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Araştırma Makalesi Research Article

Investigation of Manufacturing of a Pelton Turbine Runner of Composite Material on a 3D Printer

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Keywords

Pelton Turbine
Additive Manufacturing
Composite Turbine-Runner

Abstract

Nowadays, different methods are used in manufacturing sector. One of these is the production technique on 3D printers, which is also described as additive manufacturing. In this study, Pelton turbine bucket was produced from composite material (carbon + thermoplastic) on a 3D printer and tested. Analytically, the special pelton turbine bucket designed at TEMSAN has a special form structure. Through additive manufacturing, the turbine runner was manufactured faster and more cost-effectively compared to production out of steel material. Tests were carried out in TEMSAN Hydraulic Test Laboratory at 5-7.5 bar pressure range and 26 l/s and 46 l/s flow rates. The highest breaking strength value was determined as 1775 N.

Cite

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1. INTRODUCTION

The 3D additive manufacturing method is used in different fields in the industry day to day. However, studies and product developments using different material types (polymer, composite, metal) do continue. For many years, products have been produced from polymer based materials by additive manufacturing method and used in many areas of the industry; automotive, medical, advertising and promotion sectors in particular. In the energy industry, too, various studies are carried out on the equipment produced on 3D metal printers. In addition to this, different designs and cost-reducing studies are effectively urged upon in connection with the equipment that generate power from renewable energy sources. Generation of energy from renewable energy sources increases in value with day to day due to low carbon emissions as well as environmental and climatic conditions. Approximately 15% of the world's energy demand is provided by hydraulic energy (Chouhan et al., 2017). In hydraulic energy, generation of energy is provided by using different turbine types depending on flow rate and head. Pelton turbine is preferred in projects with higher heads (pressure). In the study carried out by Takagi et al. (2014) it was conducted on a Pelton turbine that had been manufactured by means of additive manufacturing technique with nylon resin fibreglass matrix to accelerate the production time of the Pelton turbine and reduce the costs and it was stated that the design errors were detected earlier. In addition, it should be considered that the corrosion resistance of composite materials is higher and this will provide an advantage for use in micro turbine systems (Shirisha et al., 2014). In reducing the total weight, it is possible to manufacture lighter turbine runners with 1/7 composite materials, especially when compared to steel. Manufacturers can also reduce costs by reducing the processing rate and total production time on conventional machines (Albertani, 2013).

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In this study, the turbine bucket of a Pelton Turbined, which is one of the hydraulic turbine types, was produced from composite material by 3D additive manufacturing technique and information about the tests carried out for the product manufactured is presented.

2. MATERIAL AND METHOD

While the products and materials used in engineering have physical, electrical, magnetic, chemical, mechanical and production properties, they should also possess properties such as material cost, product shape, environmental impact, usability, cultural aspects, aesthetics and recycling (Adhikary et al., 2013).

In hydroelectric power plants, the potential energy of water is stored in construction structures such as reservoirs and dams. This potential energy is transferred to the turbine-generator shaft as mechanical power by transmitting the potential and kinetic energy to the hydraulic turbine which is located at different heads by means of penstock pipes. The higher the potential energy of the water, the faster the water velocity when entering the turbine runner. Water that hits the turbine runner at high speeds causes wear on the turbine runner (Neopane et al., 2011). With this in mind, the material to be used in the turbine runner is designed to meet the incoming loads and withstand this abrasive and corrosive effect.

Today, hydraulic turbine runners are usually made of heat treated stainless steel (for example: X5CrNi13-4) through long processes such as casting, machining and welded manufacturing methods. In order to prevent erosion corrosion due to sediment in steel materials, special coating or paint systems need to be applied onto the materials made of metal (Gummer, 2009). These days, hydraulic turbine runners are endeavoured to be produced using different materials and production techniques. For instance, composite material that is a material system consisting of a mixture or combination of two or more micro or macro components provides the better material properties such as hardness, durability and toughness (Shirisha et al., 2014).

The use of 3D metal, polymer and composite printers is one of the new production techniques. While there are advantages in this method such as rapid prototyping, material wastage, easy production of complex parts, there are also disadvantages such as design and difficult dismantling of the supports, long manufacturing times, unexpected defects during manufacturing, high surface roughness and environmental conditions. Recently, methods called FDM (Fused Deposition Modelling) and SLS (Selective Laser Sintering) are used in 3D printers.

3D printers, referred to as FDM or FFF (Fused Filament Fabrication), are printers with similar characteristics. In these printers, the filament- shaped material wound on the reels is heated at a temperature that can be shaped, usually at 240-275°C, and passed through the sections called nozzle at certain thicknesses. Production is completed layer-by-layer, by adding filament to create part whose dimensions were previously defined on a solid modelling program on the printer table with a flat surface. In composite printers, as shown in Figure 1, additive manufacturing is performed by feeding different materials from two different nozzles. Generally, the basic matrix element is thermoplastic materials and is reinforced with materials such as carbon fibre, fiberglass and kevlar.

