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Reviewed Paper

Experimental Analysis of Functionally Graded Materials produced by Fused Filament Fabrication

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Abstract

Multi-material additive manufacturing has grabbed tremendous attention in the research community. In this investigation, a multi-material single extrusion system was used to fabricate the combination of chopped carbon fiber reinforced Polyethylene Terephthalate Glycol (CF-PETG) and Thermoplastic Polyurethane (TPU) materials with gradient transition for a more robust material interface. Various patterns such as the 20, 40, 60, and 80% by volume blend of CF-PETG and TPU materials are designed, printed, and analyzed to understand their tensile and fatigue behaviors. Tensile–tensile fatigue tests with a stress ratio of 0.1 were performed on each specimen at 80% of UTS. The characterization of functionally gradient material interface and direct transition patterns were conducted for comparison. The results showed that gradient change in material concentrations from soft to hard material has significantly enhanced the interface strength.

Keywords: Additive Manufacturing, Functionally Graded Materials (FGM), Tensile, Fatigue.

Introduction

Functionally Graded Additive Manufacturing (FGAM) is layer by layer manufacturing process. It allows for the simultaneous deposit of different materials with a predetermined mixing ratio, resulting in a microstructure compositional shift that tailors the material properties at several regions of the produced component [1]. Japanese scientists originally proposed the notion of Functionally Graded Material (FGM) in the 1980s for high temperature uses in space aircraft [2]. Fabrication of FGM combines various materials in a single manufacturing operation to create metal-to-metal, polymer-to-metal, and metal-to-metal composite material combinations at specific places. There are different ways to produce FGMs using Additive Manufacturing (AM) techniques such as binder jetting, material jetting, powder bed fusion, etc. One of the well-known AM methods to fabricate FGM is the Fused Filament Fabrication (FFF) process. FFF techniques uses the layer-by-layer deposition method to build 3D objects. This method benefits from the wide variety of materials that are readily available. like thermosets, metal-filled thermoplastic filaments, composites, and flexible elastomers [3]. It is a low-cost technology and uses a low-cost material compared to other AM methods [4]. Conventional multi-material parts are fabricated using a separate extrusion nozzle for each material in FFF technology, limiting the smooth transition of materials. Swapping materials without altering the extrusion head is a benefit of the FGAM method over traditional AM. The procedure of depositing numerous materials using the FFF approach is shown in Fig. 1.

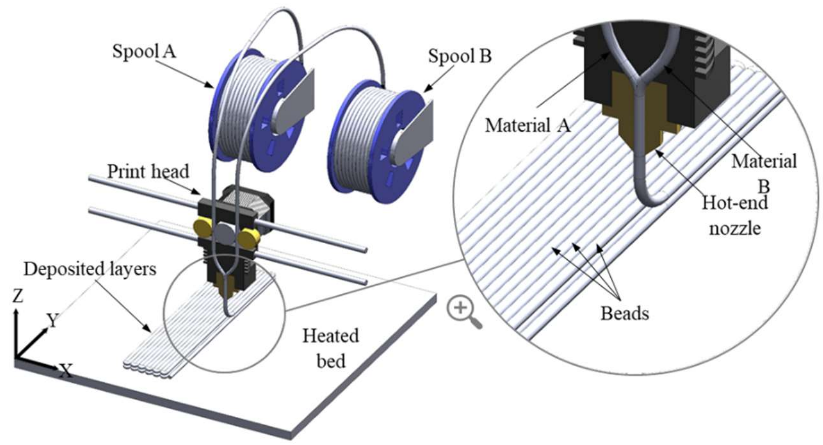

Fig 1: Description of the FFF process used in this study [12]

A limited number of studies were performed to design, manufacture, and characterize the behavior of FFF-made FGMs. Doubrovski et al. [5] demonstrated a new work path, which began with defining and representing part geometry and material attributes. Using the bitmap approach, Material attributes are converted to the material composition. They displayed workflow in a method that allows designers to improve the performance and usefulness of their products. Ituarte et al. [6] presented research on the multi-material binder jetting technique for designing and producing functionally graded structures. They created and evaluated digital material tensile specimens using a variety of processing conditions.

