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Tensile behavior of functionally graded sandwich PLA-ABS produced via fused filament fabrication process

Umut Caliskan[1,a], Caglar Sevim[2,b] and Munise Didem Demirbas[3,c*]

[1]Department of Mechanical Engineering, Erciyes University, Kayseri 38039, Turkey

[2]Department of Mechanical Engineering, Nigde Omer Halisdemir University, Nigde 51240, Turkey

[3]Department of Mechanical Engineering, Erciyes University, Kayseri 38039, Turkey

[a]ucaliskan@erciyes.edu.tr, [b]caglar.sevim@ohu.edu.tr, [c]mddemirbas@erciyes.edu.tr

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Abstract. The study investigated the tensile behavior of Sandwich Functionally Graded Material (SFGM) fabricated using Additive Manufacturing (AM) technology. SFGMs are characterized by a gradual variation in composition and structure with respect to the forming volume from the lower and upper surfaces of the structure towards the center, resulting in a corresponding change in material properties. Fused Filament Fabrication (FFF), a widely used AM process, was used in the present work to fabricate the thermoplastic polymer-based SFGM specimens. SFGM were produced by the FFF method using ABS and PLA materials and subjected to tensile tests according to ASTM D638.

Introduction

Since the history of humanity, science and technology have been making progress in an ever-increasing manner. The tools and equipment that humanity wants to acquire in line with the needs of humanity with the instinct of self-realization have been the main factors in the development of science and technology. In the development of mechanical properties in industry; Factors such as lightness, strength, production method, raw material supply, temperature effect and cost make the need for new materials and designs permanent.

In the last two decades, many studies have been conducted on the determination of the mechanical behavior of functionally graded materials (FGMs). However, the use of FGMs in the industry has been limited due to the difficulties encountered in production [1,2]. The production, which is generally made by adding materials layer by layer with a 3D model, is called the AM technique or the AM in technical literature [3-5]. With the developing production methods, the necessity of obtaining better material properties has arisen and multi-material Additive Manufacturing (MMAM) technologies have gained importance for materials that need to be printed by combining more than one material in a single process, such as composites and FGMs[2,6,7]. Among these multi-material Additive Manufacturing technologies, techniques such as Fused Deposition Modelling (FDM), Fused Filament Fabrication (FFF), and Vat photopolymerization (VP) have gained importance. With the spread of these technology, the difficulties experienced in the production of this FGM have disappeared and these materials with certain variations in the volume/surface of the components have been started to be produced. Thus, studies investigating the mechanical behavior of FG materials have entered the literature and continue to do so.

First of all, studies on polymers planned to be produced using the AM technique in FG structure will be reviewed. Afterward, the studies that have been made and what will be done in the case of producing these polymers as FG will be emphasized. Kumar and Narayan [8] produced PLA, a biodegradable material, by the AM technique according to ASTM D638 Type I standards and investigated its behavior under tensile load. They stated that the properties of PLA material produced with the AM technique show similar properties to those produced traditionally, and they confirmed the data they obtained with FEM.

In this study, a tensile test was applied to FG-Sandwich structure samples produced by the FFF technique, and the gradation effect on mechanical strength was investigated. The basic parameters affecting the layer structures determined to create the sandwich structure; layer thickness, volume ratio and total thickness were investigated.

Experimental Study

PLA filament, made entirely from PLA granules by Filameon company [9] and ABS filament, containing 100% ABS granules, used in this study. The filaments were in the form of a continuous wire and fed from reels into a 3D printer that had a 300mm x 300mm heated printing area and linear sliding ball bearings in each movement axis. The printer had two input and one output printing nozzles that allowed for printing with different materials and adjusting mixing ratios using G-CODEs. Figure 1 shows the printing principle of the 3D printer with two inputs and one output. The printer had linear plain bearings and ball carriages in the X, Y, and Z axes, providing stable and accurate movements. The filament feeding was done directly with the feeder motor unit on the movable print head on the X-axis. Each test sample was printed individually and under identical conditions. Table 1 provides details on the printing parameters used for each test sample.

