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GRADUATE SCHOOL OF SCIENCE AND ENGINEERING

IMPROVEMENT GEOMETRICAL PRODUCT SPECIFICATIONS OF ADDITIVE MANUFACTURED PARTS

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M.Sc. THESIS

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A thesis submitted by Hulusi Bugra BAGCI in partial fulfillment of the requirements for the degree of M.Sc is approved by the committee on 12.05.2022 in Department of Mechanical Engineering, Manufacturing Program.

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Hulusi Bugra BAGCI

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Dedicated to my family

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LIST OF SYMBOLS

E_v	Energy Density
h	Hatch Spacing
J	Joule
L_t	Layer Thickness
P	Laser Power
E_v	Energy Density
v	Scanning Speed
W	Watt

LIST OF ABBREVIATIONS

3D	3 Dimensional
3DP	3-Dimensional Printer
AM	Additive Manufacturing
ANOVA	Analysis of Variants
CAD	Computer Aided Design
CF	Confocal
CMM	Coordinate Measuring Machine
DMLS	Direct Metal Laser Sintering
EDM	Electrical Discharge Machining
FV	Focus Variation
LM	Layered Manufacturing
LPBF	Laser Powder Bed Fusion
RP	Rapid Prototyping
SEM	Scanning Electron Microscopy
SFF	Solid Freedom Fabrication
SLM	Selective Laser Melting
STL	Stereolithography
UV	Ultraviolet

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ABSTRACT

Improvement Geometrical Product Specifications of Additive Manufactured Parts

Hulusi Bugra BAGCI

Department of Mechanical Engineering Manufacturing Program

Master Thesis

Supervisor: Assoc. Prof. Dr. Binnur SAGBAS

Additive Manufacturing, (AM) has been widely used in recent years. AM process, which offers layer-on-layer processing, provides possibility to produce complex shapes with improved cost and time. It's very important to control the parameters to ensure the dimensional accuracy of the parts and improve the surface properties.

Since Laser Powder Bed Fusion (LPBF) is a method of AM technology it uses metal powder as a raw material. Direct Metal Laser Sintering (DMLS) is a lower-level classification for LPBF process. There have been several studies about process parameters and their effects on the final product quality in the literature. However, dimensional accuracy and surface quality of additively manufactured parts have not yet reached the desirable level. For this reason, studies on parameter optimization remain up to date. In this thesis, the focus is on improving dimensional accuracy and the surface quality of functional parts produced by AM technology. For this purpose, bolt-nut mechanism from mechanical fasteners was chosen as functional part. By using different parameter sets, dimensional accuracy and surface quality of the parts which is produced with LPBF technology were measured with precision metrology systems, and most appropriate set was determined by statistical analysis method.

Keywords: Additive manufacturing (AM), LPBF, dimensional accuracy, surface quality

ÖZET

Eklemeli İmalat Yöntemi ile Üretilmiş Parçaların Geometrik Mamul Özelliklerinin İyileştirilmesi

Hulusi Buğra BAĞCI

Makine Mühendisliği İmal Usulleri Anabilim Dalı

Yüksek Lisans Tezi

Danışman: Doç. Dr. Binnur SAĞBAŞ

Eklemeli imalat sağlamış olduğu avantajlar sayesinde son yıllarda yaygın bir şekilde kullanılmakta olan üretim teknolojisidir. Katman katman işleme gerçekleştiren bu proses, karmaşık şekillerin üretimini mümkün hale getirmekle birlikte, zaman ve malzeme tüketimi açısından da oldukça iyileştirilmiş özelliklere sahiptir. Sağlamış olduğu bu avantajların yanında prosesin doğası gereği bazı dezavantajlara sahiptir. Parçaların boyutsal doğruluğunu sağlamak, yüzey özelliklerini iyileştirmek için prosese etki eden parametrelerin kontrol altına almak AM teknolojisini tanımak için son derece önemlidir.

Lazer , AM teknolojisinin bir yöntemi olmakla birlikte, hammadde olarak malzemenin toz formunu kullanmaktadır. Daha önce literatürde proses parametreleri ve parametrelerin son ürün kalitesi üzerindeki etkilerini inceleyen pek çok çalışma gerçekleştirilmesine rağmen eklemeli imalat parçalarının yüzey kalitesi ve boyut hassasiyeti henüz istenen düzeye ulaşamamıştır. Bu nedenle parametre optimizasyonu üzerine gerçekleştirilen çalışmalar güncelliğini korumaktadır. Bu tez çalışmasında eklemeli imalat ile üretilen fonksiyonel parçaların boyut hassasiyeti ve yüzey kalitesinin iyileştirilmesi konusuna odaklanılmıştır. Bu amaçla, tez çalışmasında fonksiyonel parça olarak mekanik bağlantı elemanlarından somun-vida mekanizması seçilmiştir. Farklı parametre setleri kullanılarak lazer toz yatak füzyon teknolojisi ile üretilen parçaların boyutsal

doğruluğu ve yüzey kaliteleri hassas metroloji sistemleri ile ölçülerek, istatistiksel analiz yöntemleri ile en uygun parametre seti belirlenmiştir.

Anahtar Kelimeler: Eklemeli imalat, toz yatak füzyon, boyutsal doğruluk, yüzey kalitesi

1

INTRODUCTION

1.1 Literature Review

Additive manufacturing (AM) has been a significantly spreading non-traditional manufacturing method in last decades. AM methods are based on putting powder, wire, or some other form of the initial material layer by layer until getting a solid object from 3D Computer Aided Design (CAD) data [1]. It was first developed by Charles Hull in 1980 and named stereolithography. Additive manufacturing also known as 3-Dimensional Printer (3DP), Rapid Prototyping (RP), Layered Manufacturing (LM) and Solid Freedom Fabrication (SFF). In recent years, AM has become a widely used manufacturing technology by being applied in engineering fields such as medicine, automotive, defense and aerospace, as well as being used in the manufacturing of souvenirs and daily tools [2].

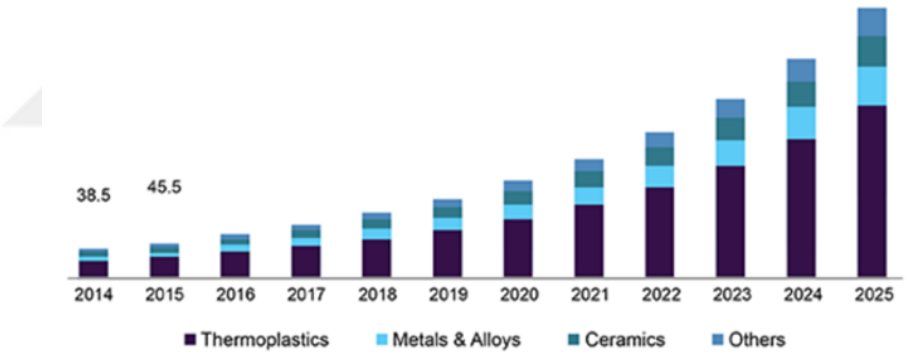


Figure 1.1 Rapid Prototyping Material Market Size, Share & Trends Analysis Report By Material (Thermoplastics, Metals & Alloys, Ceramics), By End Use (Healthcare, Transportation), By Region, And Segment Forecasts, 2019 – 2025 [3]

The graphic above shows that, US's material market size (USD Million) of rapid prototyping since 2014 and forecast to 2025. Rapid prototyping, which is used in various application areas in different industries, will be popular in the coming years.

AM is a nontraditional manufacturing method which offers to build complex structures layer by layer without any tools, mold or fixtures. In addition, AM also offers less set-up time and low level of wasted material compared with traditional methods. Because of these advantages, AM becomes a top topic and research continue in academic and industrial fields. [4]

It is possible to make different headings for comparison AM with conventional methods. To examine with a process approach; it is possible to define those conventional methods are “top-down” and AM method is “bottom-up” process. This definition describes the conventional methods of processing a large mass to form a smaller mass, while additive manufacturing describes the combination of small masses (for example powder) to form a large mass. Below figures represents stage of methods.



Figure 1.2 Top-down method stages, a) Top stage (beginning of process), b) middle stage, c) down stage (end of process) [2]

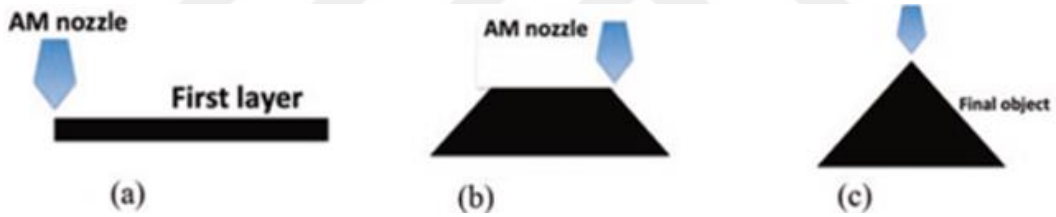


Figure 1.3 Bottom-up method stages, a) Bottom stage (beginning of process), b) middle stage c) up stage (end of process) [2]

On the other hand, in conventional methods, machining is required to switch from a large mass to a small mass and therefore chip formation occurs. However, since the additive manufacturing method switches from a small mass to a large mass, no chip formation occurs. (post-process chips are ignored) Due to the nature of the machining process, production is unthinkable without chips and involves material waste. So, in most application AM is more sustainable than traditional methods.

A different comparison can be made according to the raw material properties of the work part. In the additive manufacturing method, a whole is obtained by using powder or filaments and process parameters play a key role while obtaining this whole. By changing these parameters, which have a major influence on the process, it is possible to achieve the desired efficiency in surface properties. Thus, the process

can be optimized according to requirements. In subtractive methods, there is no change in the mechanical properties of the material in the form of mass, except for the conditions that will occur due to tool wear. In other words, according to conventional methods in additive manufacturing, the process can be controlled at a level that can affect the mechanical properties of the part.

