by SLS are summarized in Table 2. Jansson & Pejryd [14] showed that the tensile strength of CF/PA12 composites was influenced by printing orientations. The materials printed in the x direction exhibited the highest tensile strength, approximately 66.7 MPa. On the other hand, the materials printed along the diagonal direction showed lower tensile strength at around 30 MPa, which is approximately half of those printed in the xy plane. Moreover, the mechanical performance of SLS printed FRCs increases with the increase of carbon fiber weight percentage. Yan et al. [15] found that the flexural strength of CF/PA12 composites increased from 76 MPa to 113 MPa with the carbon fiber percentage increases from 30 wt% to 50 wt%. Furthermore, the usage of PEEK further improved the mechanical properties of FRCs. In order to fully melt the PEEK
materials, Yan et al. [16] increased the processing temperature from 240 to 380 degrees, the tensile strength of CF/PEEK composites reached 110 MPa at 5 wt%, which was 37.5% higher than that of the pure PEEK.

Table 2. Mechanical properties of fiber reinforced composites manufactured by SLS.

| Source       | Material (Reinforcement/Matrix) | Tensile Strength (MPa) | Tensile Modulus (GPa) | Flexural Strength (MPa) | Flexural Modulus (GPa) |
|--------------|---------------------------------|------------------------|-----------------------|-------------------------|------------------------|
| Jansson [14] | CF/PA12 x direction             | 66.7                   | 6.3                   |                         |                        |
|              | CF/PA12 y direction             | 54.0                   | 3.6                   |                         |                        |
|              | CF/PA12 diagonal of xy plane    | 56.7                   | 4.1                   |                         |                        |
|              | CF/PA12 diagonal of xz plane    | 31.3                   | 2.4                   |                         |                        |
|              | CF/PA12 diagonal of yz plane    | 31.9                   | 2.1                   |                         |                        |
|              | CF/PA12 diagonal                | 30.9                   | 2.1                   |                         |                        |
| Yan et al. [15] | 30 wt% CF/PA12               | 76.0                   | 2.7                   |                         |                        |
|              | 40 wt% CF/PA12                 |                         | 97.0                  | 3.2                     |                        |
|              | 50 wt% CF/PA12                 |                         | 113.0                 | 4.7                     |                        |
| Yan et al. [16] | 10 wt% CF/PEEK              | 110.0                  | 7.1                   |                         |                        |

2.3. Direct Ink Writing

Direct ink writing (DIW) technology uses viscous inks as matrix materials. The reinforced ink preparation process is simple by mixing reinforcing fibers with epoxy resin at 2000 rpm for three minutes [17]. The fiber cannot be automatically aligned during DIW process unless additional shear forces are applied. Lewis et al. [18] modified the standard inkjet-based printer by adding a screw into the extruder to apply shear stress during extrusion process and an impressive alignment was achieved. The stiffness of the printed materials containing fibers aligned in the loading direction was nearly 10 times higher than that of many 3D printed pure polymers.

The tested results of composites manufactured by DIW are summarized in Table 3. Nashat et al. [17] found out that both the flexural strength and moduli were increased along with the increasing in fiber volume fractions. The flexural strength and flexural modulus increased from 78.3 MPa and 3.84 GPa at 3.5% Vf to 108 MPa and 4.23 GPa at 6.3% Vf, respectively. Invernizzi et al. [19] mixed photocurable resin with polyamide so that UV light could assist the printing process as an additional curing source. In general, with the addition of glass and carbon fibers, both tensile strength and modulus of printed composites were improved. Moreover, carbon fibers exhibited better performance-enhancing abilities than glass fibers. For fiber reinforced B33 materials, the tensile strength was enhanced by 18.8% to 41.7 MPa with additional glass fibers. While for fiber reinforced B50 materials, the tensile strength was improved by 91.7% to 30.6 MPa with additional carbon fibers. Furthermore, the additional nano SiO₂ further increased the tensile strength and modulus of carbon fiber reinforced B50 by 10% since SiO₂ enhanced the bonding between printing layers.
Table 3. Mechanical properties of fiber reinforced composites manufactured by DIW.

