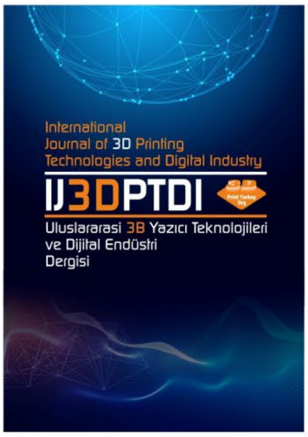

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Yazarlar (Authors): Alperen DOĞRU*, Muazzez KAÇAK , M.Özgür SEYDİBEYOĞLU

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EXAMINATION OF MECHANICAL PROPERTIES OF FASTENERS PRODUCED WITH PET AND PLA MATERIALS IN EXTRUSION-BASED ADDITIVE MANUFACTURING METHOD

Alperen DOĞRU[a]*, Muazzez KAÇAK[b], M.Özgür SEYDİBEYOĞLU[b]

[a] Ege University, Aviation HVS, Aircraft Technology, TURKIYE
[b] İzmir Katip Çelebi University, Metallurgical and Materials Engineering, TURKIYE

* *Corresponding Author:* alperen.dogru@ege.edu.tr

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ABSTRACT

Additive manufacturing methods, with their potential to revolutionize many areas, especially spare parts production, enable the optimization of the supply chain in production processes with an on-site production approach. The increased number of users of additive manufacturing methods and easy access to material extrusion-based methods can potentially transform the manufacturing industry. In this study, to investigate the production performance of fasteners, which are indispensable components of the manufacturing industry, with additive manufacturing. This study focuses on the torque strengths, hardness, and microscope images of bolts and nuts produced by material extrusion-based additive manufacturing (MEX) using PLA (Polylactic Acid) and PET (Polyethylene Terephthalate) polymers with different production parameters. Unlike conventional manufacturing methods, M8x50 DIN (German institute for standardization) 933 bolts and M8 DIN 934 nuts were produced. The bolts produced were positioned on the MEX device in two different positions. The torque forces applied to the bolts were measured in mechanical tests. Hardness was measured, and bolt thread surfaces were examined using a stereo microscope. Data on the usage limits of polymeric bolts were determined with the data obtained.

Keywords: PLA, PET, Additive Manufacturing, Material Extrusion, Fastener

1. INTRODUCTION

Most fasteners are made of low and medium-carbon steels[1,2]. Parts exposed to repetitive vibrations may be damaged after specific periods of time. Due to this fatigue, problems may occur in the use of steel materials [3-4]. For these reasons, in the fasteners used today; polymer materials are becoming widespread for the raw material diversity of bolts and nuts, and new production methods have started to be tried [5]. Among these new production methods, additive manufacturing methods have become popular in recent years with technical advantages such as design flexibility, weight reduction with optimized structures and materials, and shorter production time for fewer production runs [6–8]. In addition, nearshoring is changing the understanding of the supply chain, and factors such as reduced storage costs can create a faster and more flexible production process. Additive manufacturing processes stand out with their potential to revolutionize the traditional supply chain and have great potential in many industries with their decentralized production and supply structure [9].

Polymeric materials constitute the most widely used material variety in additive manufacturing methods, offering important opportunities for spare parts production. The method in which polymeric materials are most preferred is the material extrusion-based additive manufacturing method (MEX), which has the most users [10].

Polymers are increasingly used in various industrial applications, especially in producing fasteners, due to their advantages over metal alloys, such as lightweight, corrosion resistance, flexibility, and ease of processing [5]. Polymer bolts are becoming increasingly popular, especially in marine, chemical, and outdoor applications where corrosion and metal fatigue are significant problems. Lighter than metal bolts, they are energy efficient and require less maintenance, reducing long-term costs [11-12].

Much research on metal fasteners has been carried out in literature [13–15]However, there are only a limited number of studies on fasteners produced by the MEX method. Considering the advantages of using polymeric materials in fastener production with the MEX method, it is critical to know the materials' performances in this sense.

