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EFFECT OF FIBER-LAYER POSITIONS ON MECHANICAL PROPERTIES OF CARBON FIBER REINFORCED MATERIALS MANUFACTURED BY FUSED DEPOSITION MODELING

VPLIV LEGE PLASTI VLAKEN NA MEHANSKE LASTNOSTI Z OGLJIKOVIMI VLAKNI OJAČANIH MATERIALOV, IZDELANIH Z OBLIKOVNIM NANAŠANJEM MATERIALA Z ZLIVANJEM

Yakup Furkan Polat, Volkan Yılmaz*
Gazi University, Ankara 06500, Turkey

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In recent years, with the increasing needs from industry, various manufacturing methods have begun to be widely used. Additive manufacturing is one of these methods. These recent manufacturing methods, which allow the production of designed essential parts without any limitations, have also gained an advantageous position in industrial fields due to a variety of raw materials used. Additive manufacturing makes production possible using metal and polymer materials. In this research, continuous carbon fiber was used to strengthen the structure of a polymer material and printing was conducted with fused deposition modeling, which is one of the additive manufacturing methods. Tensile tests were performed on printed specimens and then the results were evaluated. Onyx was used as the polymer material and carbon fiber was used as the continuous fiber material. Comparisons were then made between the fiber specimens and onyx specimen that was printed without any fiber. It was found that the specimen made of onyx reached a tensile strength of 16 MPa, while by adding continuous carbon fiber reinforcement to the structure, a value of 58 MPa was obtained for the printed specimen. On the other hand, the highest tensile strength of 80.2 MPa was obtained by changing the layer location of the samples. This value is 38 % higher than the tensile strength of 58 MPa recorded for the sample that included also carbon fiber and was printed as a regular and symmetrical structure. In line with these results, it was observed that the addition of carbon fiber to the structure had a positive effect on the tensile strength. The carbon-fiber density also affected the tensile strength. Moreover, it was also observed that the tensile strength values improved with the change in the locations of the polymer and carbon-fiber layer.

Keywords: additive manufacturing, tensile test, polymer, fiber, FDM

V zadnjih letih se je v industriji močno povečala potreba po posebnih izdelovalnih postopkih, ki so se začeli tudi vse bolj uporabljati in uveljavljati. Med temi postopki so najbolj uveljavljene tako imenovane dodajalne tehnologije (AM; angl.: additive manufacturing). Ti najnovejši izdelovalni postopki omogočajo izdelavo in oblikovanje kompleksnih izdelkov brez oblikovnih omejitev in so se že znašli na prednostnem seznamu industrije izdelovanja različnih zelo zahtevnih in za oblikovanje težavnih kombinacij združevanja različnih materialov. V pričujočem članku avtorji opisujejo eno od teh metod oblikovanja s katero lahko oblikujemo in izdelujemo kovinske in polimerne materiale. V tej raziskavi so avtorji uporabili kontinuirna ogljikova vlakna za ojačitev strukture iz polimernega materiala in pri tem so tiskanje izvajali s t.i. postopkom oblikovanja izdelka z nanašanjem oz. zlivanjem (FDS; angl.: Fused Deposition Melting). To je eden od novejših postopkov dodajalnih tehnologij izdelave kompleksnih izdelkov. Avtorji so s to metodo izdelali oziroma natiskali natezne preizkušance in na osnovi preizkusov ovrednotili rezultate. Kot polimerni material so uporabili oniks in kot ojačitev so uporabili kontinuirna ogljikova vlakna. Za primerjavo so uporabili natezne preizkušance iz oniksa brez dodanih ogljikovih vlaken. Ugotovili so, da imajo preizkušanci iz Oniksa natezno trdnost 16 MPa, medtem ko so imeli FDM preizkušanci ojačani z ogljikovimi vlakni natezno trdnost 58 MPa. Po drugi strani pa so imeli preizkušanci s spremenjeno lokacijo plasti natezno trdnost 80,2 MPa. Ta vrednost je za 38 % višja od natezne trdnosti preizkušancev pri katerih so s FDM izdelali pravilno in simetrično strukturo oziroma usmeritev ogljikovih vlaken. Poleg teh ugotovitev je pomembno tudi to, da se z dodatkom ogljikovih vlaken v strukturo močno poveča natezna trdnost izdelanega polimernega kompozita materiala glede na gostoto dodanih vlaken in spremembo njihovega položaja (lokacije).

