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Experimental Fatigue Studies of Additively Manufactured Fiber Reinforced Thermoplastic

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Abstract

Additive manufacturing (AM) is a field of study that is gaining importance due to quick manufacturing techniques while providing viable flexibility in design modifications. In comparison with conventional manufacturing methods, AM uses easier processes to manufacture intricate components. AM products maintain consistency as it is constructed by robust universal AM machines. In the present study, a continuous carbon fiber thermoplastics (CFRTP) as a replacement to aluminum alloy (Al6061-T6) material is used for additively manufacturing bicycle crank components. The results from the tensile test and fatigue behavior of the component indicate a strong dependence of percentage concentration of the reinforcement in the CFRTP. A finite element analysis is performed to ascertain the stress distribution for a static load condition as mimicked in the real world situations. To explore the brittle fracture nature of the CFRTP specimen, a SEM image depicting the microstructural nature is provided. It is imperative to note that the comparative studies indicate the light weight CFRTP crank specimen stands out to be a viable replacement to the Al 6061-T6 material.

Keywords: *Additive manufacturing, Carbon fiber reinforced plastic, tensile testing, fatigue testing*

1.0 Introduction

Additive manufacturing is a technology that deals with the building of material from bottom up approach involving the addition of layers in Z direction with X and Y directions controlled using motors giving the area of the build and Z direction for the volume. Hence, it is also called as 3D Printing where complex parts can be manufactured layer by layer using the Computer Aided Drawings (CAD). Considering the technology being in nascent stage there is lot of scope for researchers to enhance the designs and material properties in various fields such as aerospace, medical, military and general manufacturing.[2]

The process of AM is generically is split into various stages as below [1]:

1. Design of a product through CAD
2. Saving the CAD model using tessellation format .stl
3. Slicing of the model into many layers for including features in 2D space
4. Conversion of the sliced model into G-codes for machine input
5. Setting up of the machine and raw materials as per requirement
6. Operation of the machine for a predefined time layer by layer
7. Removal of the part from the machine's work platform
8. The part undergoes post processing to finish in application

According to American Society for Testing and Materials (ASTM) group "ASTM F42 – Additive Manufacturing" various processes based on the raw materials, process characteristics and source of energy [3]. The process of material extrusion involves the use of polymer filaments like

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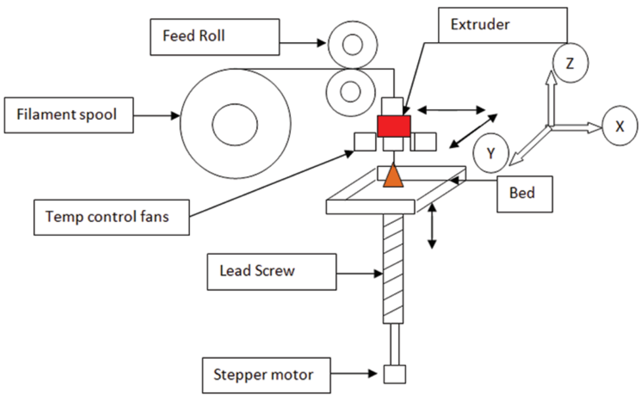

Figure 1: Process flow of material extrusion

Acrylonitrile Butadine Styrene (ABS), PolyLactic Acid (PLA), Poly Carbonates (PC), Nylon and Polyethylether Ketones (PEEK) etc. through a nozzle on to a heated or controlled environment for obtaining layers of an object as explained in Fig. 1. The nozzle's temperature is near the melting point of the polymer to obtain a thixotropic material for flow on to the build platform. Then subsequent layers are connected using the adhesion between the materials forming a 3D printed part geometry.[11]

The field of additive manufacturing has a lot of applications and is used commercially in major fields such as, aviation, defence, medicine, biotechnology, automotive field, etc. With the help of additive manufacturing the topology optimisation helps in proper distribution of material to ensure the material obtains its highest possible strength and stiffness [4]. In the medical field and Biotechnology field, Additively Manufactured components and products are rigorously been used. It is being used in complex builds such as the bionic heart, prosthetics, tablets, tooth fixtures, artificial jaws, skull fixtures, implants of various parts of the body, etc.[5]. Formula one cars use additive manufacturing widely due to manufacturing custom made components and parts [6]. In the field of Aerospace fixtures, rocket nozzles, mounts, etc. are manufactured due to ease of manufacturability and custom made products. Mainly AM is used to reduce the weight of the aircraft thereby improving the fuel efficiency [7].

