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The influences of international standards on structural performance and fracture behaviour of 3D printed long fiber composite structures

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Abstract. The material properties of the additive manufactured composite structures are usually done following international standards, that show some difference dimensionally. This study focuses on the impact-induced on the tensile properties of the 3D printed continuous carbon fiber reinforced composite part due to the standards applied for sample preparation. The specimens were fabricated by Markforged® Mark two 3D printing machine using carbon fiber as reinforcement and Onyx® as matrix material based on ASTM D638 and ASTM D3039-D3039M standards. The experimental results revealed that the specimens fabricated based on ASTM D638 showed a premature failure at the location where the straight gauge section of the specimen ends, and the curved transition regions begin due to stress concentration. The tests based on ASTM D3039-3039M standard showed better tensile strength and less stress concentration compared to ASTM D638. Fracture test with SEM reveals fiber breakage, debonding, and fiber pullout, which created cavities and voids between layers as the reasons for the tensile failure.

1. Introduction

Current developments in additive manufacturing (AM) have made popular manufacturing methods for, their low material waste, ease of manufacture, advantage of design freedom, and environmental friendliness. ASTM F2792−12a defines additive manufacturing as material joining to make an object from 3D model data, commonly layer upon layer, as opposed to the conventional machining method. [1,2]. According to ISO 17296-2 standard AM is grouped into seven based on the faction of machine parts as; material jetting, vat photopolymerization, powder bed fusion, binder jetting, Material extrusion, Directed energy deposition, and Sheet lamination. Additionally, the AM technique can be categorized based on the types of materials used and the deposition technique [3].

Additively manufactured parts have weaker when the load is applied at an angle to filament orientation than when applying load along its orientation, resulting, in AM parts being mostly used as a prototype than functional parts [4]. In the aircraft industry, the application of additive-manufactured parts especially composite parts is increasing because of low maintenance costs, weight, and better reliability of the parts printed from additive-manufactured composite [5]. The development of using composite fibers in the production of additive manufactured parts increases the functionality of the parts due to the improvement of the parts' properties [6]. Therefore, to have high-performance additive manufactured polymer products with high strength, reinforcing with high-performance reinforcement composite polymers is important [7]. Reinforcement of 3D-printed polymers can be done Using both long and segmented fiber reinforcement. Short fiber-reinforced additively produced parts have poor mechanical properties compared to continuous reinforced parts. The development of long fiber reinforcement 3D printed composites like Markforged Mark Two changed 3D printed composite parts into commercial products [8].

Though the start of AM technology lasted several decades, there is still a lack of understanding of the fundamental character of parts produced by AM technology. The study done to improve the mechanical properties of 3D printed composite parts is progressing as the core of research in 3D printing field. In tensile testing of AM composite parts, the cause of fiber fracture that occurs is induced by stress concentration due to the geometry of the specimen. Fiber fracture that occurs at an angle is coordinated fracture and propagates the matrix cracks from the fiber break points. The stress concentration causes the failure of many fibers at similar locations [9]. Another study done by Garrell M G et al. on stress concentration in tensile specimens produced based on ASTM D638 standard using finite element analysis concluded that the specimen failed at the end of the gauge area and where the curved regions begin, this is because the geometry difference which induces high stress at the location [10].

The properties like strength and structural efficiency of 3D printed composite parts are highly influenced by crystal structures, such as void content, geometry of the fiber, and harmony of both fiber and matrix ally. Based on the technique of digital imaged correlation, it is shown that crack tip strain has resulted ahead of the inter-layer fracture, reinforcement failure at different levels, and adherence to a short fiber connection. Different studies have been conducted to understand the properties of fiber-reinforced polymer parts. The failure behavior of 3D-manufactured long fiber reinforced polymer parts and stress concentration due to the geometry of the specimen has not been well understood either experimentally or numerically. Understanding the failure mechanism of 3D printed composite parts in designing and production of the parts [11].

The tensile properties of plastics and polymer matrix composite materials can be determined by ASTM D638-14 and ASTM D3039-3039M [12]. Whereas for characterization of tensile properties of conventional produced plastic parts that showed isotropic ASTM D638-14 was used. In contrast, 3D-printed reinforced plastic parts have shown anisotropic properties or transverse isotropic properties. Because of the anisotropic nature of the 3D material and tensile test specimen geometry, crack initiation at fillets results in premature failure. So, it is important to choose a different standard to reduce stress concentration [13]. ASTM D 3039/D 3039M is the standard method used with continuous or short fiber, to determine in-plane tensile properties of polymer matrix composite materials reinforced by high-modulus fiber. The standard method used straight tab and has less stress concentration compared to ASTM D638-14 standard [14].

