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A Novel Production Method of Polymer Bolts and the Effects of the Printing Orientation on Tensile and Shear Strength of the 3D Printed Bolts

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Abstract

Lightweight structures are one of the most studied topics today. Many metal machine elements can be produced from lightweight polymer materials with 3D printer technology. In this study a novel manufacturing method is proposed for the polymer bolts and the effects of the printing directions on the tensile and shear strength are investigated experimentally. Firstly the bolt shafts are produced FDM method by using 3D printer for different print orientations and the final diameters of the bolt shafts are determined by the turning process. A special apparatus is designed and manufacture for threader tool. The screw pitches are opened by using this special apparatus with threader tool. After the manufacturing process, the performance of the produced tensile and shear test samples are defined by using tensile and shear tests. A special tensile test apparatus is also developed in this study. It is seen that the printing orientation has great effects on the tensile and shear durability of the bolts. It has been determined that the strength of the bolts produced with a production angle of 0º is the highest, and the strength of the bolts produced with 45º is the lowest.

Anahtar Kelimeler: Additive manufacturing, Fused deposition modelling (FDM), 3D printing, Tensile and shear strength, Polymer bolts

Polimer Cıvatalar için Yeni Bir Üretim Yöntemi ve Farklı Baskı Yönlerinin Polimer Cıvataların Çekme ve Kesme Dayanımı Üzerine Etkisi

Öz

Hafif yapılar günümüzde en çok çalışılan konulardan birisi olarak karşımıza çıkmaktadır. Metalden üretilen birçok makine elemanı 3D yazıcı teknolojisi ile hafif polimer malzemelerden üretilebilmektedir.

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Bu çalışmada, polimer cıvatalar için yeni bir üretim yöntemi önerilmiş ve baskı yönünün çekme ve kesme mukavemeti üzerine olan etkileri deneysel olarak incelenmiştir. Öncelikle cıvata şaftları farklı baskı yönleri için eriyik yığın modelleme (EYM) yöntemiyle üretilmiştir, ardından şaftların son çapları tornalama işlemi ile belirlenmiştir. Diş açmada kullanılacak olan pafta için özel bir aparat tasarlanmış üretilmiştir. Cıvata dişleri bu özel aparat kullanılarak pafta ile açılmıştır. İmalat sürecinden sonra, üretilen çekme ve kesme test numunelerinin performansları çekme ve kesme testleri ile belirlenmiştir. Çekme ve kesme testleri için ayrıca özel aparat tasarımları da gerçekleştirilmiştir. Gerçekleştirilen çekme ve kesme testleri sonucunda baskı yönünün cıvataların çekme ve kesme dayanımları üzerinde oldukça etkili olduğu görülmektedir. 0º üretim açısı ile üretilen cıvataların dayanımının en yüksek, 45º ile üretilen cıvataların dayanımının ise en düşük olduğu belirlenmiştir.

Keywords: Eklemeli imalat, Eriyik yığın modelleme (EYM), 3D yazdırma, Çekme ve kesme dayanımı, Polimer cıvatalar

1. INTRODUCTION

Screws and bolts are one of the most important joining elements in the industry. They make important contributions to the increase of the construction mass. Today, the creation of lightweight structures is at the top of engineering studies. In order to lighten the structures, it is possible to use polymer bolts instead of metal bolts with in the 3D printer technology. The 3D production technique is a method based on the production of the part to be produced as a single piece, in layers. In this production technique, the raw material is heated and fluidized and passed through a nozzle, allowing the part to be produced in layers. Ngo et al. [1] lists the advantages of additive manufacturing as freedom of design, customization, waste minimization, and the ability to produce complex structures in comprehensive review studies, Popescu et al. [2] comprehensively summarized the effects of FDM production parameters on the mechanical properties of polymer test specimens. It is emphasized that the most decisive mechanical properties for materials produced by additive manufacturing are tensile, compression, bending and impact strengths.