Various types of fibres are currently manufactured with regard to their strength to weight ratio such as carbon fibre, fibre glass, glass fibre, chopped carbon fibre, etc. There are different types of matrix too such as ABS, Nylon, PEEK, PLA, etc. Composites can be aligned based on their application; various angles of orientation are used depending on the property of the material. Unidirectional angled arrangement has proven to acquire highest strength when compared to other directions . [10]

The fatigue cycle in polymer composites are measured by the universal testing machine (UTM). The process is usually calculated by preparing specimens according to ASTM D3479 standard. The tests cycles are repeated by varying loads from 90% to 50% to calculate the fatigue bearing capability of the material. The values are plotted on a graph and the values are connected to show the fatigue data [8].

Additive manufacturing processes may require the creation of molds to produce parts with complex geometry. The part geometry can be divided into steps that would take a skilled operator an hour to create conventionally manufactured products with the usage of carbon fibre reinforced matrix combined with reinforcements such as Carbon Fiber, Aramid Fiber, Fiberglass, and HSHT fibreglass.

Additive manufacturing process is created by melting the raw materials and injecting them into the mold. The raw material is generally layer by layer hardened using high precision x, y, z axes so as to attain the designed geometry. The fused material can be used to build parts out of ceramic or metallic powders. There are various processes of building parts in additive manufacturing depending upon the type of material used; different processes are suited to different kinds of materials [2].

2.0 Experiments Conducted

The type of material used in the printing of parts in the Markforged machine is either Onyx or Nylon. The strength ratio of Onyx to ABS is 2:1 due to addition of chopped carbon fibres in Nylon which are the ingredients of Onyx. The material Onyx has a melting temperature of 145ºC. The material Onyx can be combined with materials that are manufactured by Markforged such as carbon fiber, fiberglass, or HSHT fiberglass, which improve the strength of the components. The .STL file is uploaded to the Eiger software and later corrections are performed to ensure the design is accustomed according to its need. [12]

3.0 Design of CFRT Bicycle Arm

The bicycle crank arm was scanned with the help of a 3D scanner and made into a perfect solid filled structure by filling the gaps that the scanner could not scan with the help of Solidworks software. Later the file was transferred to Ansys software where the analysis was performed.

The specimens were printed by Markforged Mark Two 3D printer. After the designing the file is saved in .STL format and uploaded in the Eiger™ software as shown in Fig. 2. The printer recognizes the data stored in the pen drive/flash drive and after we click on the saved file, the printing commences. Once the printing is done on the print table, the specimens are removed with the help of wedges provided by the manufacturer. The carbon fibers are sandwiched by Onyx