Another reason for the development of additive manufacturing in recent years is the ability to manufacture geometries that cannot be produced by conventional methods. In addition to the geometric freedom, there is no requirement for any additional processing during manufacturing.

If all these comparisons are summarized as advantages and disadvantages.

Advantages of Additive Manufacturing

- *Reducing material usage;* AM is decrease material usage because machining methods are not used in this process, so it provides to eliminate scrap material. It is also more sustainable.
- *Efficiency of time;* AM process doesn't need any tools for manufacturing such as cores, fixtures, cutting tools. As a result, set-up time is reduced. Also, for small parts can be produced closed to customers. So leading time shortens.
- *Flexible production and parts;* AM has not costly setups so it provides preparing prototypes for costumer demands before total production. In any discussion prototype could be changed easily. Also, there is no restriction for material geometry, it provides possible to produce complex parts as a single piece.

Disadvantaged of Additive Manufacturing

- *Limitation of size;* production size depends on printer, so it causes restriction. Different printers are needed for specific processes.
- *Surface quality;* after 3D printing material has rough surface. Because of that, other finishing methods such as machining or polishing need to be use if super finished parts desired.
- *Economic;* AM is not able to high volume production because some processes need additional equipment including high-cost printers.

The steps to be followed in the process of obtaining the final piece with additive manufacturing method; 3D part design is performed with the help of CAD program. The designed part is saved in *"stl"* format. The *"stl"* created is the representation of the data piece geometry as a point cloud [5]. The obtained file is transferred to the device where 3D manufacturing will be performed and the parameter values are determined, and production is started. After the part manufacturing is completed, post-processing is performed if necessary and the part is made ready for use [6].

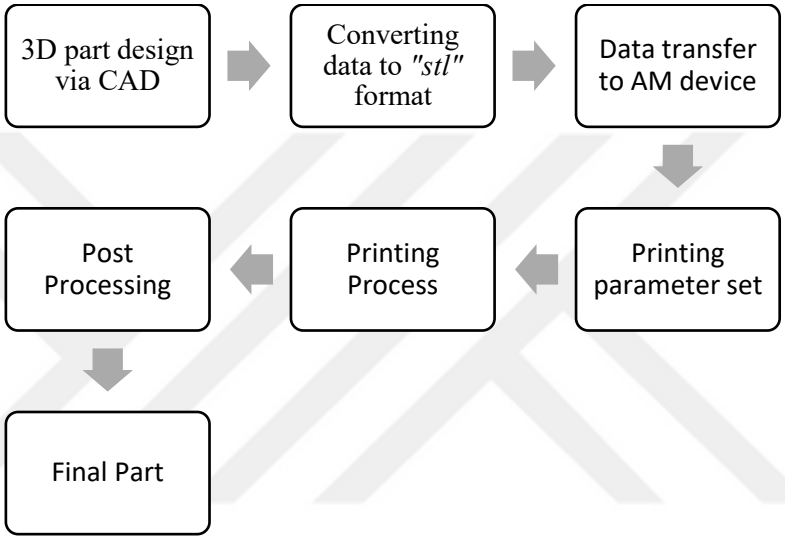


Figure 1.4 Steps of additive manufacturing

1.1.1 Classification of Additive Manufacturing Process

There are several methods used to classify AM methods. In 2010 ASTM declares 7 kind of AM methods according to techniques [7].

- *VAT Photopolymerization:* The photopolymer resin is exposed to an energy that solidifies the material layer by layer. It is generally used in the production of thermoset plastics.
- *Material Jetting:* Special printheads spray the material in layers. Generally, this sprayed material is a light sensitive plastic resin that solidifies with UV light.
- *Binder Jetting:* It uses a nozzle to spread the liquid binding agent over a bed of powder. Powders are bonded to form a piece.

- *Powder Bed Fusion:* Powder bed fusion uses an energy beam to melt the top layer of powder and it continues layer by layer until getting a solid part.
- *Material Extrusion:* It is obtained by heating the material and shaping it from the extruder end.
- *Direct Energy Deposition:* Similar with PBF. Material melted via energy source onto layer by layer.
- *Sheet Lamination:* Sheet laminates are successfully glued or joined together. It has an energy source that cuts it until it gets a solid piece.

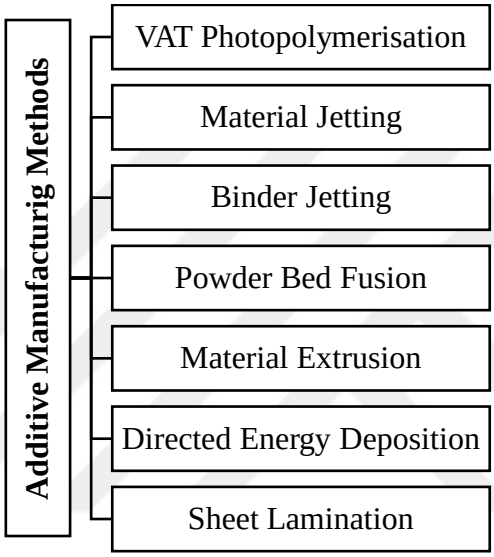


Figure 1.5 Additive manufacturing methods ASTM F42 [7]

It is also possible to classify AM methods according to their feedstock materials. This classification can be made as solid, liquid or powder-based raw materials. However, classification in this way may not be fully explained since some production methods are carried out with more than one feedstock material.

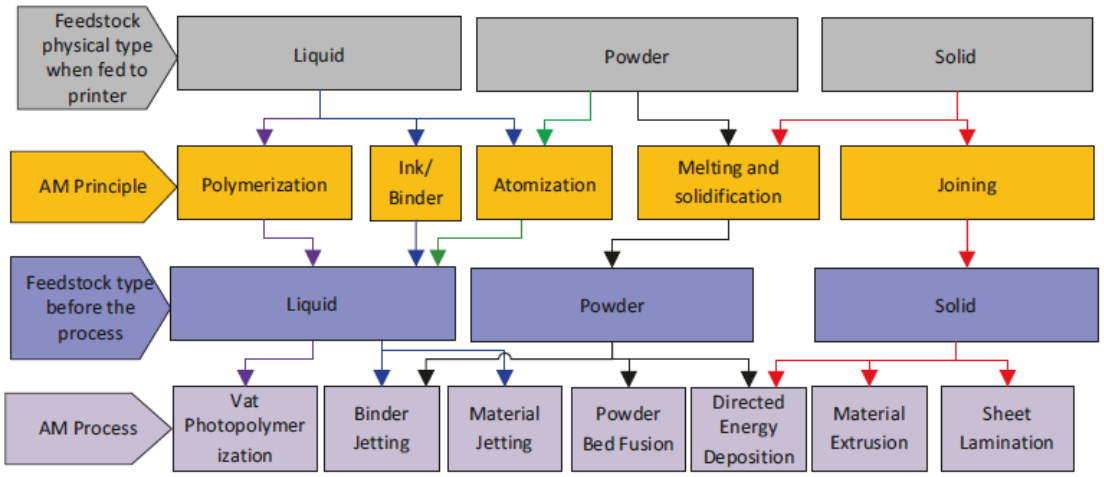


Figure 1.6 Classification methods of additive manufacturing techniques based on feed stock material [8]

1.1.1.1 Powder Bed Fusion

Powder bed fusion is the AM method which fuses materials by melting them with an energy source. PBF separates 2 types according to energy source as laser melting or electron beam. The following formula determines the energy density which is the key parameter of AM process [9].

$$E_v = P/ (v*L_t*h) \ (J/mm^3) \ (1.1)$$

Where the E_v is energy density, P is laser power, v is scanning speed, L_t is layer thickness and h is hatch spacing.

System includes several utility tools. Main idea of process; There are mirror(s) that allow the laser beam movement with melting on the planer table. These movement follows the path of melting route. After a layer of material is melted, another layer sprinkled with the spreader and melting process is repeated until getting a solid part. The process carried out in an air gas shielded (usually N or Ar element) atmosphere as it prevents oxidation. [10]

1.1.1.2 Parameters of PBF Based AM Methods

In PBF-based systems, it is possible to classify parameters according to system integrity. Those are laser-related parameters based on laser source, process-related parameters based on scanning system equipment, powder-related parameters based on feedstock material and build chamfer related parameters [11].

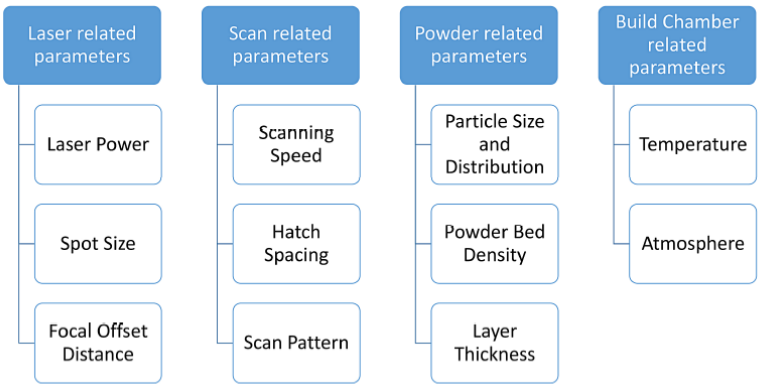


Figure 1.7 Additive manufacturing parameters [11]

Laser Power: It is depending on laser source.

