

STRENGTH CHARACTERIZATION OF DISSIMILAR MATERIAL SAMPLES PRODUCED VIA FUSED FILAMENT FABRICATION

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ABSTRACT. Fused Filament Fabrication is a 3D Printing technology that uses molten thermoplastic material forced through a nozzle to manufacture parts additively. This technology can use many thermoplastic grades and can produce single or multi-material parts depending on printer configuration. However, when printing a component with multiple materials, their compatibility must be considered to ensure proper bonding. The main issue of using non-compatible or low compatible material is that material will not fuse, resulting in poor mechanical properties. This study aimed to investigate if the mechanical properties of standard polymers, Polylactic Acid and Polyethylene Terephthalate can be improved using reinforcing strings of engineering-grades polymers, Polyamide 645 and Polyamide with 20% short carbon fiber reinforcement. The reinforcements were designed as simple strings cores, enveloped by a standard polymer material. The investigation was planned using a Taguchi L8 matrix. The results showed that the mechanical properties and specimens' integrity made of standard polymers could be improved by adding reinforcing strings of engineering-grade polymers.

KEYWORDS: Fused Filament Fabrication, multi-material, composite, low compatibility, reinforcing sting, tensile strength

1. INTRODUCTION

Nowadays, 3D Printing techniques have become a common solution for the rapid manufacturing of many products, from concept prototypes to functional ones and from aesthetic models to fully functional replacement parts [1].

Fused Filament Fabrication-FFF is a 3D Printing technology which use thermoplastic materials in the shape of a filament to build parts additively based on three-dimensional data, known as mesh. This mesh is a simplified representation of external and internal surfaces of the reference 3D model. To manufacture the 3D data, the model must be transformed into manufacturing instructions (e.g., g-code) [2]. This process takes place in the machine's software which is known as the slicing tool. In order to satisfy the needed characteristics of the desired part, multiple parameters must be adjusted (e.g., extrusion temperature, layer height, line width, wall thickness, deposition speed) [3].

Multi-extrusion systems introduced new manufacturing possibilities, allowing the use of soluble supports or other materials with low compatibility with the main part. It also introduced the possibility of producing multi-color or multi-material components with the price of losing a certain quantity of material on a transition block (prime tower). Compared to the single extrusion, multi-material printing requires distinct meshes; one 3D data for each material is merged in the slicing tool and printed in the same additive way [4].

For the parts that require the use of multiple materials (e.g., Acrylonitrile Styrene Acrylate-ASA and Polycarbonate-PC), the process parametrization must be done for each material separately because of the different melting ranges and flow behavior.

Ribeilro et al. evaluated the interface mechanism of multi-material samples of similar materials, PLA-PLA, and dissimilar materials, PLA-TPU (Thermoplastic Polyurethane), for tensile strength. They concluded that a simple face-to-face interface is not sufficiently resistant, so an interlocking geometry is necessary [5].

Tamburrino et al. investigated the bond formation through tensile tests between TPU-PLA, PLA-CPE (co-polyester), and CPE-TPU pairs of polymers. They showed that the mechanical interlocking effect is influenced by material deposition order and the density of the intermediate interfaces [6].

Ahmed et al. evaluated the bending properties of FFF-made sandwich samples with a flexible core made of TPU 95A in a shell of Polyamide 12 reinforced with 15% glass fiber, demonstrating their ability to absorb energy [7].

This paper aims to evaluate the mechanical tensile properties of "hourglass" type composite specimens made of dissimilar thermoplastic materials using PLA and PET for the matrix and two PAs as materials for the reinforcing strings.

2. MATERIALS AND METHODS

Two materials with natural transparent color were considered for the composite specimen's matrix, a PLA from BASF and a PET from BasicFill. As for the reinforcements, the performance of two PAs was studied, a PA645 (a PA6.6 based material) from Taulman and a PACF20 (reinforced with 20% short carbon fibers) from NylaForce. A string shape was considered for the reinforcement body and placed in the length of the specimens (1BA of ISO 527:2), parallel with the load direction. Thus, they cover the specimen's entire length and not just the gauge length.

As the design of the experiment method, a Taguchi L8 setup was considered with seven factors and two levels of variation. All parameters information (Table 1) and the results were processed using the Minitab 19 statistic tool. This experimental setup was used to determine which factors have the greatest influence over the tensile properties of the composite specimens.