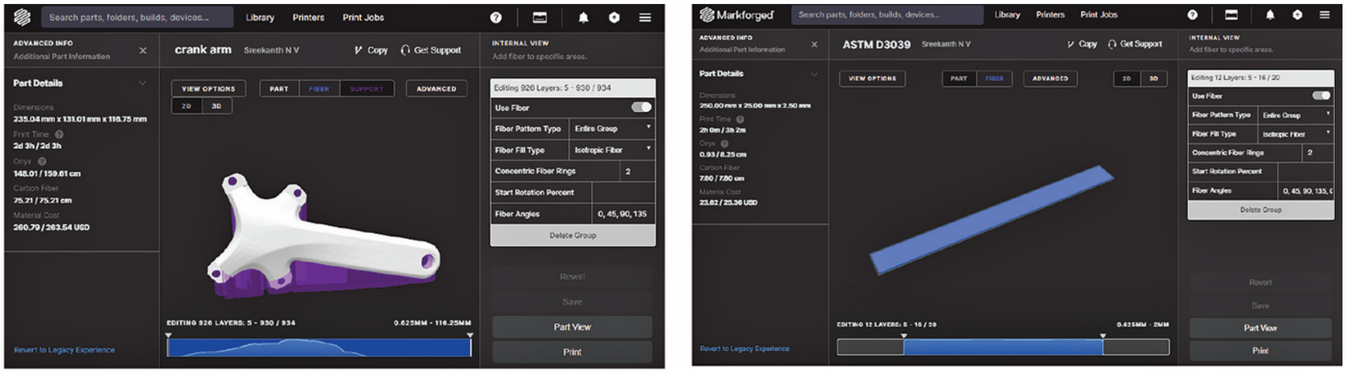

Figure 2: Design of the bicycle crank and Test specimen by Eiger software

reinforcement, which were arranged in the following sequence 0º, 45º, 90º, 135º and 180º by the Eiger™ software.

The tensile specimens are designed according to the ASTM 3039] and ASTM 3479 standards.

4.0 Mechanical Tests

The tensile and fatigue tests were performed by the MTS Landmark universal testing machine with a 25 kN load cell. The universal testing machine consists of a water cooled system to run vigorous thermomechanical based tests. This system is a servo hydraulic type system. This machine has a capability of upper and lower axial displacement. It consists of vertical columns with a displacement of shoulder arm up to 1.5m. Maximum force that can be applied is 250 kN. It also consists of a centralized controller for precision control of the actuator in testing machine. This system is equipped with an extensometer and crack opening displacement gauges as shown in Fig.3. This machine is capable of performing quasi static tensile and compression tests, high cycle and low cycle fatigue test, Fatigue crack growth rate analysis, block loading and also performs fracture toughness tests.

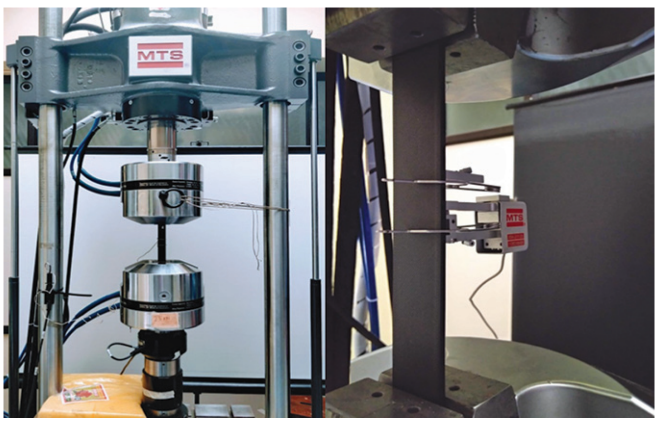

Figure 3: Testing on MTS Landmark UTM with extensometer.

5.0 Results and Discussions

1. Mechanical Tests

The tensile and fatigue tests were performed by the MTS Landmark universal testing machine with a 25 KN load cell. The results are shown in Table 1 which denotes the total tensile test specimen data.

The tensile tests that were conducted by ASTM 3039 standard, determined the load of the specimen was found to be 20.85 kN, which exceeds the strength of Al 6061-T6 [9]. The data shown below in Fig.4 and Fig.5 are the readings plot from the MTS universal testing machine.

The fatigue tests were conducted by the ASTM 3479 standard. The range of hertz was controlled between 7-10 Hz to ensure the universal testing machine did not overheat.

The fatigue test data depicts the number of cycles mounted above 2 lakh cycles at 60%. At 90% the specimen failed at 9081 cycles. At 80% the fatigue test specimen failed at 21,364 cycles respectively. At 70% the fatigue test specimen failed at 2 million cycles. This denotes the material is capable of withstanding loads applied on the cycle crank.