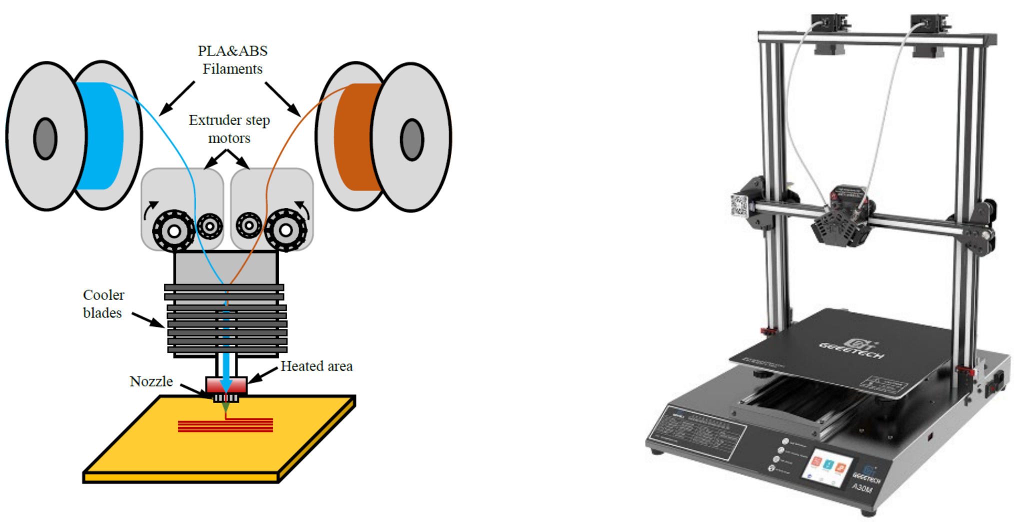

Figure 1. The design of the 3D printer used in this study.

Since the printing conditions of PLA and ABS are partially different from each other, the printing conditions must be adjusted according to the material structure when printing the composite structure. This situation is neglected by many researchers in the literature. For the best printing properties, as the ABS ratio in the composite structure increased, the printing nozzle temperature and the table temperature were increased gradually, and the cooling fan was turned off when the ABS ratio exceeded 20%. The designed test samples were converted to .stl format via the CAD program and their GCODEs were created with the Ultimaker CURA V4.10.0 slicing program [10]. Mixing ratios and temperature adjustments are adjusted by editing GCODEs by us.

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Table 1. Printing parameters

Layer thickness	0.2 mm
Filler fiber thickness	0.4 mm
Wall thickness	0.4 mm
Print speed	30 mm/sn
Nozzle temperature	200-230 ^{0}C
Table temperature	60-100 ^{0}C

The properties of PLA and ABS materials produced under the conditions described above are detailed in Table 2. In this study, the tensile strengths of the samples produced by determining the functionally specific volume ratios were investigated.

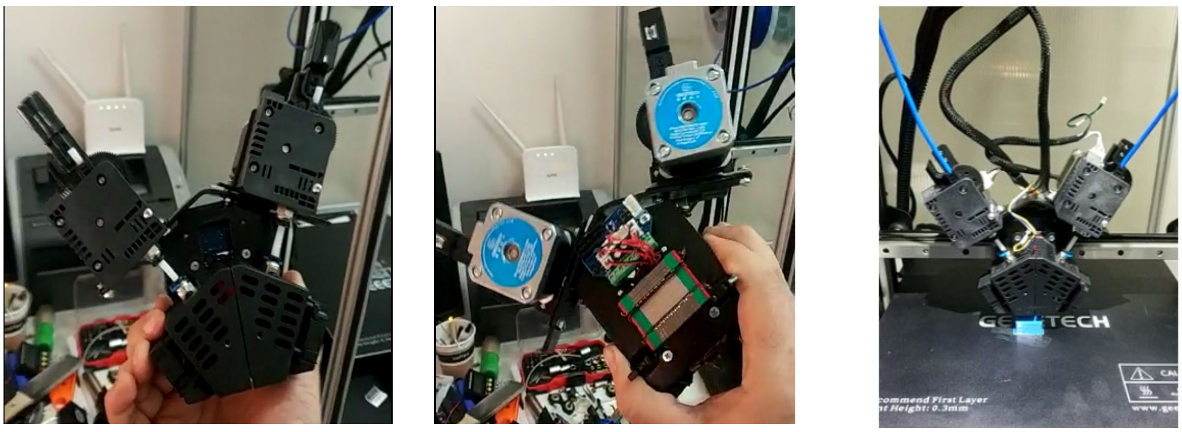

Figure 2. Designed double nozzle system

Table 2. Thermal and mechanical properties of ABS and PLA [11]