Scanning Speed: Scanning rate describes how long the beam acts on the powder bed. There is an inverse proportion with energy density. Sometimes, working with high scanning speeds cannot provide sufficient energy density in metal systems, so the necessary process competencies cannot be achieved. Therefore, scanning speed should be at the optimum level. [2]

Layer Thickness: It is the thickness of *"layer-by-layer"* definition. Higher layer thickness causes higher shrinkage after melting, which will decrease the surface integrity and smoothness. [2]

Hatch Spacing: Hatch spacing is distance between 2 beams center. For making thin geometries smaller hatch spacing should be applied. [2]

Energy Density: The unit energy amount that affects a volume or area is defined as the energy density. Equation has been given for energy density at previous chapter. (1.2.1) It is affected with laser power, scanning speed, layer thickness and hatch spacing. [8]

Part Orientation: It is another important parameter which affects surface quality directly. According to part shape, orientation could be causing an overheated zones and thus visible defects be seen. [11]

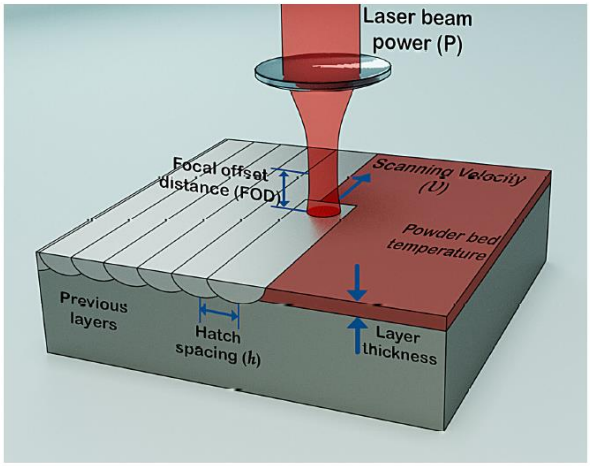


Figure 1.8 Additive manufacturing process [11]

In the literature, the effect of AM parameters on aluminum alloys was investigated. Those studies have shown that, energy density is a significant variable which is related with laser power, scanning speed and hatching distance. Samples were produced between 27 – 65 J / mm^3 energy density and the lowest surface roughness as 4.5 µm was obtained at the highest energy density which is 65 J / mm^3. [12] Another parameter which affects surface quality is scanning direction. Tarun Bhardwaj et al. proved that one-way scanned samples shown almost 2 times higher roughness results than multi directional scanned samples. It's also noted post-processing reduced surface roughness [13].

Surface roughness and dimensional accuracy have been studied by Han et al. According to their paper, there was a critical v_c value which affects surface quality when the hatching distance was fixed. Scanning speed and dimensional accuracy shown linear behavior when scanning speed lower than v_c. On the other hand, when the scanning speed was higher than v_c, dimensional accuracy exhibited steady results [14].

In a study by Sing et al, 3 levels of 3 parameters were experimented. These are scanning speed, laser power and layer thickness. Experimental results shown that laser power was the key parameter for SLM produced samples. It has been stated that controlling laser power affects surface quality [15]. In comparison between 2 methods of additive manufacturing, DMLSed parts shown better deviation results than SLMed parts. It has been also found that surface roughness and dimensional accuracy are related [16]. Krishnan et al. conducted a study on process parameters

in additive manufacturing method using AlSi10Mg material. According to their research, hatching distance is the parameter that affects the mechanical properties the most. At the same time, scanning speed is another important parameter affecting the mechanical properties. Using the DOE method, optimum values were determined for the analyzed parameter sets [17].

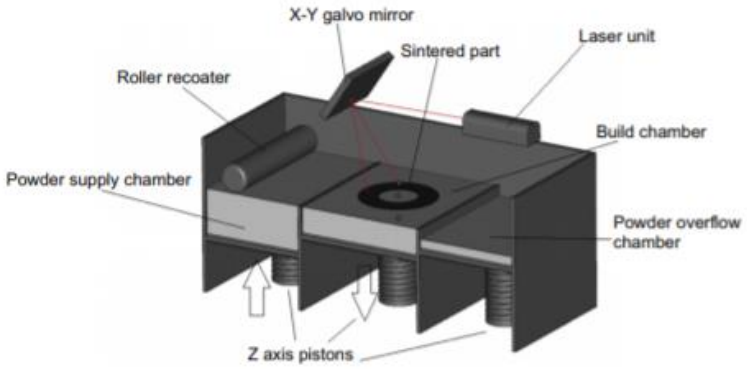


Figure1.9 PBF process and equipments [18]

Direct metal laser sintering is a PBF based AM method, which uses metal powders and laser as an energy source. Previous research shown that there are several parameters which have an effect on DMLS process. Parameters such as laser power, scan speed, hatch distance and build angle affect the geometric product specifications and mechanical properties of printed part. There are studies that focused on different parameter values to increase dimensional accuracy [19].

1.1.2 Al and It's Alloys

It is the most used material in engineering structures after steel. It is frequently used in applications where lightness is required. Aluminum has less heat and electrical conductivity than copper, but its specific heat capacity and electrical conductivity is higher than copper. [20] It is also a cheaper material than copper.

Since an oxide layer is formed on the surface of aluminum, its corrosion resistance is good. There is a tendency to form a galvanic cell with the alloying elements included in it. Therefore, it is recommended to be used in pure form. However, it is not common to use it as pure due to the weaknesses in its mechanical properties. Hot-cold forming properties are good. It is possible to produce parts with complex geometries by the extrusion method. Aluminum properties vary depending on the

alloying element and microstructure. The most important alloying elements involved are copper, silicon, magnesium, and zinc.

Table 1.1 Al and it's alloys [21-25]

Series	Explanation and Applications
1xxx	Pure Aluminum. Electric and chemical industry
2xxx	Al-Cu alloys. Aerospace industry
3xxx	Al-Mn alloys. Pipes, tanks and architecture applications
4xxx	Al-Si alloys. Thermal expansion coefficient is low, corrosion resistance is high. Welded structures, automotive industry
5xxx	Al-Mg alloys. Mg increases hardness and strength but decreases ductility. It is used in the maritime industry because of its good corrosion resistance
6xxx	Al-Mg-Si alloys. It has high shaping capability and is frequently used in the production of parts produced by extrusion.
7xxx	Al-Zn alloys. It is the series with the highest strength. It is used in aircraft parts.
8xxx	Al-Li alloys. It has good fatigue resistance and toughness strength. It is used in the aviation and space industry.

AlSi10Mg material has a wide range of uses according to some distinctive features. These distinctive basic features are very lightweight material with improved mechanical properties, good thermal conductivity, and improved corrosion resistance. Demands of the automotive and aerospace industry makes widely use of AlSi10Mg material [26].

In a study on AlSi10Mg material, samples were produced with different parameters. The relationship between heat treatment and thermal conductivity has been studied for AM parts. It was noted that there was no significant change in porosity after heat treatment, and the thermal conductivity values have shown similar results [27].

1.1.3 Geometrical Product Specifications

There are ASME GD&T (ASME Y14.5: 2018) and ISO: GPS (ISO 1101: 2017) standards that are used to define geometric variations that determine the acceptable limits of a manufactured part. In addition to defining geometric variations, themes such as terminology, part specification and measurement / control methods are also prepared in the form of international standards. It is extremely important to consider tolerance when choosing the production method [28]. According to ASME, geometric tolerance can be examined under headings. Some of these are dimensional tolerances, form tolerances such as straightness and flatness, orientation tolerances such as parallelism and perpendicularity.

It is possible to say that the geometric shape of a surface is surface texture. Geometric shape is caused by deviations of the surface, which are roughness and waviness basically. The roughness consists of maximums and minimums defined as valleys and hills on the surface. [29]

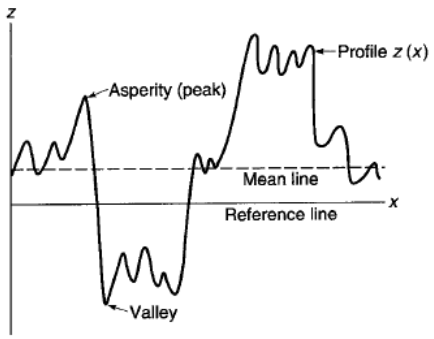


Figure 1.10 Shape of surface texture and terms [29]

According to GPS, surface characterization specified as; [33]

- P-Profile; primary value
- W-Profile; waviness value
- R-Profile; roughness value

Process-induced and AM ability-induced problems in additive manufacturing method are defined by Ameta et al [30]. Process induced problems defined in this section as follows.

- *Build Direction and Location;*

Building orientation has been determined to have a significant effect on the fatigue resistance of the part. At the same time, the surface quality also varies according to the scanning orientation.

The location of the printing process influences the final part. If the distance between two parts produced in a single printing process is too small, thermal interaction occurs between them and affects the surface properties. Another example of positioning is that the part printed in the center of the printing pad has better geometric properties than the part printed in the corners.

- *Layer thickness:*

Layer thickness, which is an important parameter in additive manufacturing method, is also an important factor which is affecting the surface quality. In powder bed systems, the layer thickness affects the solidification time of the part.

- *Support Structures;*

Support structures are needed in the production of some parts in the additive manufacturing process. However, these support structures, which are cleaned after the production is completed, affect the surface quality. Therefore, it is necessary to position the support structures according to the part usage needs. Also support shapes and numbers are important for final item.

Another study in literature, Das et al. examined the effects of support structures on surface quality and stated that the size of the support structures and the size of the surface in contact with the part should be optimized in order to improve the surface quality [31].

- *Heterogeneous Material Considerations;*

When scanning with 2 or more materials, there may be a boundary between material grains. This is a situation that negatively affects the surface.

