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Reviewed Paper

FATIGUE ANALYSIS OF SHORT CARBON FIBER REINFORCED COMPOSITE COMPONENTS MANUFACTURED USING FIBER-REINFORCED ADDITIVE MANUFACTURING

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Abstract

Fiber-reinforced additive manufacturing (FRAM) has become quite popular in several industries. The technology offers an opportunity to improve the existing mechanical performance of the part. This research study has presented a successful methodology to fabricate the FRAM-based composite parts with improved fatigue properties. Most engineering applications are subjected to cycling loading which makes the fatigue study an important analysis. The scope of this paper is to present the fatigue properties of short carbon fiber-reinforced Polyethylene Terephthalate Glycol (SCFs/PETG) of 13.78% by weight. The fatigue behavior was analyzed by varying the 3D printing process parameters i.e., infill orientation (0°, 45°, and 90°), and infill layer heights (0.2 and 0.3 mm). The tests are carried out on 1600 N as a maximum load of fatigue cycle with a 0.1 stress ratio, for the specimens with 90° and 45° orientations with 0.2 and 0.3 mm layer heights. For 0° orientation, both 0.2 and 0.3 mm layer height specimens are applied to 2600 N as maximum load, keeping the stress ratio the same as 0.1. Analysis of Variance (ANOVA) is used to statistically analyze the testing data to understand the influence of input variables on fatigue properties.

Keywords: FRAM, Tensile strength, Fatigue strength, ANOVA, Fatigue life

Introduction

The well-known additive manufacturing (AM) technologies are Fused Deposition Modeling (FDM) also known as Fused Filament Fabrication (FFF), Selective Laser Melting (SLM), Stereolithography Apparatus (SLA), and Selective Laser Sintering (SLS). The FRAM is the additive manufacturing technology used to manufacture the components with fiber-reinforced composite materials, which integrates the advantages of AM and composite materials. Fiber-reinforced composite materials are the materials produced by using fiber as reinforcement in a matrix material. Commonly used polymer matrix materials are nylon, polyester, epoxy, polycarbonate (PC), acrylonitrile butadiene styrene (ABS), polylactide (PLA), polyamide (PA), etc. The reinforcement elements have categories as material-based and structural-based. Material-based reinforcements include Kevlar, Carbon, Fiber Glass, etc. while, structural-based reinforcements incorporate short fiber, continuous fiber, unidirectional, randomly oriented fibers, etc. [1]. By appropriate selection of fiber, and fiber volume fraction, length, type, and orientation, the mechanical, electrical, and thermal properties can be improved [1]–[3]. Fig. 1 shows the schematic view for the FRAM process using SCF reinforced filament.

Recent advancements in AM made it applicable for using polymeric structures in various structural and load-bearing applications. Cyclic loads cause fatigue, which is the development of structural damage, which leads to catastrophic failure at lower stress if compared with normal mechanical loading [4]. So, it is of utmost importance to study the fatigue behavior of the composite parts manufactured by AM. FRAM allows the researchers to explore more options in the materials with a combination of various matrix materials, fiber materials, and variations in the form of fibers. Fatigue tests are conducted in various loading conditions such as tension, compression, bending, torsion, fracture mechanical, or a combination of these in case of more complicated fatigue analyses. In fatigue testing, the simplest stress sequence uses a constant stress amplitude in which all the cycles are identical as given in fig. 2. For each cycle, σ, σ_m, σ_{max}, and σ_{min} are the alternating stress, mean stress, maximum stress, and minimum stress respectively. The stress ratio is expressed as, $R = \frac{\sigma min}{\sigma max}$.