However, using only thermoplastic materials does not meet the mechanical strength requirements (Peng et al., 2018). Supporting with materials such as carbon, kevlar and fiberglass improves the strength properties of the product (Blok et al., 2018). Comparing the fiber reinforcing investigated, it was found that the nylon composite strength was in the following order: Carbon fiber > Glass fiber > Kevlar fiber (Dickson et al., 2017). Among the carbon, glass, and basalt fibers typically used in manufacturing of FRP (fiber-reinforced-polymer) bars, the carbon fibers were the strongest and most resistant to the various corrosive environments (Cousin et al., 2019). The effects of the type of reinforcement and fiber volume content on the impact damage performance of reinforced nylon specimens were of particular significance (Caminero et al., 2018). Kussmaul et al. (2017) in their study showed that carbon fiber reinforced polymers (CFRP) offered outstanding weight-specific properties and high design freedom.

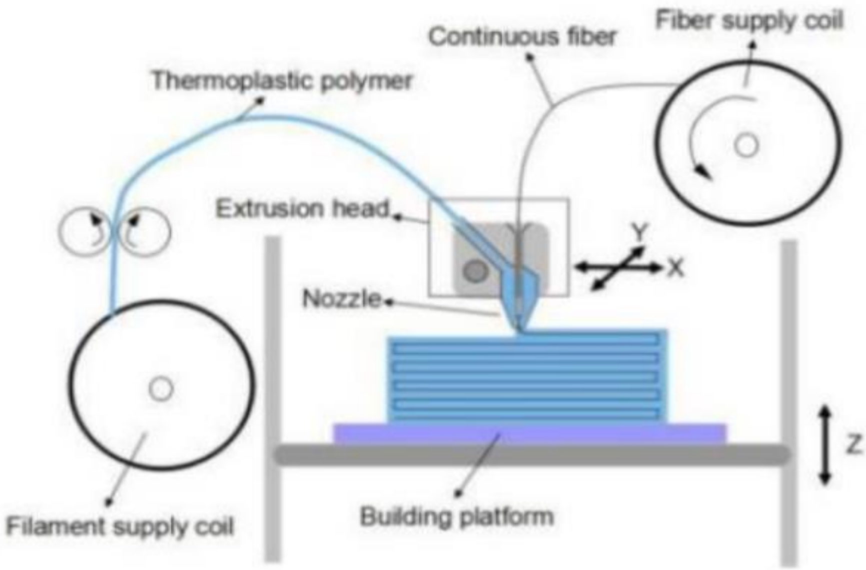

Figure 1. *Schematic Representation of Composite Printer Operation (Zhao et al., 2019)*

When making production on composite printers, first of all, software for preparation for printing that comes with the printer is used. To which layers the reinforcement materials (carbon fibre, fiberglass or kevlar) will be added is designated on this software and therefore all layers of the work piece are organised separately. In areas where stresses are critical, it is important to add the reinforcing materials at the right angle based on the density and direction of the stress formed. After the piece is prepared for printing, it is loaded onto the printer's memory for production and the production process begins. The printing process takes place on the printer thanks to composite and thermoplastic materials fed from two different nozzles Figure 2 shows 3D printing process.