The Markforged Mark Two 3D printing machine uses a dual nozzle system. The machine can print different materials like carbon fiber, Kevlar, glass fiber as reinforcement, and onyx and nylon as matrix material. Markforged Mark two 3D printing works in a similar way as material extrusion technology, where melted filament is extruded through a nozzle onto the 3D printer platform, by adding multiple layers to form the component [8]. However, since the machine is a newly developed technology (Markforged Inc., USA), its products are not well studied [13].

The composites' nature and process variation make 3D-printed composite parts not easy to predict mechanical and microstructural properties, because of the composite nature and process variation. In view of these factors, further study is needed to understand and predict the performance of continuous fiber-reinforced 3D-printed composite parts [15]. The aim of this work is to study the influence of international standards on the tensile properties of additively manufactured carbon-reinforced composite 3D printed parts.

2. Experimental methods

2.1. The material

Continuous carbon fiber and Onyx® materials supplied by PLM Group Norway AS were used as raw materials for the current study. Additively manufactured Carbon and Onyx as composite parts attain high strength

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and stiffness and they can be printed in different shapes [16,17]. Onyx is a combination of nylon-based thermoplastic and chopped carbon fiber made into filament. It was used as a matrix. The carbon as shown in Figure 1, is made from many micro-size continuous carbon filaments bundled together by sizing agent to form carbon filament as a reinforcement material [18]. The printing materials used in this work have a density of 1.4 gm/cm^3 and 1.2 gm/cm^3 of onyx and carbon respectively.

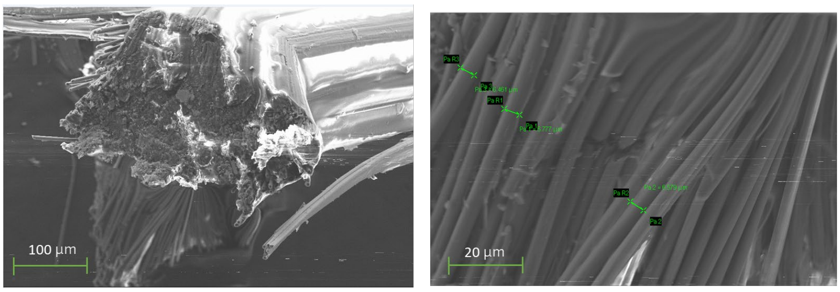

Figure 1. SEM image of carbon filament.

2.2. Model preparation and printing

The geometry of the sample was designed and converted to Stereolithography (STL) using Autodesk inventor 2023. The STL file is imported into the Markforged Eiger software for slicing, adjustment of printing parameters, material selection, etc. [19,20]. The test samples were manufactured by Mark Two desktop type 3D printing machine manufactured by Markforged. The machine has a printing volume of 0.584 m × 0.330 m × 0.355 m and has a pair of nozzles, through which fiber and material board on the printing platform. As shown in Table 1 the nozzle temperature for carbon is 252 $°C$ and that of Onyx is 277 $°C$. As Onyx filament passes through the nozzle during printing it melts, and the carbon fiber is heated to give adhesion to the matrix.

The printing parameters applied are shown in Table 1 for both matrix and fiber. Test specimens for tensile test were printed with orientations of 0° based on ASTM D638 and D3039-3039M standard method. For ease of reading, we refer ASTMD638-14 as S1 and ASMT D3039-3039M as S2, hereafter. Schematics that illustrate the geometry of the two standards are displayed in Figure 2. The geometry of the test sample manufactured based on S1 is rectangular while that of S2 is closer to the dog-bone type. The sample dimensions for both standard types are shown in Figure 2. To reduce experimental error, five test samples were fabricated using the same printing parameters for each standard as given in Table 1.

Table 1. Printing parameter used to create samples.

