İmalat Teknolojileri ve Uygulamaları
Cilt: 4, No: 1, 2023 (25-36)
Araştırma Makalesi
e-ISSN: 2717-7475

Manufacturing Technologies and Applications
Vol: 4, Issue: 1, 2023 (25-36)
Research Article
e-ISSN: 2717-7475

Comparison of Strength, Surface Quality and Cost of Different Additive Manufacturing Methods

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ARTICLE INFORMATION

Received: *15.03.2023*
Accepted: *03.04.2023*

Keywords:
Additive manufacturing
Cost analysis
Strength
Surface quality

ABSTRACT

Additive manufacturing is a manufacturing method that includes systems that produce using many different methods. The most widely used and accessible methods of additive manufacturing can be listed as Fused Deposition Modeling (FDM), Selective Laser Sintering (SLS) and UV light assisted Stereolithography (SLA). Today, it is quite easy to produce thermoplastic products suitable for direct use in low quantities with these three methods. In addition, the production success of the parts produced in geometric difficulties also increases this demand. The most important problem is the lack of sufficient studies and information about the strength limits, surface quality and costs of the parts produced for additive manufacturing methods with such advantages. In this study, the comparison of three different production methods in terms of surface roughness, strength and cost is discussed in order to eliminate this deficiency in the literature. For this purpose, the tensile strength and surface roughness values of the samples produced using FDM, SLS and SLA methods were determined. In addition, cost analyzes were made depending on the production time of the produced samples. In the study, the lowest cost was obtained in the SLA material with a value of $ 0.19. Again, the lowest values were obtained for the samples produced from SLA material, with a production time of 17 minutes and a surface roughness of 1.96µm compared to other methods. However, when evaluated in terms of strength, the highest strength value was obtained as 57.67 N/mm^2 in the FDM method.

Farklı Katkılı Üretim Yöntemlerinin Dayanım, Yüzey Kalitesi Ve Maliyetlerinin Karşılaştırılması

MAKALE BİLGİSİ

Alınma: *15.03.2023*
Kabul: *03.04.2023*

Anahtar Kelimeler:
Eklemeli İmalat
Maliyet analizi
Mukavemet
Yüzey kalitesi

ÖZET

Katmanlı imalat, birçok farklı yöntem kullanılarak üretim yapan sistemleri içeren bir imalat yöntemidir. Katmanlı imalat yöntemlerinden en yaygın kullanılan ve erişilebilir yöntemler Fused Deposition Modeling (FDM), Selective Laser Sintering (SLS) ve UV ışık destekli Stereolitografi (SLA) olarak sıralanabilir. Günümüzde bu üç yöntem ile düşük miktarlarda doğrudan kullanıma uygun termoplastik ürünler üretmek oldukça kolaydır. Bunun yanında geometrik zorluklarda üretilen parçaların üretim başarısı da bu talebi arttırmaktadır. Bu kadar avantaja sahip katmanlı imalat yöntemleri için üretilen parça dayanım limitleri, yüzey kalitesi ve maliyetleri hakkında yeterli çalışma ve bilgi olmaması en önemli sorun olarak karşımıza çıkmaktadır. Bu çalışmada literatürdeki bu eksikliği gidermek amacıyla üç farklı üretim yöntemi yüzey pürüzlülüğü, mukavemet ve maliyet açısından karşılaştırılması ele alınmıştır. Bu amaçla FDM, SLS ve SLA yöntemleri kullanılarak üretilen numunelerin çekme dayanımları, yüzey pürüzlülük değerleri belirlenmiştir. Ayrıca üretilen numunelerin üretim süresine bağlı olarak maliyet analizleri yapılmıştır. Çalışmada en düşük maliyet 0.19 $ değer ile SLA malzemede elde edilmiştir. Yine SLA malzemeden üretilen numuneler için 17 dakika üretim süresi ve 1.96µm yüzey pürüzlülük değerleri diğer yöntemlere nazaran en düşük değerler elde edilmiştir. Ancak dayanım açısından değerlendiğinde en yüksek dayanım değeri FDM yönteminde 57.67 N/mm^2 olarak elde edilmiştir.