| Source               | Material (Reinforcement/Matrix) | Tensile Strength (MPa) | Tensile Modulus (GPa) | Flexural Strength (MPa) | Flexural Modulus (GPa) |
|----------------------|---------------------------------|------------------------|-----------------------|-------------------------|------------------------|
| Nashat et al. [17]   | 3.5% Vf Kevlar/Resin            | 78.3±1.38              | 3.84±0.30             |                         |                       |
|                      | 6.3% Vf Kevlar/Resin            | 108.00±13.3            | 4.23±0.2              |                         |                       |
| Invernizzi et al. [19]| 1B33 (33 wt% resin/PA)          | 35.1                    | 2.6                   |                         |                       |
|                      | 2B50 (50 wt% resin/PA)          | 16.0                    | 2.7                   |                         |                       |
|                      | GF/B33                          | 41.7                    | 3.5                   |                         |                       |
|                      | CF/B50                          | 30.6                    | 3.9                   |                         |                       |
|                      | CF/B50 with SiO$_2$              | 33.8                    | 4.4                   |                         |                       |

1B33 represents liquid phase PA with 33 weight percent of the photocurable resin.
2B50 represents liquid phase PA with 50 weight percent of the photocurable resin.

2.4. Stereolithography

Stereolithography (SLA) uses laser to irradiate the surface of the light-cured material so that it can complete the printing of one layer from point to surface. SLA printed materials have the highest precision (approximately 50 μm) [20]. SLA technology uses a specific intensity of laser to focus and irradiate the surface of a light-cured material layer by layer until the final product is fabricated. A high intensity ultra-violet (UV) light is subsequently applied to the part to complete the polymerization process.

The mechanical properties of FRCs with different fibers manufactured by SLA are listed in Table 4. Sano et al. [21] found that both tensile strength and Young’s modulus of glass fiber reinforced light-cured resin composites increased with the weight percentage of glass fibers. Strictly speaking, SLA printed composites using chopped glass fibers was unsuccessful because the fibers cannot be self-oriented and thus only distributed in the top layers. Therefore, only powder-based (instead of chopped fibers) glass fiber reinforced light-cured resin (LCR) composite specimens with different weight percentages (from 10 wt% to 50 wt%) were printed and mechanically tested in Ref. [21]. The highest achieved tensile strength was 22 MPa, which was 110% times higher than that of the pure resin. Moreover, nano reinforcement could be employed to enhance the mechanical performance of SLA printed composites. For instance, 70% improvement in tensile strength was achieved by adding carbon nanotubes (CNTs) into neat stereolithography resins (SLRs) [22], 20.6% improvement in tensile strength was achieved by employing nano SiO$_2$ (with the same printing resolution) [23], and the tensile strength was improved by two times when graphene oxide (GO) was added and annealed under 100 degree [24].
### Table 4. Mechanical properties of fiber reinforced composites manufactured by SLA.

| Source            | Method                        | Material (Reinforcement/Matrix) | Tensile Strength (MPa) | Tensile Modulus (GPa) |
|-------------------|-------------------------------|---------------------------------|------------------------|-----------------------|
| Sano et al. [21]  | SLA                           | Light cured resin (LCR)         | 10.0                   | 0.2                   |
|                   |                               | 10 wt% GF/LCR                   | 15.0                   | 0.2                   |
|                   |                               | 20 wt% GF/LCR                   | 16.0                   | 0.2                   |
|                   |                               | 30 wt% GF /LCR                  | 17.0                   | 0.4                   |
|                   |                               | 40 wt% GF/LCR                   | 20.0                   | 0.5                   |
|                   |                               | 50 wt% GF/LCR                   | 22.0                   | 1.0                   |
| Hengky et al. [22]| SLA with thermal curing      | Neat SLR                        | 29.0                   | 0.6                   |
|                   |                               | 0.25 wt% CNTs/SLR               | 50.0                   | 0.9                   |
| Weng et al. [23]  | SLA                           | Pure Resin                      | 44.7                   | 1.7                   |
|                   |                               | 1.0 wt% SiO₂/Resin              | 46.1                   | 1.7                   |
|                   |                               | 3.0 wt% SiO₂/Resin              | 49.5                   | 2.0                   |
|                   |                               | 5.0 wt% SiO₂/Resin              | 53.9                   | 2.7                   |
| Manapat et al. [24]| SLA with annealing process   | Pure Grey Resin                 | 20.0                   |                       |
|                   |                               | 0.1 wt% GO /Resin               | 45.0                   |                       |
|                   |                               | 0.5 wt% GO /Resin               | 55.0                   |                       |
|                   |                               | 1.0 wt% GO /Resin               | 60.0                   |                       |