The effects of different production parameters such as extrusion temperature, table temperature, nozzle diameter, and infill density, pattern and build orientation, on the tensile strength are examined the most in the literature. Geng et al. [3] investigate effects of printing parameters on the mechanical properties of polyphenylene sulfide (PPS). The tensile and bending strengths of PPS samples can be improved by increasing the melt extrusion parameters. Nevertheless, the impact strength is restricted by excess melt extrusion. Rodriguez et al. [4] conduct bending and fatigue test to define the influence of six different production parameters on the mechanical properties of the polylactic acid (PLA). As a result of the study, the layer orientation is founded as the most influential parameter on the mechanical properties of the 3D printer PLA test specimens. Moreover the fatigue behaviors of the 3D printed samples are discussed in the study. Lee et al. [5] investigated the effects of processing parameters on the mechanical properties of fused deposition modelling (FDM)-printed carbon fiber-filled polylactide (CFR-PLA) composites by employing an orthogonal array model. The tensile and impact strengths of the composites are evaluated. Bed temperature is defined the most influential parameter. On the other hand, the bed temperature and the print orientation are the key parameters for the impact strength.

There are few studies in the literature, about the 3D printed bolts and screws. Generally the 3D printed bolts are used in the biomedical fields and aerospace applications due to the lightweight advantages. Nguyen et al. [6] developed a 3D printed screw-and-nut based droplet generator. The two components of the droplet generator are fabricated by a 3D printer and assembled simply by a bolt-and-nut combination. Thanks to the novel production method, the proposed 3D printed droplet generator is defined as rapid, simple and cost – effective to be fabricated without need of lithographic processes. Dhandapani et al. [7] used 3D printed screws for the biomedical applications. They produce biodegradable porous orthopaedic screw. The porous screws showed significantly increased vascularization in a rat subcutaneous implantation as compared to control screws. Feng et al. [8] produced bolts by using 3D printing technology and characterized these bolts based on digital image correlation and infrared thermography. According to the test results, the die steel bolts are more durable than the 3D printed prototype bolts also the 3D printed bolts have a high bearing capacity. Some researchers are designed and ISO standard bolts and nuts via 3D printer by using PLA and ABS materials. They investigated the shear strength of the 3D printers both numerically [9] and experimentally [10]. It is seen that PLA is more durable than the ABS according to the shear strength.

Printing orientation is one of the most significant production parameter which is effected the mechanical properties of 3D printed products. There are a number of studies in the literature about the effects of printing orientation on the mechanical properties of the test samples. Tensile, compressive and bending strength are the one of the most important properties for 3D printed samples. Yesil et al. [11] investigated the effects of printing parameters on the bending strength of the 3D printed PLA beams. Three point bending tests are conducted. The filling orientation, 0°-90°, provides better distribution of stress throughout the length of beam and hence, obtaining higher stress and modulus parameters. Keles et al. [12] investigated the effects of build orientation on the mechanical reliability of the 3D printed ABS material. Three different build orientations XY, C+45 and XZ are used in the study. It is found that the XZ orientation has the highest strength. However the C+45 orientation has the lowest strength. Markiz et al. [13] produced ten different tensile test specimens (1–5 at 0° and 6–10 at 90°). The tensile tests are conducted according to the ASTM D638 standard. It is found that the build orientation has great effect on the tensile strength of the ABS. 0° printing direction specimens are approximately %44.7 stronger that the 90° printing direction specimens. Another study is conducted by Valean et al. [14] and the effects of manufacturing parameters on tensile properties of FDM printed specimens is investigated experimentally. The tree different spatial orientation 0°-45°-90° is investigated. It is found that the spatial orientation has fewer effects on the young modulus however, has higher influence on the tensile strength. The creep behaviors of PLA and PLA composite material are searched by Tezel et al. [15]. The effects of printing parameters such as printing orientation and layer thickness are investigated experimentally via creep test apparatus. The creep resistance increase with the increase in the layer thickness for PLA however, decreases for PLA composite. Moreover first rate creep characteristic is seen for the 90° printing orientation. The effects of build orientation and infill density are experimentally investigated by Gonabadi et al. [16] with digital image correlation. As a result of the study the build orientation and infill density has significant effect on the mechanical properties.

