Evaluation of Tensile strength and repeatability of 3D printed carbon fibre materials and processes.

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Abstract

As additive manufacturing (AM) with composite materials becomes more widely used in industry to create high strength components, it's vital to have quantified material properties that provide designers and engineers accurate data to decide which materials are suitable for their applications. This study replicates the build processes and tensile tests undertaken by AM material manufacturers to compare tensile strengths achieved, to those stated on manufactures' data sheets. This is important data to research and analyse as it will either corroborate properties given by the manufactures and provide confidence in the values provided, or it will show that the manufacturer values cannot always be achieved, and that designers and engineers must be more critical about the values manufactures are providing when using the materials in their own applications.

Tensile tests were performed on additively manufactured specimens that had been built using the same parameters that were used during the manufacturers testing procedures. Digital image correlation was used to accurately measure strain in the test samples, enabling material properties to be determined. Microscopy analysis enabled the visual inspection of the print quality, the identification of defects, and the determination of volume fraction with the samples.

The results show inconsistencies between the tensile strength results achieved during this study and the tensile strengths stated by manufactures. Results show two materials exceeded the expected values and one material did not reach the expected value. Analysis of the 3D printed specimens show that poor fibre-matrix wetting, large voids, and weak interfacial bonding were accountable for the lower-than-expected tensile strength results. While good print quality, low void percentage, proper fibre-matrix wetting, and good control measures were accountable for results that exceeded expectation. These results show that designers and engineers cannot solely rely on material data sheets to establish the mechanical properties of their 3D printed components.

Introduction

Fused Filament Fabrication (FFF) printing technology is the most widely used across the AM industry. Its popularity is attributed to its large range of application fields, printable materials, printing simplicity and printing controls [1,2]. Currently the two main types of 3D composite printing are variations of FFF technologies. The two approaches are printing with short reinforcement fibres mixed with a thermoplastic matrix, and continuous composite printing. FFF composite printing allows reinforcements to be accurately placed and structures to be optimised per layer, allowing increased design freedom and mechanical performance [3].

Continuous strands of carbon fibre can absorb and distribute loads across their entire length, therefore when placed within a thermoplastic matrix, the part can handle higher loads and absorb larger impacts in predicted orientations[4]. Chopped strand carbon fibres are chopped into small pieces and mixed into a matrix at uncontrollable angles resulting in the fibres absorbing some of the applied stresses on the part, and increasing properties such as strength, stiffness, and dimensional stability across the entire part in multiple orientations[4].

Mechanical properties of thermoplastics used are low in comparison to common engineering materials [3] such as aluminium and steel, so adding a reinforcement into the material can increase its mechanical properties and broaden its range of applications. The addition of short carbon fibres (~ 0.1mm) mixed with a thermoplastic polymer can increase the strength and stiffness of the printed material by 65%, however due to the FFF printing technique the strength increase can be limited, as fibre pull out may occur before fibre breakage [3].

Continuous composite printing involves extruding continuous strands of a reinforcement material, such as carbon fibre into the 3D print. Printing with continuous carbon fibres provides significant increases in performance over unreinforced thermoplastics [3,5]. The use of continuous composite 3D printing has opened new applications for fabrication and the manufacture of high strength, light weight components for industry [3]. 3D printing with continuous carbon fibre can produce components '8x stronger than ABS and 20% stronger than the yield strength of aluminium', resulting in parts of strength and stiffness of 700MPa and 50GPa respectively [3]. A drawback to this type of composite printing is the continuous fibres cannot be deposited freely through small steering radii and sharp angles, meaning some geometries are impossible to print using continuous composite printing [3].

In conjunction with the material chosen for part production, the mechanical properties of a 3D printed component can be influenced by the print process. Print parameters that have been found to influence the mechanical properties of a component include layer height, wall thickness, orientation, temperature, infill density, and infill pattern [6]. Specifically for composite 3D printing the infill pattern has been found to significantly impact mechanical properties [7]. Naranjo-Lozada et al., reports increased tensile strength when using triangular infill pattern over rectangular infill pattern for composite 3D printing.

