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https://doi.org/10.5109/2349296

出版情報：Evergreen. 6 (3), pp.207-214, 2019-09. 九州大学グリーンテクノロジー研究教育センター
バージョン：

EVERGREEN Joint Journal of Novel Carbon Resource Sciences & Green Asia Strategy, Vol. 06, Issue 03, pp207-214, September, 2019

Experimental and Computational Investigation on Mechanical Properties of Reinforced Additive Manufactured Component

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(Received Jun 25, 2019; accepted September 20, 2019).

Abstract: Fused deposition modelling (FDM) is the one among various additive manufacturing techniques which can fabricate component of multi material. However, the tensile strength of FDM component is naturally low and hence it is difficult to use for the engineering application. For enhancing the mechanical properties, this study explores a novel methodology by adding the high strength material in between matrix material as reinforcement in the additive structure. In this study, ABS and PLA based reinforced composites are prepared. ABS and PLA are used as matrix material whereas PETG is used for the reinforcement. Unidirectional tensile test is performed to check the effect of reinforcement on tensile strength of the fabricated component. Experimental results depict that addition of PETG reinforcement material improves the tensile strength of ABS by about 70% and tensile strength of PLA material is improved by about 8%. Computational analysis is also performed under similar boundary condition to physical model. It is observed that computational results are close approximation to the experimental results. The methodology proposed in this study could be very useful for the fabrication of high strength component by using low cost FDM technology.

Keywords: Multi materials; reinforced additive manufacturing; mechanical properties; computational analysis; fused deposition modelling

1. Introduction

Over the past few years, industrial demand of biodegradable materials has suddenly increased due to the biodegradability, renewability of the base materials and less greenhouse gas emissions and recycling [1]. ABS, PLA and PETG have been extensively used in the medical industry, packaging industry, automobile industry, aerospace industry etc due to its biodegradability[2]. However, poor mechanical, thermal properties and higher cost limit to use in large scale in the industry. Therefore many researchers have made effort to improve the mechanical properties of ABS and PLA material by varying the process parameters like raster angle, orientation, infill pattern, infill density, layer thickness, shell thickness etc. Some studies were carried out to improve the mechanical properties by mixing the reinforcement fiber into the extruding wire. Significant improvement in the mechanical properties was found due to the addition of reinforcement fiber in the matrix material.

Panes et al.[3] have performed an experiment to characterize the tensile strength of ABS and PLA part printed by FDM process. The process parameters used in this study were layer thickness, infill density and orientation. Pruska i3 printer was used for the fabrication of test samples and HAYTOM HM-D was used for the tensile test. Mansour et al. [4] have conducted a series of experiments to find out the dynamic and mechanical behavior of 3-D printed material. Reinforced carbon fibers PETG material was used for the fabrication of specimen. The reinforcement direction of the fibers was 0° and 90°. It was observed that due to addition of carbon fibers, modulus of elasticity and hardness increased by 30% whereas compressive strain increased by 66%. Masood et al.[5] have performed an experiment to investigate the effect of FDM process parameter orientation on tensile strength and surface roughness of PLA material. Along y-axis uneven surface roughness was observed and tensile strength of material was more along x-axis as compared to y-axis. At an angle of 45°, tensile elongation was nearly same for all the three orientation.

Wu et al.[6] have highlighted the influence of layer thickness and raster angle on the mechanical properties of 3-D printed component. It was found that for higher layer thickness, tensile strength of ABS and PETG material tends to maximum at 0° degree and 90° orientation. Lanzotti et al.[7] have highlighted the impact of process parameters such as infill orientation, layer thickness and number of shell on tensile strength of PLA component fabricated through FDM process. Results shows that on increase of orientation, ultimate tensile strength of the material was found to be decreased. On increasing the number of shell from 2 to 6, ultimate tensile strength was increased from 42 MPa to 52 MPa. Whereas when the layer thickness increased from 0.10 mm to 0.20 mm, minute changes were observed in the ultimate tensile strength of material.