In this study, a novel manufacturing technique for polymer bolts is presented and the effects of the printing direction on the tensile and the shear strength of the bolts are investigated experimentally. The polymer bolts with different printing orientation are produced via additive manufacturing and turning process. A special threader tool arm is designed and produced to open screws properly. The produced tensile and shear test specimens are experimentally test by using tensile test machine. As a result of the study, the proposed manufacturing method can be used to obtain lightweight constructions in special productions. The printing direction has great effects on the tensile and shear strength of the polymer bolts.

2. MATERIAL AND METHOD

The polymer bolts are produced by combining additive manufacturing, turning and threading processes. Ultimaker brand PLA (Polylactic Acid) filaments which has 2.85 mm diameter are used as a material of the bolts. PLA can be economically produced from the environmental–friendly renewable sources and it has good mechanical properties. Thus, the PLA is the most common used polymer filament in 3D printing applications.

The tensile and shear specimens are produced with Ultimaker 2+ Extended 3D printer. The printing area is 230x230x305 mm and the resolution is 12.5 µm–12.5 µm - 5 µm for the x – y – z axis respectively. The test specimens are designed in Solidworks software with 16.1 mm diameter and 200 mm length. The designed data are converted stl file format and send to the Ultimaker Cura software for the definition of the 3D manufacturing parameters. The G – codes are also created in Ultimaker Cura software. The manufacturing parameters of the test specimens defined in Ultimaker Cure are given in Table 1. Printing orientation is changed as 0° – 45° – 90°.

The created G – codes and the manufactured test samples is seen in Figure 1. The test samples are produced with the same G – codes and one by one in the middle of the printing table in order to produce the test samples as similar as possible. Each specimen is produced three times for the repeatable experiments.

After 3D printing process, the diameter of the bolt shafts is decreased from the 16.1 mm to 16 mm by using turning operation for removing the high surface roughness caused by the 3D printing process. The turning process is seen in Figure 2.

Table 1. Test samples manufacturing parameters

Parameter	**Value**
Material	Ultimaker PLA
Extrusion temperature	210 °C
Table temperature	60 °C
Nozzle diameter	0.4 mm
Layer thickness	0.2 mm
Infill density	100 %
Printing speed	60 mm/s
Infill pattern	Zig – Zag

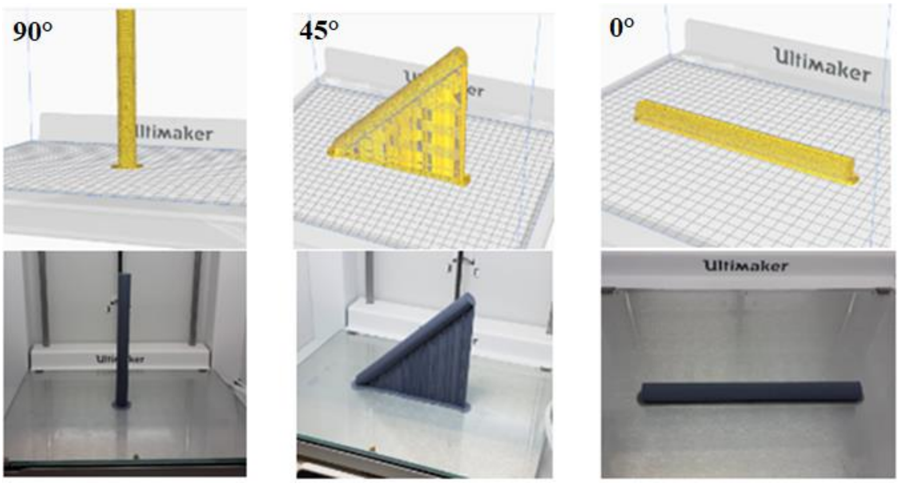


Figure 1. G code view and produced bolt shafts

The screws on the shaft are opened using a threader tool. At first a conventional threader tool is used for the threading operation. However, it was not possible to thread a 200 mm long shaft using a conventional threader tool and tool arm. It was determined that the teeth opened were different from each other. In addition, eccentricity has occurred between the opened teeth. For this reason, a new structure is needed to tolerate the errors that occur in the traditional threader and threader arm.