Figure 2 shows the tensile properties of composites manufactured by DIW, SLS, SLA, FDM and modified FDM technologies. Please note that all reinforcements used in this figure are carbon fibers. Generally speaking, composites produced by DIW have relatively low tensile strength due to the difficulties of fiber alignment (i.e. random fiber orientations). The tensile strength and modulus of FRCs produced by SLS are slightly higher with magnitudes of approximately 60 MPa and 6 GPa, respectively. The tensile strength and elastic modulus of SLA manufactured FRCs are the lowest among those fabricated by AM technologies, which are approximately 50 MPa and 0.9 GPa, respectively. FDM technology can print composites with very good mechanical properties (approximately 80 MPa in tensile strength and 30 GPa in tensile modulus). For modified FDM technology, after increasing the production temperature and adding a consolidation step during filaments preparation, the tensile strength of the printed composites can be over 200 MPa.
3. Mechanical properties of 3D printed composites with continuous fibers

In addition to discontinuous fiber reinforced composites, the 3D printed continuous fiber reinforced composites (CFRCs) have been developed and advanced during the past decade [25]. Before 2016, the reported highest tensile strength and elastic modulus of reinforced filaments with only raw fibers were 464 MPa and 35.7 GPa, respectively [26]. With the innovation of production technology, the sizing process has been applied to manufacture impregnated filaments and the high-temperature extruder has also been introduced which has the ability to completely melt the sizing agent to further improve the bonding strength [27]. Justo et al. [28] reported that the average tensile strength of printed composites increased to approximately 700 MPa with impregnated carbon fiber filaments, which was three times stronger than that of the composites printed with raw material filaments (without sizing agent).

The mechanical performance of continuous fiber reinforced composites printed by different AM technologies, FDM, SLA and LOM in published papers will be summarized and compared in the following sub-sections.

3.1. Composites printed by standard FDM printers

Markforged Inc. published their first commercialized 3D printer for FRCs in 2014. Table 5 lists some mechanical test data from Markforged for FRCs with fibers single-oriented. The tensile strength is almost four times larger than that of the composites produced with discontinuous fibers, and flexural strength also shows significant improvements when using continuous fibers. The addition of continuous carbon fibers enhances the mechanical properties of printed composites to the level of aluminum alloy, while reduces the weight by half.
Table 5. Mechanical properties of fiber reinforced composites produced by MarkTwo [29].

| Mechanical Properties         | Pure Nylon | Glass Fiber | Carbon Fiber | Kevlar Fiber |
|-------------------------------|------------|-------------|--------------|--------------|
| Tensile Strength (MPa)        | 53.8       | 590         | 800          | 610          |
| Tensile Modulus (GPa)         | 0.17       | 21          | 54           | 27           |
| Flexural Strength (MPa)       | 50         | 200         | 540          | 240          |
| Flexural Modulus (GPa)        | 1.4        | 21          | 26           | 22           |

Tensile properties of FDM printed CFRCs are summarized in Table 6. The data ranges from a tensile strength of 140.2 MPa with a corresponding modulus of 14.1 GPa for a carbon fiber reinforced Nylon material with 6% Vf to a strength of 750 MPa with a modulus of 40 GPa for an Aramid fiber reinforced Nylon material with 50% Vf. In general, fiber reinforced PLA materials [30-32] show lower strengths and moduli comparing with fiber reinforced Nylon materials [33, 34]. Moreover, carbon fiber reinforced materials yielded the highest strength and modulus at the same fiber volume percentage. Furthermore, the tensile properties are dependent on the fiber volume fraction, for example, a carbon fiber reinforced Nylon material exhibited 750 MPa with 50% Vf fibers while the tensile strength was only 150 MPa when the fiber fraction was 6.7% Vf [34].