Sugavaneswaran et al.[8] have conducted experimental and analytical investigation for the effect of reinforcement and its orientation on elastic modulus of structures manufactured by polyjet 3D printing technique. Vero black “ABS like” material was used as reinforcement and darus white as matrix material. Instron machine was used for tensile testing and rom equation was used to find out analytical results. The results shows that due to presence of reinforcement, elastic modulus increased by 6.79% in transverse direction (90°), 21.9% along the longitudinal direction at (0°) and 14.88% along inclined direction at (45°). There was good correlation between experimental and analytical results. Afrose et al.[9] have carried out experimental study to investigate the impact of orientation on tensile properties of the PLA thermoplastic material FDM AM technique. The specimens were printed at three orientations namely X, Y and 45°. The shape of the specimen was used similar to dog bone. Result shows that maximum tensile strength was found along the X orientation. Summary of some other research work related to FDM technology is reported in table 1.

Recent development in the field of additive manufacturing is to fabricate heterogeneous material by using multi material. In present work, an attempt was made to investigate the effect of unidirectional reinforcement of PETG material on mechanical properties of ABS (material) and PLA (material). Significant improvement in the tensile strength was found due to the reinforcement of PETG material.

2. Materials and Method

The present study focuses on development of reinforced composite material by using multi material. In additive manufacturing softer material is referred as matrix material and harder material is referred as reinforcement material [17]. Development of AM for the fabrication of multi material had improved the mechanical properties, specific functional requirement and design feature for the new product design. In this work, effect of unidirectional reinforcement of PETG material on mechanical properties of ABS and PLA material was investigated. The next sub section will provide the details of matrix and reinforcement material used in this investigation.

2.1 Matrix and reinforcement material

In this work, two separate cases were considered for selection of matrix material. In first case, ABS was considered as matrix material and PETG was used as reinforcement material. In second case, PLA filament was used as matrix material and PETG was considered as reinforcement material. Three different reinforcement percentages were used for the preparation of test samples viz., 15%, 25% and 35%. ABS was the weakest material and PETZ was the stronger material among all the three material. The schematics arrangement of matrix and reinforcement material is shown in Fig.1. The characteristics of ABS, PLA and PETG materials are shown in table 2.

Table 1 Summary of the characterization of mechanical properties in FDM technology

Investigator Name	Material	Raster angle	Other process parameters	Mechanical properties
Durgun et al. [10]	ABS	0°, 30°, 45°, 60°,90°	Orientation (horizontal, vertical and perpendicular)	Tensile strength
Ravari et al.[11]	PLA	Constant	-	Compressive strength, collapse stress
Onwubolu et al.[12]	ABS	Constant	Layer thickness, part orientation, raster angle, raster width, and air gap	
Dawoud et al.[13]	ABS	0/−90, 15/−75, 30/−60, 45/−45	Raster gap	Tension, bending, impact
Espin et al.[14]	PC	constant	orientation	Young’s modulus, ultimate strength, elastic constant, poission’s ratio, shear modulus
Chacon et al.[15]	PLA	constant	Build orientation, layer thickness and feed rate	Tensile strength and bending strength
Mohamed et al. [16]	PC-ABS	0°, 45°and 90°	Slice height, air gap, part print direction, bead width and number of shells	Creep displacement (μm)