- *Scan Direction;*

The scan direction describes the path the header follows during the scanning process. It influences residual stress especially in metal parts during part manufacturing. Determining a scanning strategy is an important parameter in terms of ensuring surface quality.

1.1.4 Measurement Systems Used in AM

Surface could be described as any face of a part which interacts with the environment. Due to the environmental and human effects, it is inevitable that deterioration/defects will occur in the area defined as the surface. Chemical and physical events such as corrosion and abrasion begin on the surface. It also carries certain traces of process on the surface during the processes in the manufacturing process of the part. When all this is brought together, the surface; defines the functionality and appearance of the part and affects the part performance. Because of these definitions of the surface; improving, controlling and analyzing the surface has been one of the researched subjects.

As mentioned in the previous paragraph, surface deterioration occurs because of various factors such as process traces. If the surface is defined under 3 headings.

- *Nominal Surface:* The part surface to be produced or drawn.
- *Real Surface:* Formed by the effects that occur during the manufacture of the part.
- *Measured Surface:* Could be obtained as a result of measuring the real surface. It is inevitable to get different measurements to the precision of the instrument.

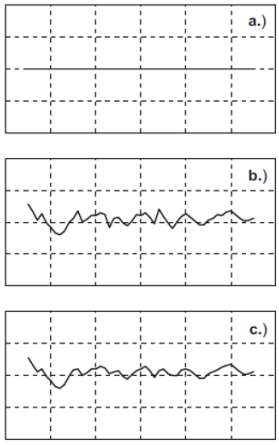


Figure 1.11 Surface texture, a)nominal surface, b) real surface, c)measured surface [32]

There are 2 ways to achieve surface measurements, defined as profile and area measurement. In profile measurements, a measuring tip, called a probe or laser, moves along a linear line and the height change resulting from this movement is measured.

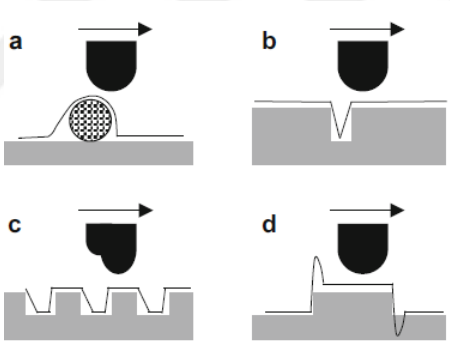


Figure 1.12 Surface measurements from different surfaces [32]

In area measurements, by providing a 2D measurement, compared to profile measurements, more complex measurements can be taken (e.g., homogeneity), reproducible results are obtained, operator influence is less. Despite these advantages, small areas are examined at once and the measurement time is longer [32].

The geometry of the part surface must be kept under control in order to get the requirements where it will be used. Several parameters could affect surface texture as material, process parameters, process methods etc. Measuring with different sensitivities according to the usage needs, devices check whether the part is within the specified limits. Measurement systems are divided into destructive (such as

mechanical profilometer and AFM) and non-destructive (such as optic profilometer and SEM) methods [33] [34].

All tactile sensors work within the main idea of physically contact with sample part. Since it's a tactile process, measurement has disadvantages. However, despite these cons, there is a pro such as ability of measuring several mm in few nm, which make this method useful [32].

1.2 Objective of the Thesis

Additive manufacturing is the method of producing solid parts with CAD program without using any tools or fixture etc. In this method, CAD data converted to STL format and separated into layers dot by dot in cloud interface. Various kind of CAD programs could be used to get "STL" data such as Siemens NX, SolidWorks. It's based on obtaining 3D part by creating layers of raw material.

In summary production without the need for cutting tools has prevented the negativities caused by tool wear and it has become quite easy to fabricate complex geometries. Raw material waste has been minimized. The time and material savings provided by additive manufacturing, and opportunity to have final part are extremely useful but surface quality of the parts obtained after the process is low.

Surface quality could be improved with two different methods. These are the optimization of the parameters that inevitably affect the process and the post-processing. However, post-processing is naturally time-consuming and a costly method as it requires additional equipment. For this reason, parameter optimization provides an effective opportunity.

In this study, DMLS method was used. In this method, high power laser is applied on the powdered raw material to be used in the process and the material is heated up to just below the melting temperature. Therefore, a layer is formed on the powder bed. The process parameters were determined (energy density, scanning angle) and the surface characterization of the produced parts (AlSi10Mg) was achieved by optimizing these parameters. These parameters affect the surface character of the part like surface roughness and dimensional accuracy. Increasing the surface quality is important that the material can be produced without an additional post-

processing. Surface measurements of the obtained piece were carried out using appropriate methods and their comparison has been done.

Objective of this thesis is, determining the effect of process parameters such as laser power, scanning speed, beam offset and scanning angle parameters on dimensional accuracy and surface quality of laser powder bed fusion manufactured AlSi10Mg functional parts. Optimum process parameters were defined by design of experiment and some statistical methods.

1.3 Hypothesis

Additive manufacturing method is a production technology that is increasingly preferred due to factors such as possibility of manufacturing complex geometries, rapid prototyping, time, and material reductions. Therefore, the correct determination of the process parameters, which are the most important factors of production, and the examination of the effects of these parameters on the final part is a necessity in terms of understanding the process. So, the hypothesis of this thesis study is, there is a significant relation between surface quality, dimensional accuracy and process parameters.

In this study, dimensional accuracy and surface quality of screw-nut mechanical parts produced by DMLS method have been examined. It is not possible to perform analysis on all parameter sets in terms of time and cost. However, it is possible to provide the most appropriate set by performing sampling according to the Taguchi Orthogonal experimental set. Laser power, scanning speed, beam offset and scanning angle parameters were determined in different sets in the produced screw-nut parts and 9 samples were produced.

Density measurements of the obtained samples were completed, and precise measurements were carried out with CMM. Dimensional accuracies were analyzed with these measurements via Minitab. In addition, the roughness values were measured on the surface by an optical profilometer, and the surface topography was analyzed by SEM device. According to all the results obtained, the most suitable parameter set was determined.

2
MATERIAL AND METHODS

2.1 Designing of Samples

In literature, there are several studies about additive manufacturing parameters. This study aimed to optimize process parameters in manufacturing of functional parts. For this reason, bolt-nut samples, which are widely used, were chosen. So, bolt-nut fasteners were designed within the scope of the project in order to examine and improve the effectiveness of additive manufacturing methods in functional parts manufacturing. The designs were carried out in Autodesk Fusion 360 program. 3D CAD data were converted into stereolithography (STL) files and made ready for the manufacturing process. Sample designs are shown in Figure 2.1.

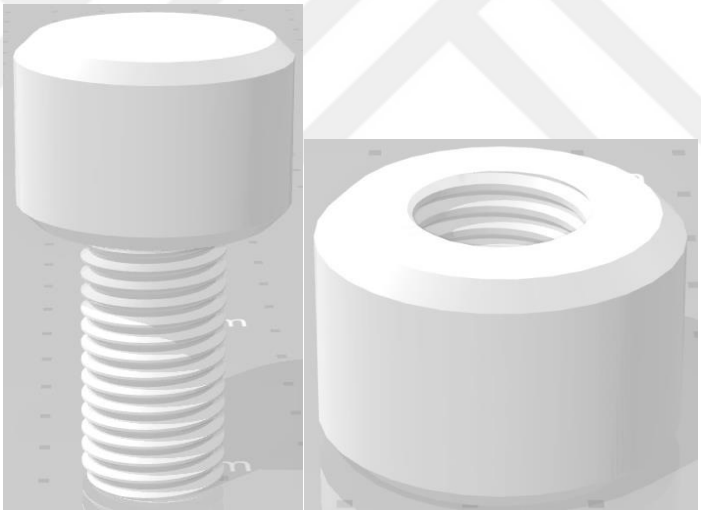


Figure 2.1 Designed Samples

2.2 Defining Process Parameters

When the literature studies were investigated, it was seen that there are many parameters affecting the dimensional accuracy and surface quality in direct metal laser sintering (DMLS) additive manufacturing method. The application of each parameter at different levels has a significant impact on the results. In addition, the effect of the parameters to be applied may differ depending on the material and design criteria. For this reason, many studies have been done on parameter

optimization in DMLS process, but the most suitable parameter combination has not been fully achieved yet. In the project work planned from this point, laser power, scanning speed, beam offset, and sample angle parameters were determined to be applied at 3 different levels. Hatching distance and layer thickness have been taken as constant. Experimental design technique was used, as it would be extremely costly to try all combinations of each parameter set in order to determine the effects of its parameters on dimensional accuracy and surface sensitivity. The parameters and levels of the 9 experimental sets created using Taguchi's L9 orthogonal experimental design material are as indicated in the table below.

Table 2.1 Taguchi L9 array

Laser Power	Scanning Speed	Beam Offset	Scanning Angle
1	1	1	1
1	2	2	2
1	3	3	3
2	1	2	3
2	2	3	1
2	3	1	2
3	1	3	2
3	2	1	3
3	3	2	1

Table 2.2 Process parameters

Laser Power (W)	Scanning Speed (mm/s)	Beam Offset (mm)	Scanning Angle
270	900	0,02	0
270	1300	0,04	30
270	1600	0,06	45
330	900	0,04	45
330	1300	0,06	0
330	1600	0,02	30
370	900	0,06	30
370	1300	0,02	45
370	1600	0,04	0

2.3 Production of Samples

In this study, AlSi10Mg light metal alloy, which is widely used in aerospace, aviation and automotive industries, was used. AlSi10Mg powder supplied from EOS company, which was obtained with gas atomization method and the average particle size is about 30 µm. The chemical composition and scanning electron microscope (SEM) record of the AlSi10Mg alloy is shown in Table 2.3 and Figure 2.2.