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To cite this article: *M. M. Sofu, H. Varol Özkavak, S. Bacak, M. Fenkli, Comparison of Strength, Surface Quality and Cost of Different Additive Manufacturing Methods, Manufacturing Technologies and Applications, 4(1), 25-36, 2023. https://doi.org/10.52795/mateca.1265509*

1. INTRODUCTION (GİRİŞ)

Additive manufacturing (AM), also known as 3D printing, is a technology used in many fields such as aerospace, biomedical, automotive and turbomachinery in the industry. In addition, the AM method is also used in the production of auxiliary elements such as tools, gauges and fasteners used in manufacturing [1]. AM has many advantages such as prototyping for new designs, enabling the manufacturer to be more agile, reducing the time required for innovation, taking direct physical outputs from the digital form, and thus revealing new design ideas. Although many AM techniques have been developed since the 1980s, this technology, whose commercialization has been delayed, has become an important place in the material and service sector after 2016 [2]. The AM method is used in many areas such as sports and musical instruments, lightweight prosthetic legs, dental splints and injection molding. with AM, significant changes are expected in the automotive, aerospace and medical industries [3]. While AM causes a significant decrease in fuel consumption due to the production of complex and light parts for the aviation industry, the patient-specific production with the AM method in the medical industry and the rapidity of this production have made the costs affordable. This is particularly effective in hearing aids, prostheses and surgical guides and models [3]. In the automotive industry, it provides advantages such as shortening the production time of special parts in small groups, increasing the delivery time and saving costs. In addition, many chemical companies and research industries have started to use the AM method for the production of special materials [4]. With the increasing demand for AM manufacturing, AM equipment companies have started to invest heavily in technological innovations. The best example of the innovations made is printing more than one material at the same time using multiple print heads [5,6].

There are many polymer AM techniques for rapid prototyping in industry. These techniques have been examined by ASTM in 7 groups and these are 1. Material extrusion, 2. Powder bed fusion, 3. Vat photopolymerization, 4. Binder spraying, 5. Material spraying, 6. Directed energy deposition and 7. Layer lamination. The common theme between these methods is to produce the 3D part by producing the materials layer by layer. When the methods are considered in general, while the filament is used as the feeding material in the FFF (Fused Filament Fabrication) method; 20-150 µm powder material in SLS (Selective Laser Sintering) method; Liquid resins are preferred in SLA (Steriolithography) method. The comparison for each method is given in Table 1. Figure 1 provides a comparison of technical capabilities for various AM methods.

Table 1. Comparison of different AM techniques [1] (Farklı AM tekniklerinin karşılaştırılması)

Technology	SLS	FDM	MJF	SLA
Category	Powder bed fusion	Materials extrusion	Powder bed fusion	Vat photopolymerization
Feed Stock	Powder	Filament	Powder	Liquid resin
Materials	Metals,thermoplastics,glass,ceramics	Large variety of thermoplastics	Nylon 11 and 12, TPU	Photopolymers
Resolution(microns)	60-150	50-500	21	25
Support (for complex printing)	Not requried	Requried	Not requried	Requried
Recyclability	Manual	N/A	Automatic	N/A
Machine Price (USD)	> 250.000	> 200	> 300.000	> 3500