Ključne besede: dodajalna tehnologija, natezni preizkus, polimer, vlakna, FDM

1 INTRODUCTION

Additive-manufacturing methods have already become some of the most widely used manufacturing methods. Since they can meet numerous demands, projected products can be produced in a short time by means of these manufacturing methods. Since they make it possible to produce parts with different and complex geometries, they offer unlimited freedom to manufacturers in terms of the design of their products. The properties and wide range of uses of polymer materials are also among the reasons for the widespread use of additive-manufacturing methods.[1] The fused deposition method (FDM), one of the additive-manufacturing methods, is a method, for which polymer materials are widely used and 3D printing devices are used to this end. Thanks to these devices, it is possible to add reinforcement materials to polymer structures. Sectors such as aviation, automotive industry, medicine and food production stand out as the fields where this method is widely used.[2] In the studies

*Corresponding author's e-mail:
volkan@gazi.edu.tr

carried out with the fused-deposition method, reinforcement fibers are used to improve the properties of the resulting products. Examples of these fibers are carbon fiber, glass fiber and kevlar. While working with polymers and carbon fiber, factors such as fiber proportion in the structure, fiber type, fiber orientation, layer thickness of the part to be printed, printing speed, temperature of the printing process and temperature of the build plate affect the mechanical properties of the part to be produced.

Recent research has primarily focused on producing parts with desired properties using these inputs. There are two ways of incorporating fibers into polymer structures – continuous and discontinuous integration in the structure.[3,4] The mechanical quality of the products obtained with discontinuous fibers is higher than that of the polymer materials printed as pure polymers. In a study (10, 12 and 15) *w*/% of carbon-fiber material was added to the structure sequentially. Their mechanical properties were compared through tensile, bending and hardness tests. As for the tensile test results, the highest tensile value was obtained for the discontinuous carbon fiber reinforced specimen with a rate of 15 *w*/%.[5] The parameters used in another study conducted with discontinuous short fibers were the layer thicknesses, infill pattern, infill density, rim temperature, build-plate temperature and writing speed. The authors selected layer thicknesses of 0.2 mm and 0.4 mm, a linear and concentric filling pattern at ± 45°, filling density ration of 100 % and 60 %, rim temperature of 260 °C, printing layer-surface temperature of 100 °C and writing speed of 50 mm/s. The highest stress value was obtained for a concentric infill model with 0.2 mm layer thickness and 100 % infill density ratio.[6] Yet in another study, the effects of different parameters such as layer thickness, infill pattern and infill density on the wear resistance of discontinuous CF (carbon fiber) reinforced PLA material produced with the FDM method were investigated. As a result of this study, it was understood that the abrasion resistance could be increased with a low layer thickness and high infill.[7] In another study of the tensile strength, the specimen with an angle of 0° showed a maximum Young's modulus of 128 MPa and a maximum tensile force of 3.96 GPa. Another parameter, the plate temperature, had a direct relationship with the tensile force and the interfacial adhesion. As a result, the voids in the structure decreased with the increase of the temperature of the plate.[8] In another study, the effect of production process parameters on the tensile strength of carbon fiber reinforced PLA produced with the FDM method was investigated. In this study, layer thickness, infill pattern and extrusion temperature were selected as the parameters and their effects on the tensile strength of the final product were investigated. The reason for the highest tensile strength at 0.1 mm was a high adhesion area between the layers. Due to this fact, layer thickness had a great impact on the tensile strength.[9] When the results of the tensile test in another study were examined, a tensile strength of 32.12 MPa was obtained under a constant layer thickness and 100 % infill density. At the 20 % infill density, this value increased to 17.38 MPa. A cleaner surface was obtained at the 100 % filling density, which was attributed directly to the air bubbles inside the structure. In the light of these values, it was concluded that a high infill density would cause a high tensile strength and low surface roughness.[10]