The first two factors show the matrix and reinforcement materials that were presented above. The next four describe the reinforcement width and height, followed by their distribution across x and z-directions. The last considered parameter is Merged meshes overlap, an experimental process factor available in Cura 4.11.0 slicing tool. This parameter adjusts the overlap between multiple meshes of the same body to enhance the bond between walls.

Table 1

Taguchi L8 considered parameters

Factors	Parameters/Level	L1	L2
A	Matrix material	PLA	PET
B	Reinforcement material	PA645	PACF20
C	Reinforcement width (mm)	0.8	1.6
D	Reinforcement height (mm)	0.2	0.4
E	No. of reinforcement x	1	3
F	No. of r reinforcement z	1	3
G	Meshes overlap (mm)	0	0.15

All specimens' geometries for the matrix and reinforcements were designed according to the experimental setup provided by Minitab. To ease the design process of the specimens' bodies, Boolean operations were used. First, the specimen's body was considered as a blank and the reinforcement as subtractors. Then, their sum was used to generate the matrix bodies and the reinforcements as an independent body. Finally, all 3D data was exported as a mesh in STL (Standard Tessellation Language) format. The resulted geometries of the composite specimens are presented in Figure 1.

Table 2

Constant parameters of the experimental setup

Matrix		Reinforcement	
Layer thickness[mm]		0.2	
Extrusion width [mm]		0.4	
No. of walls	5	*Rf. z dist. [mm]*	*0.2*
Top/bottom layers	5	*Rf. x dist. [mm]*	*0.8*
Speed [mm/s]	40	Speed [mm/s]	20
Extr. temp. [°C]	210/**235**	Extr. Temp. [°C]	250/**260**
Max. fan spd. [%]	100/**80**	Max. fan spd. [%]	5
Bed temp. [°C]		60/**90**	
Abbreviations: - extr. – extrusion; - spd. – speed;		- temp. – temperature; - rf. – reinforcement.	
Values in Bold are associated with PET/PA material. *References in Italic are CAD parameters.*			

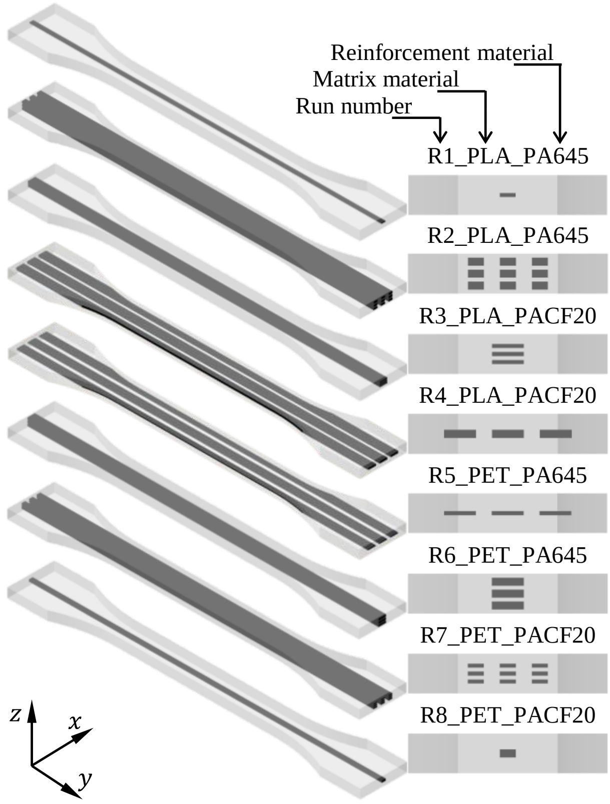


Figure 1. CAD set up of the specimens 1BA

The printing files were generated using Cura 4.11.0 and produced using an Ultimaker S3. For each setup, five samples were processed using the setup presented in Tables 1 and 2. As a benchmark, two sets of five specimens were printed using only the matrix materials. Each set of specimens was printed separately.

All specimens were tested for tensile strength using an Instron 4411 universal testing machine in an environment having 24°C and 60% moisture level at 1mm/min speed for PLA, respectively 5mm/s for PET. The resulted average tensile strength was used as a response for the Taguchi design table in Minitab 19.