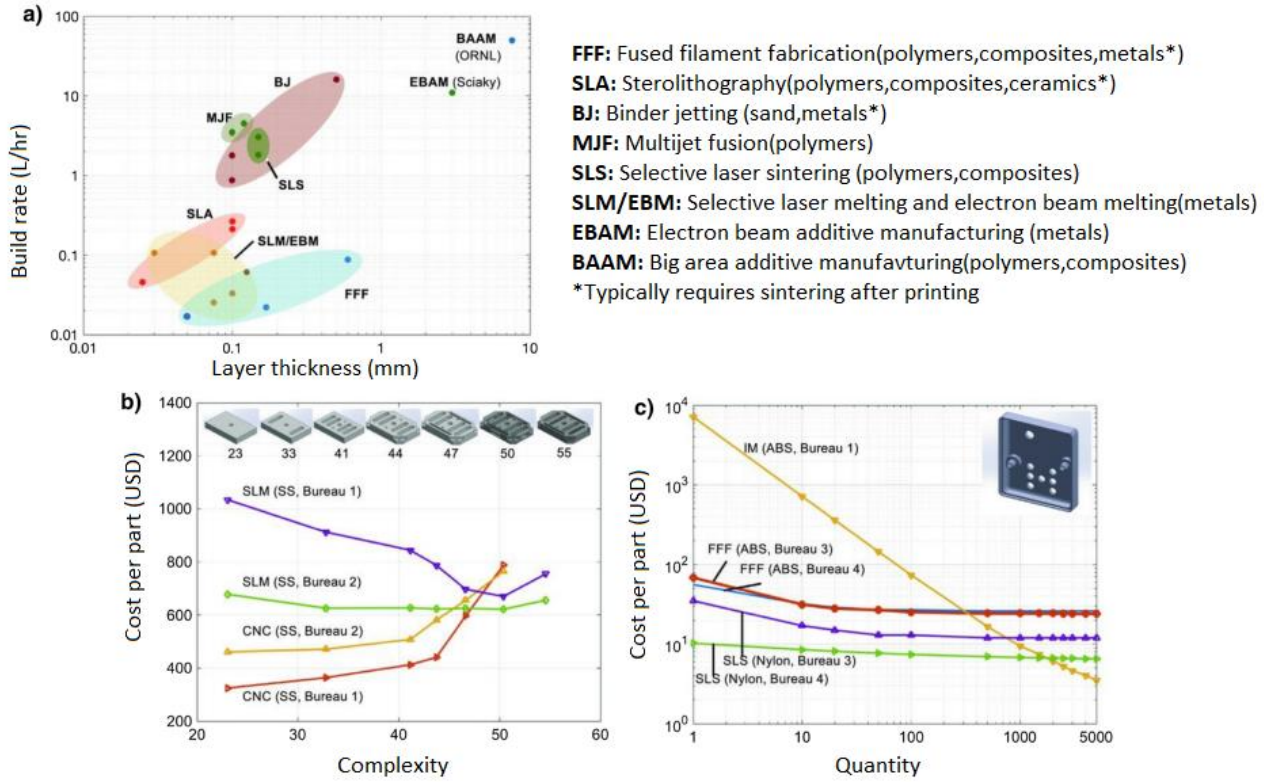

Figure 1. A comparison of technical capabilities for various AM methods [1] (Çeşitli AM yöntemleri için teknik yeteneklerin karşılaştırılması)

Although many materials have been developed for each AM method, certain materials are commonly preferred for each method. For this reason, developing materials for the AM method is currently the subject of studies. FDM rapid prototyping is a widely used AM method for composite component design due to its many superior features such as rapid production and low cost [7]. Compared to other traditional methods, the FDM method has lower mechanical properties due to the porosity that occurs during the printing process. However, for applications in tissue engineering, such as skeletal design, high porosity may provide some advantages. In addition, thanks to the space density control and filament orientation, the customization of the mechanical properties is provided by the FDM method. Considering all these, it is clearly observed that there are many parameters that affect the quality and properties of the part in the FDM method. In the FDM method, the mechanical properties depend on parameters such as filament material property, space density and fiber-to-fiber bond strength [8]. When the studies on the FDM method are examined, the parameters affecting the process quality are determined as nozzle temperature, layer thickness, and raster and structure direction [9]. Es-Saeid et al. In their study, they examined the effect of sheet orientation on mechanical properties. In this Study, it was determined that the best features were obtained at 0° orientation, and the lowest features were obtained at 45° orientation. In addition, it was determined that the breaks were obtained along the layer interface in the study [10]. Maloch et al. They discussed the effect of extrusion nozzle and layer thickness on the mechanical properties of the samples produced from ABS material by the FDM method. The authors concluded in this study that the best properties are obtained at low thicknesses, and that good melting is achieved between adjacent layers with increasing nozzle temperature [11]. Radriquez-Panez et al. examined the mechanical properties of PLA and ABS thermoplastic materials produced by the FDM method. At the end of the study, it was determined that the mechanical properties of the samples produced from PLA material were higher than the samples produced from ABS. It was also determined that ABS showed lower variability [12]. Examining the tensile properties of ABS and PC parts, Cantrell et al. determined that the structure and raster orientation have significant effects on Young's Modulus and Poisson's Ratio. PC samples showed anisotropic behavior [13]. Warnung et al. in their study, used 8 different materials in the FDM method. The authors concluded that the strongest material was obtained in the case of using PA wire, while the hardest material was obtained in the case of using wire made of PET material reinforced with carbon fiber [14]. Valean et al. investigated the effect of process parameters (print direction, layer thickness/size effect) on the tensile properties of PLA material produced by FDM method. In their study, they reached the following results: While the Young's modulus changes 1.8% according to the compression direction; tensile strength changed by more than 8%. In addition, both tensile strength and Young's modulus decreased with increasing layer thickness [15].