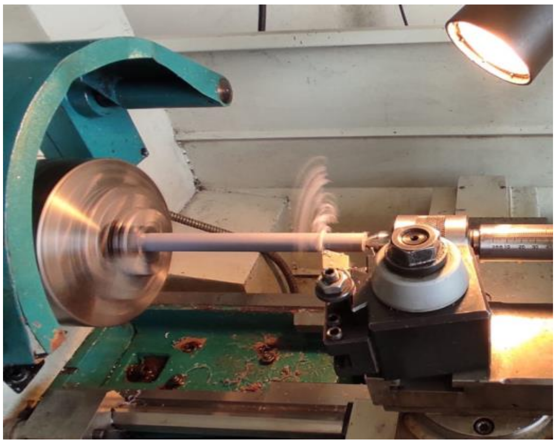


Figure 2. Turning process for 3D printed bolt shafts

In order to get rid of this problem, a new threader arm design has been made. New threader guide and arm are designed in Solidworks software and produced by using rapid prototyping via 3D printers.

Thanks to the new guide, the possible eccentricity is prevented by bearing the bolt shaft 30mm before reaching the cutter and 30mm after exiting the cutter. The developed unique thread guide system allows the polymer chips that result during use to fall completely through the guide. This design prevents damage to the produced polymer threads and the tool. The Solidworks design of the manufactured unique threading tool, it's assembled and unassembled components and the usage status during production of the threads are shown in Figure 3.

Figure 3. Design and produced novel threading tool

At the beginning of the study, the main goal was to create the teeth directly on the 3D printer. However, since a proper bolt and nut connection could not be obtained with the 3D printer, the methodology described above was developed. A suitable tooth profile could not be obtained because the tooth profiles produced with a 3D printer deflect towards the direction of gravity. For this reason, the production method proposed in this study for bolts that cannot be produced using a 3D printer reveals the innovative aspect of the study. In addition, the special apparatus designed for threads that cannot be opened with a traditional threading tool reveals another innovative aspect of this study.

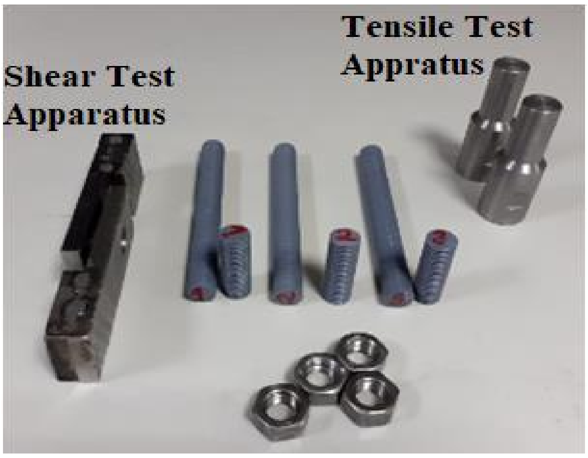


Figure 4. Produced test apparatus and test samples

After the threading process the bolt is divided into two pieces as shown in Figure 4 by using turning machine cutter tool. The length of tensile test samples are 150 mm and the shear test specimens are 50 mm. Moreover two different test apparatus are design and manufactured which is suitable for the tensile test machine. Newly designed and produced tensile and shear test apparatus is seen in Figure 4. The tensile test length is determined as 100 mm by mounting 25 mm on the front and back of the bolt pulling the apparatus.

The mass of the produced tensile and shear test specimens are measured to determine the stability of the production method. Mass measurements are made with a KERN PLS 6200-2A (capacity: 6,200 g, accuracy: 0.01 g) precision balance. The mass measurement results of the tensile and shear test specimens are given in Table 2. It is seen that the mass values are very close to each other when the mass values of the samples are examined. For this reason, it is seen that the bolts produced with the proposed production method do not have different properties from each other.