Parameters	Carbon fiber	Onyx
Orientation Angle	0°	±45°
Layer thickness (mm)	0.125	0.125
Number of layers	12	14
Infill density (%)	100	100
Roof and floor		4
Number of walls	2	
Fiber nozzle temp ($°C$)	252	
Plastic nozzle temp ($°C$)	277	

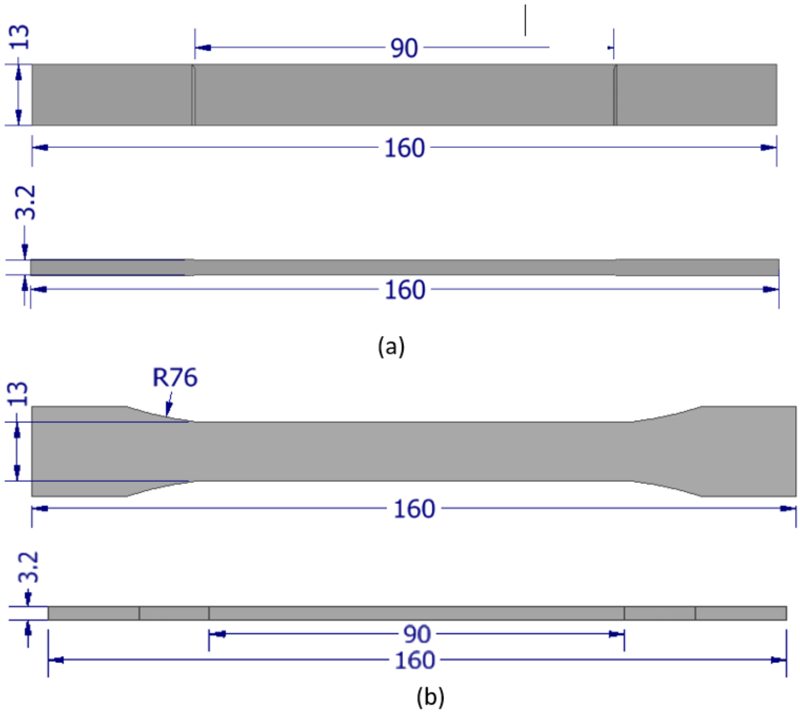

Figure 2. Tensile specimens manufactured by (a) S2 and (b) S1 standards.

Five samples were printed for each standard group (S1, S2) with the same amounts of carbon fiber onyx ratio, and stacking sequences as listed in Table 1. They were printed in unidirectional (0°) orientation of carbon fibers for both standard groups as displayed in Figure 3.

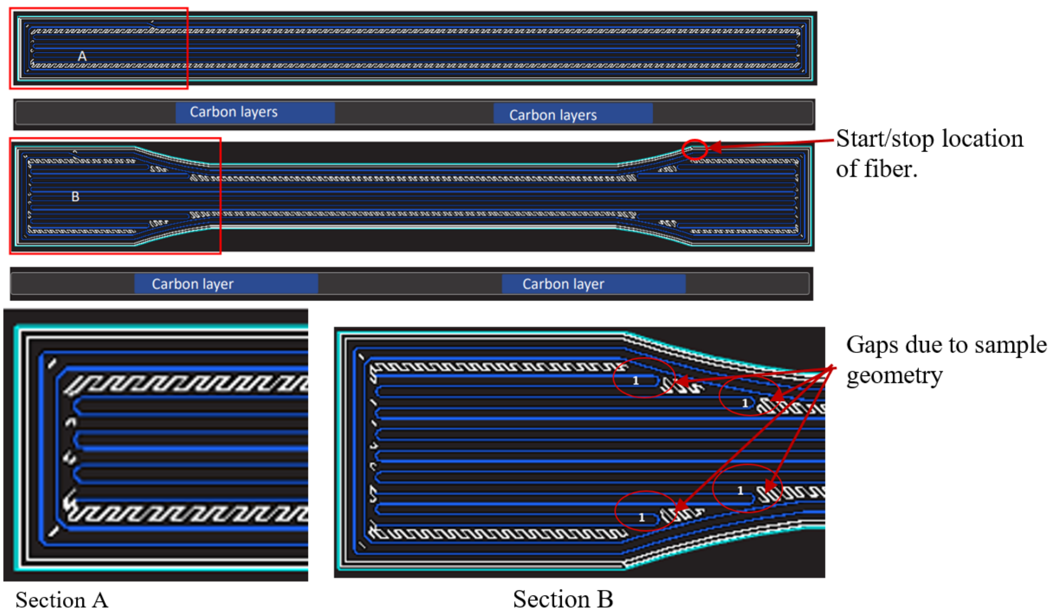

Figure 3. Fiber arrangement of S2 (A) and S1 (B) Specimen.

2.3Tensile test

Instron 5985 testing machine which has a load cell capacity of 250kN was used for tensile testing. Testing was done at room temperature and a strain rate of 1mm/min. The schematic drawing of the sample is seen in Figure 2.