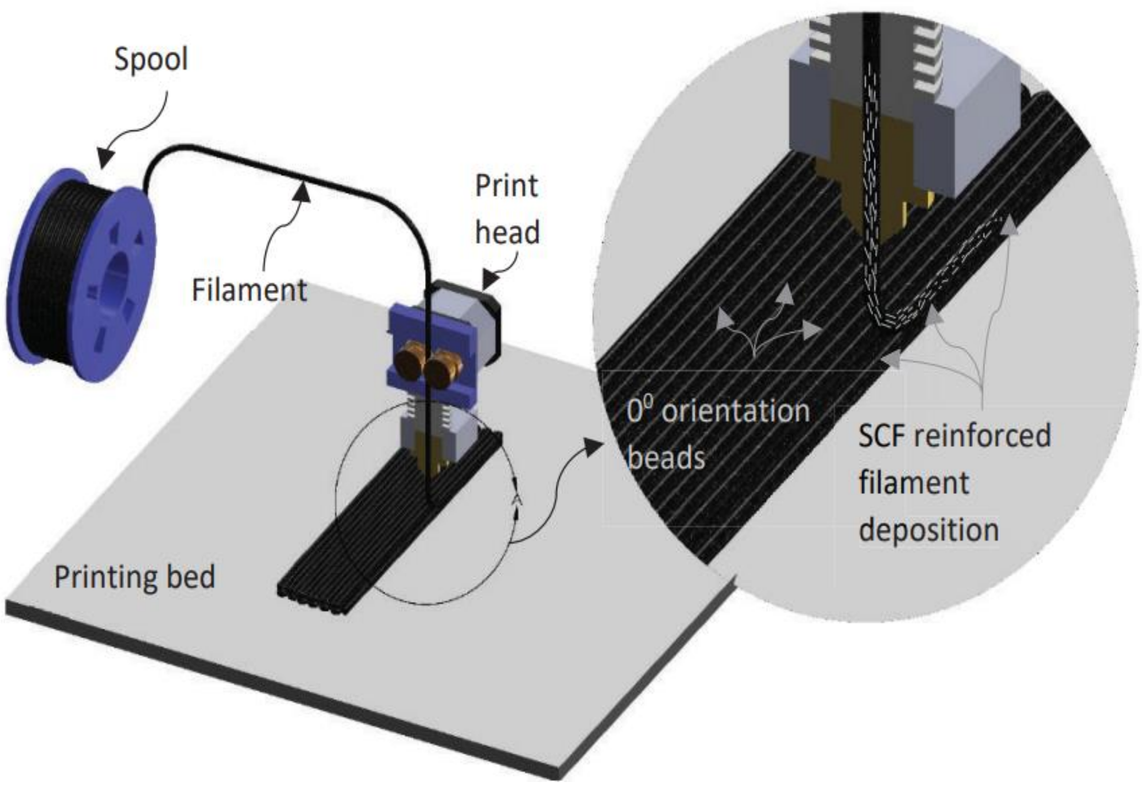


Fig. 1. Schematic view of FRAM process [5]

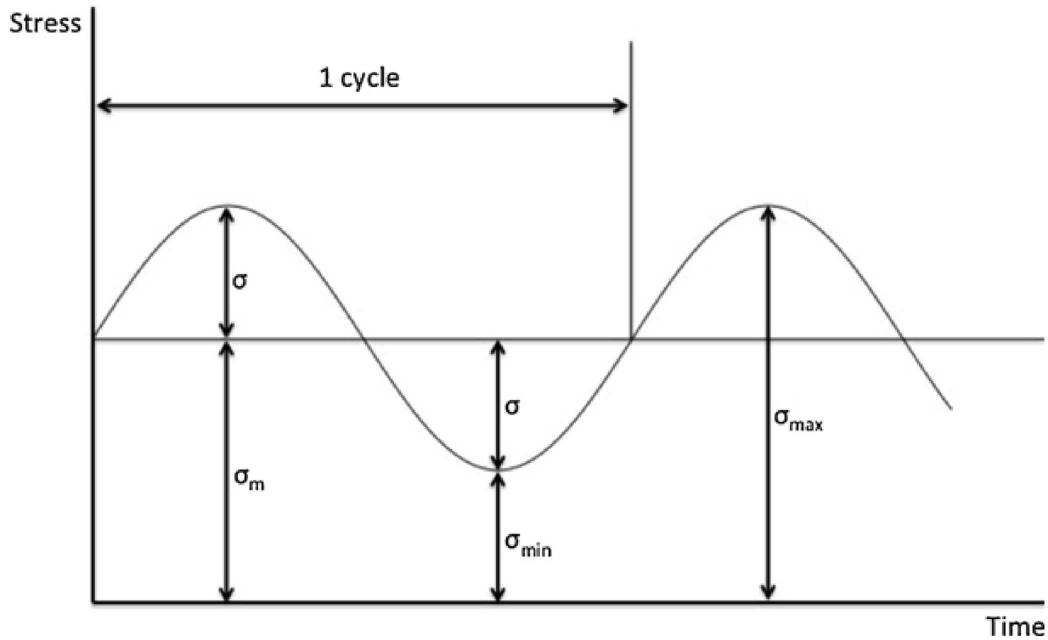


Fig. 2. Nomenclature of the testing parameters in constant amplitude loading [6]