Table 2.3 Chemical composition of AlSi10Mg

Al (%)	Si (%)	Fe (%)	Cu (%)	Mn (%)	Mg (%)	Ni (%)	Zn (%)	Pb (%)	Sn (%)	Ti (%)
Balance	9.0-11.0	0.55	0.05	0.45	0.2-0.45	0.05	0.10	0.05	0.05	0.15

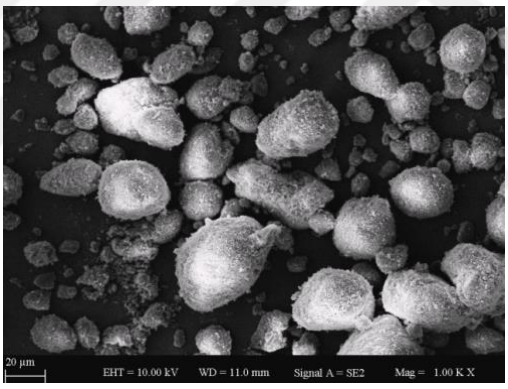


Figure 2.2 SEM image of AlSi10Mg

Hatch distance and layer thickness were determined as fixed parameters for samples manufactured with EOS M290 device with direct metal laser sintering (DMLS) system. Laser energy density (J/mm^3) was calculated with the help of the formula below.

$$E = \frac{P}{V * D * T}$$

Where the E_v is energy density, P is laser power, v is scanning speed, L_t is layer thickness and D is hatch spacing.

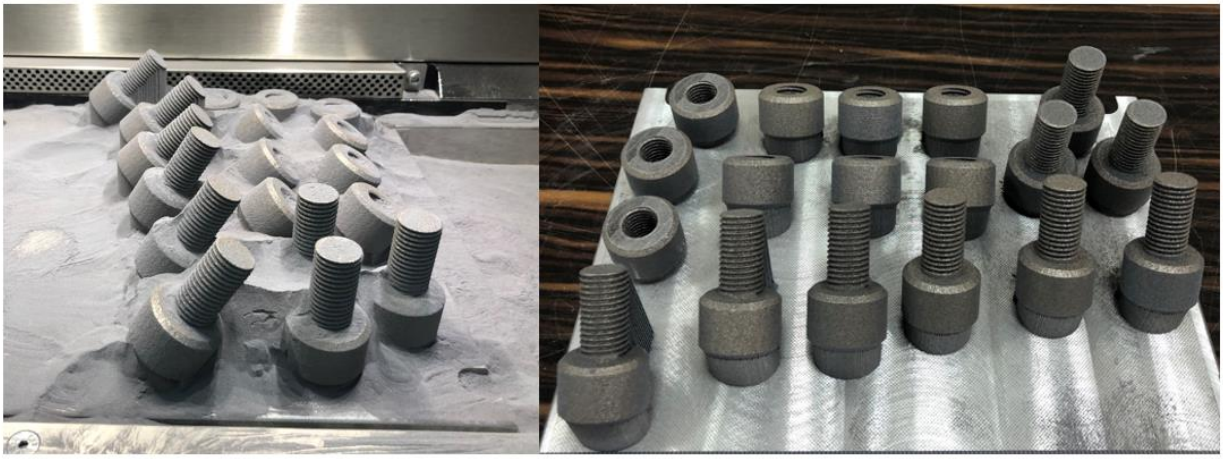


Figure 2.3 Production of the samples

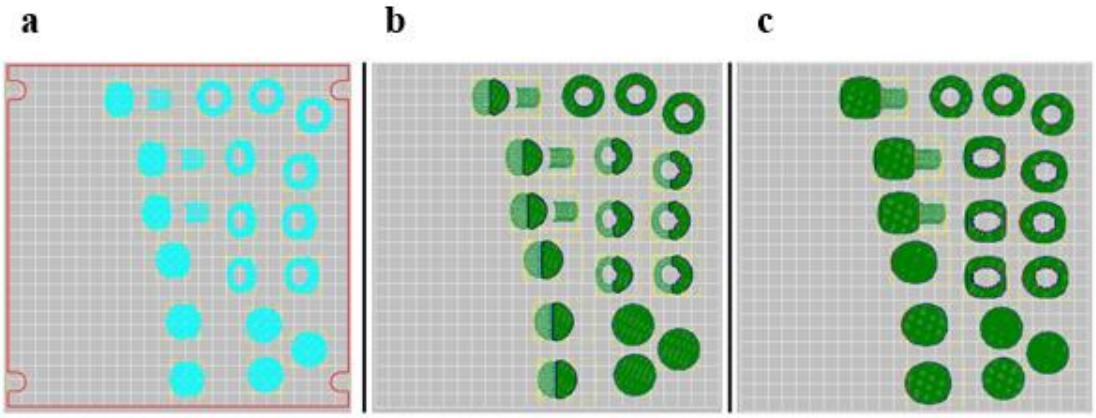


Figure 2.4 Stages of processing a) Starting stage of printing b) middle stage of printing c) final stage of printing



Figure 2.5 Cleaning support structures

2.4 Measurement and Inspections

2.4.1 Dimensional Measurements

After the samples were manufactured, support structures were cleaned manually, and excessive powders were removed by pressurized air. Three repeated measurements were taken for each dimension of the samples by Hexagon 100907 CMM delicately in accordance with related standard (ISO 14253-1:2017)



Figure 2.6 CMM measurement of samples

Statistical evaluation of dimensional measurement results obtained with CMM;

Dimensional measurement values determined with CMM are compared with nominal measurement values specified on the manufacturing technical drawing, the difference between them is calculated and notes as the deviation value.

Deviation Value = Nominal Value - Measured Value

In the Taguchi experimental design method, the signal / noise ratios were calculated according to the "smaller is better" criterion and the effects of the parameters and their levels on dimensional measurements were tried to be determined.

2.4.2 Density Measurements

Density measurements were carried out according to Archimedes' principle, using the Precisa XB220A precision balance and a density kit.

2.4.3 Surface Inspection

The Sensofar Compact 3D Surface Profiler device, which allows measurement with confocal and focus variation methods, was used for the surface measurements of the

samples. Measurements performed with the confocal method were completed by taking measurements from 3 different points along the sample periphery.

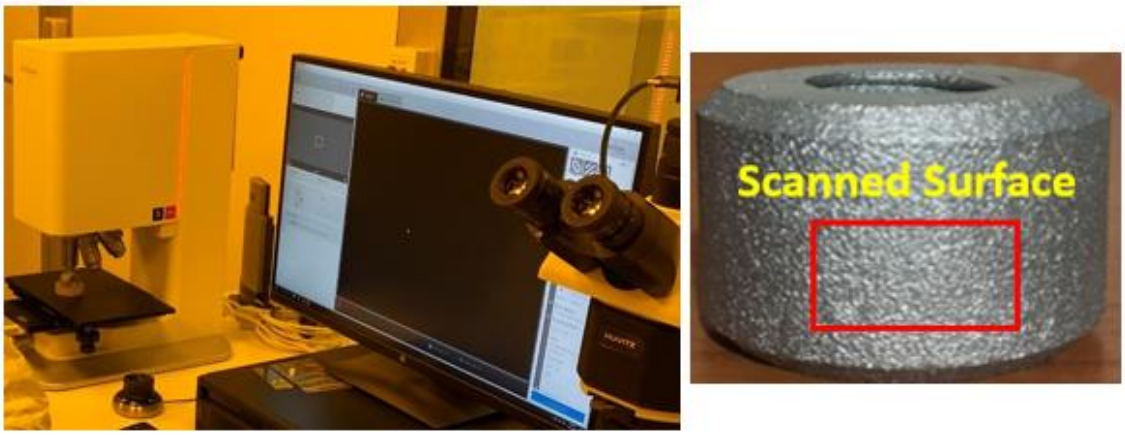


Figure 2.7 Surface inspection and scanned surface

For SEM surface analysis, samples were prepared by cutting in accordance with the dimensions of the device by wire EDM. Sample surfaces were analyzed with the ZEISS EVO LS15 SEM device. In order to compare the SEM measurement results with the optical profilometer measurement results, both analyses were carried out by taking measurements from the same regions.

3
RESULTS AND DISCUSSION

3.1 Density Measurements

Density measurements have been completed following to Archimedes Principle, by with the ability of Precisa XB220A precision scale and density kit together. Results and equations are given below.

Relative Density = $\frac{(\boldsymbol{Measured})\ \boldsymbol{Density}}{\boldsymbol{AlSi10Mg\ Density}}$

Porosity = 1- Relative Density

%Porosity = Porosity*100

Table 3.1 %Porosity of manufactured nut samples

Sample No	Density	Relative Density	Porosity	%Porosity
1	2.674	0.998	0.002	0.224
2	2.673	0.997	0.003	0.261
3	2.657	0.991	0.009	0.858
4	2.660	0.993	0.007	0.746
5	2.680	1	0	0
6	2.666	0.995	0.005	0.522
7	2.650	0.989	0.011	1.119
8	2.676	0.999	0.001	0.149
9	2.668	0.996	0.004	0.448
AlSi10Mg	2.68			

There are several studies in the literature which focus on relative density of additively manufactured parts. According to these studies, Kempen et al. noted that, achieved lowest relative densities have been produced with low or high energy density. Also mentioned that highest relative densities could be seen when the energy input is optimum for melting pool [35]. Another study, Shah et al. investigated effects of process parameters on relative density. In this paper, various samples were produced with different level of scanning speed, laser power and

hatching distance. It's possible to say that when the calculated energy density was high, the measured relative density was low. That's the result of evaporation/vaporization of powder [36]. Giovagnoli et al. studied a relation between energy density and relative density and different relative density results were recorded at the same energy density. According to this article, there are some parameters that affect the process differently from energy density. Such as insufficient parameters or irregular shaped pores. [37].