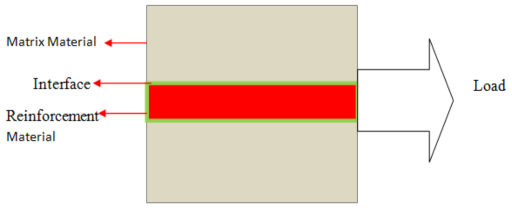


Fig.1: Reinforcement direction of fiber and matrix material

Table 2 Characteristic of ABS, PLA and PETG

Properties	Acrylonitrile Butadiene Styrene (ABS)	Polylactic Acid (PLA)	Polyethylene Terephthalate Glycol (PETZ)
Nozzle Temperature (°C)	245	200	245
Filament diameters (mm)	1.75	1.75	1.75
Tensile Strength (MPa)	27	37	53.08
Temperature Resistance	Resistant to high temperature.	Poor resistant to high temperature.	Poor resistant to high temperature.
Environmental Friendly / Recyclable	Recyclable, but not environmental friendly, Based on Petroleum	Environment al friendly, made from corn & sugarcane, Recyclable	Recyclable
Heated Bed Temperature (°C)	100-110	50-60	60-70

2.2 Selection of specimen geometry and 3D modeling

American society for testing and materials (ASTM) has fixed some standards for testing of materials under different tests [18)-23)]. The D638 series corresponds for tensile testing of plastic and polymers. ASTM D638 specifies methods for testing the tensile strength of plastics and other resin materials and for calculating their mechanical properties [24)]. Fig. 2 show the ASTM D638 Type-IV specimen which was fabricated through FDM printer. ASTM D638 specimen has the dog bone like structure [25)]. Specimen has shoulders at the both ends, which are wider than other portion of the structure. In this work, Autodesk Fusion @360 was used for the 3D modelling of the specimens shown in Fig. 2. 3D CAD model of specimen is shown in Fig. 3. The next section will give the fabrication method of test specimens.

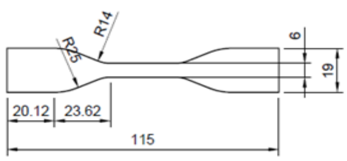


Fig.2: Drawing of ASTM D638 type-IV specimen

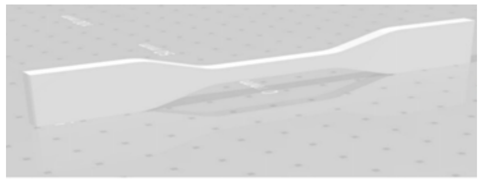


Fig.3: CAD design of specimen in .STL format

2.3 Fabrication method

Fused deposition modelling additive manufacturing technique was used in this research work for the preparation of test specimens. Three different materials were used for the fabrication of the specimen viz., acrylonitrile butadiene styrene (ABS), polylactic acid (PLA) and polyethylene terephthalate glycol (PETG). Printer used for the fabrication of test specimens was PRUSA MK3. This printer can manufacture the component of single material only. Additional machine mosaic pallet 2 was attached with PRUSA MK3 for fabrication of multi materials samples. For fabrication of specimens, all the process parameters were fixed and used at optimum levels. The process parameters used for the fabrication of samples are shown in table 3. Three different reinforcement percentages were used for the preparation of test samples viz., 15%, 25% and 35%. Fig. 4 shows the research methodology used for the improving part strength in the flow diagram. Experimental plan used in this research work is presented in Table 4. Figure 5 shows the schematic representation of dual extrusion nozzle used to fabricate test specimen. Figure 6 shows the fabricated samples, with and without reinforcement.

Table 3 Process parameters used for the sample fabrication

Process parameters	Value
Nozzle Diameter	0.4 mm
Infill Density	100%
Print Speed	60mm/s
Raster Angle	45°
Orientation	0° with respect to x axis
Layer Thickness	0.2 mm
Infill Pattern	Hexagonal