When the studies conducted with discontinuous fibers were examined, it was seen that the fiber materials added to the structure increased the mechanical properties of the final product. Fiber materials can be added to a structure discontinuously as well as continuously; and certain studies concerning this processes were carried out. A single raw material cannot be produced by integrating a continuous fiber into the polymer material like a discontinuous fiber. Since fiber is added to the structure continuously, a two-edged machine is required, in which the polymer and fiber material will be extruded separately. For this reason, the machine must be capable of printing with continuous fiber. In a study, it was stated that the appropriate fiber ratio is an important detail in providing the desired mechanical properties. Aramid, carbon and glass fibers were used in this study. It was also stated that continuous fibers used in the process gave the same superior mechanical properties to the structure that would discontinuous fibers do.[11] In another study, the effects of the process parameters such as fiber type, fiber orientation and infill density on the tensile, fatigue and creep properties of the final product were investigated. Carbon fiber, glass fiber and kevlar were used as fiber-reinforcement materials, and nylon was used as the polymer. Considering the test results, carbon-fiber-reinforced specimens generally showed better mechanical properties compared to the other specimens. As regards the test results, creep properties were also more favorable with the carbon-fiber-free specimen.[12] Another study focused on different process conditions of 3D-printed PLA and ABS polymers. The parameters included the infill density, infill speed and infill pattern. During this study, some other tests in addition to the tensile, bending and compression tests were applied to the printed specimens.[13] In another study investigating the mechanical performances of carbon-fiber and glass-fiber-reinforced PLA materials, bending and tensile tests were applied to the printed specimens. While the glass-fiber specimen broke due to its brittle nature, the carbon-fiber-reinforced specimen showed good resistance to elongation.[14] In another study, the mechanical properties of the composites reinforced with continuous kevlar fibers produced with the FDM method were investigated. The parameters were the direction of the continuous kevlar fiber, number of kevlar fiber layers, position of the fibers and angle of the nylon material. The test results showed that these parameters had an impact on the mechanical properties.[15] In another study, the effects of the parameters of the 3D printing machine on the strength and stiffness properties of CF-PETG materials printed with FDM were investigated. It was then stated that the print speed, layer thickness and infill density, which were the test parameters, were significant factors for the tensile and bending strengths, and hardness.[16] In another study investigating the mechanical properties, surface quality and porosity of a PEEK composite reinforced with carbon fiber and glass fiber, (5, 10 and 15) *w*/% of fibers were added into the PEEK material. The surface roughness decreased to the minimum level for the specimen with 5 *w*/% fiber.[17]

In another study, the mechanical properties of specimens were investigated through tensile and bending tests. The fiber types used in this study were continuous kevlar, carbon fiber and glass fiber. It was stated that kevlar specimens were observed to have very little residue in the SEM images. It was also stated that the reason for this was a low adhesion of kevlar to nylon. Therefore, kevlar specimens were observed to be weak in load bearing. The air voids in the structure were found to be directly related to the adhesion quality, and the air voids in the kevlar specimens to be more numerous.[18] In another study, PLA as the matrix material and carbon fiber as the fiber material were selected and a PLA-CF specimen was printed. During this study, the PLA layer thickness and CF layer thickness were examined. As a result of the tensile tests, the tensile strength of the carbon-fiber material was observed to have increased with the increase in the layer thickness.[19] The effect of the layer thickness and fiber volume on the mechanical properties of composite components produced with 3D printers was investigated in another study. To investigate the mechanical properties of these specimens, in addition to the tensile test, a bending test was performed at three different points. Any increase in the fiber volume was found to be directly proportional to an increase in the strength of the direction of printing.[20] In another study, onyx-glass fiber material was used for the structure produced and the mechanical properties of the printed specimens were examined. Infill-density ratios of (30, 40 and 50) % were used for the specimens. As a result of this study, it was determined that an increase in the infill density would have a positive effect on the production of high-quality products.[21] Fiber-supported polymer structures were produced using FDM carried out with the onyx material. It was stated that the strength and ductility of the specimens were dependent on the carbon fiber concentration in the specimens, and that the strength would also increase with the increase in this concentration, while the ductility would decrease.[22] In another study, it was stated that the fibers continuously incorporated into the structure resulted in negative effects on the mechanical behavior. It was determined that this application reduced the adhesion while increasing the voids, and it was observed that these voids adversely affected the mechanical properties of the structure.[23] In another study, PLA reinforcement of a thermoplastic polymer and carbon-fiber reinforcement for a continuous fiber were made, and thermoplastic composites with high mechanical properties were investigated.[24] In another study, the strength of continuous-fiber-reinforced open-hole tensile specimens were investigated. HSHT (high-strength high-temperature) glass fiber was used as the reinforcement material and onyx as the polymer matrix. It was found that the continuous HSHT fiberglass reinforcement added to the onyx polymer matrix increased the strength by 2.5 times.[25] In another study, it was determined that the production of thermoplastic matrix composites with added carbon fiber (in varying contents and lengths) affected the mechanical properties.[26]

When these studies are reviewed, it is seen that polymer and fiber layers were printed in a sequential and regular manner throughout the printed structures. Polymer and carbon fiber layers came out one after the other in an orderly and sequential manner. However, in this study, while a regular and symmetrical structure was disrupted when the samples were produced, the effect of the designed layer locations on the tensile strength was investigated. In this context, 19 samples were printed, each made up of 12 polymer and carbon fiber layers. In addition to this, the continuous fiber reinforced sample and the sample made of pure onyx were compared and the data obtained with the tensile tests were evaluated. Thus, the change in the mechanical properties, caused by the change in the layer locations, of the samples produced under the same production conditions was examined.