Experimental tests are operated according to ASTM – D638 – 14 [17] which describe the standard test method for tensile properties of plastics. Since no standard is found on the shear strength of polymer bolts in the literature search, the same standard method is also used for shear tests.

Table 2. Test specimen masses

Production Orientation and Sample Number	Tensile Test Specimen Mass (g)	Shear Test Specimen Mass (g)
0° - 1	30.78	10.51
0° - 2	30.50	10.34
0° - 3	30.65	10.34
45° - 1	29.21	9.97
45° - 2	29.34	10.08
45° - 3	29.57	10.21
90° - 1	30.38	10.17
90° - 2	30,50	10,24
90° - 3	30.29	10.15

Tensile and shear tests are carried out using designed tensile and shear apparatus, with 100 kN capacity Zwick/Roell Z100 tensile test device at 1mm/min speed. The experimental tests are conducted at room temperature. Tensile tests are continued until the specimen fracture. In shear experiments, the tensile test device is set to stop automatically when the measured force value falls below 20% of the maximum force. In shear tests, it is necessary to wait for a very long time for the sample to break. In addition, since polymer samples are used in the experiments, the samples generally elongate in case of shear test, but rupture is not observed.

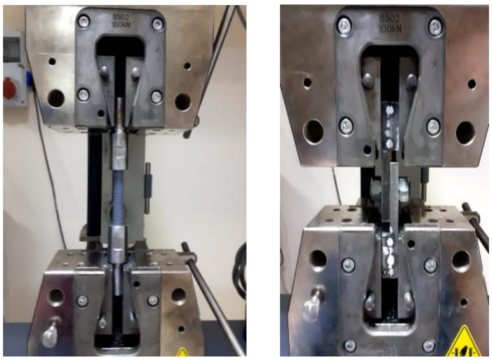
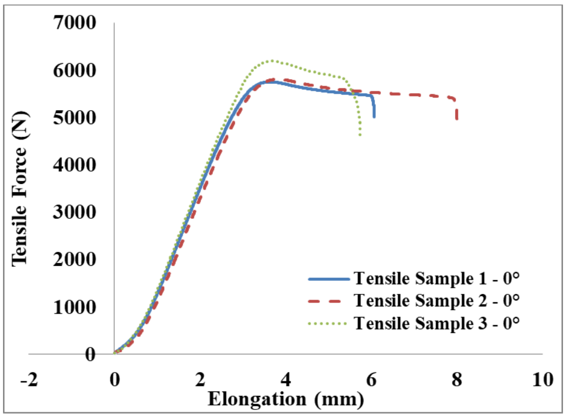
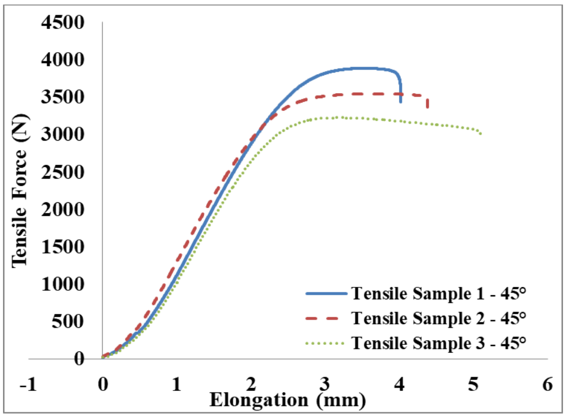


Figure 5. General view of tensile shear tests

3. RESULTS AND DISCUSSIONS

The effects of printing orientation on the tensile and shear strength of the bolts are investigated experimentally in this study. The tensile test results depending on the printing orientation are given in Figure 6. The tensile test results depending on the printing orientation are given in Figure 6. When the test results are examined, it is seen that the repeated test results are very close to each other. Thus, it has been determined that the experiments carried out are consistent and accurate. The maximum tensile strength is determined for the samples with 0° printing orientation. The tensile strength is approximately same for 0°-45° printing orientation. Specimens with 0°-45° printing orientation behaves as ductile material. However, the samples with 90° printing orientation behaves like brittle material.