Table 6. Tensile properties of continuous fiber reinforced materials manufactured by FDM.

| Source               | Material (Reinforcement/Matrix) | Fiber Volume Fractions (Vf %) | Tensile Strength (MPa) | Tensile Modulus (GPa) |
|----------------------|---------------------------------|------------------------------|------------------------|-----------------------|
| Ryosuke et al. [30]  | CF/PLA                          | 6.6                          | 185.2                  | 19.5                  |
| Tian et al. [31]     | CF/PLA                          | No given data                | 256.0                  | 20.6                  |
| Bettini et al. [32]  | AF/PLA                          | 8.6                          | 203.0                  | 9.3                   |
| Justo et al. [28]    | CF/Nylon                        | 39.0*                        | 701.4                  | 68.1                  |
|                      | GF/Nylon                        | 45.1*                        | 574.6                  | 25.9                  |
|                      | GF/Nylon                        | 8.0                          | 156.0                  | 3.3                   |
|                      | CF/Nylon                        | 10.0                         | 212.0                  | 4.9                   |
|                      | CF/Nylon                        | 6.0                          | 140.2                  | 14.1                  |
|                      | CF/Nylon                        | 18.0                         | 464.4                  | 35.7                  |
|                      | AF/Nylon                        | 6.7                          | 150.0                  | 14.2                  |
|                      | AF/Nylon                        | 20.0                         | 330.0                  | 24.5                  |
| Hou et al. [34]      | AF/Nylon                        | 30.0                         | 360.0                  | 26.6                  |
|                      | AF/Nylon                        | 40.0                         | 660.0                  | 40.0                  |
|                      | AF/Nylon                        | 50.0                         | 750.0                  | 40.0                  |

*Volume percentage was calculated from the known weight percentage.

Figures 3 and 4 show the tensile moduli and tensile strengths, respectively, of CFRCs manufactured by FDM processes in approximately 35 published papers. The results indicate very scattered distributions of both strength and modulus. This is due to not only the deviation in the choice of materials and formulation (polymer, fiber type, fiber volume percentage among others), but also different processing parameters and printers. In addition, it should be noted that there are currently no specific standards for the design of specimens to evaluate the mechanical properties of 3D printed composites, thus specimen geometry varies which influences the test results as well.
Figure 3. Tensile strength vs. fiber volume fraction of different continuous fiber reinforced composites.

Figure 4. Tensile modulus vs. fiber volume fraction of different continuous fiber reinforced composites.
3.2. Materials printed by modified FDM printers

In order to prevent a large number of voids formed in the printing process and increase the interfacial shear strength between beads, compaction during 3D printing was proposed, which was named as modified FDM technology. Thermoplastic filaments and continuous carbon fibers are separately supplied to a 3D printer, while compaction roller can consolidate fiber reinforced layer right after the extrusion of impregnated filaments. A few researches comprehensively analyzed the effects of compaction on the mechanical properties of CFRCs [35, 36] and the enhancement of the mechanical properties due to the compaction roller was confirmed.