Table 1: Data of the tensile test specimens

Width	25.4 mm
Thickness	2.59 mm
Area	65.786 mm^2
Extensometer Gauge Length	25 mm
Max. Axial Load	20.84969 KN
Ultimate Tensile Stress	319.6619 MPa
Elastic Modulus	22.53705 GPa

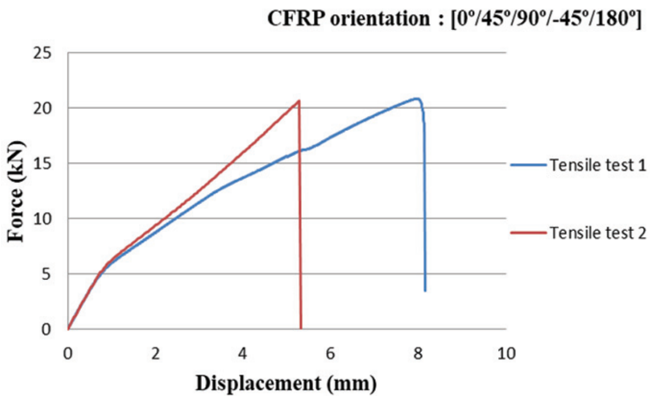

Figure 4: Tensile test data of universal testing machine

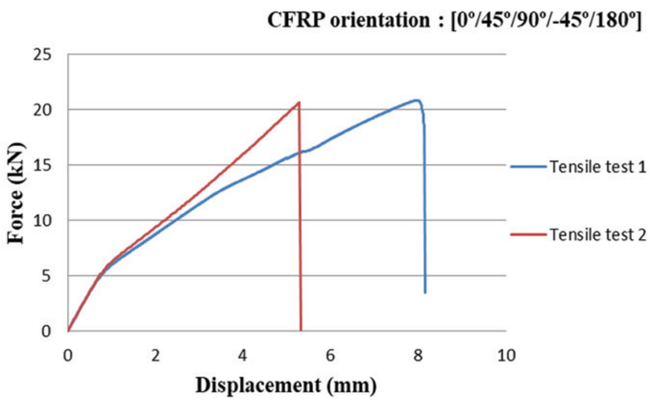

Figure 5: Fatigue Test data of the ASTM 3479 specimens

2. Finite Element Analysis

The mechanical analyses are performed with the help of ANSYS 2021 R2 software. The crank arm is subjected to a load of 700 N, which is equal to the average weight of a human being.

Equivalent stress: The maximum Von-Mises stress calculated by Ansys software was 215.17 MPa which is shown in Fig.6.

Total deformation: The maximum total deformation occurred in the crank when the load of 700 N was applied was estimated to 0.56372 mm is shown in Fig.7.

Table 2: Data of the total deformation

Load	700 N
Target element quality	0.95
Maximum stress	215.17 MPa
Minimum stress	7.9356×10^{-6} MPa
Total Deformation	0.56372 mm