From this study, it's clearly seen that the relation between energy density and relative density in below analysis. Calculated minimum relative densities are where the energy density is minimum with 29,61 J/mm^3 as sample-3 and maximum with 72,12 J/mm^3 as sample-7.

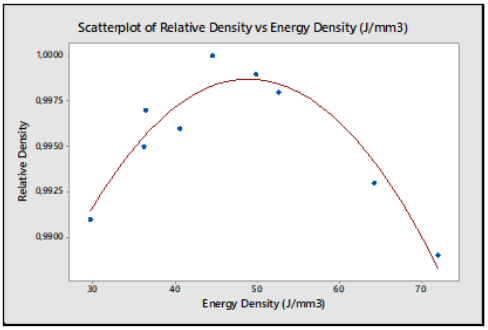


Figure 3.1 Relative density - energy density scatter-plot diagram of nut samples

3.2 Dimensional Measurements

Dimensional measurements for bolt taken by CMM device are given in the table 3.2 and nominal values also given in the bottom of the table. The points where the measurements were taken are shown in the figure 3.2.

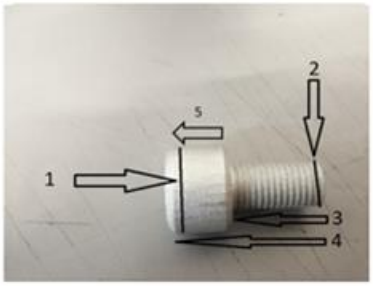


Figure 3.2 Measured references of bolt

Table 3.2 Measured values of bolt samples

		Dimension-1 (mm)	Dimension-2 (mm)	Dimension-3 (mm)	Dimension-4 (mm)	Dimension-5 (mm)	Between Teeth (mm)
SAMPLE NO	1	29.78	15.81	29.99	50.24	19.87	2.12
	2	29.78	15.87	29.96	50.15	19.89	2.42
	3	29.68	16	29.83	49.9	20.07	1.93
	4	29.71	15.98	30.07	50.09	19.92	2.16
	5	29.8	15.88	29.9	50.18	19.82	2.18
	6	29.71	15.88	29.86	50.09	20.07	2.16
	7	29.74	15.8	29.92	50.21	19.78	1.94
	8	29.8	16.06	29.87	50.04	19.94	2.01
	9	29.79	15.88	29.86	50.03	19.98	1.85
Nominal Value		30	16	30	50	20	2

Table 3.3 Deviation values of bolt samples

		Deviation-1 (mm)	Deviation-2 (mm)	Deviation-3 (mm)	Deviation-4 (mm)	Deviation-5 (mm)	Deviation Teeth (mm)
SAMPLE NO	1	0.22	0.19	0.01	0.24	0.13	0.12
	2	0.22	0.13	0.04	0.15	0.11	0.42
	3	0.32	0	0.17	0.1	0.07	0.07
	4	0.29	0.02	0.07	0.09	0.08	0.16
	5	0.2	0.12	0.1	0.18	0.18	0.18
	6	0.29	0.12	0.14	0.09	0.07	0.16
	7	0.26	0.2	0.08	0.21	0.22	0.06
	8	0.2	0.06	0.13	0.04	0.06	0.01
	9	0.21	0.12	0.14	0.03	0.02	0.15

As explained section in 2.4.1. deviation values calculated as difference between nominal value and measured value. After all measurement and calculations, measurements analyzed with the help of Minitab Taguchi analysis, using smaller is better method.

Deviation Value = Nominal Value - Measured Value

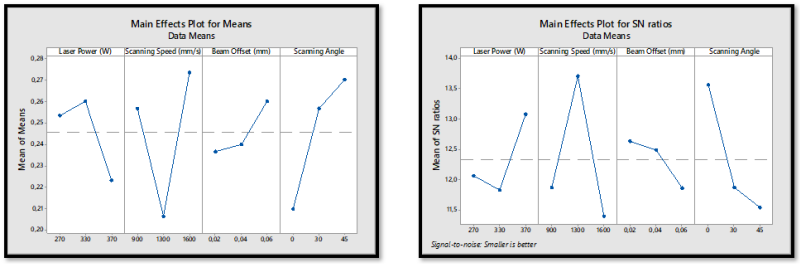
Firstly, dimension-*1* deviation values have been investigated and it's calculated that the range varies between 0,2 mm to 0,32 mm, where sample-5 and 8 minimum and sample 3 is maximum.

To understand parameter effects better, according to smaller is better analysis, key parameters for *dimension-1* has been defined as scanning speed and built angle. When scope on scanning speed it's revealed that 1300 mm/s scanning speed is an optimum value for this dimension. However, it's important the note that, scanning speed is not affect the dimension linearly. Mean deviation calculation in 1300 mm/s is 0,20 mm. Obtained maximum deviation is calculated when scanning speed is 1600 mm/s and average deviation amount is 0,27mm.

Look under another parameter build angle, minimum deviation of *dimension-1* calculated as 0,20 mm with samples have been built 0- and 45-degree angle. On the other hand, mean of deviations calculated minimum when scanning with 0 degree as 0,21 mm. Moreover, maximum values calculated at 45 degrees. When all values are combined it's shown that built angle affects *dimension-1* linearly, dimensional accuracy increases when the built angle decrease.

The optimum process parameters for *dimension-1*;

Where the laser power is 370 W, scanning speed is 1300 mm/s, beam offset is 0,02 mm and 0 degree of built angle.



Response Table for Signal to Noise Ratios
Smaller is better

Level	Laser Power (W)	Scanning Speed (mm/s)	Beam Offset (mm)	Scanning Angle
1	12,07	11,87	12,63	13,56
2	11,83	13,70	12,49	11,87
3	13,08	11,40	11,86	11,54
Delta	1,25	2,30	0,77	2,02
Rank	3	1	4	2

Figure 3.3 Dimension-1 of bolt Taguchi analysis

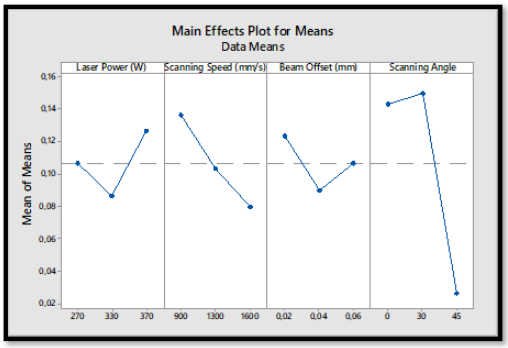
Continue with *dimesion-2*, minimum deviation is 0 mm on sample-3 and maximum deviation calculated as 0,19 mm on sample-1. When the effects of parameters are investigated, built angle steps much further than other.

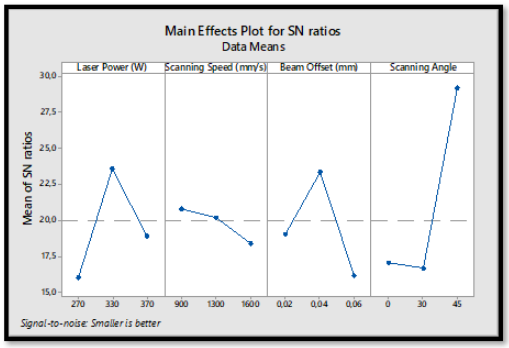
45-degree of built angle significantly effects on samples, where the mean value is calculated as 0,02 mm. When the manufacturing processes carried out at 0 and 30 degrees were examined, the averages were measured as 0,14 mm and 0,15 mm, respectively. Besides these slightly different values, the 45-degree built angle has improved the accuracy of the process in an undeniable way.

Naturally, other parameters have some effect on samples but not as much as built angle. Another notable orientation is, scanning speed and dimensional accuracy shown inverse proportion.

The optimum process parameters for *dimension-2*;

Where the laser power is 330 W, scanning speed is 900 mm/s, beam offset is 0,04 mm and 45-degree of built angle.





Response Table for Signal to Noise Ratios
Smaller is better

Level	Laser Power (W)	Scanning Speed (mm/s)	Beam Offset (mm)	Scanning Angle
1	16,07	20,79	19,09	17,09
2	23,60	20,19	23,37	16,71
3	18,94	18,42	16,20	29,21
Delta	7,53	2,38	7,17	12,50
Rank	2	4	3	1

Figure 3.4 Dimension-2 of bolt Taguchi analysis

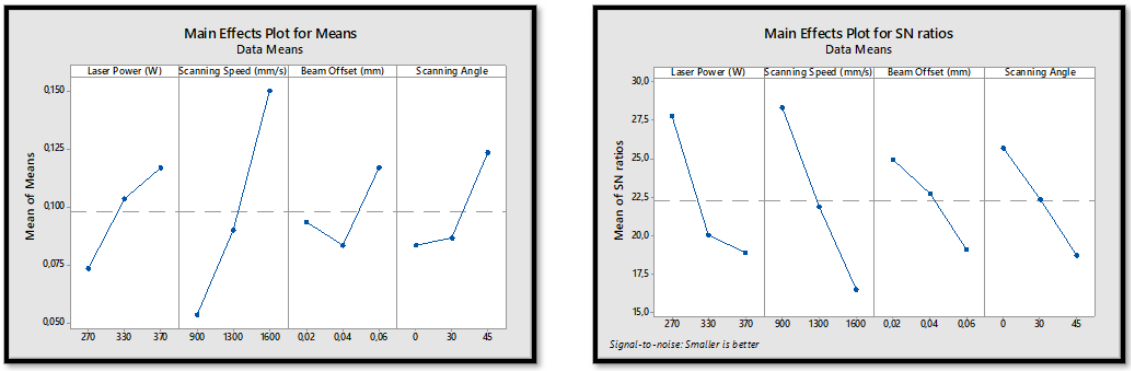
Analysis results show that, scanning speed is considerable parameter for *dimension-3*. A direct correlation was found between deviation amount and scanning speed. When the speed input is 900 mm/s, average deviation calculated as 0,05 mm and if the input increased to 1600 mm/s, average changes to 0,15 mm, which is 3 times higher.