3. RESULTS

The first group of specimens was made using PLA material for the matrix and the two PAs for the reinforcing strings. The aspect of the resulted probes can be seen in Figure 2. For R1 and R2 probes that used the PA645 material as a reinforcement, a "wavy" path of the extrusion lines can be observed. The defect is known as inconsistent extrusion. The assumption is that because PLA and PA are incompatible materials, the PA did not stick on the PLA layers, and for this reason, string lines did not fuse properly. The defect occurred on all specimens from the R2 group. For the R1 group, this aspect could not be appreciated due to the low visibility of the string.

This adhesion issue was considered from the process parametrization stage. For this reason, the deposition speed of the reinforcement was set at 20 mm/s (see Table 2), which is half of the deposition speed of the matrix. Using a higher speed for the reinforcement could lead to print failure. For the second half of the PLA specimens, reinforced with PA with a 20 % short carbon fiber, the extrusion consistency was much better than PA645. This fact confirms that adding carbon fibers in a PA matrix offers more stability to the printing process.

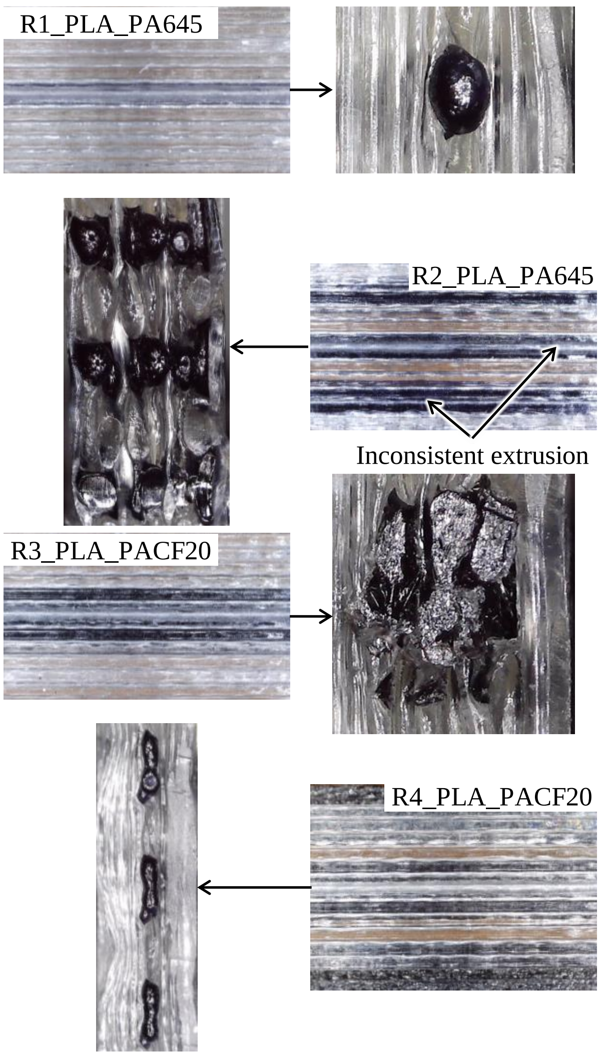


Figure 2. Bond formation in PLA matrix for the composite specimens

The second group of samples was made using PET for the matrix, and their print quality can be observed in Figure 3. Compared with the PLA matrix, PET and PA645 seem to have better compatibility. The adhesion between the two materials was better, and no inconsistent extrusion was observed. As for the PACF20, the same consistency offered by the carbon fiber content was maintained, like in the case of PLA matrix samples.