The mechanical properties of continuous fiber reinforced composites fabricated by modified FDM technology are summarized in Table 7. Zhang et al. [35] found that the tensile strength and bending strength of specimens were enhanced to 644.8 MPa and 401.2 MPa by employing compaction, while the tensile strength and bending strength were 109.9 MPa and 163.1 MPa without applying any pressure during the fabrication process. Moreover, Ueda et al. [36] compared both the tensile and flexural properties of carbon fiber reinforced Nylon composites printed by modified FDM and conventional FDM technologies. The average tensile strengths were approximately 1031 MPa and 777 MPa for the composites fabricated by modified FDM and conventional FDM, respectively. The results showed no difference in the tensile modulus between the two methods due to the same percentage of fibers, while the tensile strength of the modified FDM specimen was approximately 33% higher than that of the conventional FDM fabricated specimen due to the lower void percentage.

| Source          | Material (Reinforcement/Matrix) | Tensile Strength (MPa) | Tensile Modulus (GPa) | Flexural Strength (MPa) | Flexural Modulus (GPa) |
|-----------------|---------------------------------|------------------------|-----------------------|-------------------------|------------------------|
| Zhang et al. [35] | CF/PLA 10% Vf                   | 644.8                  | -                     | 401.2                   | -                      |
| Ueda et al. [36]  | CF/Nylon 35% Vf                 | 1031.0 ± 59.0          | 71.2 ± 0.7            | 945.0 ± 60.0            | 65.7 ± 3.7             |

3.3. Composites printed by other AM technologies

In addition to FDM, SLA [21, 37] and LOM [38, 39] technologies were also reported to have the abilities to produce CFRCs with continuous fibers. However, only limited work could be found.

The mechanical properties of continuous fiber reinforced composites fabricated by SLA and LOM technologies are summarized in Table 8. For SLA printed FRCs, the fibers can be either fiber filaments or woven fabrics. Sano et al. [21] reported that the tensile strength and Young’s modulus of FRCs with continuous glass fiber woven fabrics showed significant increase. The tensile strength was 80 MPa, which was 10.5 times higher than that of the pure resin. Moreover, Lu et al. [37] performed tensile tests on pure polymer and carbon fiber reinforced composites produced by both FDM and SLA technologies. The results showed that with embedded carbon fibers, an increase of elastic modulus by 110.49% and 23.69% for FDM and SLA fabricated composites, respectively. The SEM analysis revealed that the presence of pores at the fiber-matrix interfaces in both the SLA and FDM printed composites caused the failure of fiber-matrix bonding and reduce the tensile properties.

For LOM technology, Chang et al. [38] employed a novel method to produce carbon fiber reinforced PEEK composite using prepreg composite sheets with 59% fiber volume fractions. The tensile strength and modulus of the printed composite were 1513.8 MPa and 133.1 GPa, respectively. Such high tensile strength is fully comparable with the strength of materials manufactured by the manually layered autoclave method. Moreover, Parandoush et al. [39] used the same technology to manufacture carbon fiber reinforced PA6 composites, which had the highest tensile strength of 668.3 MPa among all AM manufactured PA6 composites reported. SEM analysis revealed superior interfacial bonding and a high volume fraction of continuous carbon fibers (55% Vf).
Table 8. Mechanical properties of continuous fiber reinforced composites manufactured by SLA and LOM.

| Source                  | Method | Material (Reinforcement/Matrix) | Tensile Strength (MPa) | Tensile Modulus (GPa) |
|-------------------------|--------|---------------------------------|------------------------|-----------------------|
| Sano et al. [21]        | SLA    | GF/Light cured Resin            | 79.0                   | 1.8                   |
| Lu et al. [37]          | SLA    | CF/Accura60 Resin              | 60.0                   | 1.02                  |
| Chang et al. [38]       | LOM    | CF/PEEK                        | 1513.8                 | 133.1                 |
| Parandoush et al. [39]  | LOM    | CF/PA6                         | 668.3                  | 18.0                  |