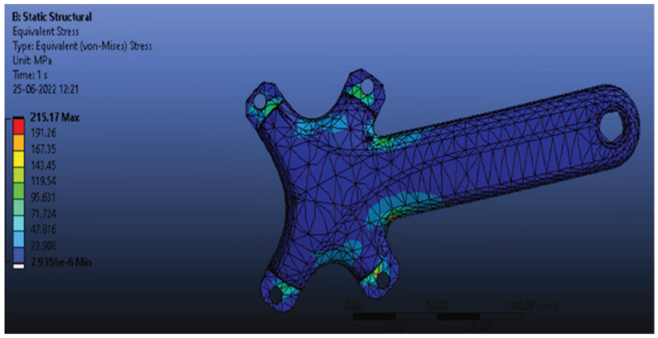

Figure 6: Von-Mises Stress of the crank arm

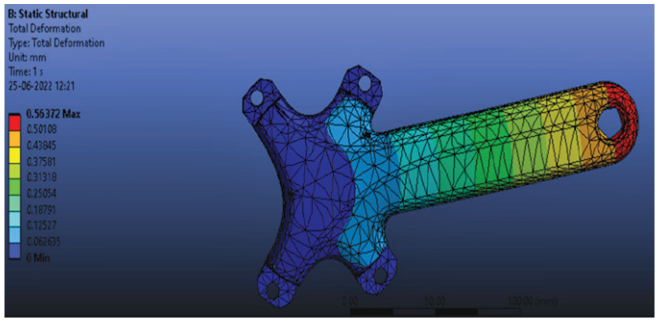

Figure 7: Total deformation of the crank arm

3. Observations from SEM Analysis

The SEM used was VEGA3 TESCAN. The analysis was performed by capturing images by the SEM ranging from 100X magnification to 1000X magnification to view the internal structure and orientation of the given samples. The microstructural analysis was taken from the tensile and fatigue specimens that were printed by using carbon fibre. The microstructure showed fibre breakage, fibre pull-out and delamination.

i. The cross-section of each carbon fibre strand was measured around 5.97µm - 6.95µm as shown in Fig. 8 and the external circumferential diameter of a strand of carbon fibre was 6.18 µm and the scanning electron microscope was used to examine feature size of 5µm. 5-7µm fibre size ensures minimum porosity in fibres and enhances the packing efficiency between fibre and matrix.

ii. The microstructure showed brittle fracture due to the use of carbon fibre which is brittle in nature. The microstructural analysis showed fibre breakage, fibre pull-out and delamination.

iii. The failure of the samples happened in three stages: (a) Crack initiation and (b) Delamination. Brittle failure was observed in tensile and fatigue tests as shown in Fig.9. The fibre orientations are arranged in the sequential manner [0º, 45º, 90º, 135º, 180º] which makes