In the FFF process, first, the required geometry is designed using CAD software and then sliced into the layers accordingly. Various printing parameters need to be taken into account such as printing speed, plane, orientation, infill density, infill patterns, layer height, layer width, extrusion temperature, bed temperature, etc. [4]. Various studies showed that these parameters affect the printing quality and mechanical and thermal properties. Researchers have also reported the fatigue behavior of various materials by FFF. The following section discusses various research studies reported till now considering printing parameters and materials. Alberto D. Pertuz et. al. [7] studied the continuous fiber-reinforced composites (CFRC), in which nylon is used as matrix material, under static as well as fatigue loading. The study has shown the effects of infill pattern, infill density, the orientation of the fibers, and the material of fibers (fiberglass, Kevlar, and carbon fiber). From the study, in the end, it is concluded that nylon matrix reinforced with carbon fiber shows better performance for fatigue response at 0° orientation. Astrit Imeri et. al. [9], [10] in their study have shown the effect of fiber orientation and fiber materials (carbon, glass, and Kevlar). The study concluded that carbon fiber with zero and one concentric ring has high resistance to failure. Furthermore, Mst Faujiya Afrose et. al. [11] have investigated the effects of build orientations on the fatigue behavior of FDM processed-PLA under 50%, 60%, 70%, and 80% of ultimate tensile strength of respectively oriented specimens. The study concluded that specimens built in 45° achieved the highest fatigue life compared to specimens built in X and Y orientation. J. Antonio Travieso-Rodriguez et. al. [8] in their study explained the fatigue behavior of a polylactic acid-based composite reinforced with wood fabricated by FFF through rotating bending fatigue tests. The effects of layer height, nozzle diameter, infill density, and extrusion velocity are verified in this study, from which except extrusion velocity, all other parameters are influential on the fatigue life. A thorough search of relevant literature yields that there is a limited number of studies that have been reported dealing with the fatigue behavior of SCFs/PETG with different printing parameters.

The common advantages of the PETG material are, that it provides high processability, excellent chemical resistance, good tensile toughness, flexibility, high durability, low shrinkage, and good adhesive properties between the layers [12]–[14]. The right amount of reinforcement of short carbon fiber in the matrix material has shown better mechanical properties [5]. Considering the requirement of industrial applications, it is highly necessary to study more and more options of commercially available materials under fatigue loading. Furthermore, a comprehensive understanding of the effects of process parameters on the fatigue behavior of FRAM printed parts is necessary for its further application. In this study, the FRAM is used to fabricate the specimens made by SCFs/PETG is the study aims to present the fatigue behavior of the chosen material taking into account the printing parameters such as layer height and infill orientation in the XY plane. The ANOVA is used to analyze the data obtained from the experimental results. From the literature review, it is concluded that no in-depth investigation has been done to show the effect of layer height and printing orientation on SCFs/PETG.

Materials and Methods

In this section, the method of the investigation of the process parameters on the fatigue properties of FRAM printed parts by SCFs/PETG is presented.

Phase I: Set up of FRAM and DoE

Material, geometry, and machine

The filament used for the research is commercially available SCFs/PETG (or carbon fiber reinforced PETG (CF-PETG)) by Push Plastic. As discussed earlier, PETG is a strong, versatile material having high heat resistance. Unlike some of the other materials, it does not have warping issues. PETG can also be used for food containers and tools used for food consumption. Reinforcement of carbon fibers improves the properties of the matrix material such as high tensile strength, high stiffness, and low weight [15]. As compared to continuous fibers, SCFs can be molded into complex shapes. SCFs are easy to manufacture and low cost. The properties from the manufacturer’s data sheet are as given in Table 1.

Table 1. Material Properties of SCFs/PETG [16]

Properties	**Test Method**	**Values**
Tensile Strength at Yield	ASTM D638	14,000 (PSI) or 96.52 (N/mm2)
Tensile Elongation at Break	ASTM D638	4.00%
Flexural Strength	ASTM D790	20,500 (PSI) or 141.34 (N/mm2)
Flexural Modulus	ASTM D790	1,000,000 (PSI) or 6894.75(N/mm2)
Specific Gravity	ASTM D792	1.31

To determine the percentage by weight of carbon fibers in the matrix material, samples or filaments are cut out and incinerated in thermogravimetric analysis (TGA) system i.e., SDT 650 to burn off the PETG. Using a heating program in the presence of Nitrogen the TGA is performed with a temperature profile ranging from 25 $^{\circ}$C to 786.94 $^{\circ}$C with a rate of 10 $^{\circ}$C per minute. The obtained result concludes that the CF is 13.78% by weight. The graphical representation of the TGA is shown in fig. 3.