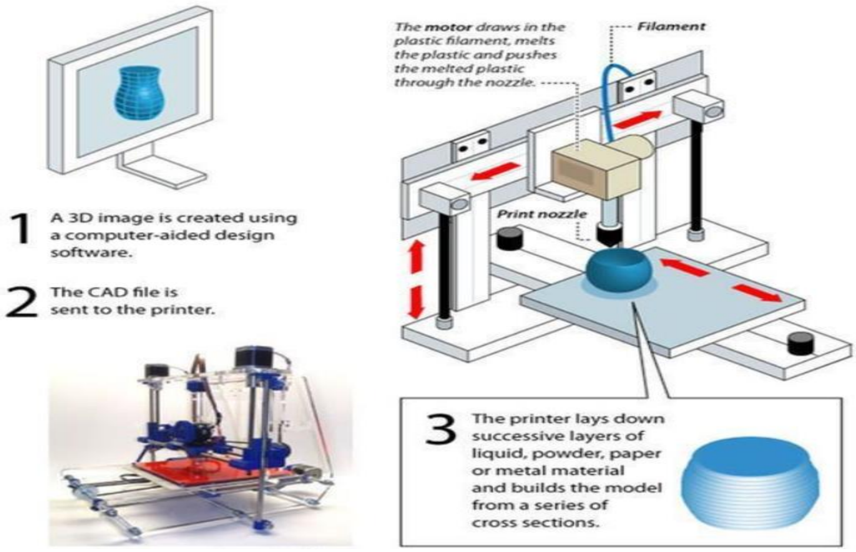

Figure 2*. 3D Printer Design and Production Process (Dronesrate, 2021)*

3. TEST STUDY AND RESULTS

In this study, Mark Two model printer of Markforged company was used. The plate dimensions are 320 mm x 132 mm x 154 mm. It is an FDM type printer with polymer matrix and supported by materials such as carbon fibre, kevlar and fiberglass. The pelton bucket developed, shown in Figure 3, by R&D Department of TEMSAN, whose dimensions are determined by analytical formulas, was produced out of composite materials with the help of this printer.

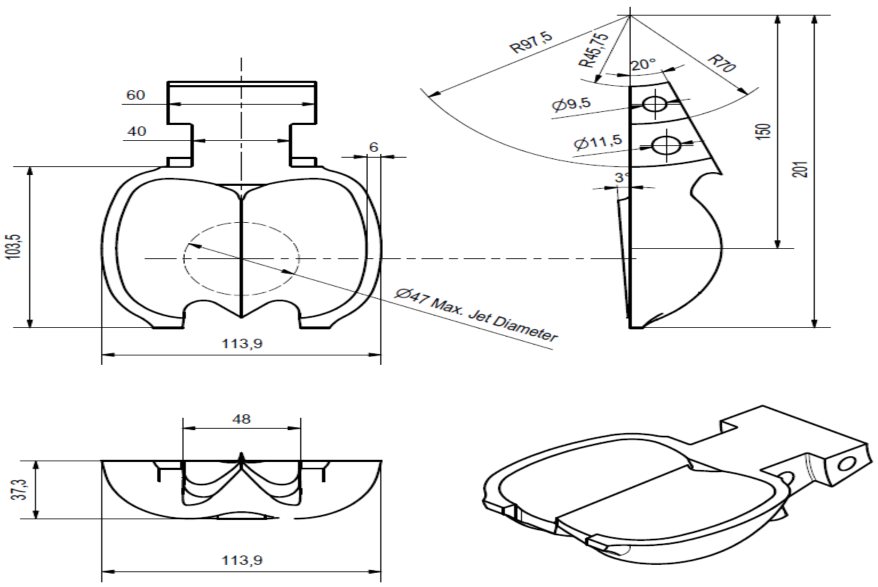

Figure 3. *Dimensions of Pelton Bucket*

In the production of Pelton bucket, the filament thermoplastic materials with a trade name of ONYX of the Markforged company were used as carbon reinforcement in the ratio of 22.9% initially and 36 % afterwards. In both test samples and production of the piece, the material fill rate was 100%. Test specimens containing 22.9% and 36% carbon (4 mm x 10 mm x 80 mm) were subjected to flexural strength test in the Mechanical Testing Department of METU Central Laboratory in accordance with ISO 14125 (2010) standard. The test results are given in Figure 4 and Figure 5.