2.4. Fracture properties

The fracture surface morphology of the tensile specimen was analyzed using scanning electron microscopy (SEM) (Gemini SUPRA 35VP ZEISS) equipped with EDAX energy dispersive X-ray spectroscopy (EDS).

3. Results and discussions

3.1. Tensile test

The effect of fiber stress concentration due to standard method selection on mechanical properties was studied under tensile load. Every test was done until the complete failure test sample. The tensile test results of the specimens were shown in Table 2 and the stain versus stress curve was also shown in Figure 5 (a) and (b).

Table 2. Tensile test result.

Standard type	Load (kN)	Strain (%)	Stress (MPa)	Modulus (MPa)
S1	10,51	4,79	245,51	6591,81
S1	10,61	4,26	247,96	7451,93
S1	11,8	4,76	275,75	7726,67
S1	10,17	4,12	237,61	7617,56
S1	11,24	4,55	262,67	7111,25
S1	11,5	4,7	268,75	7472,61
Average. *	*10,97*	*4,53*	*256,38*	*7328,64*
StDev. *	*0,64*	*0,28*	*14,89*	*416,66*
S2	12,06	5,58	281,7	8926,95
S2	12,04	5,87	281,22	8674,66
S2	13,93	4,52	325,49	8937,28
S2	12,2	4,82	285	9729,34
S2	13,09	5,22	305,78	9752,32
Average *	*12,66*	*5,20*	*295,84*	*9204,11*
StDev. *	*0,830*	*0,548*	*19,424*	*501,182*

The test results show brittle behavior as can be seen in Figure 5 (a) and (b). This shows that the specimens were influenced by the carbon fiber properties.

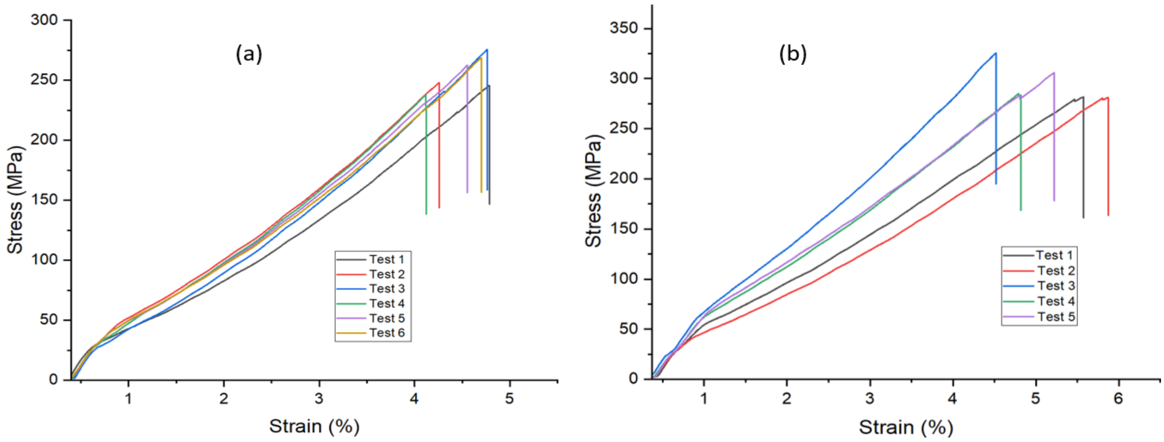

Figure 4. Tensile test stress vs. strain (a) S1 method, (b) S2 method

Both samples were printed with the same orientation, layer stacking, infill density, and percentage of carbon fiber filaments versus Onyx but with different standard methods as shown in Table 2. The samples tasted according to S2 Standard showed an average tensile strength of 295.84 MPa ±19 and elongation of 5.20 % ± 0.55, whereas the specimens produced according to S1 showed an average tensile strength of 256.38 MPa ± 14 and elongation of 4.28 % ± 0.28. The samples manufactured based on S2 standard have better strength and ductility compared to the samples produced based on the S1 standard. Using S1 standard for continuous reinforced composite 3D printed polymer has lower tensile strength and elongation values by 7.1% and 10.64% respectively, than that of S2. The S1 test result showed less deviation compared to S2.

S1 is a standard method used to arbitrate the tensile characteristics of plastic and composite parts that have isotropic properties. However, 3D-printed reinforced composite polymers have orthotropic/ transversely isotropic properties. Therefore, it is not easy to determine the properties of additively produced composite parts [13]. The result from the S1 standard shows lower strength, strain, and modulus of elasticity.