The authors employed a regression-based material model for the mechanical characterization of digital materials such as Young's modulus, tensile strength, and elongation at break. To describe and simulate FGM structures, prescribed and automatic methodologies were used. Interface qualities of additively built multi-material components have been studied in several studies. Freund et al. [7] FFF technique explored the parameters influencing the interface strength of additively built multi-material components. In this study, roll peeling tests and peeling resistance of numerous stiff and flexible materials were carried out to identify and quantify significant adhesion mechanisms. The findings indicated that materials' polarity and mechanical interlocking significantly impacted the interface strength of components made using the FFF process. Another one-of-a-kind study was conducted by Garland et al. [8] outlined the difficulties and solutions experienced when developing and producing FGM parts using a commercially available FFF 3D printer. Results of the study contributed to the fabrication of multi-material structures with the optimal material distribution. Guessasma et al. [9] studied the manufacturing of multi-material objects using droplet-based AM methods. A two-extrusion head printer was used to create a composite material made of TPU and acrylonitrile butadiene styrene (ABS). 3D imaging methods were used to accomplish the porosity investigation. It was found that the interface quality and orientation influenced multi-material printed parts.

Another one-of-a-kind investigation was carried out by Lopes et al., [10] which examines the mechanical properties of multi-material printed parts, with particular attention to the interface zone's geometrical boundaries. Various tensile specimens were evaluated using a mixture of PLA, TPU, and PET materials. The results revealed that multiple materials in pairs of PLA-TPU and PLA-PET exhibit a more significant reduction in Young's modulus and tensile strength. In this case, in addition to the physical issue of the boundary interface, there is also the chemical issue to address. There is a limited number of studies on the functionally gradient of AM materials; and the impact of processing parameters are layer height, printing speed and plane of orientation on the tensile and fatigue strength of AM plastic components [13-15]. This research study investigates the tensile and fatigue characteristics of two polymers having gradient compositions. Furthermore, the interface bonding strength of tensile specimens is investigated by mixing two materials at various concentrations. For fatigue analysis, the obtained UTS is utilized to set stress levels. At 80% of nominal UTS of each specimen type, tensile–tensile fatigue experiments with a stress ratio of R = 0.1 were performed. For fatigue testing, different printing planes are explored.

Materials and Methods

Material Selection

To examine amorphous polymers with various material characteristics, several materials were used. Amorphous polymers such as Thermoplastic Polyurethane (TPU) and chopped carbon fiber Polyethylene Terephthalate Glycol (CF-PETG) were employed in this study, Due to lack of research study on this material, it is being used. This type of FGM material can be applied to robotic grippers and prosthetic socket applications. Parameters used for printing the specimens as shown in Table1.

Table 1: Fixed processing parameters

Parameters	Values
Nozzle temperature (ºC)	245
Bed temperature (ºC)	75
Infill density (%)	100
Infill pattern	Line (0/90)
Layer width (mm)	0.35
Layer height (mm)	0.23
Printing speed (mm/sec)	15

TPU is a highly flexible material with good tensile strength. It is very resistant to abrasion, oil, and grease. The appropriate parameters for printing TPU specimens are bed temperature of 60 ºC, nozzle temperature of 220 ºC, and printing speed should below 15 mm/s. TPU Material occasionally won't mix correctly with CF PETG if the printing speed is greater than 15mm/s. The most critical aspect is that the retraction settings be turned off. It is utilized in several applications since it combines the advantages of both plastic and rubber, such as aerospace, automotive, wires, mobile covers, cables, etc. [16-19]. CF-PETG has high impact strength. It has good chemical and impact resistance properties. It is utilized in various applications, including prototypes and models, food and drink containers, medical and pharmaceutical applications, etc. Some materials are commonly used in both regular life and the 3D printing industry. Table 2 shows the typical characteristics of TPU and CF- PETG polymers.