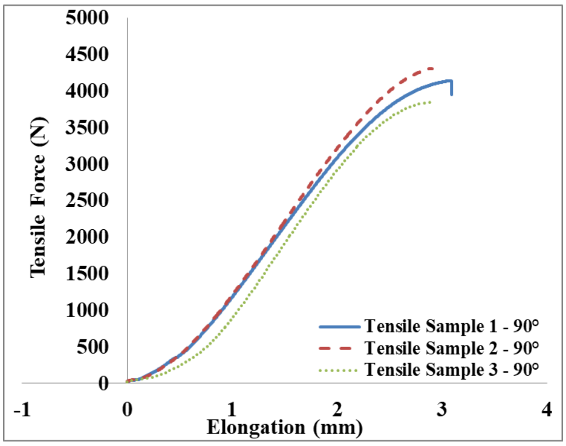


Figure 6. Tensile test results

The shear test results depending on the printing orientation are given in Figure 7. Similar to tensile tests, maximum shear durability is seen for the samples with 0° printing orientation, approximately 5000 N. The shear durability for the 45°-90° printing orientation is nearly same around 4500 N. When the shear curves are investigated it can be said that, there is long a linear region for the 0°-45° printing orientation samples. However, the linear region is very limited for the samples with 90° printing orientation. As the layers start to break one by one, the plastic zone is seen directly and this situation causes the material to be damaged quickly before it is sufficiently elongated.