The geometry selected is based on the ISO 11782-1:1998(E) [17] as given in fig. 4. The SOLIDWORKS is used to generate the CAD model and then saved in STL format. This STL file is imported into the PRUSA slicing software where the printing parameters are assigned as given in table 2. The printing plane is XY and the infill orientations used are 0°,45°, and 90° as shown in fig. 5(a) and 5(b). After slicing the G-code is generated and it is provided to the PRUSA i3 MK3 printer with a hardened steel nozzle of 0.4 mm diameter.

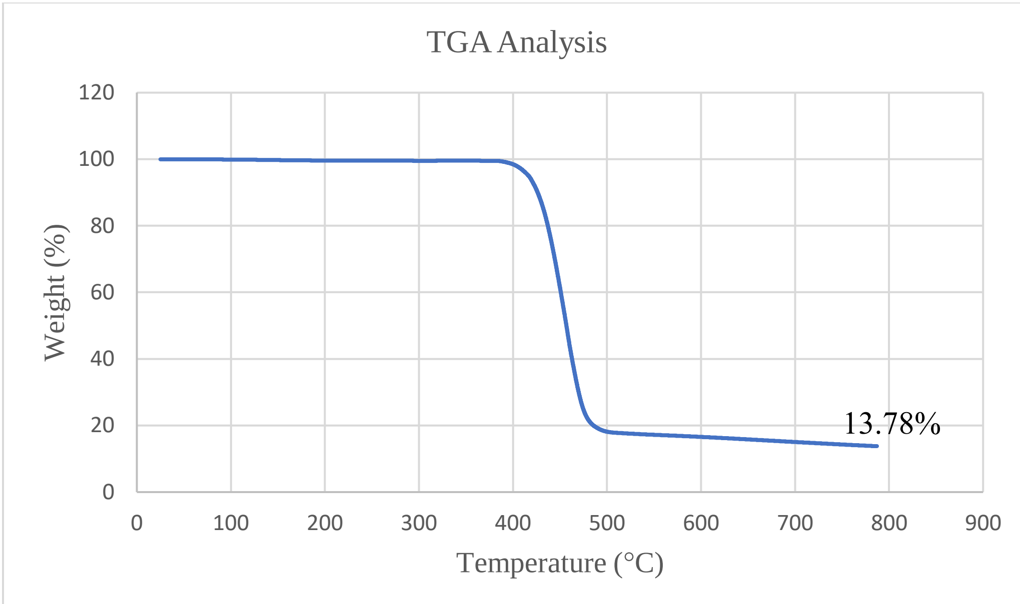


Fig. 3. The graphical representation of the data obtained from TGA

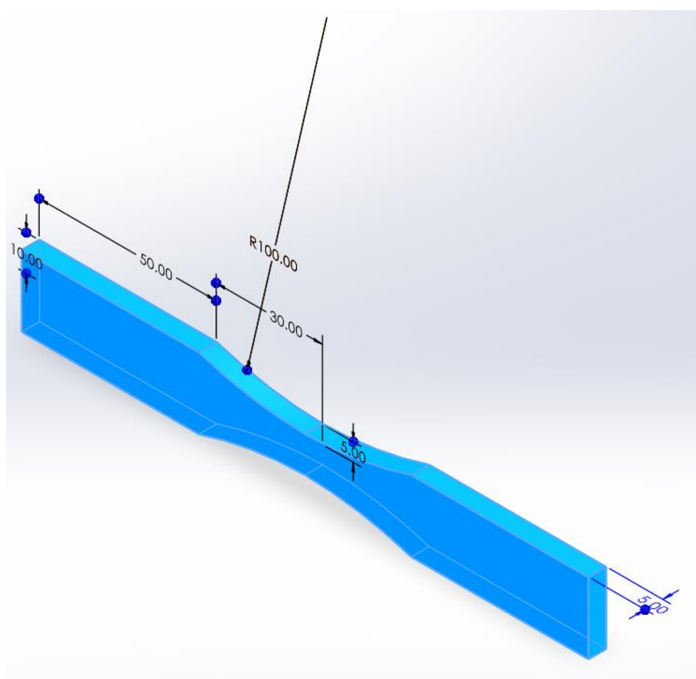
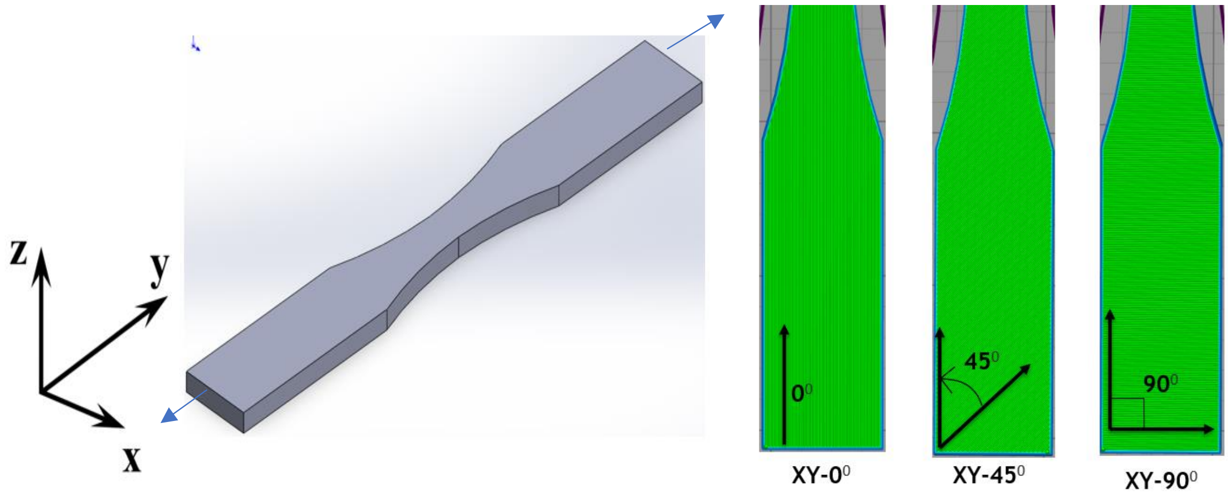


Fig. 4. The CAD model generated in SOLIDWORKS for the geometry of the specimen (All dimensions are in mm)



(a) (b)

Fig. 5. (a) The printing plane, (b) Infill orientation

Parameters and their variation ranges for DoE

Two process parameters and their interaction are considered here as factors in the design of the experiment: Layer height (LH), and infill orientation (O). The values of fixed printing parameters and the levels of factors (varying printing parameters) in DoE are shown in Tables 2 and 3 respectively. For each level of factors, a total of 12 repetitions are tested.

Table 2. Fixed printing parameters

Printing Parameter	**Values**
Nozzle temperature	240 °C
Bed temperature	90 °C