Table 2: Typical properties of TPU and CF-PETG

Properties	Values	
	CF-PETG	TPU
Melting Point (◦C)	230-250	210-230
Density (g/cm3)	1.23	1.23
Tensile strength (MPa)	45.8	26
Glass transition temperature (◦C)	82	60
Bed temperature(◦C)	70-75	60-65

By managing the deposition feature of materials at the voxel scale, voxel-based three-dimensional printing allows to producing digital structures at the mesoscale [11]. There is a variety of ways to create the FGM specimen. FGM specimens were designed using a voxel. A voxel is a graphic data unit that defines a point in three-dimensional (3D) space. Pixels create a point in two-dimensional (2D) space, initially, the object must be made in a CAD model, prepped, and exported into the Standard Tessellation Language (STL) file format, and then uploaded into slicer software, which generates G-code files that 3D printers can read. In STL format, the CAD tool produces the geometrical information of the model. Voxelizer slicer imports an STL file. The design of functionally graded components utilizing a voxlizer-based technique may handle heterogeneous material information. The Voxlizer slicer allows the user to alter the distribution of materials based on their volume. In this research study a Zmorph desktop FFF-3D printer was used to fabricate FGM components with a gradient interface, as shown in figure 2.

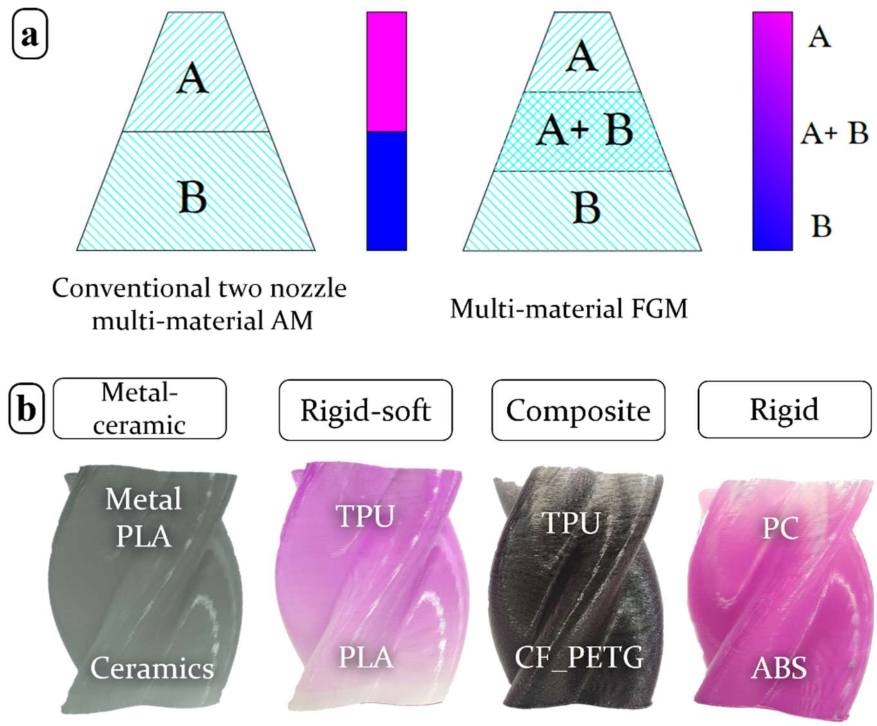

Fig 2: Gradient transition of FGM interfaces, (a) conventional versus FGM material combination, (b) fabricated components with different material combinations.

Specimen fabrication and preparation

The corrosion of metals and alloys standard ISO 11782-1 was applied for these specimens, as shown in Fig.3. The geometry is Euro standard version specifically for the fiber-reinforced plastics. The length is 160 mm, with a 5 mm thickness and a 20 mm breadth. At Gauge length, the curvature radius is 100 mm.