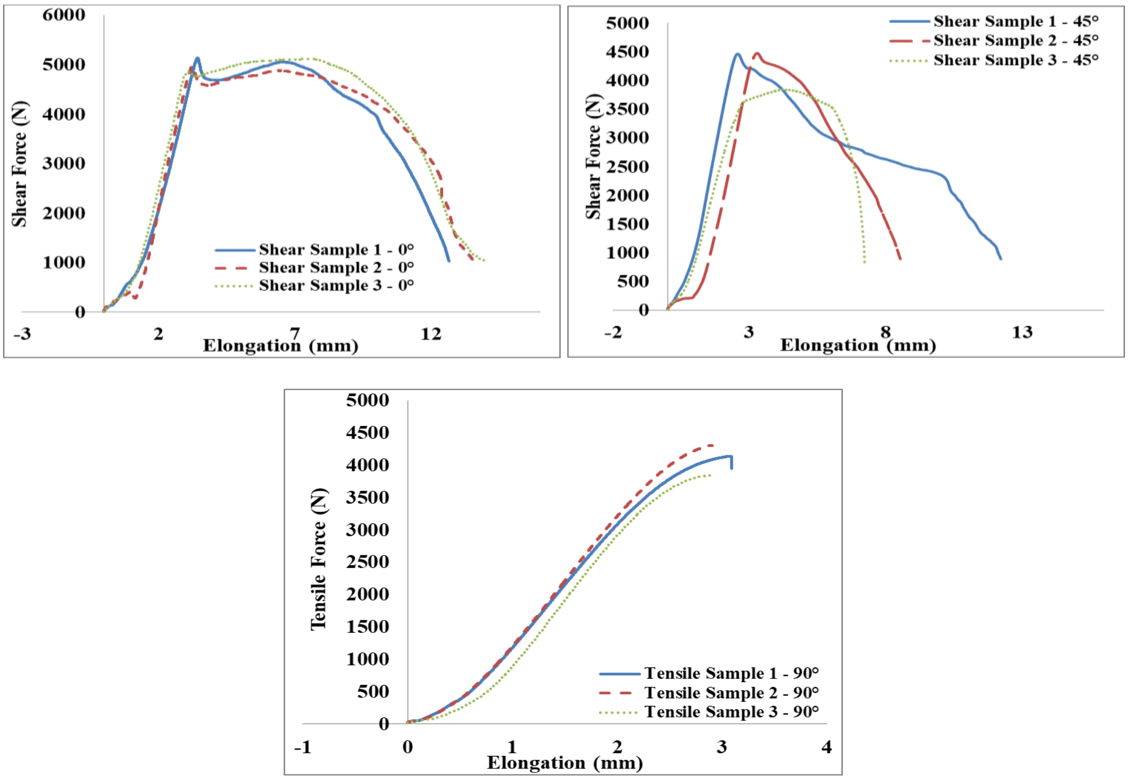


Figure 7. Shear test results

Rod tensile test samples without threads are also produced by using 3D printers in this study to define the intensity factor of the threads. The rod specimens are produced with the same length and same G–codes with the produced bolts. The tensile and shear tests are also conducted with the same properties and the tensile and shear durability of the rods according to the printing orientation is gained. The tensile force–elongation and shear force–elongation curves of the rod specimens is given in Figure 8.

The maximum tensile durability is seen for the printing orientation of 0° at 8000 N and the minimum tensile durability is seen for the 90° printing orientation. According to the average durability of the produced bolts the variation of intensity factors are given in table 3. The maximum intensity factor is seen for 45° printing orientation and the minimum is seen for 90°. Therefore, although the tensile strength of the rod with a 45° printing orientation is greater than the tensile strength of the rod with a 90° printing orientation, lower tensile strength is observed in the bolt experiments.

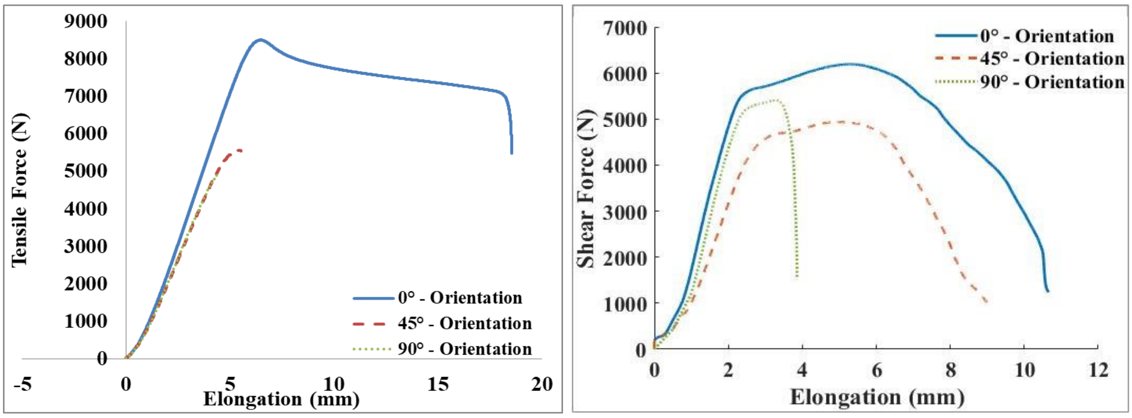


Figure 8. Tensile and shear test results for rod samples

Table 3. The variation of intensity factors for the tensile strengths

Printing Orientation	Intensity Factor
0°	1.41
45°	1.52
90°	1.14

The rod samples are also subjected to shear tests. The maximum shear durability is also seen for the printing orientation of 0° at approximately 6100 N and the minimum durability for the shear strength is defined for 45° printing orientation at 4900 N. The stress intensity factors of the shear tests for different printing orientations are given in table 4. Compared to the tensile tests, it was determined that lower stress intensity factors occurred during shear test. In addition, while the lowest strength was observed in the 90° orientation in the tensile tests, it was determined that the lowest strength was for the 45° orientation in the shear tests.

Table 4. The variation of intensity factors for shear strength

Printing Orientation	Intensity Factor
0°	1.20
45°	1.04
90°	1.11

The fracture types and surface is seen for different printing orientation is seen in Figure 9 for the tensile test specimens. The specimens with 0° printing orientation is elongated in the tensile direction. Depending on the elongation, the fibers started to break in the tensile direction and the bolt is damaged. The fracture surface makes 45° with the normal axis for the 45° printing orientation. The fibers are exposed to both tensile and shear stress thus the lowest strength is achieved in this case. There are no fibers in the tensile direction for specimens with 90° printing orientation. Thus, the fiber layers are directly broken. For this reason the test samples behaves like brittle material with 90° printing orientation.