Although data sheets are available for a variety of 3D printable composite materials, the mechanical properties of the printed component can deviate from the stock materials due to the specifics of how a structure is formed on the meso-scale during printing [3]. To ensure 3D printed carbon fibre components meet required design specifications in industrial applications, it's necessary to understand their tensile properties [8]. Whilst research has been conducted previously into the tensile properties certain materials possess when printed, research into the mechanical properties which a component has achieved compared against manufacture given values for a variety of composite 3D printed materials is sparse. This study aims to compare the tensile strength and other material properties of carbon fibre 3D printed materials against the values provided by manufacturers to assess their reliability and the repeatability. The main goal of the research is to increase knowledge in the field of 3D printing material properties and their accuracy and reliability.

Materials and Methods

Methodology

The methods used during this research aims to replicate the methodology used by the manufacturers when achieving their material properties results. Replicating the methodology and printing parameters used by manufactures will reduce variability and increase reliability in the results achieved when compared against the manufacturer values. It is vital to replicate their methodology for this comparative research as producing parts with different print parameters would provide completely different material properties. For example, building the specimens in a different orientation will affect its mechanical properties, particularly its anisotropy, and printing with different layer/fibre orientations will affect the mechanical properties of the specimen, including strength, stiffness, and ductility[5,6,9]. Specifically, the orientation of the fibres relative to the loading direction can have a significant impact on the strength of the specimen[9,109,109,108,98,9].

An in-depth review of academic literature was conducted alongside the manufacturers' build processes to ensure that print parameters that would influence the results had been accounted for. This review of academic literature resulted in the following print parameters being analysed and matched to the manufacturers build processes; fill density, layer/fibre orientation, slicing software, layer height, wall layers, roof/floor layer, total layers, build orientation, and print temperature [6,8,11-15]. These print parameters can have a significant impact on the structural and failure properties of a 3D printed specimen. Careful selection and optimisation of these parameters can help to achieve the desired mechanical properties and performance of the printed part.

Materials and 3D Printers
Research was conducted utilising two different 3D printers, and three different materials. The Stratasys F170 (Stratasys Inc., Israel) was used to create specimens in ABS-CF10, and the Markforged Mark Two (Markforged Inc., Massachusetts) was used to create specimens in Onyx, and Onyx with carbon fibre continuous fibre reinforcement.

The manufacturers have provided the following brief descriptions of their materials:

- ABS-CF10 – 'Stratasys ABS-CF10 combines standard ABS material with 10% chopped carbon fibre by weight. The result is a low moisture-sensitive FDM® thermoplastic 50% stiffer and 15% stronger than standard ABS 3D printing material.' [16]
- Onyx – 'Onyx is a micro carbon fibre filled nylon. It's 1.4 times stronger and stiffer than ABS and can be reinforced with any continuous fibre.' [17]
- Carbon Fibre continuous fibre reinforcement – 'Carbon fibre has the highest strength-to-weight ratio of our reinforcing fibres. Six times stronger and eighteen times stiffer than Onyx.' [17]

Material properties provided by the manufacturers are shown in Table 1.

Table 1. Manufacturer provided material properties

[Insert Table 1]

CAD and 3D Printing Process
3D CAD models of dog bone specimens were created in SolidWorks (software, Dassault Systèmes, Massachusetts) for each material. The specimen dimensions were composed according to which standard the manufacturer had conducted their sample research upon to ensure no geometry variables were present. Specimens in ABS-CF10 on the Stratasys F170 were created in accordance with ASTM D638 (Type I) [18]. Specimens in Onyx, and Onyx with carbon fibre continuous fibre reinforcement were created in accordance with ASTM D638 (Type IV) [18]. CAD data was then imported into the manufacturer's slicing software and the printing parameters chosen were applied. The printing parameters chosen for each specimen are detailed in Table 2.