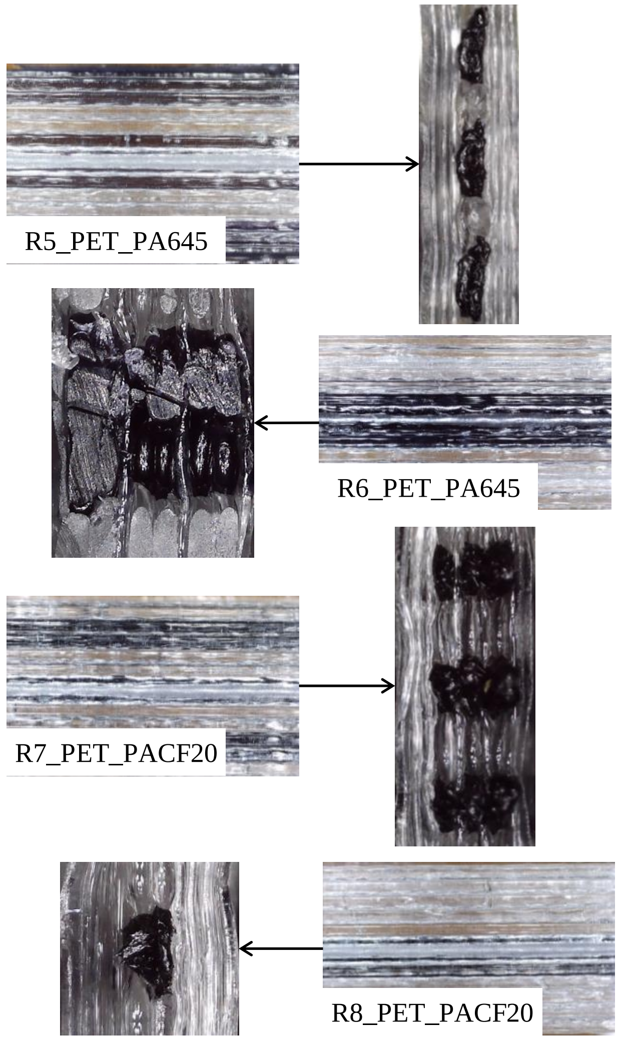


Figure 3. Bond formation in PET matrix for the composite specimens

All specimens presented similar failure behavior among each group. A higher tensile strength characterizes PLA matrix samples compared with PET-based specimens (Figure 4), but with a considerably smaller elongation at peak than the PET-based group of samples (Figure 5).

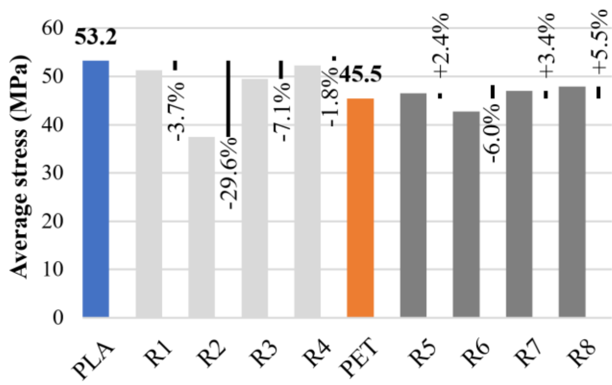


Figure 4. Average tensile strength of the experimental run specimens compared to the benchmark samples

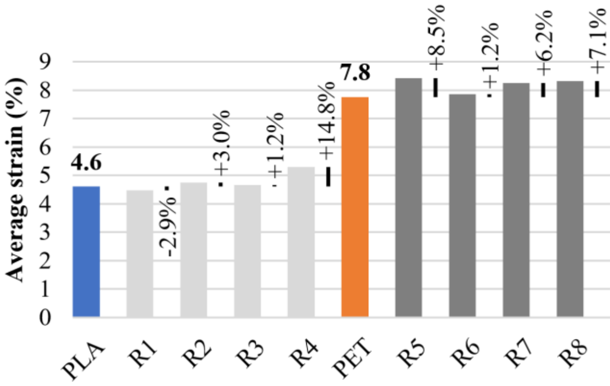


Figure 5. Average strain at the peak of the experimental run specimens compared to the benchmark probes

Furthermore, adding reinforcing strings is also helping in maintaining the structure of the specimen by holding the broken parts together. Overall, the best result for PLA matrix specimens obtained in R4 configuration reinforced with PACF20 strings resulted in a decrease of 1.8% in tensile strength but with an increase of 14.8% in strain (Figures 4 and 5). A sample of the breaking behavior can be observed in Figure 6.