Infill density	100%
Shell count	4
Infill pattern	Aligned rectilinear
Nozzle diameter	0.4 mm

Table 3. Levels of factors for DoE

Levels	**LH (mm)**	**O**
1	0.2	0°
2	0.3	45°
3	-	90°

Phase II: Experiment

Before initiating the fatigue tests, it is required to have preliminary tensile test data to define the fatigue maximum and minimum loading conditions. The maximum load of the fatigue cycle should not increase more than the ultimate tensile load. From the literature review, tensile strength is the lowest for 90° if compared to 45° and 0° infill orientation[11], [18]. Mithila Rajeshirke et. al [18] in their study have reported the lowest tensile load for CF-PETG with 90° infill orientation as 1909.48 N as compared to 45° (2158.05 N) and 0° (2574.35 N) infill orientations.

The same specimen geometry is used to determine the ultimate tensile load sustained by the specimens by 90° infill orientation with 0.2 mm LH. A total of three replicates are tested under static tensile testing with a strain rate of 5 mm/min to determine the ultimate tensile load and then the average of these three tested samples is determined. The results obtained for the tensile test are shown in Table 4. Ultimate tensile strength is obtained by dividing the area of the broken specimen. 810E4-15 Dynamic Test System is used for the tensile and fatigue tests. It has a 15 kN axial load capacity for static and fatigue testing applications.