Production with SLA is the widely used AM method for polymer materials due to its wide range of properties [16]. Production of parts with high resolution and precision can be expressed as the main advantage of SLA technology [17]. In the SLA method, the pieces are formed by the adhesion of the polymer layers to the previous layer. This situation causes no weakness to occur at the junction of the layers [18]. Jacobs discussed inhomogeneous mechanical properties of SLA models in his work. Through this work, the author determined that the mechanical properties of SLA depend on the function of the laser opener and will reduce the shrinkage that occurs during part fabrication [19]. Mahan and Bayly applied the impact test to SLA samples produced in different directions (XY, YZ, ZX) and the authors obtained the highest strength in the samples produced in the XY plane [20]. Benerjee et al. investigated the effect of post-curing time and layer thickness on the tensile strength of SLA samples. At the end of the study, the authors determined that the tensile strength primarily depends on the layer thickness and the effect of curing time on small parts such as test specimens is low [21]. Chackaligam and Jawahar investigated the effect of layer thickness on mechanical properties in their study. And with these studies, they found that an increase in tensile strength occurs when low layer thickness is selected [22].

Wohlers in this report, SLS is a 3D technology that has found application in many sectors such as hearing aids and Formula 1 vehicles. In addition, in some aircraft, parts produced with the SLS method are used. However, the parts used are limited due to low mechanical properties. For this reason, studies have focused on improving the mechanical properties of the parts produced by the SLS method [23]. Zarringhalam et al. They conducted research on the reproducibility and improvement of the mechanical properties of Nylon 12 material using the SLS method. And at the end of their research, they determined that while an increase in tensile strength was observed with some machine parameters, there was no change in Young's modulus [24].

When the literature is examined, 3D technology has become a technology used in many sectors. It is observed that this technology will be used more widely with the further improvement of mechanical properties. It is seen that literature studies focus on determining the effect of process parameters of SLS, SLA, FDM methods used in 3D technology on strength values. When the reasons for the preference of 3D technology are examined, it is also noteworthy that the costs are low. It is clearly seen that this feature has not been evaluated in the studies carried out. For this reason, one of the focal points of the study has been material cost analysis. For this purpose, samples were produced with SLS, SLA and FDM methods by choosing the optimum process parameters (100 % occupancy rate and low layer thickness) determined in the literature. Manufacturing times were also measured during the production of the samples. Surface roughness and tensile strength of the samples obtained after production were determined. In addition, material cost analysis was performed for each sample. After the experimental studies, strength-cost-production time and surface roughness comparisons were made. Thus, the selection of the method to be used for the part planned to be produced becomes more efficient.

2. MATERIAL AND METHOD (MATERYAL VE YÖNTEM)

2.1. Production of Samples (Numunelerin Üretimi)

In this study, it is aimed to select the appropriate production method by comparing the samples produced using FDM, SLS and SLA methods in terms of strength, surface roughness and material cost. For this purpose, the samples used for mechanical experiments in the study were prepared in the form of solid models in accordance with ASTM D638-IV standard and then saved in a file with STL extension in a format suitable for slicing software. In all three methods, two samples were produced on each printer at a time in order to calculate and compare the time spent while performing more than one production at the same time. In order to compare the strength values in all three methods, 100% fill density was used. In addition, for each method, the software developed by the manufacturers of the devices belonging to that method was preferred as the slicing software. When placing the samples on the printer table, the same positioning was made for each method in order not to create an imbalance in production time. In addition, the time spent between the start and the finish of production of the printer was recorded in order to determine the production time of the samples in all methods.

2.2. Production by FDM Method (FDM Yöntemiyle Üretim)

In the study, Makerbot brand 5th generation Replicator model three-dimensional printer was used for production by FDM method. The feature of this printer is the use of a special head system with a nozzle diameter of 0.4 mm, which is launched as a smart extruder. Smart extruder provides contact control with a special sensor structure and height optimization in layer thicknesses. In this way, it can reduce the layer thickness to 0.05 mm. Two samples were produced in Makerbot print slicing software with a 0.05 mm layer thickness and 95% (maximum setting) fill density (Figure 2). 1.75 mm diameter PLA+ filament material was used in the production made by FDM. The maximum stress value for the filament of the FDM manufacturer is given as 33 MPa.