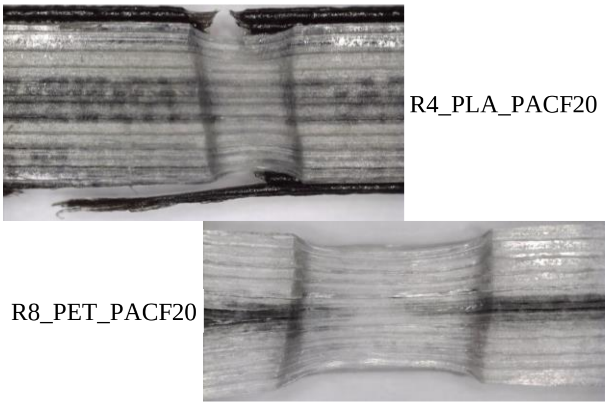


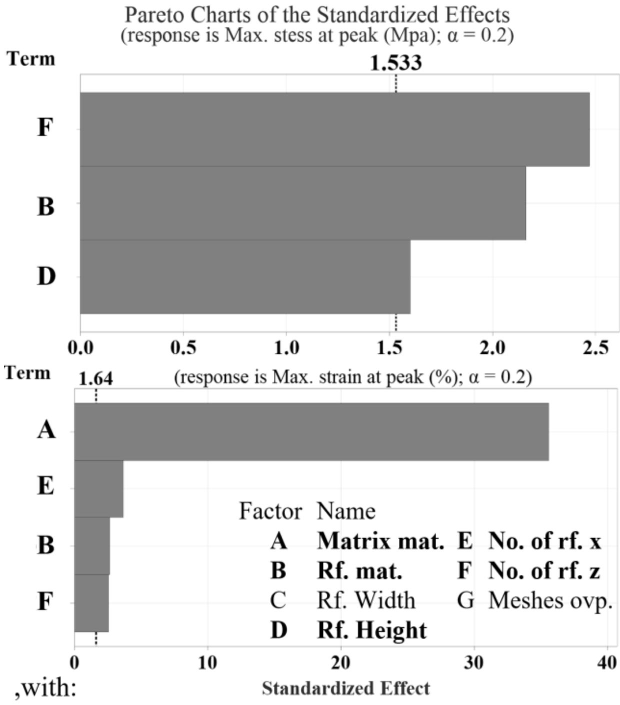
Figure 6. The failure mode of the R4 and R8 specimen's configuration

In the case of pure PET specimens (with 45.5 MPa tensile strength at 7.8% strain), adding a string of PA improves the mechanical properties. In this group of samples, only in the case of R6, a decrease in tensile strength was observed.

The best results were obtained for the R8 configuration. By adding a single string with 0.4 mm height and 0.8 mm width of PACF20, the tensile strength increased by 5.5 % and the strain by 7.1% (Figures 4 and 5). The failure behavior of the R8 group of samples is presented in Figure 6.

After determining the average tensile strength for each group of specimens, the results were used as a response for the Minitab 19 statistic tool.

The regression analysis made with the forward selection method (to consider only the significant variables), with a risk factor of 0.2, showed that the variable with the most significant influence for the tensile strength is the number of strings across z-direction, followed by the reinforcement material and string height (see Pareto chart in Figure 7). In terms of strain, the most significant factor is the material matrix followed by the number of reinforcements in the horizontal plane, their material, and the number of reinforcements across z.



,with:

+mat.-material; **+rf.**-reinforcement; **+ovp.**-overlap.

Figure 7. The Pareto chart of the main effects over the average tensile strength

4. CONCLUSIONS

FFF multi-material Additive Manufacturing offers many possibilities regarding producing hybrid and composite components. However, producing components only from engineering-grade polymers can be expensive and not always justifiable for the different applications of the parts.

The influence of adding reinforcing strings was considered with multiple cross-sections and different distribution in the base material body, alternating their position in a matrix of 3x3. Overall, the results show that the mechanical properties of standard polymers can be improved by adding a simple string of carbon fiber reinforced PA. Furthermore, adding this reinforcing is also helping in maintaining the integrity of components.

Combining standards with engineering-grade thermoplastic polymers can be a viable solution in designing and producing components with the desired mechanical properties at accessible prices. Furthermore, with this approach, it is possible to increase the mechanical properties of standard materials by using a small amount of engineering-grade thermoplastics in the most stressed regions.

5. ACKNOWLEDGEMENTS

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