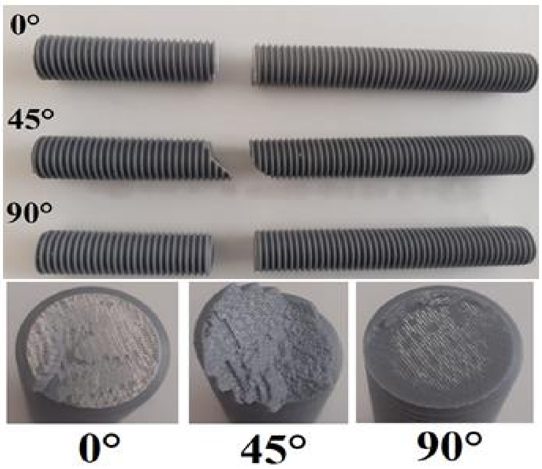


Figure 9. Tensile test samples fracture surfaces

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started to break in the tensile direction and the bolt is damaged. The fracture surface makes 45° with the normal axis for the 45° printing orientation. The fibers are exposed to both tensile and shear stress thus the lowest strength is achieved in this case. There are no fibers in the tensile direction for specimens with 90° printing orientation. Thus, the fiber layers are directly broken. For this reason the test samples behaves like brittle material with 90° printing orientation.

The fracture types and surface is seen for different printing orientation is seen in Figure 10 for the shear test specimens. The fracture surfaces for the 0º and 45º printing orientation behave similar. The printed fibers are elongates however for the 90º printing orientation layers are broken one by one. Thus the fibers cannot elongate for 90º printing orientation.

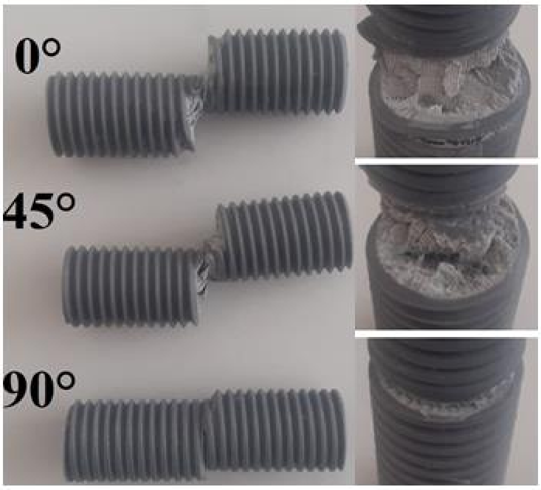

Figure 10. Shear test samples fracture surfaces

4. CONCLUSIONS

In this study a novel manufacturing method for the polymer bolts is presented and the effects of the printing orientation on the tensile and shear strength on the polymer bolts are investigated experimentally. The bolt shafts are produced with the 3D printers with different printing orientation. Then the diameter of the bolts is adjusted by using turning process. A novel threading tool is designed and manufacture for the threading operation. The threading process is done with novel produced threading tool. Thanks to this novel tool, the threads are opened perfectly on the polymer bolts. The produced bolts are subjected to tensile and shear test. Based on results of the experiments, the following conclusions can be drawn,

• Maximum tensile and shear durability is seen for the 0º printing orientation.

• The tensile and shear durability is approximately same for the 45º - 90º printing orientation.

• The intensity factor is the lowest for the 90º printing orientation. It can be said that, the threads nearly not affected the durability of the bolts for 90º printing orientation. The layers break before the bolt threads carry the load.

• The test samples behave like ductile material for the 0º and 45º printing orientation, on the other hand, the test specimens behave as brittle material for 90º printing orientation. Therefore; the fibers elongate for 0º and 45º printing orientation. However, layers are broken for the 90º printing orientation.

• The best printing orientation is defined as 0º for the production of the bolts.

The production method proposed from this study is suitable for small number of production, low loading conditions and bolt applications where lightness is at the forefront for polymer bolts.

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