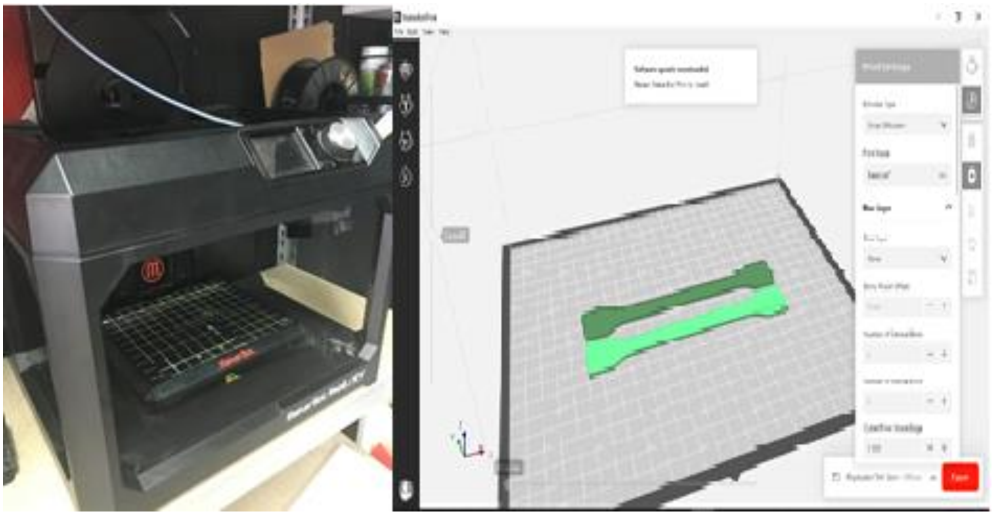

Figure 2. Makerbot printer and MaketBot Print slicing software used in the FDM method (FDM yönteminde kullanılan Makerbot yazıcı ve MaketBot Print dilimleme yazılımı)

2.3. Production with SLA Method (SLA Yöntemiyle Üretim)

Another method used in sample production is the SLA method. For the method, Anycubic brand Photon s model, a three-dimensional printer using 405 nm UV matrix light was preferred (Figure 3). A white photopolymer resin of Anycubic Company was used as the material, which reacts in UV light at a wavelength of 405nm.

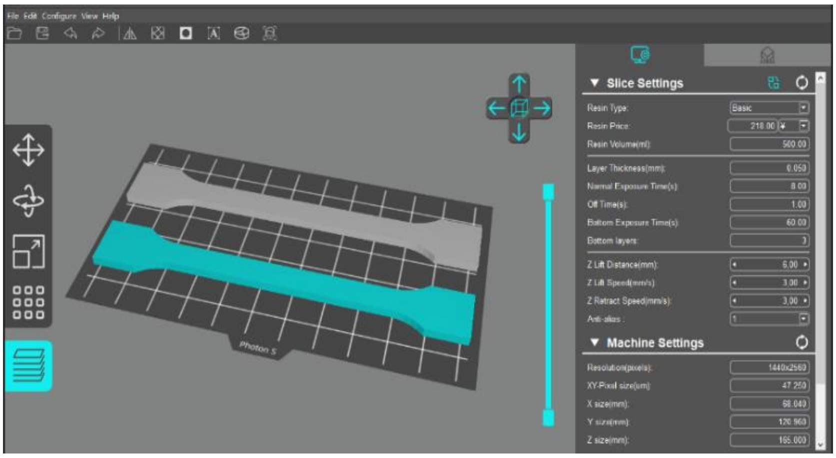

Figure 3. Preparation of samples for the SLA method (SLA yöntemi için numunelerin hazırlanması)

2.4. Production by SLS Method (SLS Yöntemiyle Üretim)

A Sinterit brand Lisa model desktop printer was chosen for the SLS method used in the study (Figure 4). The laser power of the printer is IR Laser Diode 5 W, 808 nm. For production, the temperature of the powder chamber is increased up to 178°C with halogen heaters. In this way, the printer can reach instant melting temperature by using 8W power. The minimum layer thickness of the printer is 0.075 mm.

Figure 4. Sinterit lisa brand printer and production area used in SLS method (SLS yönteminde kullanılan Sinterit lisa marka yazıcı ve üretim alanı)

The material used in the SLS printer is highly nylon; PA 12 is a nylon-based powder sold in smooth form. The tensile strength of the polyamide powder is 32 MPa, the breaking elongation is 10 %, the melting point is 185 °C and the grain size of the powder is between 18 – 90 µm. Two samples in ASTM D638-IV standard were produced with 0.075 mm layer thickness with Sinterit studio slicing software in Figure 5. Not all of the powder was used as new powder during production. In accordance with the process proposed by the company, the production was carried out by mixing 26% new powder with the previously used powder mixture.