Table 4. Result for Tensile Test (LH - 0.2, O - 90°)

Specimen No.	**Ultimate Tensile Load (UTL) (N)**	**Ultimate Tensile Stress (N/mm^2)**	**Average of UTL (N)**	**80% of the Average UTL (N)**
1	2010.69	39.85	2029.02	1623.22
2	2079.93	41.19		
3	1996.46	39.29		

Considering the approximate value of 80% of that load i.e., 1600 N is applied as the maximum load and 160 N for the minimum load for the fatigue cycle to the specimens with orientations 90°, 45° and layer heights 0.2, 0.3 mm for fatigue testing, which eventually implicates the stress ratio as 0.1. The frequency used is 3 Hz. All the tests are carried out at 53-60% of humidity and 68-70 °F temperature. Newton test machine controller/software is used to control the test parameter. Proportional/Integral/Derivative (PID) values need to be set up to control the waveform accurately. PID values used are 1400/1200, 100, and 0 respectively. The test is load controlled fatigue test, as loads are controlled. The response to the tests is recorded in the form of a number of cycles.

When the same loads are applied to the specimens (two) of orientation 0° and layer height 0.2 mm, the number of cycles under fatigue load obtained exceeded the set limit i.e., 50,000. Since the time required for such long cycles is exorbitant, it is decided to perform the tensile tests on the same specimen and then fatigue tests considering the approximate value of 80% average ultimate load sustained by the specimen as maximum load in the fatigue cycle. The results obtained for the tensile tests are shown in Table 5.

Table 5. Result for Tensile Test (LH - 0.2, O - 0°)

Specimen No.	**Ultimate Tensile Load (UTL) (N)**	**Ultimate Tensile Stress (N/mm^2)**	**Average of UTL (N)**	**80% of the Average UTL (N)**
1	3160.51	58.03	3322.81	2658.24
2	3409.73	63.82		
3	3398.20	66.30		

Considering the approximate value of 80% of that load i.e., 2600 N is applied as the maximum load and 260 N for the minimum for fatigue cycle load to the specimens with layer heights 0.2, 0.3 mm for fatigue testing. The stress ratio and frequency considered are 0.1 and 3 Hz respectively.

Result and Discussion

In this section, the results obtained from the fatigue tests and statistical analysis are discussed.

Phase I: Results

The result obtained from the fatigue tests is shown in Table 6. The response is mentioned in terms of the number of cycles sustained by the specimens. A total of 12 replicates are tested for each factor level of DoE. The load applied to each of these specimens is discussed in the experiment section. The specimens after testing for each orientation and layer height are as shown in fig. 6.

Table 6. Results of Fatigue Test (Response – Number of cycles)

O	**90°**		**45°**		**0°**	
LH / Replicates	**0.2**	**0.3**	**0.2**	**0.3**	**0.2**	**0.3**
1	3260	5106	3294	8392	362	30
2	5948	7383	5300	8168	644	140
3	5163	4393	6464	9398	176	56
4	5604	4031	6708	5339	888	23
5	9169	5387	3711	6540	504	82
6	10302	4581	7192	4716	816	33
7	2354	5512	4024	7356	674	42
8	4782	5677	4228	6912	554	106
9	4301	6122	3766	8246	696	31
10	6090	9470	7058	6606	262	35
11	9015	12252	6026	8344	660	53
12	8677	5966	10194	10424	561	106

Fig. 6. The specimens after fatigue tests for the orientations and layer height as – a) 90°, 0.2mm, b) 45°, 0.2 mm, c) 0°, 0.2 mm, d) 90°, 0.3mm, e) 45°, 0.3mm, and f) 0°, 0.3 mm

Phase II: Statistical Analysis

For O – 90° and 45°

With the aid of SAS (Statistical Analysis System) software, the ANOVA analysis is performed on the fatigue results data for 90° and 45° orientations with 0.2 and 0.3 mm (first four columns of table 6), obtained from the testing. The reason to consider only these orientations (90° and 45°) for ANOVA is, that these specimens were applied to the same loading i.e., 1600 N as a maximum load, unlike 2600 N load was applied as the maximum load to 0° orientation specimens. The analysis is done to investigate the individual input parameters and their interactions with the fatigue behavior. The ANOVA model chosen is shown in eq. (1):

$$Y_{ij} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \varepsilon_{ij} \quad (1)$$

Where μ is a constant (overall mean), α_i is the main effect for factor A (Layer Height) at the i^{th} level, β_j is the main effect for factor B (Orientation) at the j^{th} level, $(\alpha\beta)_{ij}$ is the interaction factor, and ε_{ij} is the error term. The probability value (p-value) aids to determine whether the input variable is significant or not, by comparing it with the alpha value of 0.05. If the p-value is smaller than 0.05, the input variable is considered to be significant. The ANOVA table and interaction plot are shown in Table 7 and fig. 7 respectively.