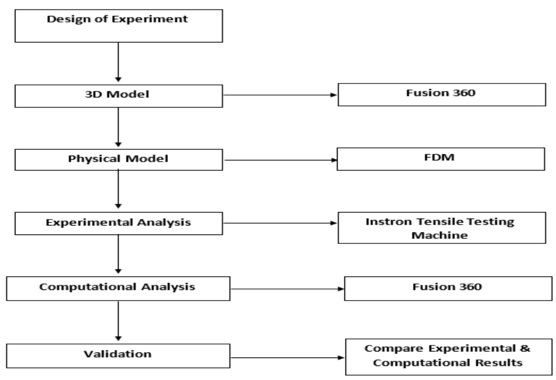


Fig.4: Flow diagram of research methodology

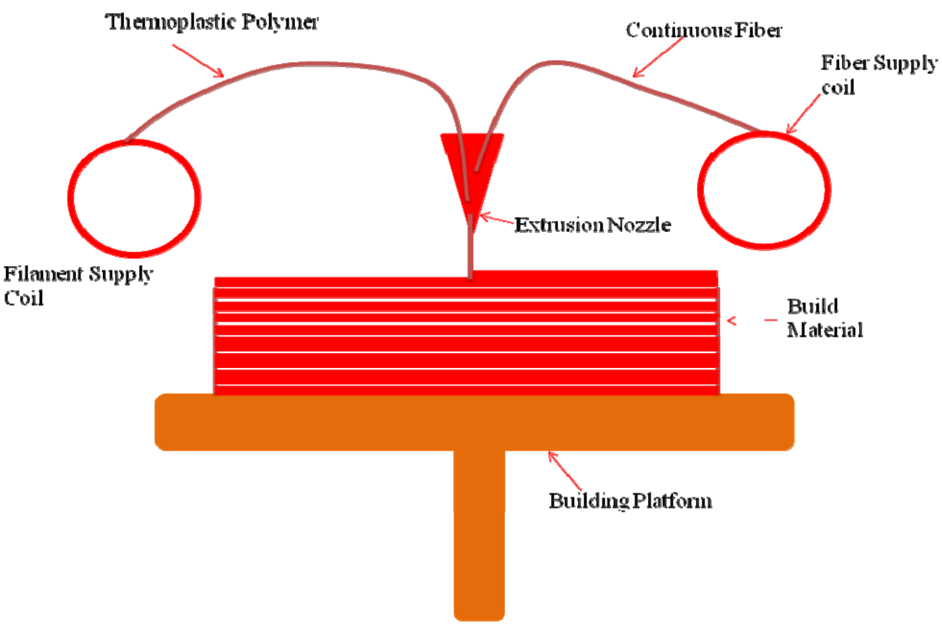


Fig. 5: Schematic layout of FDM printing process

Table 4 Experimental plan for part strength

Experiment No	Matrix material	Reinforcement fiber material	Reinforcement percentage	Tensile strength (MPa)
1	ABS	-	0%	24.05
2	PLA	-	0%	43.50
3	PETG	-	0%	49.50
4	ABS	PETG	15%	38.44
5	ABS	PETG	25%	39.42
6	ABS	PETG	35%	40.64
7	PLA	PETG	15%	45.26
8	PLA	PETG	25%	46.72
9	PLA	PETG	35%	46.85

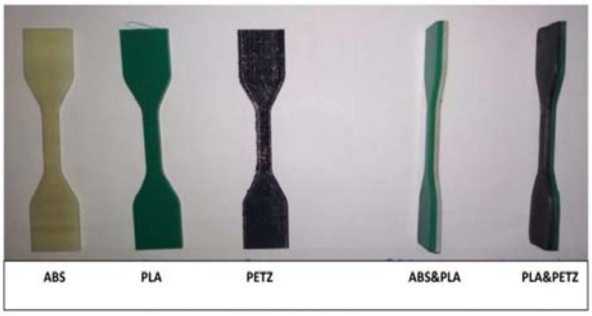


Fig.6: Fabricated specimen along the flat orientation

2.4 Experimental setup for tensile test

The tensile test of the fabricated specimen was conducted on universal testing machine Instron. The actual experimental set-up image is shown in Fig. 7. The specimen was hold between the cross head of UTM machine and axial tensile load was applied on the material at the one end. The corresponding stress-strain diagram was traced on computer according to the load. The specimens were tested at a rate of 1.5 mm/min.