2 EXPERIMENTAL PART

The designed samples were printed with a Markforged X7 3D industrial printing machine. The Markforged X7 3D printing machine can print, in a short time, parts reinforced with continuous carbon fiber. This machine can produce materials as strong as machined aluminum. With respect to its functional requirements, this 3D printing machine, which is flameproof, chemically resistant, energy absorbing and capable of high-resolution printing, is among the most preferred machines in the industry, having precision machined hardware and advanced sensors.[27] The design and dimensions of the test specimens to be subjected to a tensile test were determined in accordance with the ASTM D638-14 standards. The design of the test samples with dimensions of (165 × 19 × 4) mm was made using the Solidworks CAD program.

Within the scope of the study, fiber and polymer layer locations were chosen as the basic variables of the printed test samples. A test specimen was made up of 32 layers. The first and last four layers were made up of polymer. This arrangement is a requirement set by the machine manufacturer and the reason for it is the need to create a more rigid structure, in which the layers supporting the structure are above and below the central part. 12 of the remaining 24 layers were made of polymer and the

Table 1: Specimens numbers and locations

Location of Layers	Specimen Number																		
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**
1	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
2	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
3	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
4	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
5	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	P
6	P	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	P
7	C	P	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	P
8	P	P	P	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	P
9	C	C	P	P	C	C	C	C	C	C	C	C	C	C	C	C	C	C	P
10	P	C	P	P	P	C	C	C	C	C	C	C	P	C	C	C	C	C	P
11	C	P	C	P	P	P	C	C	C	C	C	C	P	C	C	C	C	C	P
12	P	P	C	P	P	P	P	C	C	C	C	C	P	C	C	C	C	P	P
13	C	C	C	C	P	P	P	P	C	C	C	C	P	P	C	C	C	P	P
14	P	C	P	C	P	P	P	P	P	C	C	C	P	P	P	C	C	P	P
15	C	P	P	C	C	P	P	P	P	P	C	C	C	P	P	P	C	P	P
16	P	P	P	C	C	P	P	P	P	P	P	C	C	P	P	P	P	P	P
17	C	C	C	P	C	C	P	P	P	P	P	P	P	C	C	C	C	C	P
18	P	C	C	P	C	C	P	P	P	P	P	P	P	C	C	C	P	C	P
19	C	P	C	P	C	C	C	P	P	P	P	P	C	C	C	P	P	C	P
20	P	P	P	P	P	C	C	P	P	P	P	P	C	C	P	P	P	C	P
21	C	C	P	C	P	C	C	C	P	P	P	P	C	P	P	P	P	C	P
22	P	C	P	C	P	C	C	C	P	P	P	P	C	P	P	P	P	P	P
23	C	P	C	C	P	P	C	C	C	P	P	P	C	P	P	P	P	P	P
24	P	P	C	C	P	P	P	C	C	P	P	P	P	P	P	P	P	P	P
25	C	C	C	P	C	P	P	P	C	C	P	P	P	P	P	P	P	P	P
26	P	C	P	P	C	P	P	P	P	C	P	P	P	P	P	P	P	P	P
27	C	P	P	P	P	P	P	P	P	P	C	P	P	P	P	P	P	P	P
28	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
29	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
30	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
31	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
32	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P

Table 1 notation: P – polymer, C – carbon fiber

other 12 were made of carbon fiber. The location distributions of the layers are given in **Table 1**. As can be seen in the table, the polymer and carbon fiber layers in the first sample are sequentially and homogeneously distributed throughout the structure. There is a homogeneous and symmetrical distribution in the 2nd, 3rd, 4th, 6th and 12th sample, as in the first sample. However, layers of the same type came one after the other in each sample. No such homogeneous and symmetrical situation is found in samples 5, 7, 8, 9 and 11. The layers at the end of the structure, disrupting these features, were placed in the middle of samples 13, 14, 15, 16, 17 and 18, and thus homogeneity and symmetry were ensured. Relevant layer models that could be adjusted to 24 layers were thus created. In addition, the tensile strengths of the samples with continuous carbon fiber and the sample made of pure onyx were also compared.

The triangular model was chosen as the infill model for the created samples. The printing temperature was determined as 270 °C and the fill rate as 37 %. These are the values set by the manufacturer of the 3DPrinting machine. The writing speed was also determined with reference to the value set by the manufacturer. The 37 % infill ratio chosen for the matrix material was determined as the optimum ratio between the price and performance, following a number of tests. The thickness of 32 layers in the structure was chosen as 0.125 mm, which is the minimum value for the structures containing continuous carbon fiber. The reason why this value was chosen as the minimum is the need for a better adhesion of the layers to each other over large surface areas at low layer-thickness values. The infill model was chosen to be concentric and it is shown in **Figure 1**. The two blue lines shown in the outermost layer in the image represent carbon fiber. The minimum number of carbon-fiber layers for a specimen to be printed is 2 for the concentric infill model, obtained from the standard data of the 3D machine company. In **Figure 1**, an illustration of the layer consisting of onyx is given. There is no carbon fiber in this layer. The entire layer is filled with onyx.