Properties	PLA	ABS
Filament diameter (mm)	1.75	1.75
Density (gr/cm^3)	1.24	1.04
Bed temperature (°C)	60	80-100
Nozzle temperature (°C)	190-230	230-260
Melt Flow Index (210°C/2.16kg)	6	80-120
Tensile strength (MPa)	53	45
Elongation (%)	6	10
Bending strength (MPa)	83	73
Rackwell hardness	108	108
Max service temperature (°C)	55	85

The variation of the compositional gradient exponent was considered linear in the grading of ABS and PLA materials. Functionally Graded samples for the 11 layers given in Figure 3 were produced in all ratios. However, delamination occurred in compositions with less than 70% PLA (ie more than 30% ABS) (Figure 4). Therefore, in the sample production made according to the ASTM D638 standard, the volume ratios in the Sandwich FG production were made as given in Figure 5.

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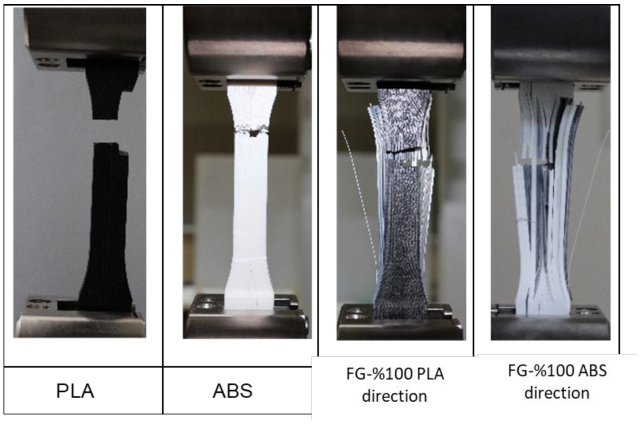
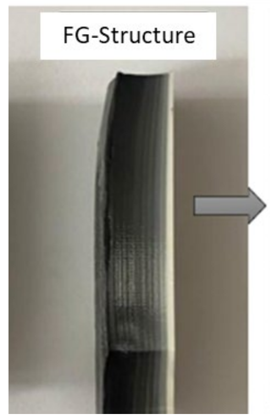




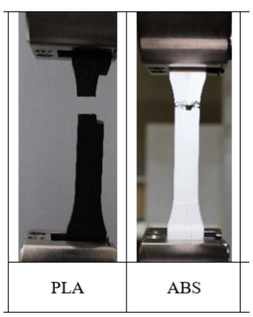
Mixing Ratio

Layer	PLA	ABS
1	%100	%0
2	%90	%10
3	%80	%20
4	%70	%30
5	%60	%40
6	%50	%50
7	%40	%60
8	%30	%70
9	%20	%80
10	%10	%90
11	%0	%100

Figure 3. Functionally Graded samples and mixing ratios

Considering the ASTM D638 standard, all dimensions change with changing thicknesses. Due to the fact that the produced materials are not isotropic, different parameters were planned and productions were made. In Figure 3, layer thicknesses were given as 0.8, 1.3, 1.6 and 2.6 mm according to the planned functional change. These thicknesses represent two different types of ASTM standards. In this respect, samples were produced both for samples of the same type and for different types of thicknesses and subjected to tensile testing.

Layer	PLA	ABS
1. Layer	100%	0%
2. Layer	90%	10%
3. Layer	80%	20%
4. Layer	70%	30%
5. Layer	70%	30%
6. Layer	80%	20%
7. Layer	90%	10%
8. Layer	100%	0%



Layer and Sample Thickness of 8-Layer Sandwich Structures Produced by 3D Printer

Layer	Thickness
0,8 mm	6,4 mm
1,3 mm	10,4 mm
1,6 mm	12,8 mm
2,6 mm	20,8 mm

Figure 4. FG-Sandwich structures samples, which were subjected to tensile tests according to ASTM D638 standard.

In order to determine the sizing in Figure 4, the 11-layer FG structure was fabricated and tensile tested as shown in Figure 3. According to this test, delamination was observed in the FG structure. Therefore, this situation is prevented by reducing the number of stratified layers. As seen in the after-tensile test shape, Reducing the ABS layers prevented the splitting considerably.