Harshitha et al. designed and analyzed bolts and nuts produced using the MEX method (International Standard Organization (ISO) standard) using PLA (polylactic acid) and ABS (acrylonitrile butadiene styrene) materials. In the analyses performed, it was determined that ABS is equivalent, and its shear stress is lower than PLA material and the results were confirmed in the tests performed on M12 bolts produced by the MEX method [16]. Labesh et al. similarly investigated the shear strength of M12 bolts produced by the MEX method using PLA and ABS materials. The analysis and test results showed that the safety factor of the bolts produced by the MEX method using PLA material is stronger than those made of ABS material [17]. These studies have shown that PLA material performs well in bolt production regarding shear load.

Eraliev et al. investigated the performance of bolts produced by the MEX method using three different materials under cyclic temperature changes. Although ABS bolts were weaker than PLA bolts at maximum preload, it was found that ABS bolts loosened 2.5 times less than PLA bolts at low-temperature cycling [18]. Alkhalaf et al. investigated the elastic modulus and dimensional stability of bolts produced by the MEX method using PLA material. They compared the mechanical properties of bolts produced with different infill density [19].

Zhang et al. investigated the wear properties of gears manufactured using nylon material using the MEX method. They concluded that under low to medium torque, the nylon gears produced by MEX outperformed the injection molded gears in terms of wear properties [20]. Chand et al. investigated the dimensional and mechanical properties of nuts and bolts produced using a multi-jet 3D printer. It was determined that the dimensional deviations of the manufactured products were within tolerance levels [13].

The studies generally focused on the shear strength, wear and environmental conditions of the fasteners produced with AM. PLA and ABS materials have been intensively discussed. These polymer-based materials are the most widely used material types in the MEX method. Another polymer that has become increasingly popular in recent years is PETG (Polyethylene Terephthalate Glycol-modified) and (Polyethylene Terephthalate (PET)[21]. These materials strike a balance between the easy processability of PLA and the mechanical strength of ABS [22-23]. Furthermore, PETG's properties, such as low shrinkage rate, high impact resistance, and chemical resistance, make it an ideal choice for a variety of industrial and personal applications[24]. Nazım et al. investigated the performance of fasteners produced with MEX using PLA, PETG, and carbon fiber-reinforced nylon materials in joining aluminum sheets. The samples produced as rivets were used to join aluminum sheets by thermo-mechanical deformation. They found that the strength values of vertically produced rivets were higher than PLA and carbon fiber reinforced nylon. PETG has a higher glass transition temperature (Tg) than PLA. This has led to better performance in fasteners due to better adhesion properties [25].

As a result of the existing studies, this study was carried out to obtain literature information on the performance of fasteners produced with PLA and PET. The use of additive manufacturing methods in producing final industrial products, using polymers instead of metals to provide advantages in terms of lightweight, corrosion resistance, etc., and sustainability, is coming to the fore day by day. Fasteners, which are indispensable components of the manufacturing sector, are also affected by this change. For this reason, using PLA and PET materials in fastener production with the MEX method will contribute to the material diversity in this field.

Determination of the performance of fasteners produced by the MEX method will guide the usage areas. In this context, in our study, M8x1,25x50 bolts in DIN (German Institute for Standardization) 933 standard and nuts in DIN 934 standard were produced by the MEX method using PLA and PET (Polyethylene Terephthalate) materials, and the hardness properties of the samples were tested, and torque tests examined performance. Additive manufacturing produces anisotropic materials and the properties change depending on the direction[26]. For this reason, the effect of infill pattern angle on torque properties was investigated in this study. All production parameters except the infill pattern angle were kept constant for each material group in the productions made with MEX. After the test, the damaged surfaces were visualized with an optical microscope.

2. MATERIALS AND METHODS

2.1. Materials

BASF's Ultrafuse PET and Ultrafuse PLA materials were used to produce bolts and nuts with the MEX. Filaments with a diameter of 2.85 mm were preferred in accordance with the MEX device used. All filaments are natural and do not contain any coloring agent.

The density values of the samples produced in the MEX method with Ultrafuse PET material are 1.329 gr/cm^3, Tg value 71°C, and melt volume rate 16.3 cm^3/10 min. The mechanical properties of the samples produced with this filament are tensile strength 33.4 MPa and impact strength 18.4 kJ/m^2 (unnotched charpy).