3.4. Comparison of tensile strength of FRCs manufactured via different AM technologies

Figure 5 shows tensile strength versus fiber volume fraction of composites manufactured by different AM technologies. It is evident that the tensile strength increases significantly when thermoplastic composite is reinforced with continuous fibers compared with those of CFRCs with discontinuous fibers. As shown in Region 1, the tensile strength of continuous fiber reinforced PLA materials (200 MPa) is almost double the strength of discontinuous fiber reinforced PLA (90 MPa). Comparing the oval Regions two, three and four shown in Figure 4 (they all utilize Nylon as matrix materials), carbon fiber reinforced composites display higher tensile strength than glass fiber and aramid fiber reinforced composites, especially at high fiber volume fraction (e.g. 40% Vf). Please note that when fiber volume fraction is over 40%, only glass fibers and aramid fibers can be successfully printed out in composites. No record shows that carbon fibers can be printed out with such a high fiber volume fraction in composites because the CFRCs tend to become fragile when carbon fiber fraction is high. In addition, recent progress in LOM technology (oval Region five) improves the tensile strength of AM fabricated composites up to 1500 MPa, which enables AM printed composite to replace materials produced by traditional autoclave consolidation process (oval Region six). Oval Region seven in Figure 4 depicts that the AM manufactured continuous fiber reinforced composites can compete with those fabricated by compression molding. Although the mechanical properties of discontinuous fiber reinforced composites (shown in oval Region eight), are enhanced compared to pure polymers, they are inferior with respect to the mechanical properties of the composites manufactured by other continuous fibers AM technologies.

In general, although FDM and LOM can produce composites with relatively high strengths (500-1500 MPa), they still fall short in comparison to the tensile strength (more than 1500 MPa) and fiber volume (up to 70%) of the conventionally manufactured composites. This leaves exciting opportunities for various AM technologies to further enhance the mechanical properties of the FRCs to be explored in the near future through material development and process enhancement.
4. Conclusions
Adding discontinuous and continuous fibers to pure polymer materials during the additive manufacturing process has become a promising trend in the production of composites. The addition of reinforcing fibers has improved the mechanical properties of the original pure polymer materials. This paper briefly reviews the five major additive manufacturing technologies (FDM, SLA, SLS, DIW and LOM) used to fabricate fiber reinforced composites. Attention has been made on the mechanical properties of AM fabricated fiber reinforced composites.

For discontinuous fiber reinforced composites, the tensile strength and modulus of composites fabricated by FDM and modified FDM are normally better than those fabricated by SLS, DIW and SLA. The mechanical performance of fiber reinforced PLA, Nylon, Ink, photocurable resin and powder are enhanced with additional fibers when using FDM, SLS, DIW and SLA technologies. However, for PEEK used in FDM technology, the mechanical properties decrease with the increase of carbon fiber percentage. Moreover, some research groups modified the FDM printer by adding the consolidation process, the tensile strength of a carbon fiber reinforced Nylon material could be 250 MPa, which is two times larger than that tensile strength of standard FDM manufactured Nylon FRCs. Furthermore, processing temperature also affects the mechanical properties of FDM fabricated composites.

For FDM manufactured continuous carbon fiber reinforced composites, the tensile strengths increase with the fiber volume fractions in general. Moreover, the carbon fiber reinforced Nylon composites show superior mechanical performance than other types of CFRCs (GF/Nylon, Aramid/Nylon and CF/PLA). The tensile strength of CF/Nylon composites can be over 300 MPa when carbon fiber volume percentage is over 20%, which gives FDM manufactured CF/Nylon composites opportunities to compete with composites fabricated by compression molding. Furthermore, some researchers confirmed the enhancement of the mechanical properties due to the additional compaction roller. The tensile strength of the modified FDM specimen was approximately 33% higher than that of the conventional FDM fabricated specimen due to the lower void formations. In addition, the maximum reported tensile strength is approximately 1500 MPa using LOM technology which is even better than using autoclave consolidation.

Although some AM manufactured fiber reinforced composites have the same level of mechanical performance as traditionally manufactured composites, voids and poor bonding are observed. Therefore,
the research of AM fabricated fiber reinforced composites is still in its infancy. The recommended areas to be investigated in the future include:

- novel matrix materials (such as thermosetting plastics and nanocomposites) are expected to be developed for discontinuous fiber reinforced composites.
- possible approaches to increase continuous fiber volume fraction and reduce the void percentage are expected to be explored to further enhance the mechanical properties of the AM fabricated composites.

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