Table 2. Specimen printing parameters

[Insert Table 2]

Five specimens per material were created, meeting the requirement of ISO 527-1 testing procedure [19]. Once printed, each specimen was measured using an Axiom too CMM (Aberlink Ltd., Gloucestershire, UK) (last calibration January 2023) across width and depth to obtain cross-sectional area and to analyse accuracy up to 2.4 micrometres.

Mechanical Testing
Mechanical tensile tests were conducted using a ZwickRoell Z030 (ZwickRoell Ltd, Worcestershire, UK) material testing machine (last calibration June 2022), with a load cell of 10KN. The testing speeds were replicated from the manufacturers' testing procedures, 2mm/min for the ABS-CF10, and 2.54mm/min for the Onyx and Onyx with carbon fibre. Test results were recorded, and data graphs were plotted using Microsoft Excel (software, Microsoft, Washington). A Dantec Dynamic digital image correlation (DIC) (Dantec Dynamics, Denmark) system was used during the mechanical

testing to measure the strain distribution on the surface of the entire sample. DIC is an optical method used to measure the deformation or strain of a material by analysing images of the material's surface before and after deformation by tracking a speckle pattern. Using DIC in conjunction with tensile testing provides a more detailed and accurate understanding of the material's mechanical behaviours as it provides a full-field measurement of longitudinal strain over the entire surface of the specimen. The Elastic modulus was calculated from the initial linear portion of the stress-strain curve using force data from the ZwickRoell Z030 and strain data from the DIC.

Microscopy

Visual inspection of the test samples was conducted using a Keyence VHX-5000 digital microscope (Keyence Ltd., Milton Keynes, UK). This allowed for detailed visualisation of the microstructure of the material and the print quality at a high resolution. It also provided information on the fibre-matrix interface, the distribution, size, and orientation of fibres, and any defects within the printed specimen.

Results & Discussion

Dimensional Accuracy

The width and depth measurements of each specimen were measured using the Axiom too CMM to verify the cross-sectional area, and to evaluate the dimensional accuracy achieved by each 3D printer.

Mean and standard deviation values for each specimen were calculated, as well as an unpaired student's t-test performed to compare the CMM measured dimensions with the nominal dimensions. A p-value of <0.05 indicates that a statistically significant difference exists. The p-value result received is consistent with other studies evaluating the dimensional accuracy of 3D printed tensile specimens [8,20], and can be seen in Tables 3 and 4. These results show that there is strong evidence to suggest that there is a real difference between the nominal and CMM measured values and it is unlikely that this difference was due to chance or random variability alone, therefore indicating that the samples did not conform to the expected dimensions The deviation of a 3D-printed component from the original CAD data is important information for designers and engineers to understand so they can account for this when designing and manufacturing their 3D printed components.

Table 3. Sample width measurement

[Insert Table 3]

Table 4. Sample depth measurement

[Insert Table 4]

Tensile Test & DIC

The mechanical properties studied from the tensile test results are ultimate tensile strength, strain at break, and Elastic modulus. Across the three materials studied, two materials outperformed the manufacturer supplied values for tensile strength, whilst one material was below the manufacturer value. The results for each material investigated are presented below and are graphically represented in Figures 1, 4, and 7. The DIC results show larges variances in strain across all specimens and materials. This is due to a combination of printing defects, fibre orientations, and the inhomogeneous material properties.

Stratasys F170 – ABS-CF10

The manufacturer given data for the tensile strength of ABS-CF10 is 37.7 MPa [16]. On average the tensile test results achieved in this research were 33.04 MPa, this gave a percentage difference of -12.36% from the stated manufacturer value. The standard deviation across the five samples was 0.34 MPa with the highest tensile strength recorded being 33.58 MPa which is 10.93% below the manufacturer value. The average strain at break recorded across the five samples was 2.47%, compared to 2.7% stated by the manufacturer. The average Elastic modulus across the five samples was 3.44 GPa, and the manufacturer stated value is 3.34 GPa. The DIC data used for two of the ABS-CF10 samples can be seen in Figure 2. The break point was consistent across the five samples with the break at the start of the gauge length, this break point is consistent with other studies evaluating tensile strength of 3D printed specimens [8,10].