The parameter that affects the process a little more than other variables is the laser power. The effect of laser power on the process was similar to the scanning speed. Dimensionally better results were obtained at 270 W.

Measured minimum deviation is already combined these 2 variables together in sample-1 as 0,01 mm.

The optimum process parameters for *dimension-3*;

Where the laser power is 270 W, scanning speed is 900 mm/s, beam offset is 0,02 mm and 0-degree of built angle.



Response Table for Signal to Noise Ratios
Smaller is better

Level	Laser Power (W)	Scanning Speed (mm/s)	Beam Offset (mm)	Scanning Angle
1	27,78	28,35	24,93	25,69
2	20,06	21,89	22,71	22,32
3	18,91	16,52	19,11	18,74
Delta	8,87	11,83	5,82	6,96
Rank	2	1	4	3

Figure 3.5 Dimension-3 of bolt Taguchi analysis

Total length of samples referenced as *dimension-4*. All defined parameters have a significant effect on dimensional accuracy of these parts. Thus, all parameters will be investigated separately in this section.

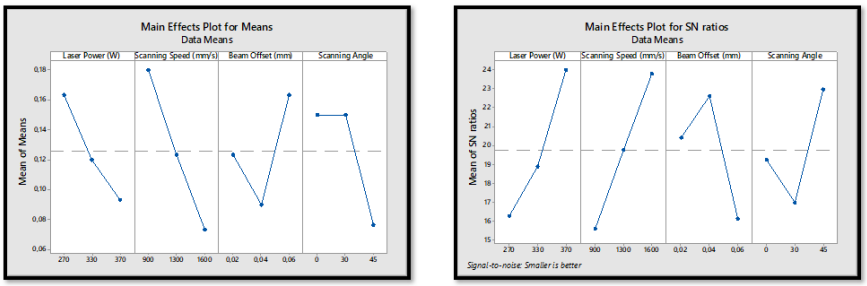
Starting with the scanning speed, minimum deviation values calculated when working 1600 mm/s as a mean 0,07 mm/s and the total minimum value detected as 0,03 mm. It's possible to say that there is a positive linear correlation between dimensional accuracy and scanning speed. Deviation of means are 0,18 mm and 0,12 where the scanning speed was 900 mm/s and 1300 mm/s.

Laser power behaves like scanning speed. Minimum deviation measured an average of 0,07 mm at 370 W laser power, while the maximum deviation was observed as 0,16 mm at 270 W laser power. Also, average deviation calculated at 330 W laser power is 0,12 mm.

Beam offset shows a quadratic behavior for *dimension-4*. Minimum values calculated 0,04 mm beam offset. However, increasing or decreasing this value doesn't affect the process positively. It is possible to mention about a critical value that negatively affects the process with the decrease or increase of the offset value after a certain point.

The optimum process parameters for *dimension-4*;

Where the laser power is 370 W, scanning speed is 1600 mm/s, beam offset is 0,04 mm and 45-degree of built angle.



Response Table for Signal to Noise Ratios
Smaller is better

Level	Laser Power (W)	Scanning Speed (mm/s)	Beam Offset (mm)	Scanning Angle
1	16,29	15,62	20,42	19,25
2	18,91	19,78	22,62	16,98
3	23,99	23,79	16,15	22,96
Delta	7,70	8,17	6,47	5,98
Rank	2	1	3	4

Figure 3.6 Dimension-4 of bolt Taguchi analysis

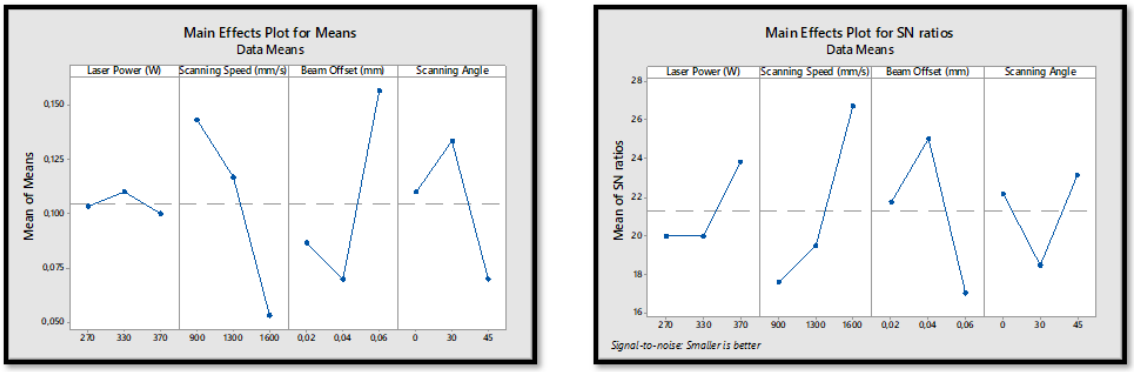
Investigation of *dimension-5* put forth that scanning speed and beam offset are noticeable parameters for scanning process.

Higher scanning speeds caused more accurate results. An average dimensional deviation of 0,05 was calculated at a scanning speed of 1600 mm/s, and at the same time, the lowest deviation value was measured as 0,02 in this parameter set.

Also beam offset acts similar with *dimension*-4. Increasing the beam offset value to 0,06 mm caused the highest deviation values from the reference measurement value. 0,22 mm maximum value was calculated in all variations and the mean of maximum deviation is almost 20 times higher than minimum as 0,15 mm at the 0,06 mm offset value, where the minimum is 0.07 mm at 0,04 mm offset.

The optimum process parameters for *dimension-5*;

Where the laser power is 370 W, scanning speed is 1600 mm/s, beam offset is 0,04 mm and 45-degree of built angle.



Response Table for Signal to Noise Ratios
Smaller is better

Level	Laser Power (W)	Scanning Speed (mm/s)	Beam Offset (mm)	Scanning Angle
1	20,00	17,60	21,75	22,20
2	19,98	19,50	25,03	18,47
3	23,86	26,73	17,05	23,16
Delta	3,88	9,12	7,98	4,68
Rank	4	1	2	3

Figure 3.7 Dimension-5 of bolt Taguchi analysis

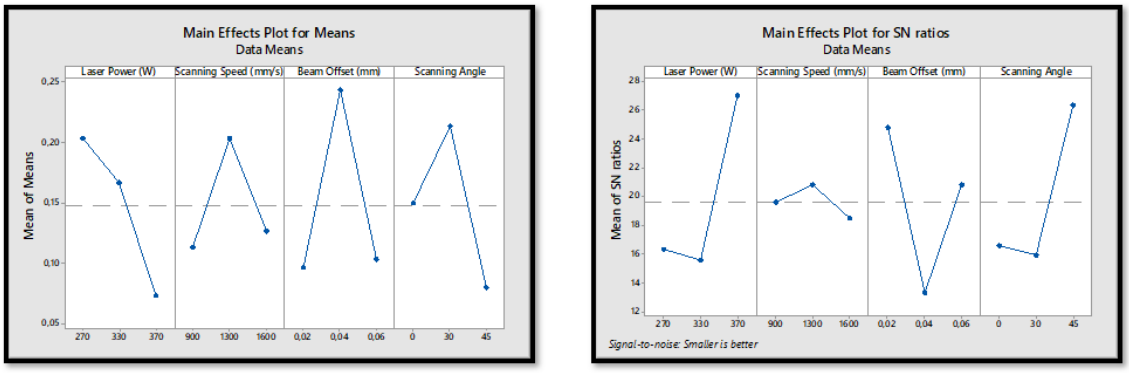
It's important to focus thread dimensions since it's the interaction region with another body. Generally, the critical tolerances of this region are determined as narrower because it affects performance of fastener.

After analyzing dimensional measurement outputs, it shows that the main parameter which effects thread dimension is beam offset. When working on 0,02 mm and 0,06 mm offset values, average deviations are almost equal, 0,09 mm and 0,10 mm respectively. However, minimum deviation was calculated as 0,01 mm in 0,02mm set. On the other hand, calculated maximum values belong to 0,04 mm offset values.

Laser power was determined according to the analysis results as the second-order parameter. Working at higher laser power to increase dimensional accuracy results in more accurate results. Deviation decreased from an average of 0,20 mm to 0,07 mm when the laser power was 270 W followed by 370 W.

The optimum process parameters for *thread*;

Where the laser power is 370 W, scanning speed is 1300 mm/s, beam offset is 0,02 mm and 45-degree of built angle.