The density values of the samples produced with Ultrafuse PLA material in the MEX method are 1.248 gr/cm^3, Tg value 61°C, and melt volume rate 21.2 cm^3/10 min. The mechanical properties of the samples produced with this filament are tensile strength 34.7 MPa and impact strength 13.2 kJ/m^2 (unnotched charpy).

2.2. Design and Production

The drawings of the bolts with the dimensions specified in Figure 1 (a) in accordance with the M8x1,25x50 DIN 933 standard and the nuts with the dimensions specified in Figure 1 (b) in accordance with the M8x1,25 DIN 934 standard were carried out with AutoCAD Fusion 360 Computer Aided Design (CAD) program.

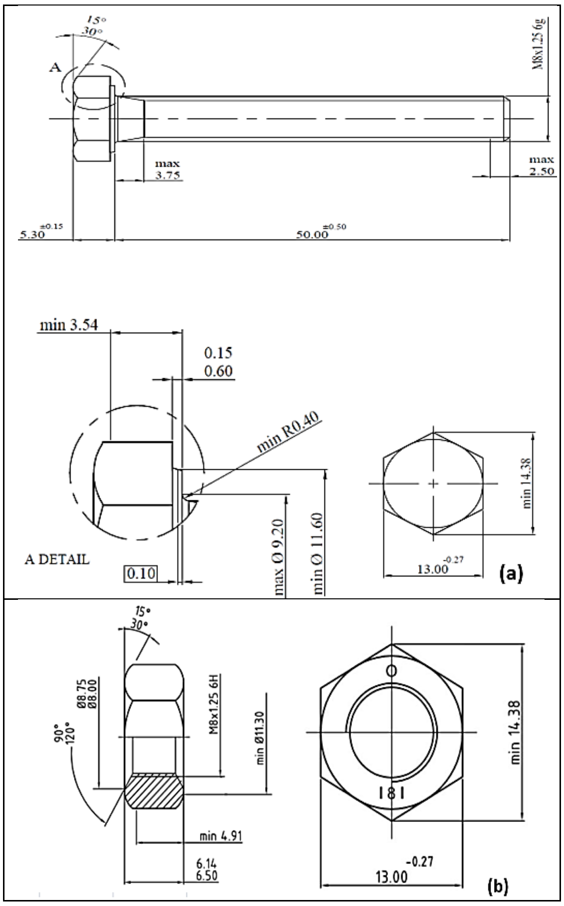

Figure 1. (a)Bolts Dimensions (b)Nuts Dimensions

The bolts and nuts whose solid models were drawn were produced by the MEX method with Ultimaker brand model 3 devices [27]. All bolts were produced with two different infill pattern angles, [0/90°] as shown in Figure 2 (a), [±45°] as shown in Figure 2 (b) and positioned on the table as shown in Figure 2 (c).

Each material group produced five pieces, each with two different infill pattern angles ([-/+45] and [0,90]). In the samples with [-/+45] infill pattern angles, the nozzle head performed extrusion at -45° and +45° angles, respectively. Similarly, those with [0/90] infill pattern angles were extruded at 0° and 90° angles, respectively. Nuts were produced in a horizontal position and with a circular pattern. In the test phase, each material was tested with a nut of its material. Polyvinyl alcohol (PVA) support material was used to facilitate the bolts' adhesion to the table and ensure their shape stability.

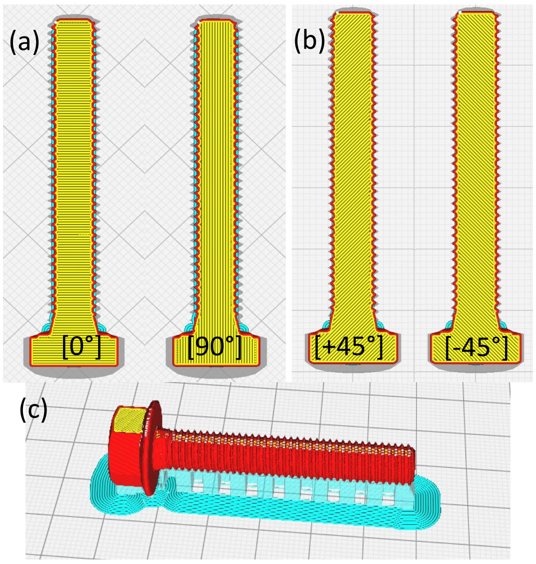

Figure 2. (a)Infill Patterns Angles [0/90] (b) Infill Pattern Angles [-/+45] (c)Bed Table Position

The filament manufacturer's recommended values were used for all printing parameters. The fixed production parameters determined to produce bolts and nuts are specified in Table 1.