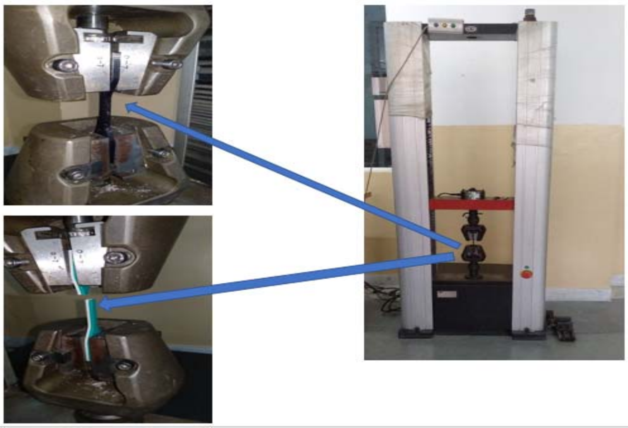


Fig.7: UTM Instron tensile testing machine

3. Computational analysis

For computational analysis, 3D CAD model of ASTM-D638 (tensile test specimen) was created by using Autodesk Fusion 360 software. The CAD model has been simulated by FEA Autodesk Fusion 360 software. A 8-node linear brick, reduced integration, hourglass control element was used for meshing of tensile specimen. After performing several mesh convergence studies 7284 elements with 1.0 seed size has been chosen for current simulation as shown in Fig.8.The bottom end of the specimen is fixed with the boundary condition Ux, Uy, Uz, Rx, Ry, Rz = 0, where Ux, Uy, and Uz are the translation in x, y and z direction respectively. Further, Rx, Ry and Rz are the rotation in x, y and z direction respectively. A velocity of 1.5 mm/min has been applied at the top surface of the specimen as shown in Fig. 9. A tie constraint has been applied to assemble the PLA and PETG in a common specimen for providing the mix effect of properties.

Total nine simulations were carried out to investigate the impact of reinforcement on mechanical properties of ABS and PLA (material). First three simulations were carried out without reinforcement to check the Von mises stress in the ABS, PLA and PETG (material) respectively. In this study, two cases were considered for the analysis. In case–I, ABS material was considered as matrix material and PETG was treated as reinforcement material. Unidirectional reinforcement material was placed between the matrix materials. The direction of reinforcement was considered in the loading direction. Three different reinforcement percentage was used i.e. 15%, 25% and 35%. In case-II, PLA was considered as matrix material and PETG (material) was considered as reinforcement material. However, the reinforcement percentage was used similar to case-I.

Material properties used for the simulation are shown in table 5. For simulation of samples without reinforcement, material was considered as single solid geometry. In case of reinforcement, two different materials system were defined; one for the matrix material and other was used for the reinforcement material

Table 5 Mechanical properties for FEA simulation

Material	Elastic modulus (E)	Shear Modulus (G)	Poisson's ratio (μ)
ABS	2110MPa	14605 MPa	0.39
PLA	30140 MPa	2310MPA	0.33
PETG	2300MPa	1640MPa	0.38

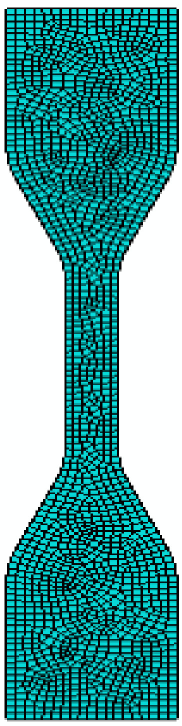


Fig.8: Mesh geometry of tensile test specimen

Fig. 9: Loading condition of test specimen

4. Results and discussion

4.1 Experimental result analysis

The average value of tensile strength for ABS, PLA and PETG materials with and without reinforcement has been calculated using 3 samples each. The effect of PETG reinforcement on tensile strength of ABS and PLA materials can be clearly seen in Fig.10. Due to reinforcement of PETG material, tensile strength of ABS and PLA material have significantly improved. Due to the uncertainty of experimental results, tensile strength is shown within the range of 5% error bar chart. The value of tensile strength of ABS material was improved by about 70% and tensile strength of PLA material was improved by about 8%.