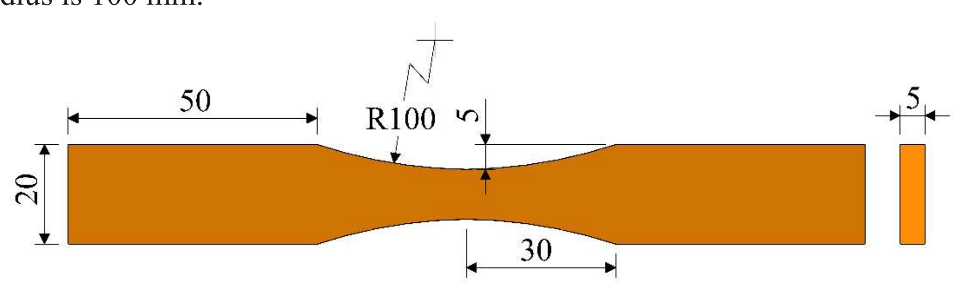

Fig 3: Dimension of tensile and fatigue test specimen as per ISO 11782-1

Experimental Setup

Tensile and fatigue tests were carried out on a Testresources 810E4 load frame with a 15 KN load cell in line with ISO 11782-1 standard test procedure for uniaxial fatigue characteristics of plastics in this investigation. The specified stress level was maintained using a PID controller. The strength of FGM samples is comparable to CF PETG and TPU materials, as seen in Fig. 4. The test can be performed at a frequency of up to 25 Hz, still not more than 5 Hz, according to the standard. Lower frequencies, on the other hand, were chosen to prevent the hydraulic actuator from being overheated.

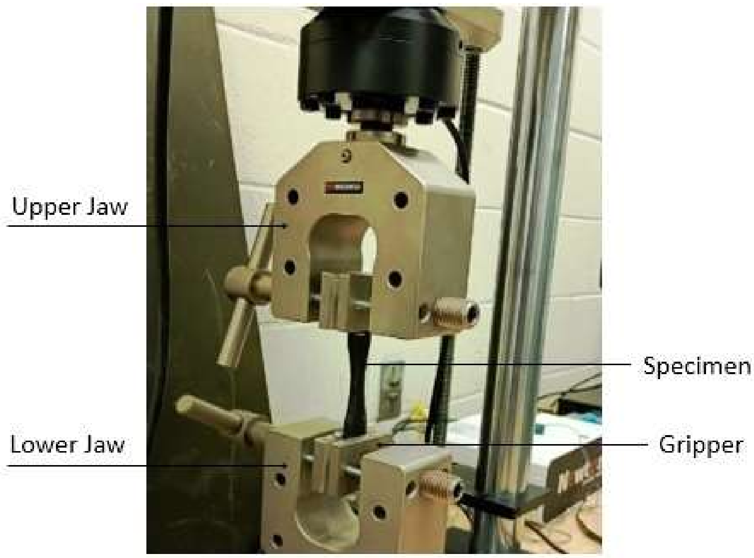

Fig 4: Experimental setup for fatigue and tensile test

Results and Discussion

Analysis of Tensile behavior

Experimental characterization of tensile and fatigue test samples has been carried out to investigate the behaviour of FGM composites under various structural loads. The tensile test results, in the form of stress–strain diagram, are given in Figure 5 and in Table 3. Engineering stress-strain diagrams for CF-PETG, TPU, and FGM printed specimens.

Table 3: Ultimate Tensile strength (MPa) of 3D printed specimens

Specimen No.	CF- PETG	FGM	TPU
1	40.43	14	8.6
2	42.53	14.01	8.74
3	43.29	14.85	9.05
Average	42.08	14.28	8.79

Table 3 shows the tensile strength of the FGM is more than TPU but less than the CF-PETG. The ultimate tensile strength for the FGM specimen is around 14 MPa. The characteristics of CF-PETG and TPU were passed down to FGM specimens. FGM is one of the methods for improving the strength of FFF Specimens' weak bonding layer.