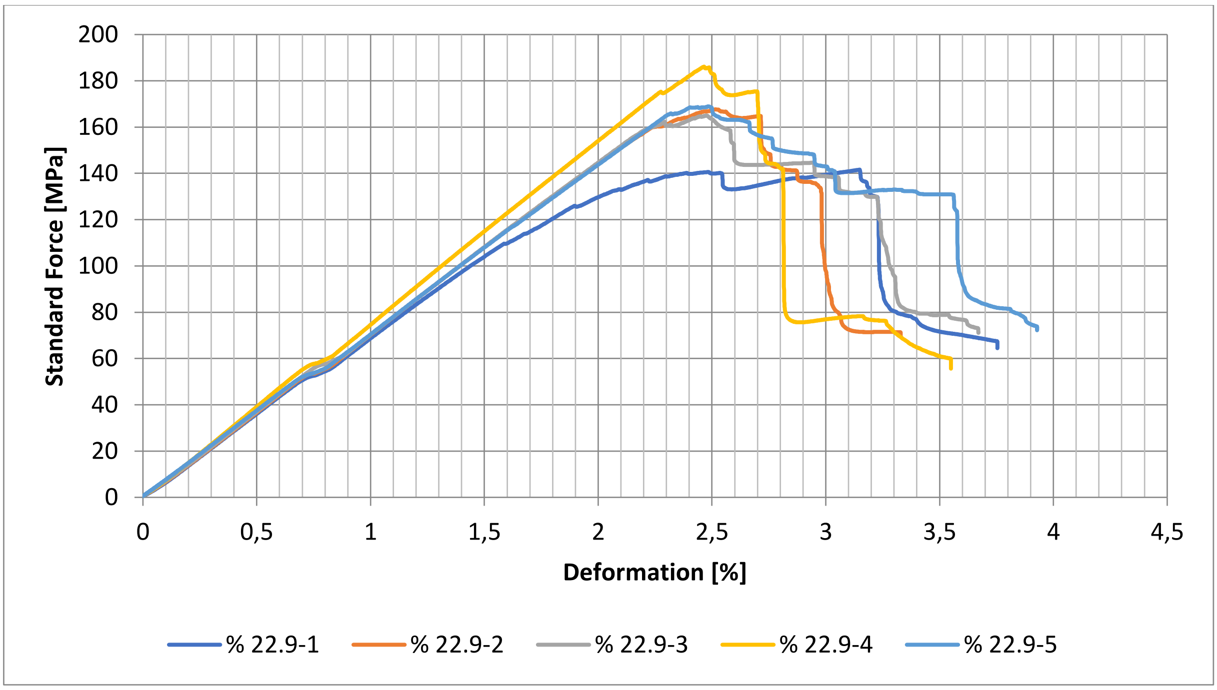

Figure 4. *Flexural Strength - Deformation Graph of Samples Containing 22.9% Carbon*

Flexural strength test at three points (ISO 14125, 2010) were performed on the universal Zwick brand testing machine as depicted in Figure 6. While the average value was 165.8 MPa (σ_m) in test samples containing 22.9% carbon filament, this value was 244.4 MPa for the samples containing 36% carbon. Table 1 and Table 2 show the average flexural strength (σ_m) tests for both carbon contents.

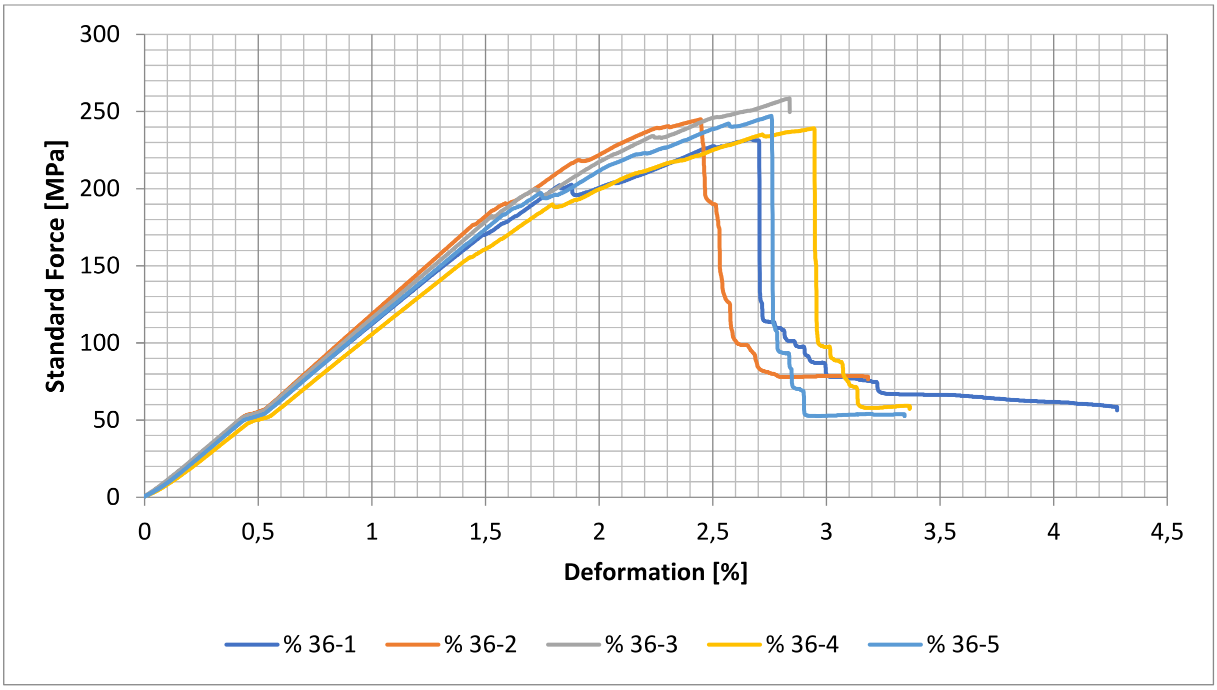

***Figure 5**. Flexural Strength - Deformation Graph of Samples Containing 36% Carbon*

While a maximum flexural strength of 186 MPa was observed in samples containing 22.9% carbon, this value reached up to 258.5 MPa in samples containing 36% carbon. Fibre reinforced composites generally aim to improve weight strength and rigidity against weight ratios (Shirisha et al., 2014). When the test results are considered, it shows that the amount of deformation increases by only 10%, although the flexural strength value increases by 47.4% with the increase in the amount of carbon by volume. This shows that the material can be more rigid with increased carbon content.