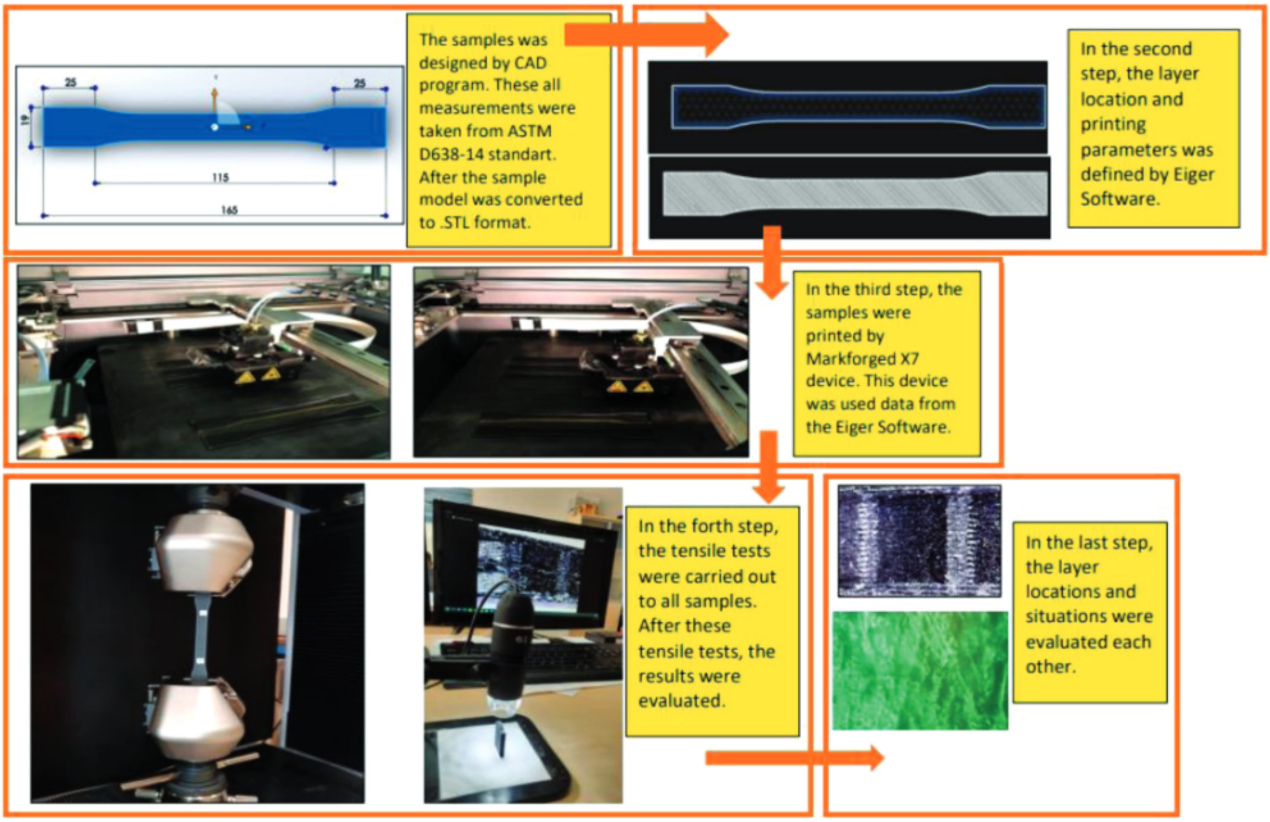

Figure 1: Workflow and steps of this study

The printing time for the specimens produced within the s cope of the study lasted around 70 min to 80 min. This duration was directly related to the carbon fiber proportion and the infill factor used in the structure. The increase in the infill density and the amount of carbon fiber cause an increase in both the printing time and costs.[7,13,18] In **Figure 1**, the conditions of the specimens printed with these parameters on the Markforged X7 3D printing machine build plate are illustrated.

A TRViewX device by Shimadzu was used for the tensile tests. TRViewX is an advanced non- contact extensometer that can measure width changes with great accuracy, and can be used for a wide variety of materials and testing applications. Mono and dual camera models and high-intensity LED lighting systems of this device are available.[28] The tensile test was applied to the produced specimens using this device and **Figure 1** illustrates the state of one of the produced specimens when connected to the device. The tests were carried out in accordance with the ISO 527-1 standards, without a preload at the initial state and with a tension rate of 5 mm/min. The data regarding the split samples were recorded in the system.