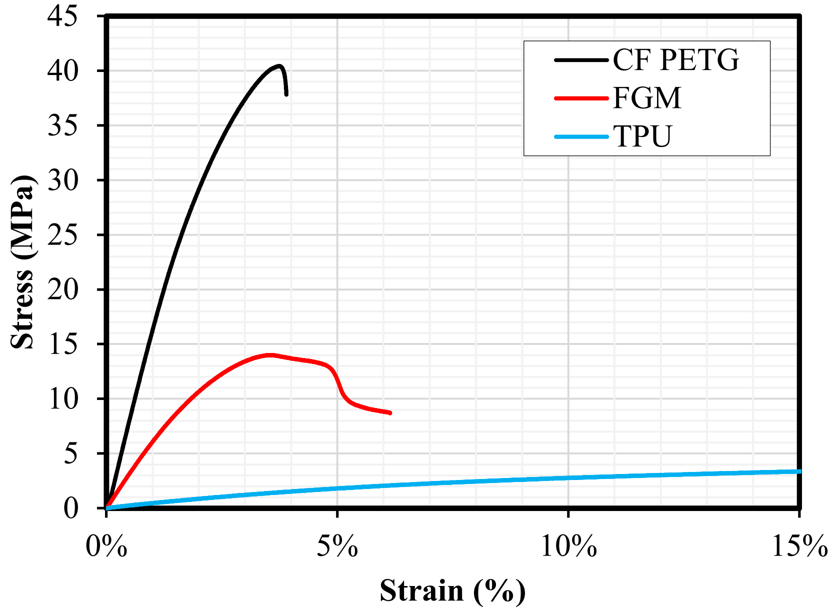

Fig 5: Stress-strain Graph of CF/PETG, FGM and TPU

Tensile test results in Figure 6 revealed the variation of material properties from neat TPU to CF/PETG. The graph shows the decreasing trend in material's strength and stiffness properties from neat TPU to CF/PETG fabricated on the XY plane. This indicates that the mechanical behavior of the structure can be tunable in FFF made FGM parts to obtain desired properties at desired locations.

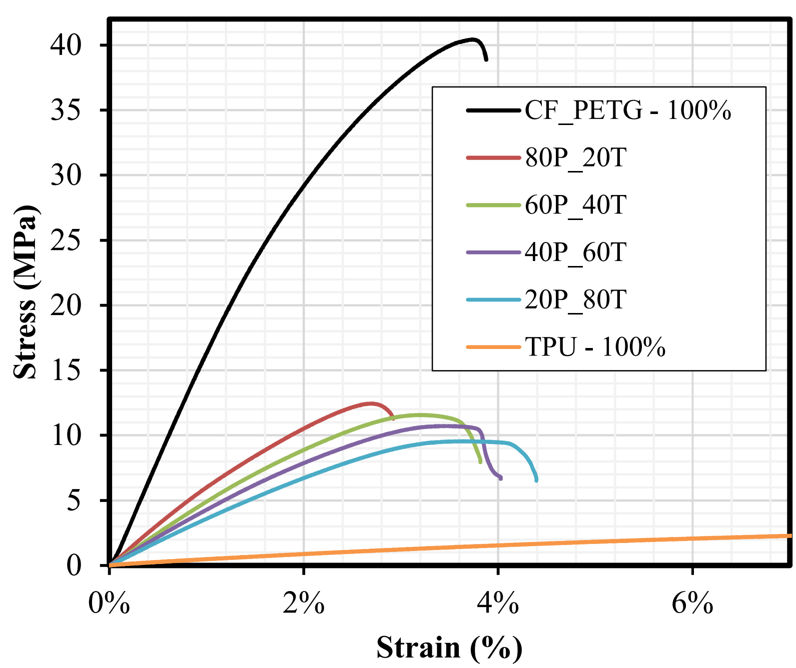

Fig 6: Stress and strain graph of various concentrations of CF-PETG and TPU materials

Fatigue test results

There is a scarcity of research articles on fatigue study of FGM and FFF specimens, as stated in the introductory portion of the paper. The tension-tension fatigue test was performed at 80% of the specimen's maximum load with a stress ratio of 0.1 and a frequency of 3 Hz. To understand the effect of orientation process parameters, two different plane orientations (XY-0) and (XY-90) were tested. Figure 7 shows the number of fatigue cycles for the various raster orientations of FGM specimens. Samples printed on XY-0 directions shown a higher fatigue life cycle than the XY-90. This is because 3D printed parts are strong if a load is applied along with the printing orientation.