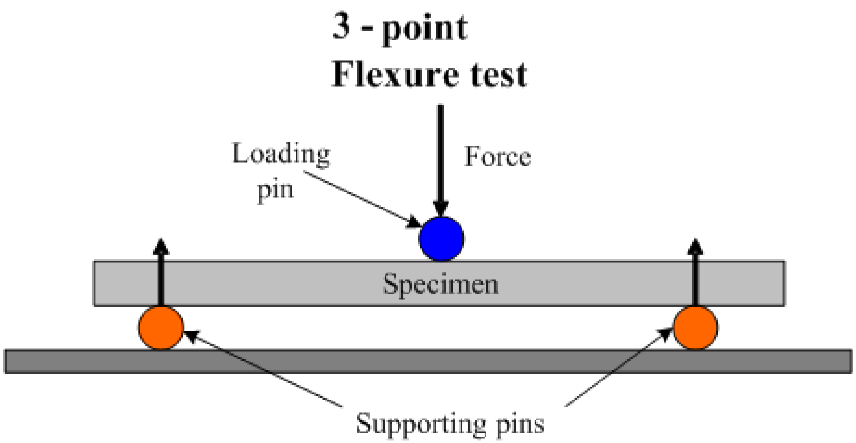

***Figure 6.** Schematic Representation of the 3 Point Flexural Strength Test (SubsTech, 2021)*

Increasing the carbon content of the test samples by volume increases the flexural strength values. Pelton turbine buckets designed for 145 m head and 120 l/s flow rate for this study were subjected to a strength test after being produced as composite in additive manufacturing method to have the same amount of carbon rate by volume. A maximum of 3100 N force is generated on the Pelton bucket under the specified operating conditions. In the analyses carried out through finite elements method on the work piece, it was confirmed that the stress value was 145 MPa ($\sigma_{Von\text{-}Misses}$). When the flexural strength values of the samples containing 22.9% and 36% carbon are taken into consideration and the safety coefficients are calculated in the Equation (5); the values of 1.14 and 1.69 are obtained respectively.

Table 1. *Flexural Strength Test Data for the Sample Containing 22.9% carbon*

Series n=5	E_{mod} (MPa)	σ_m (MPa)	F_{max} (kg)	S_0 (mm^2)
x	6948	165.88	30.6	42
s	260.9	15.91	2.73	0.25
ν	3.76	9.59	8.93	0.60

Table 2. *Flexural Strength Test Data for the Sample Containing 36% carbon*

Series n=5	E_{mod} (MPa)	σ_m (MPa)	F_{max} (kg)	S_0 (mm^2)
x	10600	244.42	45.9	42.37
s	813.2	9.79	1.93	0.36
ν	7.67	4.01	4.21	0.85

The maximum force on the Pelton bucket was calculated by taking Equation (2) into consideration (Thake, 2000). Equation (1) and Equation (3) were used for A (water jet area) and σ_{flex} respectively.

$$d_{jet} = \sqrt{\frac{4}{\pi . C_v\ \sqrt{2g}}} \cdot \frac{1}{H_n^{0.25}} \cdot \sqrt{\frac{Q}{n_{jet}}} \quad \text{m} \quad (1)$$

$$F_{jet} = \rho \cdot Q \cdot V_{jet} \quad \text{N} \quad (2)$$

$$\sigma_{flex} = F_{jet}/A \quad \text{MPa} \quad (3)$$

$$V_{jet} = C_V \cdot \sqrt{2gH} \quad \text{m/s} \quad (4)$$

$$S = \sigma_m/\sigma_{von-m} \quad (5)$$

It was decided to perform a tensile strength test taking into account the safety coefficients of samples containing 36% carbon prior to application tests. Samples containing 36% carbon were prepared in accordance with ISO 527-4 (2007) standard and tensile strength test was performed in the same laboratory. The graph for the tensile strength test results of five samples is given in Figure 7 and Table 3.