Samples of four different layer thicknesses were produced for the FG structure for sandwich type. These layer thicknesses are 0.8, 1.3, 1.6, and 2.6 mm. The number of layers without delamination is 4 and for the sandwich structure is 8 accordingly, total sample thicknesses were produced as 0.8x8=6.4 mm (Type I), 1.6x8=12.8 mm (Type III), 1.3x8= 10.4 mm (Type III), 2.6x8=20.8 mm (Type III). For these thicknesses, production was made on the basis of Type 1 and III dimensions according to the ASTM D638 standard given in Figure 5. While choosing the layer thicknesses, both the limitations in production and the standards were taken into account in order to compare the samples. Figure 5 shows the FG sandwich samples which are manufactured FFF method in different dimensions. The color change refers to the functionally changing material distribution. Specimen descriptions indicate filament thickness, layer thickness, total thickness, ASTM standard, and overall length.

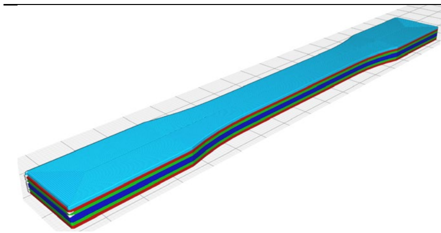
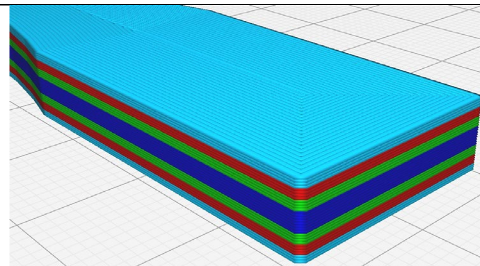
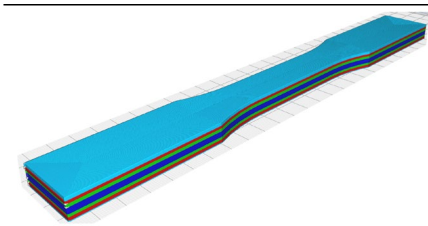
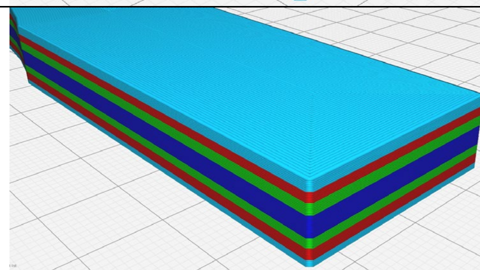
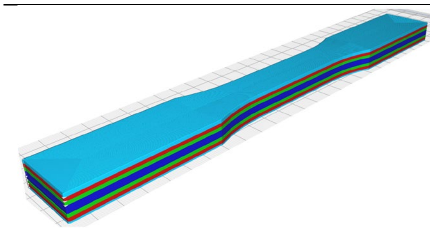
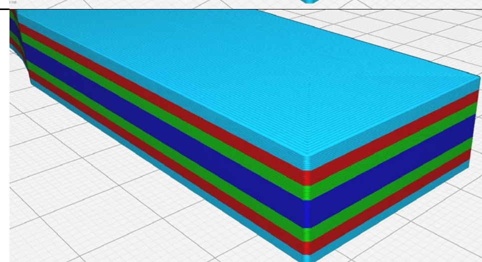
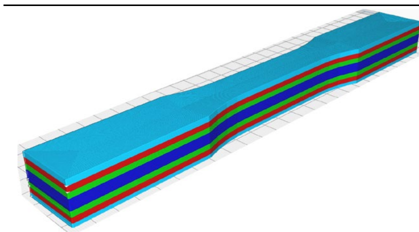
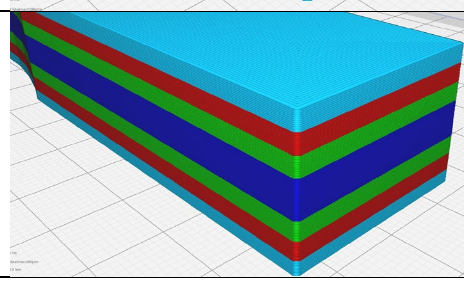
		**Filament Thickness: 0.2 mm** **Layer Thickness: 0.8 mm** **Total Thickness: 6.4 mm** **ASTMD638-Type –I** **Total Length: 165 mm**
		**Filament Thickness: 0.2 mm** **Layer Thickness: 1.3 mm** **Total Thickness: 10.4 mm** **ASTMD638-Type – II** **Total Length: 246 mm**
		**Filament Thickness: 0.2 mm** **Layer Thickness: 1.6 mm** **Total Thickness: 12.8 mm** **ASTMD638-Type – II** **Total Length: 246 mm**
		**Filament Thickness: 0.2 mm** **Layer Thickness: 2.6 mm** **Total Thickness: 20.8 mm** **ASTMD638-Type – II** **Total Length: 246 mm**