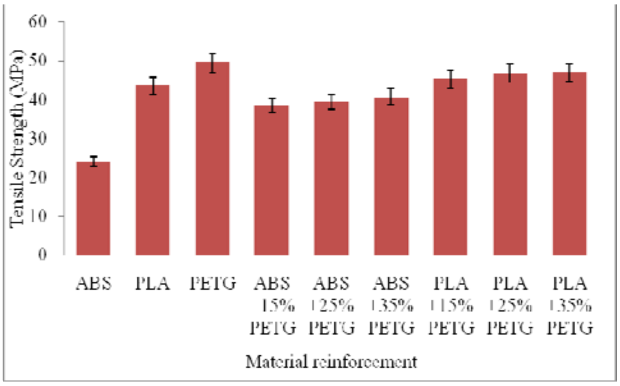


Fig.10: Effect of reinforcement on mechanical properties

4.1 Computational result analysis

Fig. 11 shows the Von mises stress of ABS and PLA materials with and without reinforcement of PETG material. It can be observed that the tensile strength of ABS and PLA materials was improved due to the reinforcement.

Results of computational study depicted that ABS samples was failed at a load of 577.2 N. The value of Von mises stress was observed 25.37 MPa at failure point. Specimen of PLA material was failed at a load of 1044 N and value of Von mises stress was found to be 46.61 MPa. Sample of PETG material was failed at a load of 1188N and value of Von mises stress was observed 53.06 MPa. Fig. 12(a), (b) and (c) shows the Von mises stress in the specimen of ABS, PLA and PETG materials respectively. The value of Von mises stress was observed maximum in PETG material.

The effect of PETG reinforcement on mechanical properties of PLA was simulated with different reinforcement percentage. Fig. 13 shows the effect of reinforcement on Von mises stress of reinforced composite. Result shows that due to the reinforcement, the maximum value of Von mises stress for the PLA composite was found to be 50.51 MPa at 35% PETG reinforcement. It can be concluded that the tensile strength of PLA material was improved about 8% due to the reinforcement.