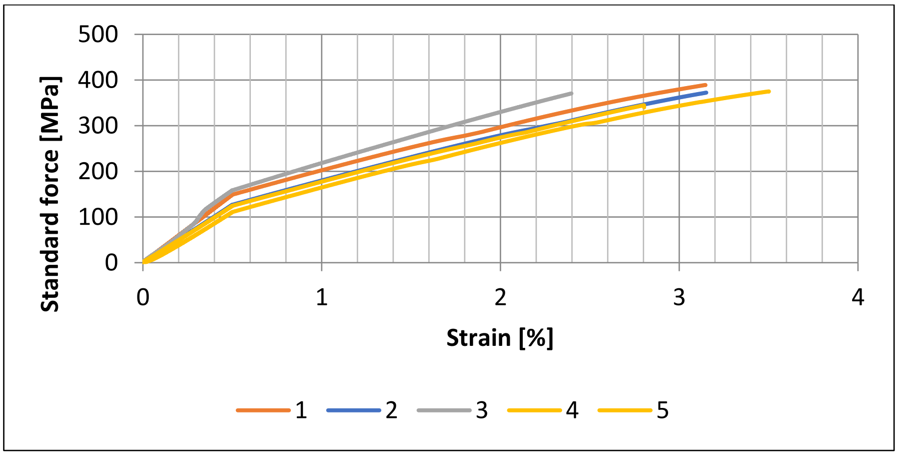

Figure 7*. Graph for Tensile Strength Test Result of Samples Containing 36% Carbon*

Table 3. *Tensile Strength Test Data of the Sample Containing 36% Carbon*

Series n=5	E_t (MPa)	σ_m (MPa)	ε_m (%)	b (mm)	h (mm)	A_0 (mm^2)
x	25500	370	3.0	25.04	2.714	67.95
s	3170	16.1	0.42	0.03271	0.0305	0.76
ν	12.41	4.35	13.93	0.13	1.12	1.12

It was decided to produce five pieces of Pelton buckets in the dimensions given in Figure 3, with a carbon content of 36% (73.5 cm^3) by volume. Application tests were performed in Hydraulic Test Centre of TEMSAN, which is shown schematically in Figure 8.

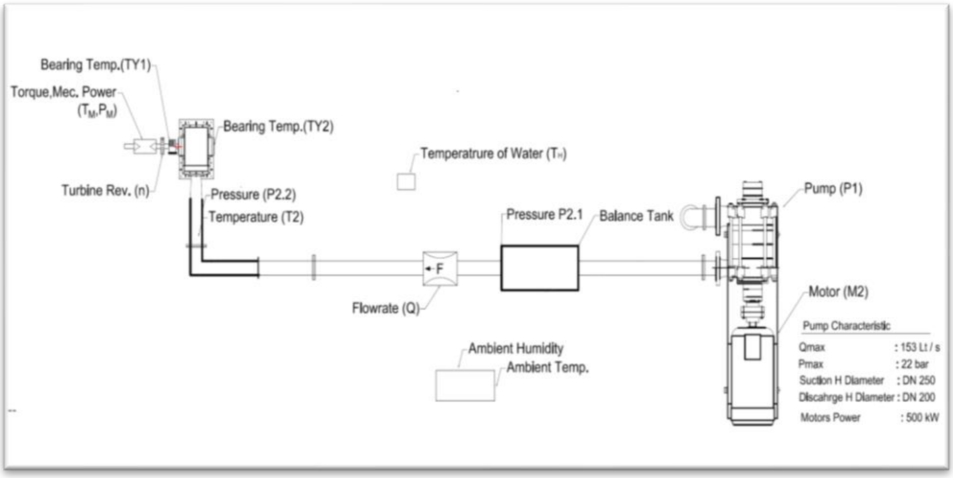

Figure 8. *Schematic Drawing of Hydraulic Test Centre*

These buckets were fixed to the shaft as shown in the schematic drawing in Figure 9 and subjected to maximum water jet force. With the help of Equations (2) and (4), breaking forces were managed to be determined. Flow rates applied in the hydraulic test centre were measured by Modmag magnetic flow meter and pressures were measured by Keller (PA-21Y) pressure transmitter. The needle opening can be adjusted automatically by means of a hydraulic cylinder and system having a measuring ruler sensor. Thanks to these highly accurate measuring elements, parameters such as flow rate, pressure and nozzle openings, which are considered to be the most significant factors affecting the operating conditions of a hydraulic turbine unit, can be controlled very precisely.

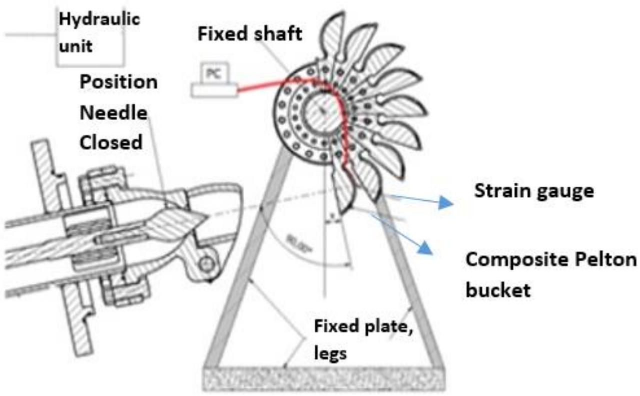

Figure 9*. Application of Water Jet on Composite Pelton Bucket*

The buckets used in the application are numbered as buckets 4, 5, 8, 10 and 11. The production of these buckets was carried out at a room temperature of (20°C) and an average relative humidity of 75%. Pelton buckets consist of 337 layers containing thermoplastic and carbon. The production time lasted 35 hours. Post-production dimensions and weights of each bucket were inspected. 400 µm thick polymer material was used in the outer layers for smoother surface and dimensional accuracy.