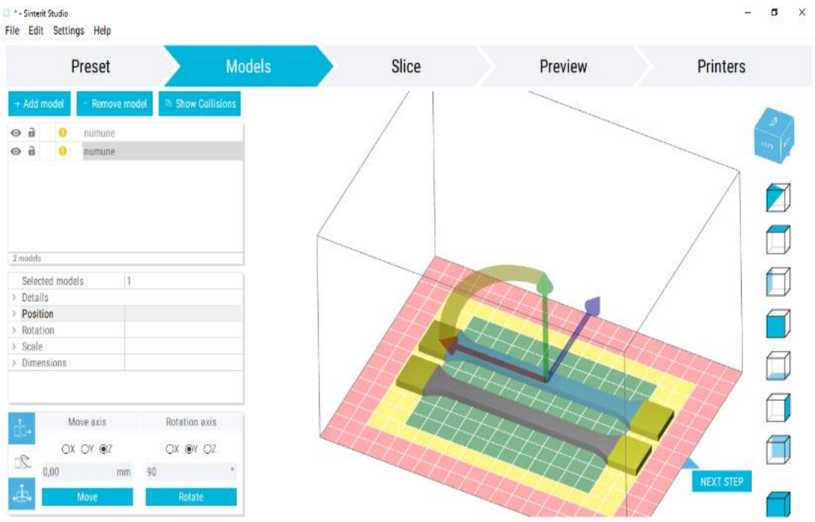

Figure 5. Positioning of samples in Sinterit studio slicing software (Sinterit studio dilimleme yazılımında örneklerin konumlandırılması)

2.5. Surface Roughness Measurement (Yüzey Pürüzlülüğü Ölçümü)

The surface roughness measurements of the samples produced horizontally on the table in three different methods selected for the study were determined by measuring from three different regions perpendicular to the layer formation directions. The measurement was made at two different points on the surface with the Hommel Verke Tester T500 device. The sampling length (Lc) was taken as 0.25 mm, the measuring length (Lm) 1.25 mm (5.Lc) and the traverse length (Lt) 1.5 mm. The measuring device gives the roughness values (Ra) in µm. This device measures Ra surface roughness parameter according to ISO 4287/1 standard.

2.6. Tensile test (Çekme testi)

In the study, it is aimed to compare the tensile strength values of the samples produced separately using three methods. Tensile tests were applied to the samples produced for this purpose as in Figure 6.

Figure 6. Tensile test and deformation (Çekme testi ve deformasyon)

Tensile tests applied to the samples were carried out in a 10KN capacity Shimadzu AGS-X brand electromechanical static test device at a tensile speed of 1 mm/min and at room temperature. The dimensions of the tensile test specimens produced in the ASTM D638-IV standard for the study are given in Figure 7.

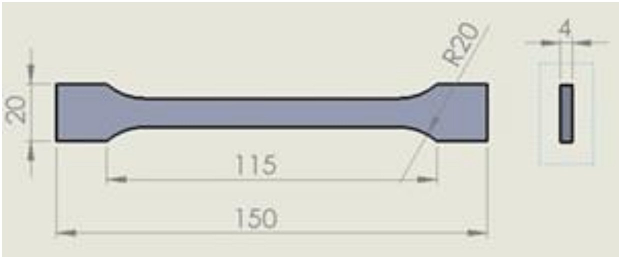

Figure 7. Tensile specimens produced in accordance with ASTM D638-IV standard used in the study (Çalışmada kullanılan ASTM D638-IV standardına uygun olarak üretilmiş çekme numuneleri)

3. RESULTS (SONUÇLAR)

In the study, it is aimed to compare the strength, surface roughness and cost of the samples produced using SLA, SLS and FDM methods, and thus to choose the most efficient method.

Surface roughness is a key property for additive manufacturing methods. The preparation of the product according to its finish properties is important for the surface roughness value. Selecting the appropriate material, working conditions and method for rapid prototyping technology has a significant effect on achieving the targeted surface roughness and extending the service life during operation. It is expected that the surface roughness of the post-production parts will be low as in other methods. Since it is a key feature for additive manufacturing and affects the service life of the produced part, surface roughness examinations of the samples produced for each method were made in the study. The results obtained as a result of the measurements are given in Table 2. When Table 2 is examined, the lowest roughness values are 1.97 µm and 2.16 µm in SLA samples; the highest roughness values were obtained as 14.68 µm and 15.63 µm in the samples produced using the FDM method.

Table 2. Surface roughness measurement results (Yüzey pürüzlülüğü ölçüm sonuçları)

Measurement (µm)	FDM	SLA	SLS
1.	14.68	1.97	8.73
2.	15.63	2.16	6.8

Sample weight is important in terms of sample cost. For this reason, the weights of the produced samples were measured using precision balances and the obtained values are given in Table 3.