[Insert Figure 1]

Figure 1. ABS-CF10 Tensile Test Results

[Insert Figure 2]

Figure 2. ABS-CF10 DIC Data

The samples were built following Stratasys' build document [21] regarding specimen standard, build orientation and layer height. Stratasys conducted their ABS-CF10 material testing on the Stratasys F370 and used Insight software (Stratasys, Israel) to control printing parameters and slicing. Insight offers more control over printing parameters such as seam control, which was not available when preparing samples to print on the F170 using GrabCAD (software, GrabCAD, Massachusetts) Print software. Research has shown that seam control does not have a significant impact on the structural properties of the samples [22,23]. Results from visual inspection work carried out on the ABS-CF10 samples can be seen in Figure 3.

[Insert Figure 3]

Figure 3. a) Cross section of ABS-CF10 filament x150 magnification. b) ABS-CF10 specimen cross section x150 magnification. c) ABS-CF10 specimen cross section x100 magnification. d) ABS-CF10 specimen cross section x200 magnification.

A sample of ABS-CF10 filament and tensile specimen were selected for analysis. Carbon fibres can be seen embedded in the ABS matrix (a), images b-d taken at the fracture surface show several defects including poor layer adhesion (1), leading to voids in the internal structure of the sample, inter-bead voids can be seen between layers (2), along with fibre pull-out at the fracture surface and associated cavities (3). The large void shown in the top of Figure c is due to the 45° infill pattern used during slicing and lead to the weakest point in the cross section of the specimen. Histogram image analysis, using the distribution of pixel intensities from the microscopy images, was used to determine the volume fraction through the cross section of the broken specimens. The average volume fraction of the specimens was 9.85%, which is slightly lower than the 10% stated by the manufacturer[16].

The density of the ACF10 material used in this research was calculated as 1.07g/cm3. This was 0.02g/cm3 less than the reported density of 1.09g/cm3 [16,24]. The average density of the CF10 specimens produced on the F170 was 1.02g/cm3. The resultant density of the printed samples was 95.33% of the density of the material itself. This shows there is a 4.67% void content in the samples.

The results of microscopy and density analysis, combined with lower-than-expected tensile test results, determine that the fibres within the ABS-CF10 specimen are not properly wetted with the matrix. This has resulted in the formation of large voids within the specimen and weak interfacial bonding. This weak interfacial bonding has led to the load transfer between the matrix and fibre being limited, resulting in a weaker composite than anticipated, and therefore resulting in fibre pull out and the lower-than-expected mechanical properties. The lower-than-expected volume fraction of the specimens also has an impact on the mechanical properties being lower than stated by the manufacturer, as more of the specimen is made up of the matrix material which has lower mechanical properties than the carbon fibre.

Markforged Mark Two – Onyx

The manufacturer given data for the tensile strength of Onyx is 40.64 MPa [17]. On average the tensile test results achieved in this research were 44.17 MPa, this gave a percentage difference of +8.66% from the stated manufacturers value. The standard deviation across the five samples was 0.7 MPa with the highest tensile strength recorded being 44.92 MPa which is 10.5% above the manufacturer's value. The average strain at break recorded across the five samples was 26% compared to 25% stated by the manufacturer. The average Elastic modulus across the five samples was 1.01 GPa, and the manufacturer value in their technical report for the same build parameters is 0.91 GPa. The DIC data used for two of the Onyx samples can be seen in Figure 4. The break point was consistent across the five samples with the break at the start of the gauge length, this break point is consistent with other studies evaluating tensile strength of 3D printed specimens [8,10]. The test samples were manufactured to the specifications in the Markforged material testing technical report [25] and printed utilising the same printer, the Markforged Mark Two. Results from visual inspection work carried out on the Onyx samples can be seen in Figure 6.