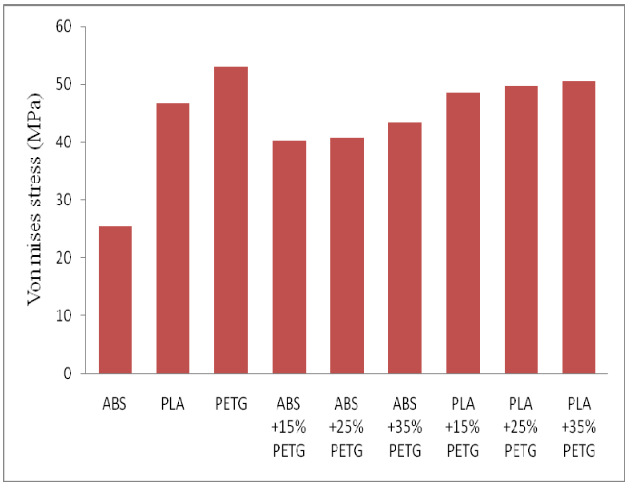


Fig. 11: Von mises stress in ABS and PLA materials

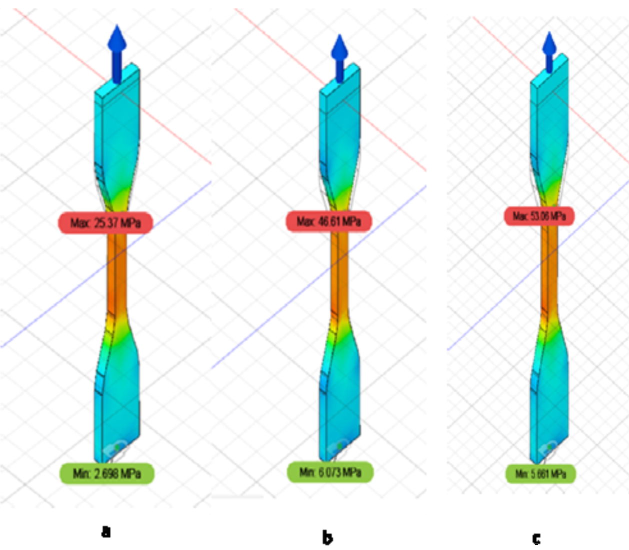


Fig.12: Von mises stress without reinforcement

(a) ABS material (b) PLA material (c) PETG material

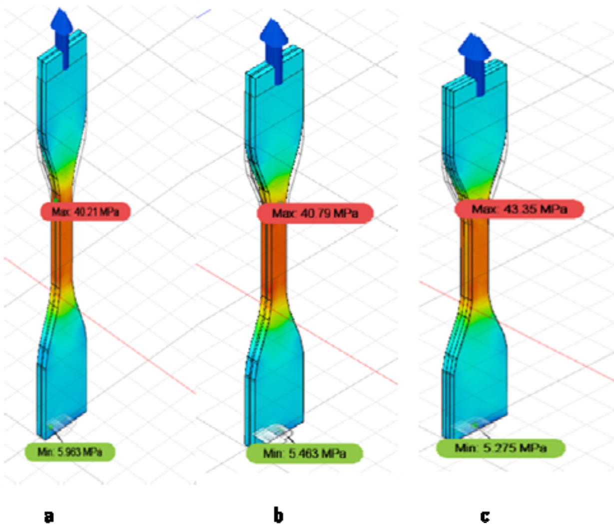


Fig.13: Von mises stress of PETG reinforced PLA composite

(a) 15% PETG (b) 25% PETG (c) 15% PETG

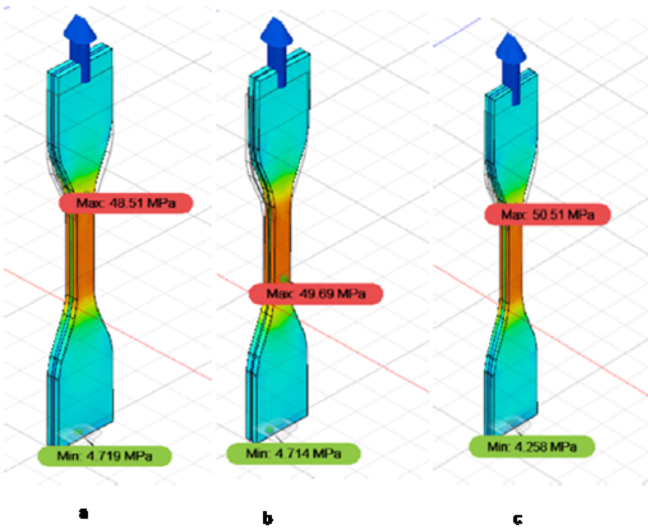


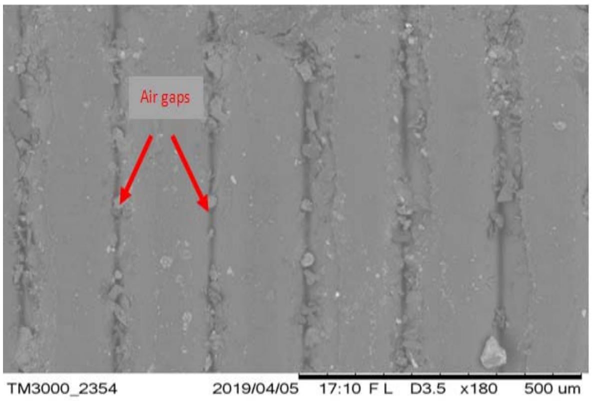
Fig.14: Von mises stress of PETG reinforced PLA composite