Table 3. Weights of manufactured parts (Üretilen parçaların ağırlıkları)

PLA +	PA 12 smooth	Resin
9.518 gr	6.992gr	9.642gr

In the parts manufactured with the additive manufacturing method, it is required to have high strength values, as in the production using other methods. Many studies have been carried out in order to obtain the desired strength values and are still in progress. In this study, it is aimed to compare the methods in terms of tensile strength as well as material cost analysis. For this purpose, samples with 100% filling ratio were produced by PA12 for SLS method; using PLA for the FDM method and resin material for the SLA method. The produced samples were subjected to tensile test. The maximum stress, elongation and breaking elongation values of the samples after the test are given in Table 4 and the graphics are given in Figure 8. When the table is examined, the highest maximum stress value of 56.67 MPa was obtained in the FDM method using PLA material. The lowest stress value was determined as 21.45 MPa in the samples produced by the SLA method. The maximum tensile value of the samples produced by the SLS method was obtained (21.78 MPa), which is very close to the SLA samples. However, the maximum elongation values of the samples produced by the SLS method are approximately 4.7 times that of the samples produced using the SLA method. This is an expected result and is a result of the characteristics of PA12 material. PA12 material exhibits high straining specialty in tensile strength.

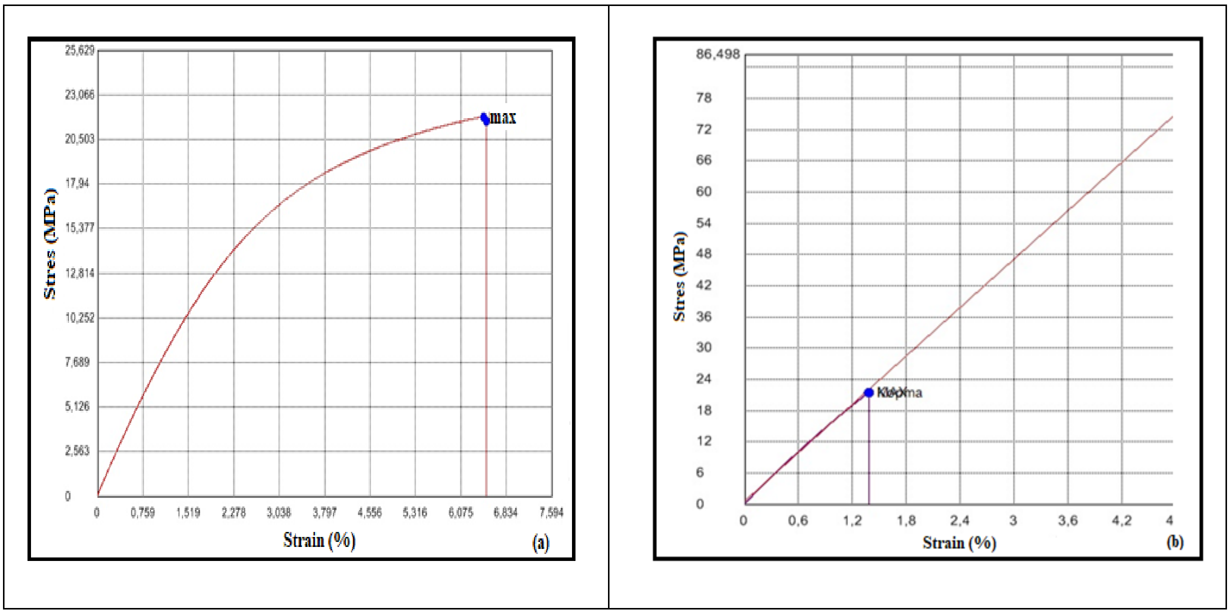

Figure 8. Stress-strain graphs of test specimens (a) PA12sample (b) resin sample (Test numunelerinin gerilim-uzama grafikleri (a) PA12 numunesi (b) reçine numunesi)

Table 4. Tensile test values obtained from the samples (Numunelerden elde edilen çekme testi değerleri)

Production Method (Material)	Maximum Stress (N/mm2)	Maximum Elongation (mm)	Breaking Sensitivity (%)
SLS (PA12)	21.78	5.81	6.5
FDM (PLA+)	57.67	2.96	4.16
SLA (Rosin)	21.45	1.24	1.38

3.1. Comparison in terms of cost and time (Maliyet ve zaman açısından karşılaştırma)

3.1.1. SLA

The production time for the UV light sourced SLA printer took 17 minutes in total. And a total of 6.930 ml of liquid resin was consumed. The price of Anycubic brand resin (1000 ml white material) on amazon.com was determined as $ 28.09, and the unit price was calculated as $0.028 /ml in ml. The weight of the sample prepared for the test is 9.642 gr. However, the value of the material used in ml determined by the software is 6.930 ml. According to this result, the price of the test sample was found to be $ 0.19.