During breaking tests, the test was halted at each pressure value until flow rate was stable. Pelton buckets were then kept under load for 10 minutes for each flow rate value. In addition to this, the buckets remained under load during the transition. Pressure transitions and stabilising of flow rate in the system lasted 10 min. In order to observe the breaking pressure and flow rate value of the bucket remotely, a strain gauge was attached to the buckets as shown in Figure 10. An Arduino-based program was composed to see the breaking value instantly. Thus, the breaking moments of the buckets were observed on the program without any problems. In order to prevent the turbine runner from rotating in the system, flanges were attached to both ends of the shaft and these flanges were mounted on a welded construction through an interconnection rod. Adjustment of flow rate was carried out with a needle driven by a hydraulic cylinder. The pressure of the system was controlled by a frequency controlled multistage pump.

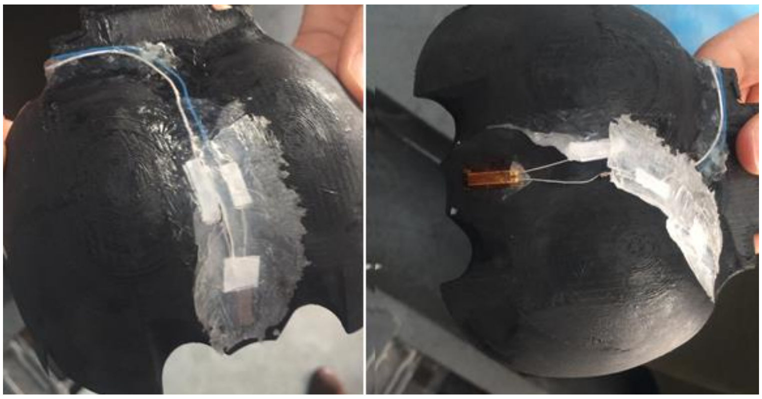

***Figure 10**. Connection of Strain Gauges on Pelton Buckets*

The densities of carbon and thermoplastic (Onyx) materials used in production are 1.4 g/cm^3 and 1.2 g/cm^3 respectively. The weight of the buckets produced in additive manufacturing method is 200 g (± 10 g). The same bucket made of steel weighs 1338 grams. There is a 85% reduction in the weight of one turbine bucket.

When the graph in Figure 11 is examined, it is seen that Pelton buckets are broken at different flow rate and pressure values. The breakage of the buckets was observed to be in 2 ways; breaking by separating from their layers and breaking by bending. The bucket #11, on which breaking by bending was observed, has a breaking pressure of 7.44 bar, a breaking flow rate of 46 l/s and a breaking force of 1775 N. Similarly, the bucket #8, which was broken in a similar manner, was broken at a force of 7.52 bars, 44 l/s and 1746 N.

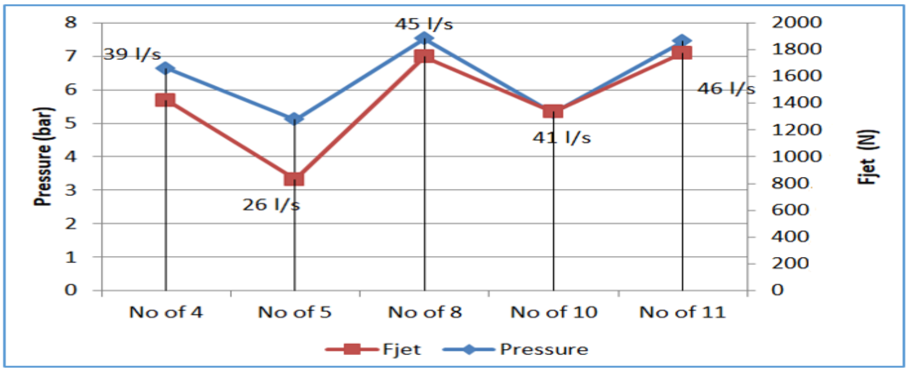

***Figure 11**. Pressure, Flow and Breaking Force Values Applied on Pelton Buckets*

Breakage occurred in both pelton bucket samples in the regions where maximum stress was formed as seen in Figure 12. The remaining three samples were separated from the layers, as shown in Figure 13. These buckets were separated from their layers at lower forces.