(a) 15% PETG (b) 25% PETG (c) 15% PETG

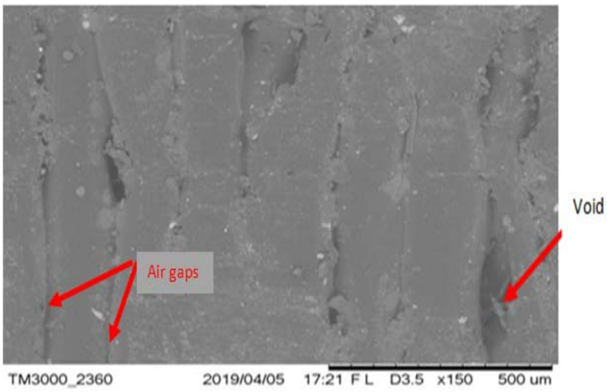
Fig.14 shows the effect of PETG reinforcement on Von mises stress of ABS material. Owing to reinforcement of PETG material, maximum value of Von mises stress of ABS was observed about 43.35 MPa at a reinforcement of 35%. Result depicted that the mechanical properties of ABS material was significantly improved. Due to the reinforcement mechanical properties of ABS was improved about 70%.

4.3 Surface morphology of fabricated specimen

For selecting the suitable orientation, surface morphology was performed. A scanning electron microscope (SEM) was used to visualize the defects in the fabricated samples. Fig.15 (a) shows the SEM image of ABS sample fabricated along flat orientation and Fig.15 (b) shows the SEM image of ABS samples prepared along the edge orientation. It was observed that Voids were present in the component fabricated along the edge orientation, which yields poor tensile strength. For analysis of tensile test all the samples were fabricated along the flat orientation.



(a)



(b)

Fig.15: SEM image of ABS samples

(a) Flat orientation (b) Edge orientation

4.3 Comparison of experimental and computational results

Fig.16 shows the results of experimental and computational analysis. It can be concluded that results of computational analysis was close approximation to the experimental results. However, the experimental value of tensile strength was found to be less as compared to computational results. From SEM analysis, it was observed that there were some air gaps and voids present in the fabricated samples, which yields lower tensile strength.

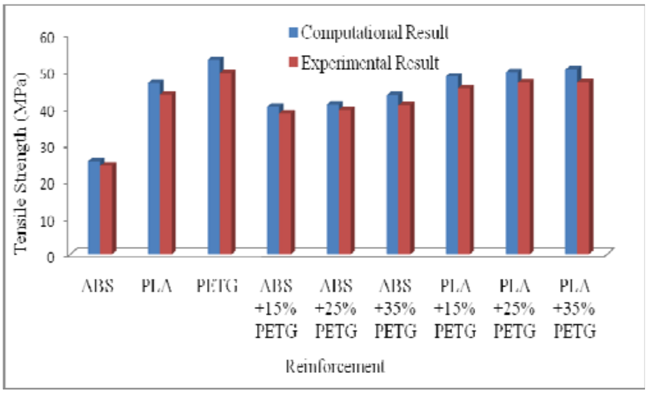


Fig. 16: Comparison of experimental and computational results

5. Conclusions from Present Work

In this study, effect of PETG (material) reinforcement on tensile strength of ABS and PLA materials were experimentally investigated. Computational analysis was also carried out in this investigation. The main conclusions of these studies are as below.

- It was depicted through surface morphology that components fabricated along the flat orientation have less defects as compared to edge orientation.
- Unidirectional reinforcement of PETG material have improved the tensile strength of ABS material by about 70% and strength of PLA material was improved by about 8%.
- From Fig. 16 it can be concluded that computational results were close approximation to the experimental results.
- However, computational results were slightly more as compared to experimental results which may be due to the presence of void and air gap between the layers of fabricated samples.

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