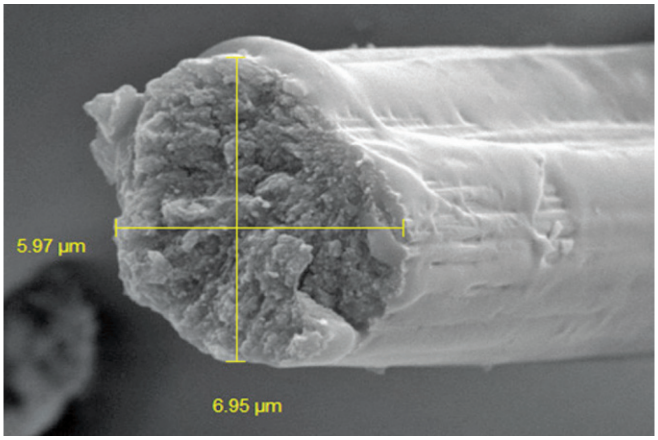

Figure 8: Thickness of each strand of carbon fibre

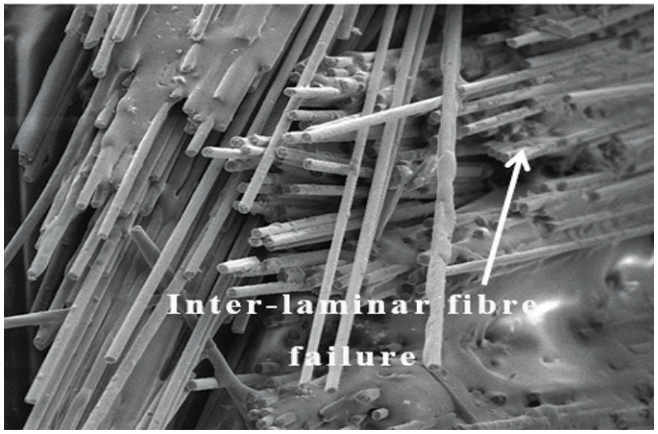

Figure 9: Interlaminar fibre failure spots in the specimen

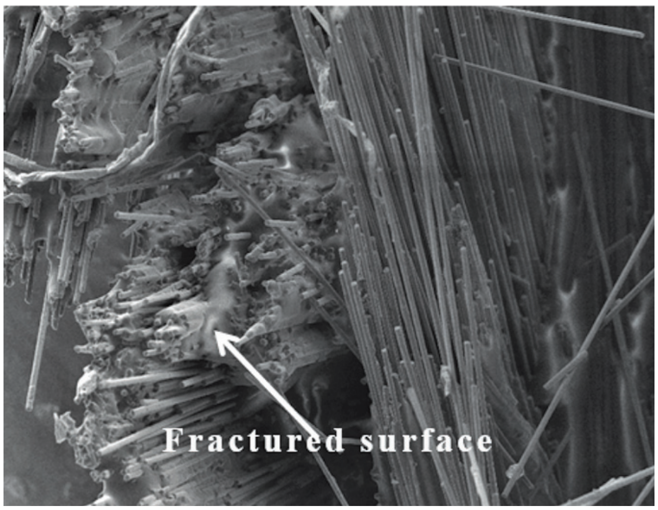

Figure 10: Fibre breakage due to brittle fracture

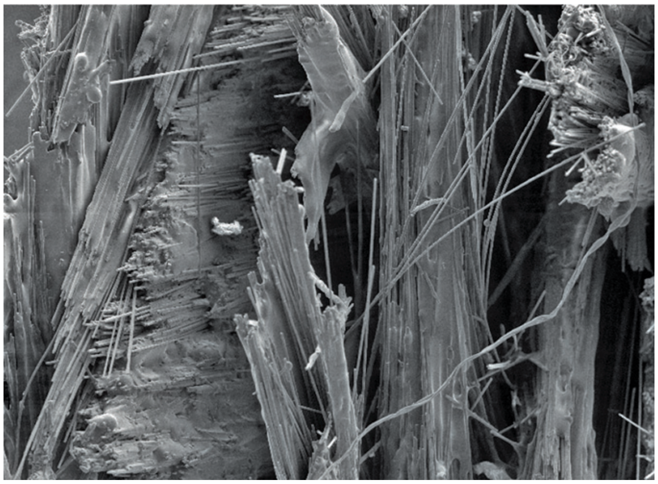

Figure 11: The arrangement of closely packed carbon fibres

the material a Quasi-isotropic material that ensures the strength and stiffness equal to respect to all sides which helps in the sturdy building of the bicycle crank arm in Fig.10.

iv. Quasi-isotropic (strength and stiffness equal in all directions) materials provide higher shear and torsional stiffness and strength to the material which is very necessary for the bicycle crank arm. The type of load subjected was tension-tension fatigue loading. The dense arrangement or the closely packed fibres helped in the internal strength of the specimens are shown in Fig.11.

6.0 Conclusions

1. According to the orientation of (0º/ 45º/ 90º/ 135º/ 180º), the specimens showed comparatively higher mechanical properties when compared to Aluminum 6061-T6 alloy (UTS is 290 MPa).
2. The tensile tests conducted reveal that CFRC's (UTS is 319.6619 MPa) can be utilized in place of Al 6061-T6 alloy which undergo uniaxial tension.
3. The fatigue tests further show that, for cyclic loads 3D printed CFRC's show reasonably good resistance to fatigue which is acceptable for applications in bicycle crank.
4. The microstructural analysis exhibit brittle fracture typical to CFRC's and provides information about the fibre orientation and size characteristics, which provides the basis of utilization of carbon fibre in Onyx® matrix as a replacement to Al alloys for the bicycle crank.

5. The analysis of the bicycle crank for equivalent stress and total deformation was conducted using the tensile test results which show that the crank load is within the required limits of operation.

7.0 Acknowledgements

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