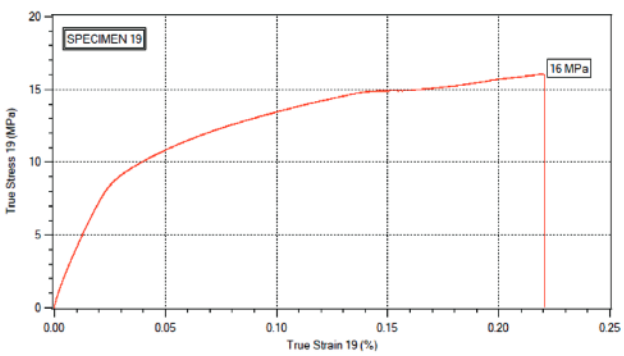

Figure 2: True stress vs. true strain graph for Specimen 19 (pure onyx)

3 RESULTS AND DISCUSSION

3.1 Effect of carbon fiber on the tensile strength and creep

The fibers added to the polymer structure improved its mechanical properties, resulting in a durable structure even when exposed to elevated forces.[3,4,6,7] When the reinforcing fiber materials were not added to the structures, the tensile strength, in particular, decreased considerably. When examining the graph of the sample, produced using pure onyx and no reinforcing fiber material in **Figure 2**, we can see that the tensile strength increased to 16 MPa. **Figure 3** illustrates the graph of the tensile test of Sample 1, which was printed using carbon fiber (**Table 1**). When the graph for Sample 1 is examined, the tensile strength value can be seen to be 58 MPa.

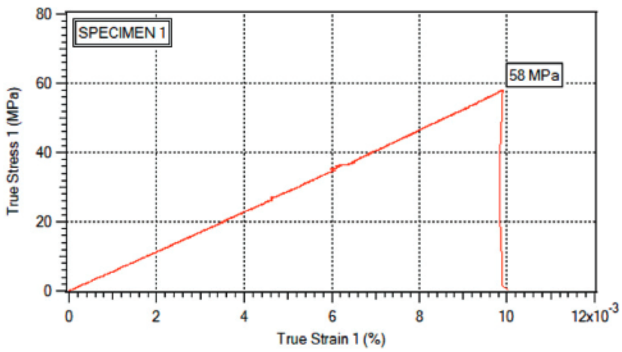

Figure 3: True stress vs. true strain graph for Specimen 1

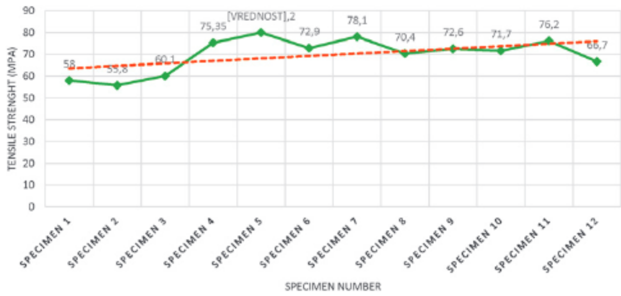

Figure 4: Comparison of tensile strengths of the first 12 specimens

The continuous fibers incorporated into the structure give the structure superior properties that were proven experimentally. In the studies examining mechanical properties such as hardness, impact strength, bending strength and tensile strength, fiber-doped polymer materials achieved high mechanical properties.[11,12,29] However, when the creep phenomenon was examined, different results were obtained, contrasting the mechanical properties mentioned above.[12–30] This was due to the ductility of the material, the main factor that affects the structure during creep. For this reason, when the graphs for the specimen printed from pure onyx and Specimen 1 are compared, the creep property of pure onyx is superior.

3.2 Effect of layer locations on the mechanical properties of the structure

In this study, changes were made to the layer locations and the effect of this change on the tensile strength was examined. As can be seen in **Table 1**, specimens containing 24 layers were created in the structure. The layer positions of Specimen 1 were printed symmetrically and in the order found in the literature, reporting on the previous studies.[14,15,31] The printing process was carried out in such a way that the layers of the same type were successive. Carbon fiber and polymer layers were brought closer to each other in each sample until 12 carbon fiber and 12 polymer layers were successive in the structure. That is, the arrangement of the onyx and Carbon fiber layers was made in such a way that one layer of Carbon fiber and one layer of polymer alternated in Specimen 1, two layers of each material alternated in Specimen 2, three layers of each material alternated in Specimen 3, four layers of each material alternated in Specimen 4, and there were twelve layers of each material in Specimen 12. In the specimens printed after the twelfth specimen, the carbon fiber and polymer layers, which disrupted the symmetrical structure of the mold in the last layers, were placed in the middle of the structure, thus providing a homogeneous and symmetrical order. By virtue of the tensile-test results, it was found that mechanical properties could also be altered by changing the layer positions.