Figure 5. FG Sandwich structure types

Results & Conclusion

The present study investigate the tensile test behavior of FG-Sandwich structure samples produced by the FFF technique, and the gradation effect on mechanical strength. The basic parameters affecting the tensile test results such as layer thickness, volume ratio and total thickness were also investigated. As it started with planned production with additive manufacturing, there were many unknown parameters. One of them was the printing speed in the FFF method. First, pure PLA material and FG sandwich structure were produced at different printing speeds and subjected to tensile testing. Figure 6 shows the effect of the printing speed for PLA and FG sandwich structure for 30 and 40 mm/s. In pure PLA material, the slower-produced material resulted in slightly greater elongation, and the strength levels remained similar. In the material produced as sandwich, while the fast produced material revealed higher force, it created more elongation.

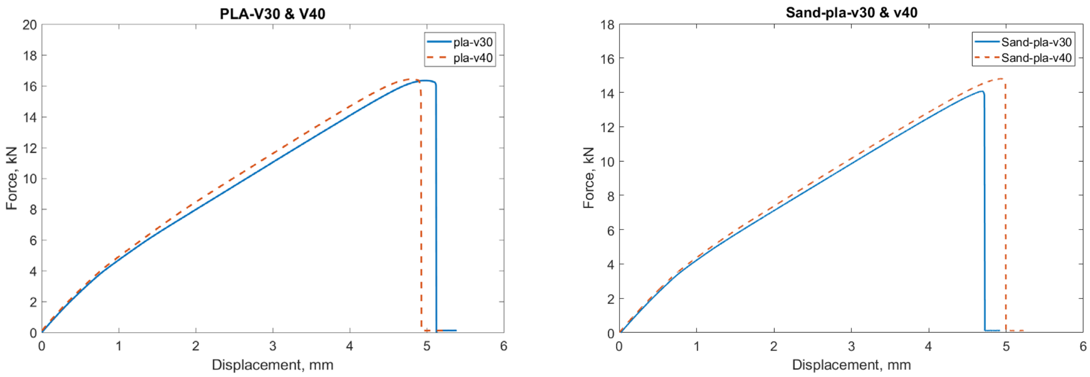


Figure 6. The effect of the printing speed for PLA and FG Sandwich materials.