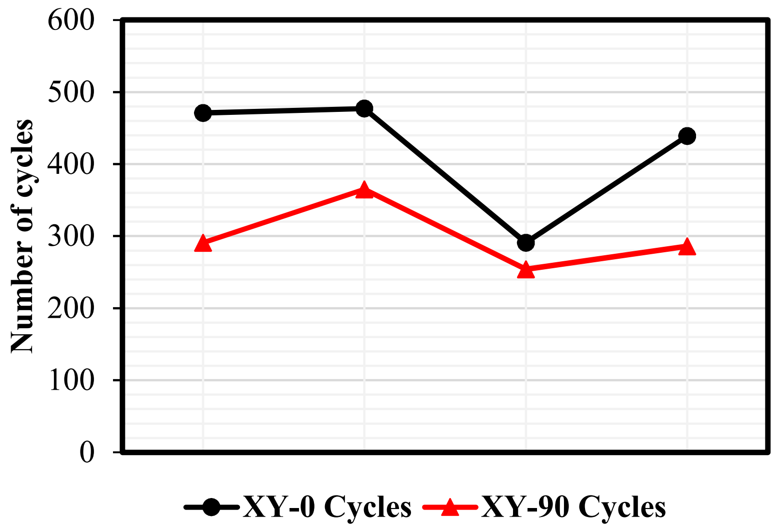

Fig.7: Fatigue cycles of the specimens fabricated on flat (XY-0) and (XY-90) orientations

In this research study, the analysis of variance (ANOVA) method was used to understand the effect of the processing parameters on the fatigue behavior of the FGM samples. The ANOVA table is given below it shows that the orientation has a statistical significance with a P-value of 0.03 which is less than 0.05. This indicates that the change in printing orientation will statistically impact the fatigue life of functionally graded samples.

Table 5: ANOVA Table

Source	DF	Sum of Squares	Mean Square	F-Value	Pr > F
Model	4	52915	13228.75	6.74	0.0744
Error	3	5887	1962.3333		
Corrected Total	7	58802			
Source	DF	Type I S S	Mean Square	F-value	Pr > F
Orientation	1	29282	29282	14.92	0.0307
Specimen	3	23633	7877.66667	4.01	0.1418

The results in Table 5 match the results of figure 7, showing the effect of the printing plane orientation. Accordingly, the XY-0 raster orientation specimen had the most extended fatigue life at the 80 percent UTS stress level, with 477 cycles to failure. Where DF, SS and Pr are Degree of freedom, Sum of Square, and Probability.

Microstructure

Scanning electron microscope (SEM) analysis was performed to examine fracture mechanisms and microstructural morphology of the composite specimens. The result of the SEM analysis revealed that fiber orientation and distribution influenced the fracture behavior of the FGM samples, as shown in Figure 8.