When **Figure 4** is examined, it can be observed that the tensile strength increased with the combination of layers of the same type from Specimen 1 to Specimen 12. Hence, the tensile strength increased or did not de crease considerably with the convergence of layers. However, as stated in the previous studies, the absence of a polymer layer between carbon fiber layers has an adverse effect on the adhesiveness of these layers to each other. Owing to this effect present in the specimens from this study, as a carbon fiber layer in the specimens contained carbon fiber consisting of 2 walls only in the form of a concentric pattern, the onyx in the layer provided the adhesiveness required for the adhesion of the layer. If the layer were made entirely of carbon fiber, the situation would be different, and especially the converging carbon fiber layers would affect the tensile strength of the structure.[23] In the designed specimens of this study, the carbon fiber in the concentric model would consist of a maximum of 9 walls, and as such, there would be a maximum amount of carbon fibers in a layer. The reason why the maximum of 9 walls could be formed is the 1.125 mm diameter of the carbon fiber, and within the s cope of this diameter, the maximum of 9 walls could be concentrically placed in the structure. In the layers produced in this way, when the layer lo cations are changed, tensile strengths will tend to increase continuously, rather than rising or falling as in this study. At this point, the adhesiveness between layers will start to play a part. Since the carbon fiber layers are completely full and there is no polymer between them, their adhesiveness will be low.[18–21] In fact, if the fractured surfaces of the specimens are examined after the tensile test, it will be seen that the carbon fiber does not have a favorable interaction with the polymer. This is due to the fact that polymers will not have any layer adjacent to the carbon fiber layer, and that they will not be able to penetrate the carbon fiber in the case of a succession of layers of the same type. As a result, voids will occur. This will not only reduce the adhesiveness between the layers, but also increase the voids in the structure.[8–18] Since the voids will have a negative impact on the structure during the tensile test, the desired high values will not be achieved. For this reason, situations such as voids that may occur in the structure and the inability of the layers to adhere to

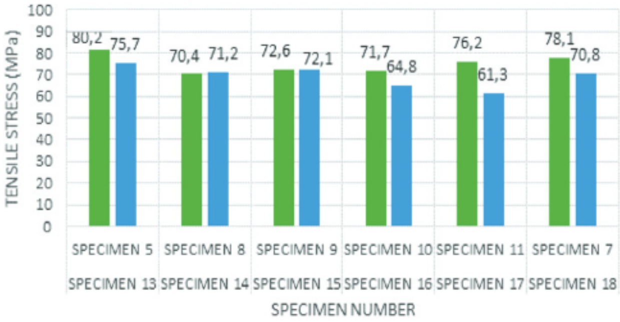

Figure 5: Comparison of the tensile strength of Specimens 13, 14, 15, 16, 17, 18, printed to create symmetry in the structure, with Specimens 5, 7, 8, 9, 10, 11, 17

each other properly will prevent obtaining the desired values in the experiments.[23]

As indicated in **Figure 5**, the layer sequences of Specimens 5, 7, 8, 9, 10, 11 were identical; however, the layers that remained in the last row and disrupted the symmetry of the layer structure were taken to the middle of the structure and thus symmetrical structures were formed. In the first stage, when the tensile strength of Specimens 5 and 13 were examined, a decline from 80.2 MPa to 75.7 MPa was observed. Although the amounts of onyx and carbon fiber and the number of layers in the structure were the same and the parameters were not changed, by switching to a more symmetrical structure, a 7 % loss in the tensile strength was experienced. When Specimens 7 and 18 were examined, a similar situation seemed to have occurred there as well. The tensile strength decreased by 10 %. When Sample 11 was examined, the degree of de crease was seen to be approximately 20 %. When the remaining specimens were examined, it was observed that the tensile strength values were quite close to each other. As it can be understood from this fact, when the last layers that disrupted the symmetry were placed in the middle and when symmetrical and homogeneous distribution was maintained, there was apparently no improvement. In fact, when Specimens 5, 7 and 11 were examined, it was observed that this symmetrical and homogeneous layer distribution in the structure resulted in a decline in the tensile strength. When **Figure 6** was examined, it could be seen that, to create a symmetrical structure, moving the last layers that upset the symmetry into the middle did not lead to any improvement. Also, when **Figure 6** was examined, it was seen that there was a de crease in the tensile strength of the specimens (with the exception of Specimens 8 and 14). This shows that when the structures are printed symmetrically and sequentially with different types of material, the tensile strength does not improve; on the contrary, it decreases noticeably in some samples. This proves that carbon fiber, the main factor in increasing the tensile strength, shows low resistance to the forces in the structures, where symmetry is intended.[11,12] The absence of polymer in the carbon fiber layer, namely, its being completely full, directly affects adhesiveness, the voids in the structure and the resistance of a specimen to the tensile force. This was found to be the main factor when changing the mechanical properties of the specimens.