3.1.2. FDM

The production time in the FDM method took 2 hours and 59 minutes. The production temperature was realized at 205 °C. Esun brand red 1kg 1.75 mm filament value is sold on amazon.com for $ 22.99. The unit price of the filament is calculated as $ 0.023 /gr. Sample total weight was measured as 9.518 g. According to this result, the material cost of the sample produced with filament is calculated as $ 0.22.

3.1.3. SLS

Total production time is 5 hours 56 minutes. The printer took approximately 2 hours and 15 minutes to preheat the powder in the powder chamber (175°C). The manufacturing time took 2 hours and 32 minutes. 1 hour and 12 minutes of cooling time was spent. A total volume of 16.5 cm^3 powder was used. Sinterit PA12 Smooth V2 Fresh Powder 2 kg powder can be accessed from the commercial site called imakr for $ 340. According to this price, the unit price is $ 0.17/gr. Since the weight of the test sample that came out of production is 6.992 gr, the cost of only this test sample was calculated as $ 1.188.

4. CONCLUSIONS (SONUÇLAR)

When the materials produced with three different methods are evaluated in terms of tensile strength, breaking elongation, surface roughness and material cost. Comparative preparation of the data of all results is given in Table 5.

Table 5. Comparative results of additive manufacturing methods (Eklemeli imalat yöntemlerinin karşılaştırmalı sonuçları)

Feature	FDM	SLA	SLS
Material	PLA +	UV resin 405nm	PA 12 smooth
Weight (g)	9.518	9.642	6.992
Surface roughness (µm)	14,68 - 15,63	1,97-2,16	8,73 - 6,8
Production time	2 hours 59 minutes	17 minutes	5 hours 56 minutes
Fullness	% 100	%100	%100
Strength (N/mm2)	57.67	21.45	21.78
Production cost (material)$	0,22	0,19	1,188
Machine Price	$ 1999	$ 239	Desktop SLS $ 8568

In this study, the fastest printing method is the SLA method. The ability of the system using UV light curing technique to print more than one part in the same time on the same layer causes it to be quite good at printing speed. On the other hand, in the SLS method, there is no bad surface formation due to the support of the parts produced thanks to manufacturing in powder without the need for support. In addition, in the SLS method, movable mechanisms can be produced as assembled very easily.

The highest tensile strength was measured at 57.67 MPa in the sample produced from PLA+ material, while the values were close to each other (21.45 MPa, 21.78 MPa) in the samples produced from resin and PA12 materials.

While the highest value of elongation at break was 6.5% in the samples produced from PA12 material, the lowest value was observed in the samples produced from Resin with 1.38 %.

The order of the surface roughness from the lowest to the highest was obtained from the samples produced from Resin - PA12 - PLA+ materials and their average values are respectively measured 2.06-7.76-15.15 µm. Burke et al., as a result of their work to obtain the best surface quality printing with PLA material, obtained the best surface roughness value of 12.4µm(0.2 mm) by printing in a flat direction using a 0.2mm nozzle diameter with a 5% core fill rate [25]. M. Launhardt et al., used the optical measurement method on the parts printed with the SLS method using PA12 material and found the best result as 13µm [26]. Pazhamanil et al., using vegetable-based liquid resin, measured the surface roughness on different samples printed with a DLP printer and obtained Ra values in the range of 0.67µm to 2.7µm [27]. This shows us that it coincides with the surface roughness values obtained in the literature. Even better results were obtained for parts produced for SLS.

In terms of material cost, the most affordable sample was obtained from resin material with $ 0.19, and the most expensive one was obtained from PA12 material with $ 1.88. The results obtained are in agreement with the literature [28].

Although the production with the SLS method seems more disadvantageous when evaluated in terms of all parameters, it is one of the advantages of this method to be able to produce without the need for support staff during manufacturing.

In production with the SLA method, partially unsupported manufacturing is also carried out. In addition, the production of the parts on the workbench, regardless of the number of pieces, can be realized in the same time and low surface roughness are among the advantages of production.

Considering the weights in the study, it also sheds light on studies involving specific strength, also known as strength-to-weight ratio or strength-to-weight ratio or strength-to-mass ratio. Specific strength is widely used in other applications, particularly in aerospace, where the weight savings are worth the higher material cost.

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