Table 1. Fixed parameters for production

Parameter	Value
Layer Height (mm)	0.2
Infill Density (%)	100
Bed Material	Glass
Support Material	PVA
Build Plate Adhesion	Brim

For PET material, the nozzle temperature was 230°C, the bed temperature was 85°C, and the print speed was 55 mm/s. For PLA material, the nozzle temperature was set to 210°C, the bed temperature was set to 60°C, and the print speed was 70 mm/s.
The produced bolts and results are shown in Figure 3 and Figure 4.

Figure 3. PET Bolts and Nuts Samples

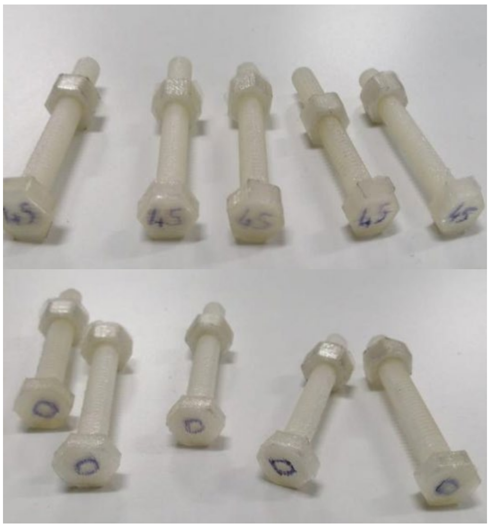

Figure 4. PLA Bolts and Nuts Samples

2.3. Post-Processing

After producing M8x1,25x50 DIN 933 bolts and M8x1,25 DIN 934 standard nuts made of different materials, the final surface treatment was applied using the round die apparatus, as shown in Figure 5. The purpose of the application is to ensure that the fasteners are connected by removing the burrs on the threads.

Figure 5. Round Dies Application

To check that the bolts produced after the final surface treatment are easily connected with nuts, controls were made with the gauge shown in Figure 6.

These quality control procedures were performed to check the correctness of the thread pitch, thread angle, minor diameter (root), pitch diameter, and major diameter (crest).

Figure 6. Quality Check with Gage

2.4. Hardness Measurement

Hardness measurements were carried out with a Frank brand Shore D hardness tester, shown in Figure 7. The measured according to the ASTM D2240 Standard Test Method for Rubber Property-Durometer Hardness standard [28]. All measurements were made from bolt heads with plate surfaces.

Figure 7. Hardness Measurement

2.5. Torque Test

Torque tests of the produced bolts were applied until the bolts were damaged. The tests were carried out to see the strength of the bolts and nuts under safe load. During the test, bolts and nuts were fixed on a fixed plate and tightened with a torque meter. Torque measurements were carried out with the Yamer brand digital torque meter shown in Figure 8.

Figure 8. Torque Tests

2.6. Stereo Microscope

After the torque test, the damage to the threads of the bolts and nuts was examined with a stereo microscope. Imaging was performed with Elite brand SX45 stereo microscope.

3. RESULTS AND DISCUSSIONS

The hardness of the bolts produced by the MEX method using PLA and PET materials was measured according to the shore D scale. Figure 9 shows the results of all measurements performed. The highest shore D value was measured in bolts produced using PLA material. The hardness values of the bolts produced with PET material were measured lower regardless of the production direction. According to the Shore D test, a scale value of 100 corresponds to a spring load of 44.45 N [28]. The highest hardness value was measured as 71.64 on average in PLA bolts produced with 0/90 orientation and this value corresponds to a load of approximately 31.84 N according to the standard. The lowest shore D hardness value was measured as 60.08 on average in PET bolts produced with -/+45 orientation, and this value corresponds to a load of approximately 26.7 N according to the standard.