[Insert Figure 4]

Figure 4. Onyx Tensile Test Results

[Insert Figure 5]

Figure 5. Onyx DIC Data

[Insert Figure 6]

Figure 6. a) Cross section of Onyx filament x150 magnification. b) Onyx specimen cross section x150 magnification. c) Onyx specimen cross section x200 magnification. d) Onyx specimen cross section x200 magnification.

A sample of Onyx filament and tensile specimen were selected for analysis. Carbon fibres can be seen embedded in the nylon matrix (a), images b-d taken at the fracture surface show fibre pull out

(3), in addition to clear uniform inter-bead voids between the layers (2). Significant voids in the print can be seen in image d (1). Histogram image analysis was used to determine the volume fraction through the cross section of the broken specimens. The average volume fraction of the specimens was 34.89%, which is consistent with other research evaluating the volume fraction of Onyx[26].

The density of the Onyx material used in this research was calculated as 1.14g/cm^3. This was 0.06g/cm^3 less than the reported density of 1.2g/cm^3[3,17,27]. The average density of the Onyx specimens produced was 1.02g/cm^3. The resultant density of the printed samples was 89.47% of the density of the material itself. This shows there is a 10.53% void content in the samples, and this result is consistent with other research investigating the void content of 3D printed samples in Onyx which range between 7 – 11%[28,29].

Microscopy analysis and mechanical test results achieved indicate good print quality. The microscopy analysis showed good layer adhesion, small inter-bead voids and no visible signs of defects such as warping, layer shifting or stringing. Visual inspection of the specimens showed evenly distributed fibres that were bonded well with the matrix, and no large voids or cracks therefore indicating proper wetting. The increase of mechanical properties observed show there was good adhesion and load transfer between the fibres and matrix, also indicating that the fibres are properly wetted with the matrix. Good quality control measures were followed including a brand-new reel of filament ensuring no degradation to the material had occurred, a new print nozzle and machine calibration. The combination of good print quality, proper wetting and quality control measures explain why the mechanical properties exceeded expectation.

Markforged Mark Two – Onyx + Carbon Fibre

The manufacturer given data for the tensile strength of Onyx with eight layers of carbon fibre, built in their technical report [25] is 106.8 MPa. On average the tensile test results achieved in this research were 123.15 MPa, this gave a percentage difference of +15.31% from the stated manufacturer's results in their technical report. The standard deviation across the five samples was 8.71 MPa with the highest tensile strength recorded being 135.61 MPa which is 26.98% above the manufacturer results in their technical report. The average strain at break recorded across the five samples was 1.65% compared to 1.5% stated by the manufacturer. All five samples of Onyx with eight layers of carbon fibre in this build orientation yielded too quickly to be able to calculate Elastic modulus from the initial linear portion of the stress-strain curve. These results are consistent with the manufacturer's technical report[25]. The break point was consistent across the five samples with the break at the start of the gauge length, this break point is consistent with other studies evaluating tensile strength of 3D printed specimens [8,10].

[Insert Figure 7]

Figure 7. Onyx + Carbon Fibre Tensile Test Results

The test samples were manufactured to the specifications in the Markforged material testing technical report [25] and printed utilising the same printer, the Markforged Mark Two. The test samples yield strength had a standard deviation of 8.71 MPa which is the largest across the material tests conducted, indicating that Onyx with added continuous strands of carbon fibre is less repeatable and less consistent than 3D printed material containing only chopped strand carbon fibre, however adding continuous strands of carbon fibre can provide significantly higher tensile strength. The stress/strain graph shows multiple drops in stress in the specimen towards the end of the test before the final break. These drops represent when individual strands of the continuous carbon fibres broke within the specimen before its final break. The presence of two linear portions on the graph indicate that Onyx + CF specimen has two different phases that respond differently to stress and have different stiffness's. The stiffness of the material reduces after the fibres stop taking effect. This is explained due to each of its constituent materials having different material properties. When the first linear portion of the graph concludes, permanent damage has occurred to the specimen although it is way below its final break. Results from visual inspection work carried out on the Onyx + CF samples can be seen in Figure 8.