As shown in Figure 3 section B the fiber arrangement shows irregularity and gaps at the transition area from gauge to tab regions which were numbered 1 with a red circle, those gaps between adjacent layers increase the probability of failure because of high stress concentration. The start/end of filament shown at the start of the tab on the same part B also contributed to the premature failure of the samples manufactured based on S1 standard.

3.2. Fracture properties

Tensile tests after the failure of S1 and S2 were shown in Figure 4. In cases of the specimens fabricated based on S1, the failure occurred at the end of the gauge section. On the contrary sample from S2 standard fails in the gauge region of the samples as shown in Figure 4.

(a)

(b)

Figure 5. Fracture profile of materials failure during tensile test (a) S1, (b) S2

After tensile test of the sample, the structural analysis was done to characterize its failure property connected with damage to continuous fiber-reinforced 3D parts. It provides information that affects the strength as a result performance of 3D-printed composite parts. Cross-sectional images from SEM were displayed in Figure 6. to study tensile fracture parts at different resolutions. The fracture surface morphology Figure 6 (a & b) reveals matrix-dominated areas with voids and weak inter-bead adhesion as well as fiber debonding from matrix areas by poor bonding interfaces. In Figure 6 (c.) pulled-out carbon fibers can be seen which create voids in the matrix. While Figure 6 (d) shows inter-bead voids induced by a pattern of manufacturing. Figure 6 (e & f) also shows weak bonding between the onyx matrix and carbon fiber as well as pull out of carbon filament from the matrix. Figure (g) shows matrix-influenced areas, with vacant filament unglued from the matrix due to poor bonding interface, and dry fibers, with damaged carbon bundles and creates a cavity in the matrix parts [18].

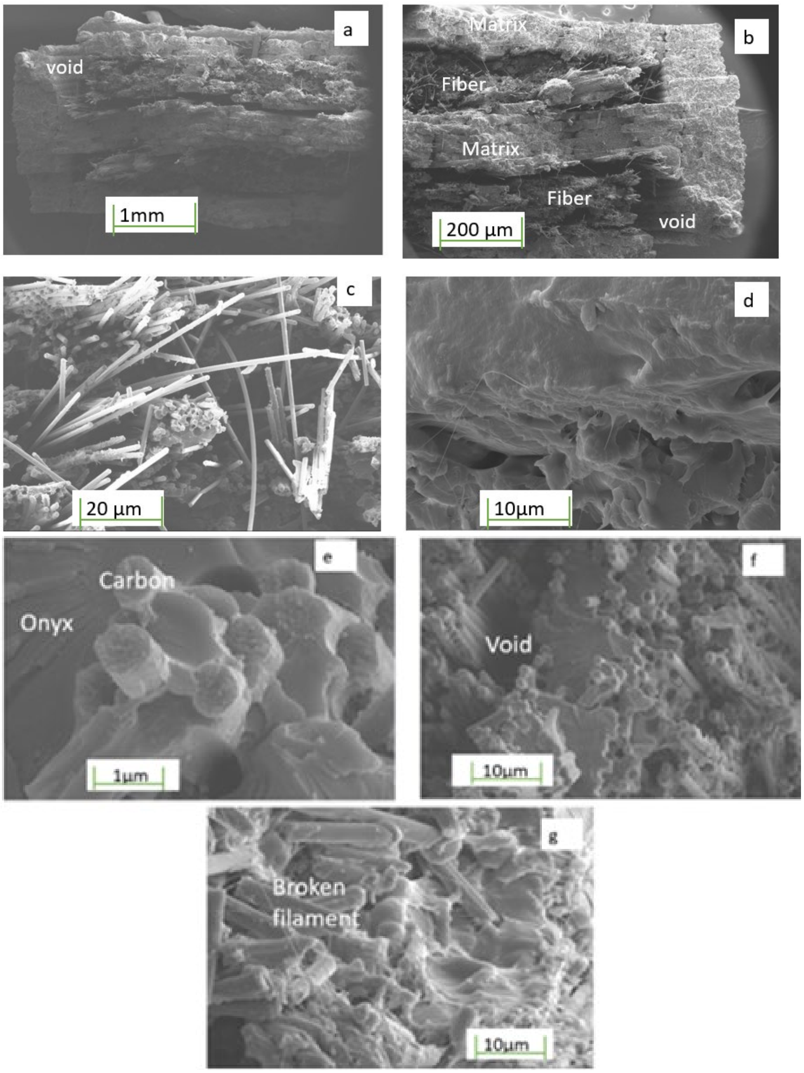

Figure 6. SEM images of the fracture surface

The engineering performance of additively manufactured long fiber reinforced polymer parts are influenced by printing defects such as inter-layer, inter-bead voids, and lack of fusion between matrix and reinforcement. As shown in Figure 3 section B the geometry of samples has a high contribution to the failure of 3D-produced parts.