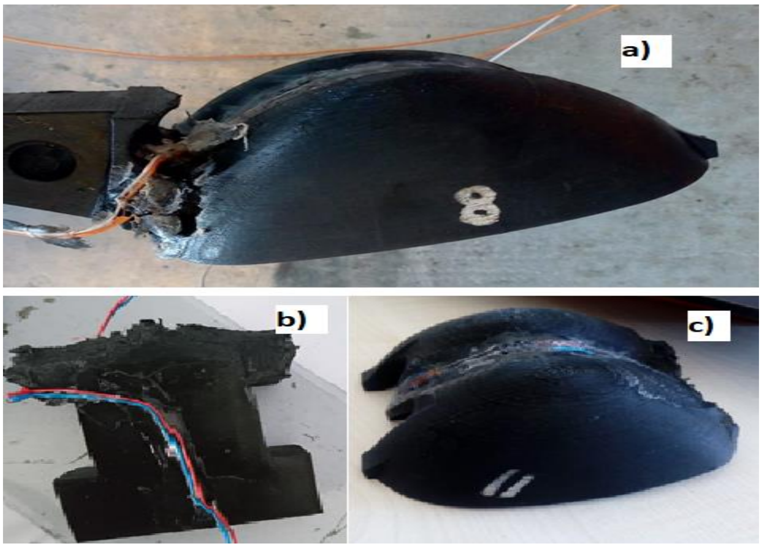

***Figure 12**. **a)** Broken bucket #8, **b)**, **c)** Broken parts of bucket #11*

***Figure 13**. Breaking photos of **a)** Bucket #4, **b)** Bucket #5, **c)** Bucket #10*

The bucket #4 has the highest breaking strength out of the buckets separated from their layers and the bucket breaking pressure of this bucket is 6.64 bars, breaking flow rate is 39 l/s and breaking force is determined to be 1420 N. When the production follow-up schedules of these buckets are examined, it is seen that production stops at the 300th layer during the production of bucket #10 for about 10 hours. Therefore, it can be thought that the cooling of ambient and piece temperature that will occur during the pauses during production affects the adhesion strength of the layers (Ali et al, 2019). In the breaking tests applied, it is seen that none of the buckets can get close to the forces, working pressure and flow rate values designated in the design values. The main reason for this is that the acceptance of the safety coefficient of (> 1.5) designated at the design stage is suitable for steel materials but the same acceptance is not suitable for a composite material produced by additive manufacturing method. It is considered that if the additive composite parts are to be used especially in machines subject to sudden load changes such as hydraulic turbines, the safety coefficient acceptance should be higher provided that the suitable production conditions are provided.

4. CONCLUSION AND DISCUSSION

The combination of different materials and the use of new production techniques (additive manufacturing) in the Pelton turbine bucket, which is one of the hydraulic turbine types, were investigated.

The Pelton turbine runner has a specially defined form. In this study, the Pelton runner produced as composite is 1/8 lighter than the steel material. This would provide the manufacturer with ease of application, such as transport and installation, as well as reduced radial forces from the turbine bearings, resulting in longer bearing life.

The composite material contains 36% C and 64% thermoplastic material (Onyx). In the mechanical tests carried out on the test specimen, the flexural strength value of 244.42 MPa and the tensile strength of 370 MPa were obtained. This value is very close to carbon steel mechanical values of 1.0037.

In breaking tests, some samples were separated from their layers and broke. Temperature and humidity are thought to be significant during additive manufacturing. It was also determined that any waiting or stopping during production affects the adhesion of the layers to each other. However, the breaking forces increased to 1775 N in two samples that demonstrated normal breaking behaviour. However, this result is considerably less than the expected value. The reason for this is that it is considered appropriate to select the safety coefficient acceptance at the design stage of the products with composite additive manufacturing in the machines with variable loads such as hydraulic turbines. In particular, testing for the safety coefficient value of >4 is recommended for further studies. However, this acceptance would not apply to all machinery equipment. For this reason, it will be appropriate to make security assumptions appropriate to the machine equipment in the production of composites with additive method.

Additive manufacturing is a new and rapidly expanding production technique. In our study, additive manufacturing technique provided the opportunity to quickly prototype and performs the tests related to the mathematically designed equipment such as turbine runners. Especially in the field of energy equipment, manufacturing method, acceptance of design and testing of different products such as fatigue will provide cost and time savings for project-based manufacturers. In this study, while the material cost of Pelton bucket produced as composite per unit was 200 €, the unit cost of the bucket made of metal is 301 €.

However, in the future, by changing the design assumptions such as the safety coefficient of the composite turbine runners produced in additive manufacturing method and increasing the carbon content, which is the support material, the use of hydraulic turbine runners manufactured by these methods can be realized in practice.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this paper.

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