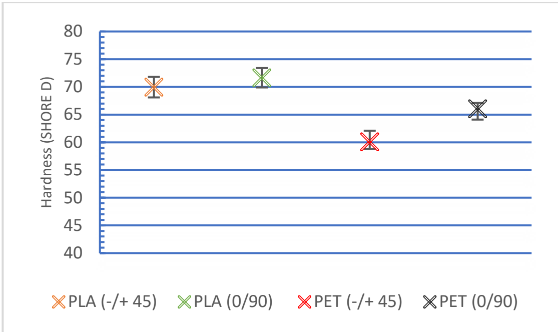

Figure 9. Shore D Hardness Results

When the results are analyzed independently of the material type, it is seen that the bolts produced in the 0/90 orientation have higher shore D hardness values than the bolts produced in the -/+45 orientation. In the deaths made from 5 points, approximately close values were measured between those with -/+45 orientation and those with 0/90 orientation in PLA bolts. This showed that hardness values were not affected by orientation in PLA bolts. In PET bolts, a slight difference was observed in hardness values depending on orientation. This is thought to be related to the cooling of the extruded polymer caused by the nozzle head's path during the PET material's orientation changes. The pattern observed at 0/90 orientation includes a shorter time for the next layer. This may have favorably affected the interaction during the joining of the layers. The production time for a single PLA bolt was 26 minutes for 0/90 and 28 minutes for the bolt with -/+45 orientation. Similarly, the production time for PET bolts is slightly lower for 0/90 orientation.

The hardness of the bolts produced with PLA was measured to be higher than those produced with PET, regardless of the production orientation. The low Tg value of PLA compared to PET material may cause it to be harder at low temperatures [29]. In addition, PET material can be more flexible when it is amorphous, and PLA has a semi-crystalline structure due to the bonds it has, which makes PLA more rigid at room temperature [30]. PLA has a higher crystallinity than PET, increasing the material's stiffness. When PET remains in the amorphous phase, it is more flexible and has a higher impact resistance, while PLA exhibits a more rigid structure [31]. All these properties caused PLA bolts to show higher hardness properties than PET bolts. Considering the results obtained, the difference in polymer material affected the hardness value more than the production orientation.

In the torque test, the bolts were tested using nuts made of the same materials. The bolts fixed to the plates were tested with a torque meter. The applied force was measured and recorded with a digital display. Five specimens from each test group were tested, and the results are shown in Figure 10.

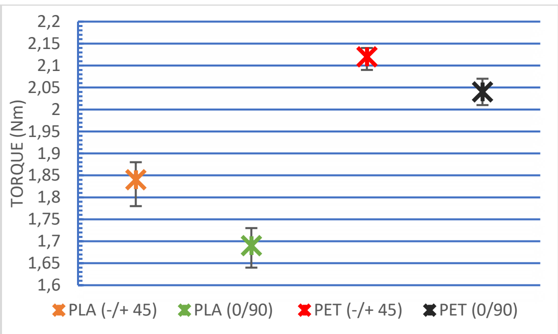

Figure 10. Torque Test Results

Higher torque values were measured for bolts with -/+45 orientation compared to bolts with 0/90 orientation. Regardless of the orientation, higher torque values were measured in bolts produced with PET material. PLA shows higher stiffness due to its rigid structure, but it has a brittle structure and is more likely to break when excessive torque is applied [32]. Moreover, it was observed that the torque value was low in PLA samples with high hardness values. In this case, it can be interpreted that the increase in hardness gives a brittle structure feature. For this reason, lower torque values were measured for PLA bolts compared to PET bolts. PET material also has higher impact strength than PLA [23]. This may have enabled PET bolts to withstand higher torques. The tough structure of PET material allows it to perform more deformations without breaking [33]. This may be why PET bolts exhibit higher torque values than PLA bolts. In addition, the technical data sheet values of the PET and PLA materials used also confirm this situation. The impact strength of the ultrafuse PET samples was 18.4kJ/m^2 [34] while it was 13.2kJ/m^2 for PLA samples [35]. These test results show the foreseeable force and safety load for the forces applied to PLA and PET bolts.

After the torque test, the bolt threads were visualized with a stereo microscope. The images of PET bolts are shown in Figure 11.