As another parameter, the percentage of elongation of the non-symmetrical specimens was seen to be higher. However, this difference was too small to be compared with Specimen 1. The rate of elongation for pure onyx was higher than for all the specimens printed with carbon fiber. This is due to the type of the material. Polymer materials are ductile, but discontinuous short carbon fiber particles in the onyx material reduce the ductility of nylon.[7,18,32] But here, pure polymer turns out to be insufficient. In cases of fracture, it can be seen that the values are 4–5 times lower when the specimen printed with pure onyx is compared to the specimens printed with continuous carbon fiber. This leads to negative situations at the points where specimens are exposed to load, especially at curve points, resulting in a failure in attaining the desired mechanical properties.[22–24] For this reason, reinforcing materials play a vital role in achieving the desired mechanical properties. The presence of such materials in

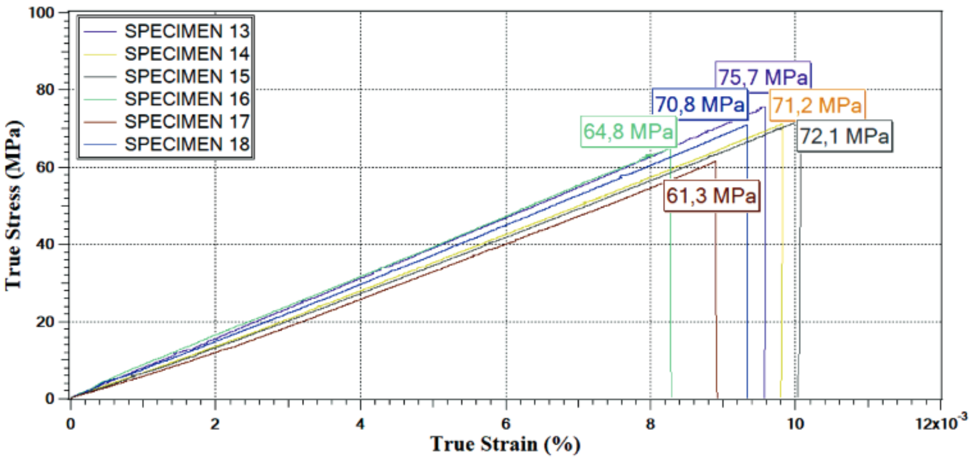

Figure 6: True stress vs. true strain graph for specimens 13, 14, 15, 16, 17 and 18

structures makes a remarkable contribution to the improvement of mechanical properties.

4 CONCLUSION

In this study, continuous carbon fiber was added to pure onyx and the tensile strengths of the specimens with an onyx matrix were compared. In addition, the polymer and carbon fiber layer locations were changed within the structure, and the effect of this change on the tensile strength was investigated.

The true stress vs. true strain graphs for the onyx material, on which tensile tests were performed, were compared with the others. In the previous studies, the structures were observed to have been printed symmetrically and the carbon fiber/polymer layers were successive. In our study, this regular and symmetrical structure was disrupted while specimens were being produced, and the effect of the designed layer locations on the tensile strength was investigated; 19 specimens were printed in this period. In accordance with the true stress vs. true strain results derived from the tensile test, the following conclusions can be drawn:

1. The tensile strength of onyx polymer printed in pure form, was found to be 16 MPa, being the minimum value among the specimens.

2. When the tensile graph for the specimen printed from pure onyx is examined, the yield point can easily be seen and its creep is better than that of the specimens containing continuous carbon fiber. However, this point cannot be clearly seen in the true stress vs. true strain graphs of the specimens with continuous carbon fiber, added as the reinforcement material. With the addition of continuous carbon fiber, the structures became brittle.

3. The tensile strength and creep were found to have changed with different layer positions. The adhesion requirements of the polymer and carbon fiber materials and the voids in the structure specified this situation.

4. The highest tensile strength was observed for Specimen 5, being 80.2 MPa. When this value was compared with that for Specimen 1, printed symmetrically and tested in this way in the previous studies, the result was found to be 38 % better.

5. After Specimen 5, the tensile strength decreased up to Specimen 12 because of the convergence of layers. Due to the fact that the adhesion requirement of polymer structures was higher than that of the structure including carbon fibers and polymer, the tensile strength began to de crease as the carbon fibers could not adhere to the structure.

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