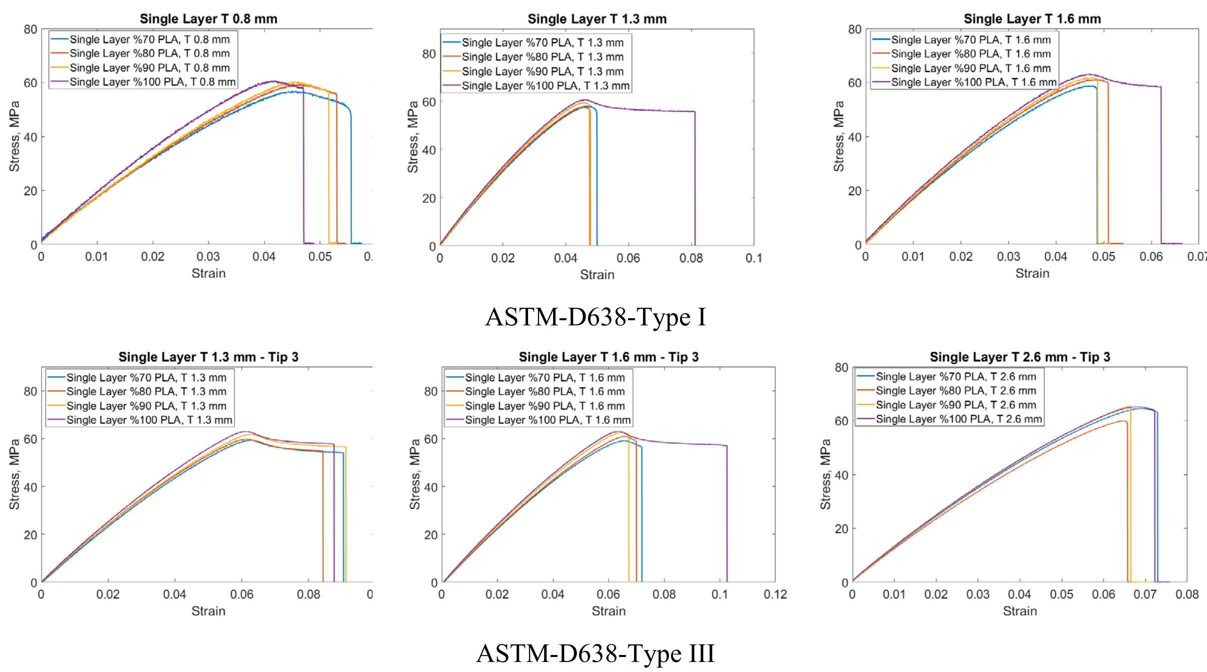
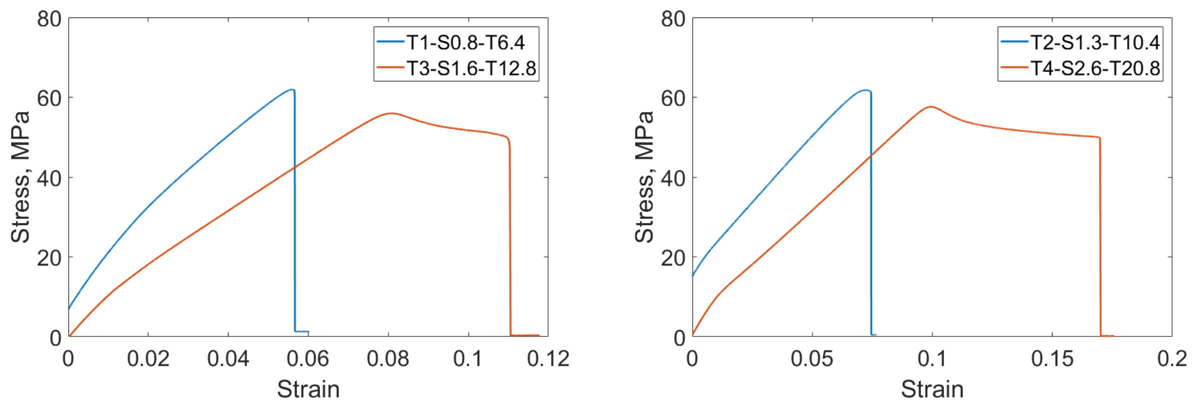


Figure 7. The effect of the changing functional gradient for single-layer specimens

In Figure 7, tensile test results of single-layer samples with different functional gradients produced according to ASTM D638 Types I and III are given. Single-layer samples have thicknesses of 0.8, 1.3, 1.6 and 2.6 mm. The functional gradient ratios are 70% PLA-30% ABS, 80% PLA-20% ABS, 90% PLA-10% ABS and 100% PLA-0% ABS. While the thicknesses of the sample produced for Type I are 0.8, 1.3 and 1.6 mm, the lengths are 165 mm. In the sample produced for Type III, the thickness is 1.3, 1.6 and 2.6 mm, while the length is 246 mm. Compared to Type I, strain increased at similar stress levels with ABS reinforcement in the 0.8 mm thick sample. In the 1.3 mm thick sample, the strain decreased with ABS additive. Similar results were obtained in the 1.6 mm thick sample. There was no significant change in the results with ABS reinforcement in the 1.3 mm thick sample compared to Type III. However, for the 1.6 mm thick sample, the strain value decreased from 0.1 to 0.07 with ABS reinforcement. Figure 8 shows the stress-strain behavior of FG sandwich structures as a result of the tensile test according to two different ASTM standards. The first comparison shows the thickness variation for Type I and Type III. The first sample Type I- had a layer thickness of 0.8 mm and an overall thickness of 6.4 mm.

The other sample, Type-III, has a layer thickness of 1.6 mm and a total thickness of 12.8 mm. When the layer and total thickness were doubled, there was no significant decrease in the stress level, while the strain value almost doubled. This result shows that the material behavior is not isotropic. And it shows that the standard gives different results in this respect. In the other comparison, it gives the tensile test result of samples of the same size (Type III). While the layer thickness of the first sample is 1.3 mm and the total thickness is 10.4 mm, the layer thickness of the other sample is 2.6 mm and the total thickness is 20.8 mm. When the layer thickness was doubled, the strain value also doubled and increased from 0.06 to 0.17. Stress levels are around 60 MPa. This result showed that the tensile behavior standard of sample ASTM D638 rigid plastics differ in terms of the results of plastics produced by additive manufacturing.



ASTM-D638-Type I & III ASTM-D638-Type III

Figure 8. The effect of ASTM standard types for FG Sandwich structure.

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