Table 7. ANOVA of fatigue results for main effects and their interaction with p values

Source	Degree of Freedom	Sum of squares	Mean square	F-value	p-value
LH	1	11908872.71	11908872.71	2.66	0.1102
O	1	1024221.78	1024221.78	0.23	0.6348
LH*O	1	9643867.89	9643867.89	2.15	0.1494

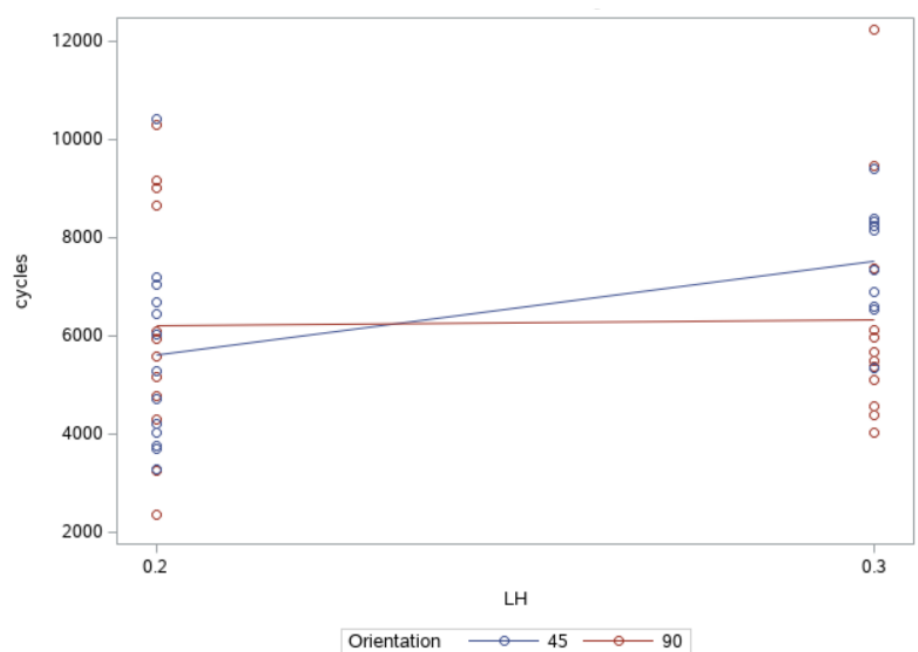


Fig. 7. The interaction plot for the response (number of cycles) for 90° and 45° infill orientations with 0.2- and 0.3-mm layer heights

From the statistical analysis, as p values for LH, O, and their interaction (LH*O) all are above 0.05, meaning that the evidence suggests there is no significance either for main effect factors (O and LH) or their interactions. From the interaction plot, fig. 7, it can be observed that the response (i.e. number of cycles) for 90° and 0.2 mm LH varies from 2354 to 10302, and for 0.3 mm LH from 4031 to 12252. For 45° infill orientation with 0.2 mm LH it varies from 3711 to 10194 and with 0.3 mm LH, from 4716 to 10424. This means, that for the lower load such as 1600N, neither the layer heights nor orientations make any significant difference in the fatigue behavior if the values for layer heights are 0.2 and 0.3 mm and orientations are 90° and 45°. The large variation in the data is because of the fact that printed parts have unavoidable defects such as pores, voids, and poor adhesion which may cause the parts to fail at a very low number of cycles. Also, manual errors while testing the specimens such as minor variations in adjusting the grippers may affect the loads and eventually the fatigue behavior. As 90° and 45° both infill orientations are not in the direction of the applied loads, are giving very low responses, and do not show much significant difference even with respect to the layer heights.

For O – 0°

As mentioned in the experiment section, when 1600 N as the maximum load is applied to the specimens (two) of orientation 0° and layer height 0.2 mm, the number of cycles under fatigue load obtained exceeded the set limit i.e., 50,000, as the fibers printed in the direction of loading conditions makes it more resistant to the applied load.