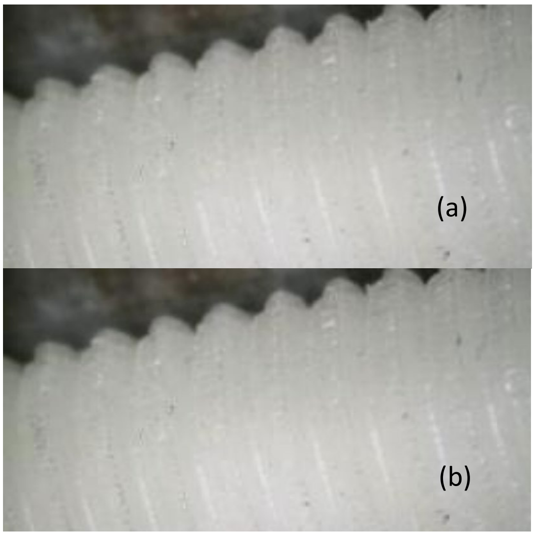

Figure 11. (a) 0/90 PET Bolt (b) -/+45 PET Bolt

It was observed that the thread depths of the bolts with a 0/90 orientation were less than those of the bolts with a -/+45 orientation. This may be the reason for the low torque values in bolts with a 0/90 orientation, as it reduces the adhesion in bolted connections.

Figure 12 shows images of PLA bolts. Similarly, less thread depth is observed in PLA bolts with a 0/90 orientation. This situation depends on the movement pattern of the nozzle during production and the positioning of the bolt to be produced.

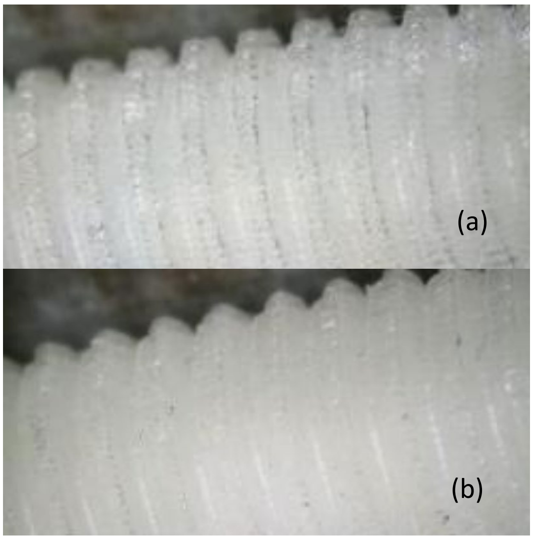

Figure 12. (a) 0/90 PLA Bolt (b) -/+45 PLA Bolt

In the movement system of the nozzle, the Ultimaker brand model 3 device used in production is moved in the Cartesian system with straight rods supported from the end. This situation is known to limit the mobility. In the newly developed CoreXY systems, corrections have been made in this regard by using fully supported linear rails [36,37].

4. CONCLUSIONS

Fasteners produced by additive manufacturing methods appear to be particularly advantageous in non-standard applications. This is especially true when large or unusually shaped fasteners are necessary to withstand low or medium loads. In this respect, the MEX process offers significant opportunities with its wide range of materials.

Hardness values were measured as 69.96 with -/+45 infill pattern angle and 71.64 with 0/90 infill pattern angle for PLA bolts. PET bolts were measured as 60.08 with -/+45 infill pattern angle and 66.04 with 0/90 infill pattern angle. Hardness increases the material's resistance to external influences and makes it more resistant to problems such as wear and deformation. For this reason, PLA bolts with high hardness values may be more advantageous for these applications.

The study measured the torque value for PLA bolts as 1.84 Nm with -/+45 infill pattern angle and 1.69 Nm with 0/90 infill pattern angle. PET bolts were measured as 2.12 Nm with -/+45 infill pattern angle and 2.07 Nm with 0/90 infill pattern angle. Considering their properties, polymeric bolts can withstand low and medium loads in areas requiring corrosion resistance. Cover assembly areas of water pumps, decoration panel cover assemblies in the white goods industry, and fasteners used in the toy industry may offer opportunities for this method.

Although polymer bolts offer many advantages, challenges such as deformation, low thermal conductivity, and fatigue over time can arise, especially in high-temperature applications. Therefore, further research and development work is needed to make polymer bolts long-lasting and reliable. In the future, with the development of new-generation polymer composites and the improvement of manufacturing techniques, polymer bolts will likely become more common and reliable.

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