In Figure 7, the energy in keV was shown on the conventional x-axis direction of the EDS, while the y-direction shows X-ray intensity. The "K" in the vertical axis implies that the values in the vertical axis are multiplied by 1000. The source of Au/Gold is from the coating of carbon to make it conductive. Therefore, it was not considered in specifying element compositions.

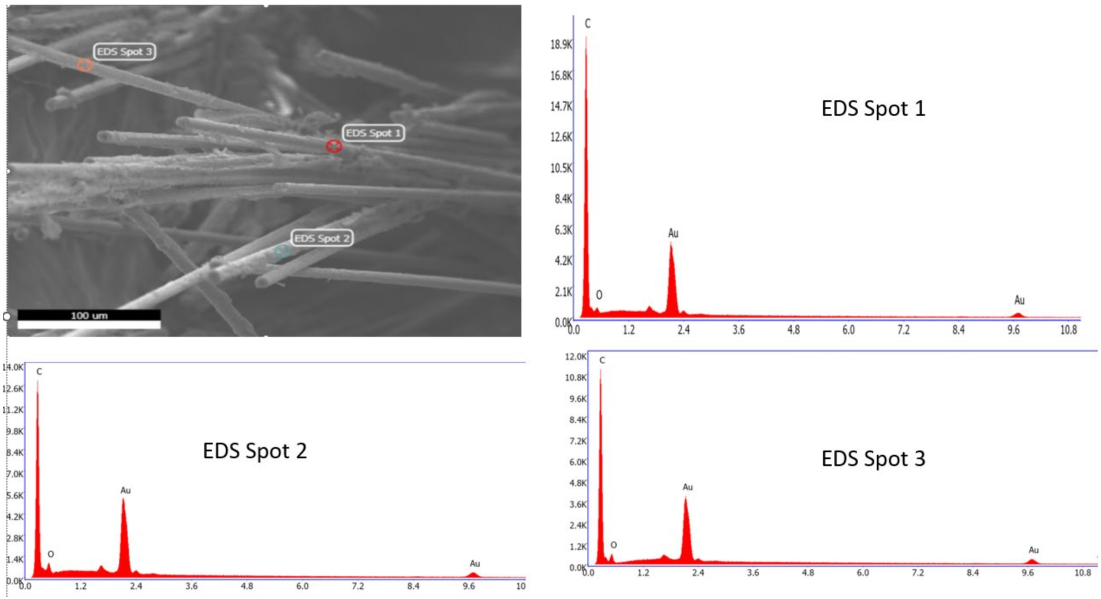

Figure 7. EDS elemental composition analysis of different carbon fiber filaments.

Table 3 shows the composition of carbon and oxygen molecules. The amount of carbon and oxygen in different filaments is different.

Table 3. The concentration of C and oxygen at different spots.

Spot	1	2	3
	Wt. %	Wt. %	Wt. %
C k	98.81	90.40	97.41
O k	1.19	9.60	2.59

4. Conclusion

In this work, the effect of international standards on tensile properties and the fracture morphology of long carbon fiber-reinforced polymer parts have been researched. The additively produced composite parts used carbon as reinforcement and Onyx as matrix materials.

In tensile testing of 3D printed parts, both ASTM D638 and ASTM D3039-3o39M were used as standards for producing and testing the parts. The test done based on the ASTM D638 standard shows lower results due to stress concentration induced by the specimen geometry. The fillet region of the specimens induces crack initiation that causes premature frailer.

The specimens produced based on the ASTM D3039-3039M standard have better tensile performance than the ASTM D638 standard. It has a straight tab and less stress concentration. Therefore, in tensile testing of 3D-printed composite parts, ASTM D3039-3039M has better performance.

A study of the failure characteristics of the printed composite part shows a lack of fusion of carbon fiber and onyx and individual fiber bundles together, so the synergetic effect of the carbon fiber bundle is lacking. It can be improved by using more printing temperature that enhances adhesion, denser composite, and minimizing voids.

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