The obtained test results for fatigue behavior for 0° orientation and the load of 2600 N as maximum load, are presented in the Box-Plot in fig. 8. Further details about applied loading conditions are discussed in the experiment section. From the chart, it is concluded that 0.2 mm layer height shows better results than 0.3 mm. In the case of smaller layer heights results in better conditions for melting each subsequent layer during the contact of the hot extrudate with the previous print layer. This phenomenon may have a decisive influence on forming the interlayer adhesion.

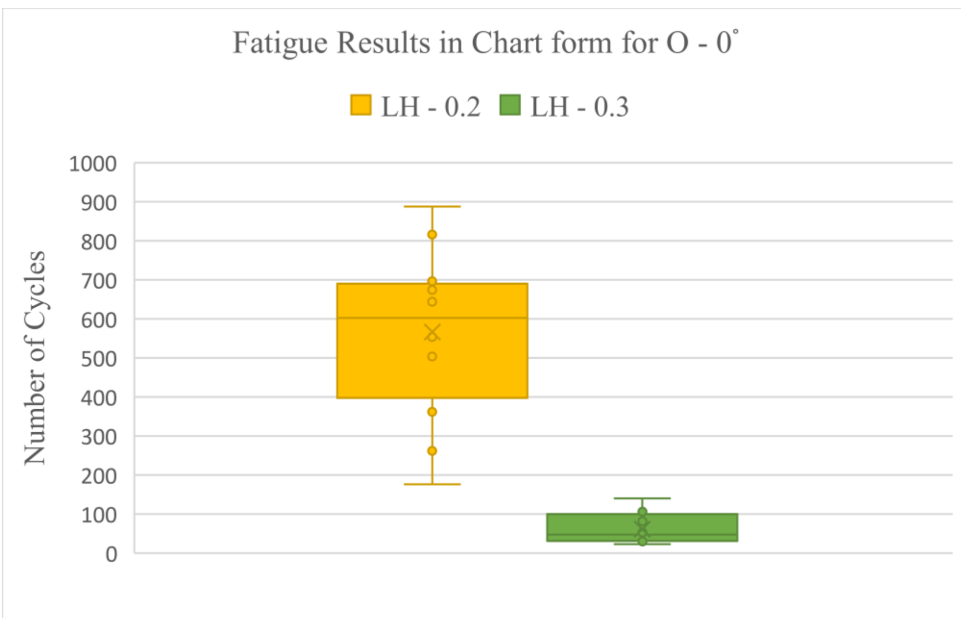


Fig. 8. The fatigue results in chart form for O - 0°

Conclusion

Using FRAM technology, the specimens were fabricated with SCFs/PETG. TGA is used to determine the weight percentage of SCF in SCFs/PETG composite. Tensile tests are performed to determine the loading conditions required for fatigue testing. The fatigue tests are performed with respect to various printing parameters and are reported in this article. Based on the analysis of the data obtained from the fatigue tests following conclusions have been made.

- For the low loads such as 1600N (as maximum load), 90° and 45° orientations do not show any significant difference in the fatigue behavior. Even for the different layer heights i.e., 0.2 and 0.3mm there is no significant difference. From the obtained result data, there is a large variation in the response. The number of cycles of more than 10,000 could be the result of lower gripping pressure. Gripping the specimens was done manually. While a very low number of cycles could have resulted from unavoidable defects in printing such as voids, poor adhesion, etc.
- For the low loads as mentioned above (1600N as maximum load), the 0° orientation can sustain more than 50,000 cycles.
- For the higher loads such as 2600N (as maximum load), the 0° orientation with 0.2mm layer height shows better performance than the 0.3mm layer height. In the case of smaller layer heights results in better conditions for melting each subsequent layer during the contact of the hot extrudate with the previous print layer. This phenomenon may have a decisive influence on forming the interlayer adhesion.

Future Scope

It should be mentioned that limited printing parameters are studied for this research and the importance and influence of various other parameters may be different. Therefore, future research should focus on more parameters such as nozzle diameter, stacking sequence, and carbon fiber percentage. Furthermore, the microstructural analysis should be carried out to have in-depth knowledge about the failure of fibers and matrix. To determine the fatigue strength of the material should also be taken into consideration. The reproducibility of FRAM in terms of fatigue properties should be verified on different geometry as well. Then more universal guidance can be accepted for fatigue behavior.

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