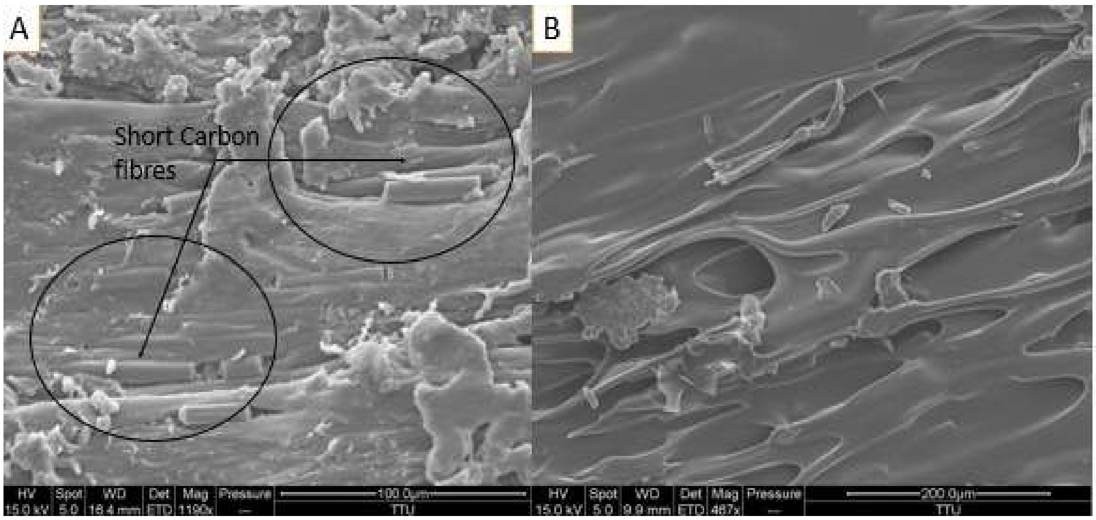

Fig. 8: Dog bone sample of FGM with 10% of short carbon fiber before fatigue testing (A) Short carbon fiber (SCF) (B) cross view

Fiber breaking, debonding, and fiber pull-out are the fracture modes following fatigue testing. The cyclic load causes fiber breakage and debonding. Some fibers are damaged, while others are yanked out of the matrix. In Figure 9, broken fibers are seen surrounding the fractured area.

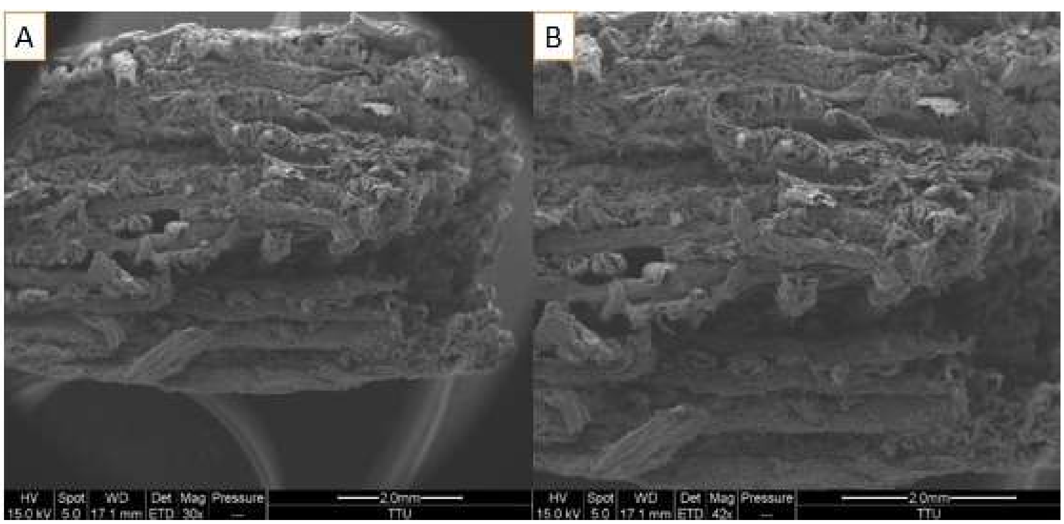

Fig. 9: FGM samples after fatigue testing (A) cross-section (B) side view

Conclusion

This study used experimental testing, SEM analysis, and the ANOVA method to evaluate the mechanical characterization, tensile and fatigue behaviors of FFF-made FGMs. The current paper summarizes the findings as follows:

- The FFF process successfully fabricated the FGM specimens using the single nozzle multi-material printing technology.
- It was found that the mechanical behaviour of TPU-CF/PETG composites can be tuneable by mixing the specific ratio of each material.
- The XY-0 printing plane orientation of the FGM specimen had the most extended fatigue life as compared to the XY-90 direction.
- The study also revealed that FGM could be used to improve the interlaminar shear strength of weak FFF parts.
- Microstructural analysis indicated that the primary failure mechanism was responsible for a weak fiber-matrix interface when applying the cyclic fatigue loading.

Future Work

The scope of the future studies is given below:

- Improving the software capabilities to design highly complex FGM patterns is needed.
- Understanding the fracture behaviour of multi material interfaces under bending fatigue.
- Fatigue modelling and characterization.

Acknowledgment

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