[Insert Figure 8]

Figure 8. a) Onyx + CF specimen cross section x50 magnification. b) ONYX+CF specimen cross section x200 magnification.

An Onyx + CF tensile specimen was selected for analysis. The transition from the central core of Onyx to Onyx + CF layers can be clearly seen (a), the addition of the continuous strand carbon fibre has resulted in less compact Onyx layers that surround the eight layers of carbon fibre leading to larger inter-bead voids. Clear fibre pull-out can be seen on the continuous strand carbon fibre section of the sample (3). Voids can also be seen throughout the sample (1).

The density of the carbon fibre material used in this research was calculated as 1.33g/cm^3. This was 0.13g/cm^3 more than the reported density of 1.2g/cm^3 by Markforged, yet it was 0.07g/cm^3 less than the reported density of 1.4g/cm^3 found in academic literature[27]. Due to the printing parameters, the density of the Onyx + CF specimens should theoretically be 1.2g/cm^3. The average density of the printed Onyx + CF specimens produced was 1.14g/cm^3. The resultant density of the printed samples was 95% of the density of the material make up. This shows there is a 5% void content in the samples, which is lower than results found from other research investigating the void content of 3D printed samples in Onyx with continuous carbon fibre reinforcement which range between 7 – 11%[28,29].

The microscopy results show the onyx sections have good layer adhesion and compaction, with an even surface finish with small voids throughout the print indicating good print quality. The density analysis of the specimens also indicates good print quality. Good quality control measures were followed including a brand-new reel of filament ensuring no degradation to the material had occurred, a new print nozzle and machine calibration. The combination of the carbon fibre material having a higher density than that stated by Markforged, good quality control measures, and the microscopy and density results showing the print has a low void content of 5% explains why the tensile test results achieved are higher than that stated by Markforged.

Conclusion

Three different composite 3D printing materials were analysed in this study, utilising two different 3D printers. Build documents were followed to create test samples, and tensile tests were then performed with digital image correlation and analysed to give mechanical properties. Data extracted from the tensile tests were analysed against material properties given by manufactures. This study shows inconsistencies between material properties stated by manufactures and those achieved by users. These inconsistencies illustrate that designers and engineers cannot rely solely on manufacturer data sheets for AM components, and testing validation should always be performed.

Stratasys's ABS-CF10 was unable to meet the manufacturer tensile strength value by 12.36%. Markforged Onyx, and Onyx + carbon fibre continuous reinforcement exceeded the manufacture values by 8.66%, and 15.31% respectively. Whilst Onyx + CF had the largest percentage increase on tensile strength, it measured the lowest dimensional accuracy and repeatability. Microscopy and density measurement were used to analyse print quality, defects, volume fraction, and fibre-matrix wetting to determine what influenced the mechanical properties of the specimens. Poor fibre-matrix wetting, large voids, and weak interfacial bonding were attributed to the ABS-CF10 material not reaching the manufacturer values. Whilst good print quality, low void percentage, proper fibre-matrix wetting, and good control measures were attributed to the Onyx and Onyx + CF specimens exceeding the manufacturer values.

Further research is necessary into the discrepancies that could exist between individual printers of the same model. A comparative study that investigates how individual printers of the same model, with the same material, and the same build file can differ will enable an analysis of the repeatability within 3D printer models.

Author Contributions

Abigail Batley: Conceptualisation, Methodology, Software, Validation, Formal analysis, Investigation, Writing – Original Draft (lead), Visualisation.

Richard Glithro: Conceptualisation, Methodology, Software, Validation, Formal analysis, Investigation, Writing – Original Draft.

Bryce Dyer: Writing – Review & Editing.

Philip Sewell: Methodology, Writing – Review & Editing.

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