Response Table for Signal to Noise Ratios
Smaller is better

Level	Laser Power (W)	Scanning Speed (mm/s)	Beam Offset (mm)	Scanning Angle
1	16,35	19,59	24,78	16,60
2	15,58	20,81	13,31	15,96
3	26,97	18,50	20,81	26,34
Delta	11,40	2,31	11,47	10,38
Rank	2	4	1	3

Figure 3.8 Dimension of bolt thread taguchi analysis

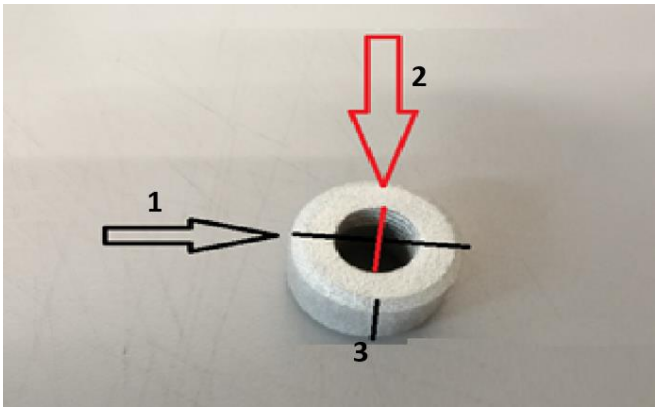


Figure 3.9 Measurement references of nut

As in the previous pages, dimensional measurements for nut samples are also examined in this section. Measured dimensions can be seen in the figure 3.9 and the mean values of the measurement results can be seen in the table 3.4.

Table 3.4 Measured values of nut samples

		Dimension-1 (mm)	Dimension-2 (mm)	Dimension-3 (mm)	Between Teeth (mm)
SAMPLE NO	1	29.78	13.94	20.33	2.21
	2	29.77	13.94	20.15	2.24
	3	29.86	13.97	20.02	1.90
	4	29.74	13.84	20.11	2.08
	5	29.74	13.92	20.31	2.08
	6	29.92	13.97	20.15	2.40
	7	29.87	13.90	20.22	1.83
	8	29.74	13.89	20.09	2.29
	9	29.84	13.96	20.32	1.73
Nominal Value		30	15	20	2

Table 3.5 Deviation values of nut samples

		Deviation-1 (mm)	Deviation-2 (mm)	Deviation-3 (mm)	Deviation Teeth (mm)
SAMPLE NO	1	0.22	1.06	0.33	0.21
	2	0.23	1.06	0.15	0.24
	3	0.14	1.03	0.02	0.10
	4	0.26	1.16	0.11	0.08
	5	0.26	1.08	0.31	0.08
	6	0.08	1.03	0.15	0.40
	7	0.13	1.10	0.22	0.17
	8	0.26	1.11	0.09	0.29
	9	0.16	1.04	0.32	0.27

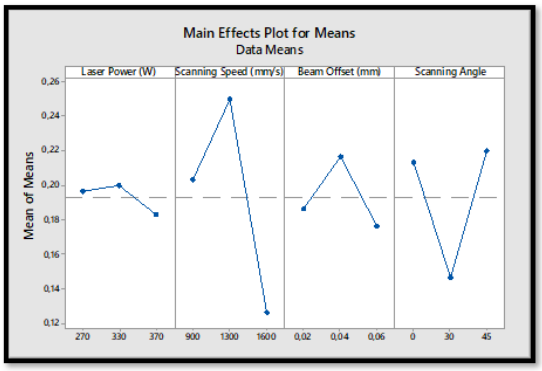
Outer dimension of nut, named as *dimension-1*, is has 30 mm of diameter in nominal. According to measurement values, deviation amounts is calculated separately, and it has been found out minimum value of deviation is 0,08 mm, where the maximum was 0,26 mm.

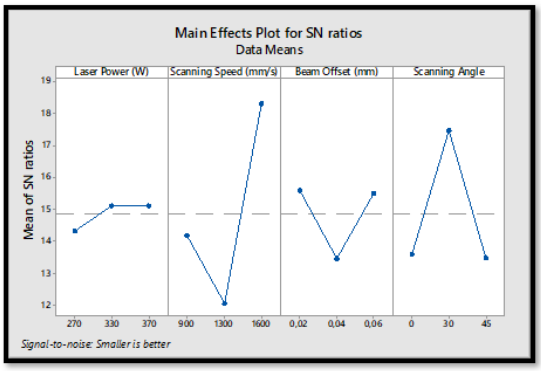
In the parameter set where the scanning speed was determined as 1600 mm/s, there was a significant improvement in the dimensional accuracy of the samples. While the average deviation amount was determined as 0,20 mm in the samples produced with a scanning speed of 900 mm/s, the deviation amount was calculated as 0,25 mm on average when the scanning speed was increased to 1300 mm/s. Then, another parameter set, 1600 mm/s, is performed, the results shown that integrity increases.

Another parameter that affects the process is the scanning angle. When the results were analyzed, the most suitable scanning angle for *dimension-1* was determined as 30-degree.

The optimum process parameters for *dimension-1*;

Where the laser power is 370 W, scanning speed is 1600 mm/s, beam offset is 0,02 mm and 30-degree of built angle.





Response Table for Signal to Noise Ratios
Smaller is better

Level	Laser Power (W)	Scanning Speed (mm/s)	Beam Offset (mm)	Scanning Angle
1	14,33	14,19	15,60	13,59
2	15,11	12,06	13,46	17,47
3	15,11	18,31	15,50	13,49
Delta	0,78	6,26	2,14	3,98
Rank	4	1	3	2

Figure 3.10 Dimension-1 of nut Taguchi analysis

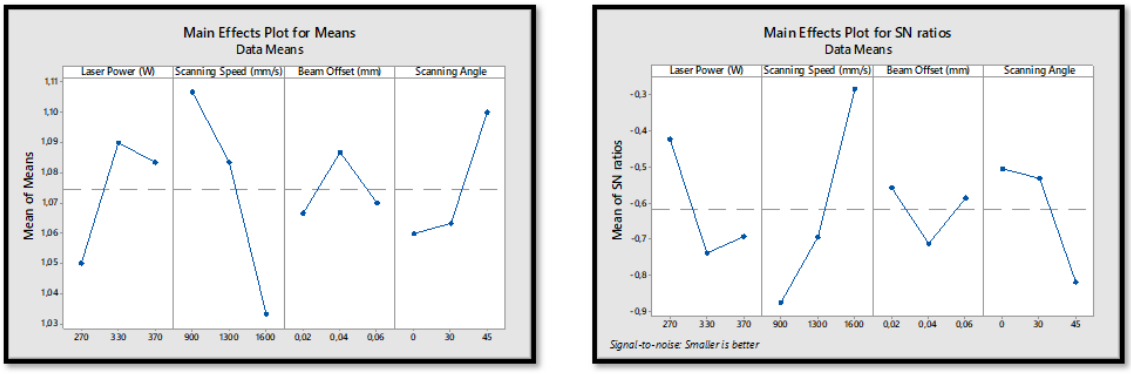
After analyzing an outer dimension, inner dimension of samples was analyzed, which is called *dimension-2*.

It can be seen from the graph that the scanning speed is the most important parameter affecting the process. Dimensional accuracy increases with increasing scanning speed.

However, when the measurement values were examined separately, independent from parameters, it was determined that the recorded results were not very different from each other. In addition, all the deviations of additively manufactured samples, it should be noted that the largest dimensional deviation occurs in the inner diameter dimension. Average of all *dimension-2* values are over than 1 mm. these deviation values are far outside the acceptable tolerance values in the assembly of functional parts.

The optimum process parameters for *dimension-2*;

Where the laser power is 270 W, scanning speed is 1600 mm/s, beam offset is 0,02 mm and 0-degree of built angle.



Response Table for Signal to Noise Ratios
Smaller is better

Level	Laser Power (W)	Scanning Speed (mm/s)	Beam Offset (mm)	Scanning Angle
1	-0,4230	-0,8744	-0,5564	-0,5051
2	-0,7381	-0,6937	-0,7120	-0,5302
3	-0,6917	-0,2847	-0,5844	-0,8175
Delta	0,3151	0,5897	0,1555	0,3124
Rank	2	1	4	3

Figure 3.11 Dimension-2 of nut Taguchi Analysis

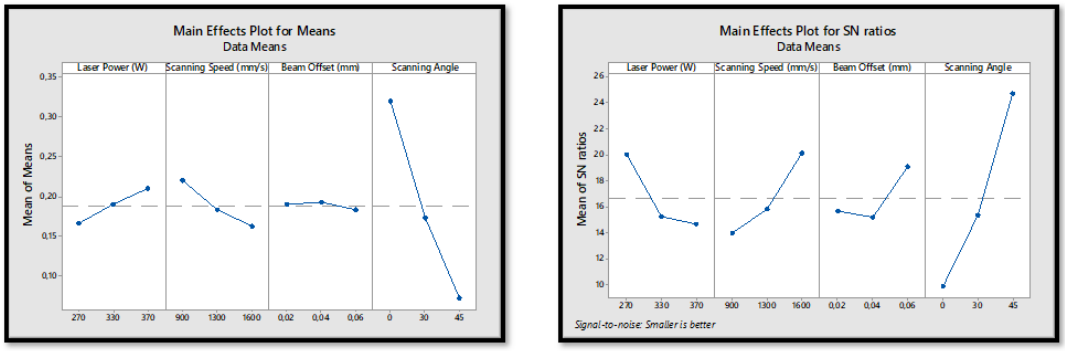
When investigate for the height of a nut, 2 minimum deviations amount were 0,02 mm and 0,09 mm, respectively. This is recorded as a rather low value when compared to the mean of the measured results. To understand main effects better, analysis results given below.

According to Taguchi analysis, scanning angle have been become a prominent. More efficient results were obtained in providing dimensional integrity when the scanning angle was increased from 0-degree to 45-degrees. A linear ratio of scan angle and dimensional accuracy was recorded. 0,07 mm of average value was achieved when working at 45-degrees of scanning angle, where the 0,32 mm at 0-degree and 0,17 mm at 30-degrees.

Scanning speed and laser power also have a slight effect on the process. However, these parameters did not cause such a significant difference that the scanning angle affected the process.

The optimum process parameters for *dimension-3*;

Where the laser power is 270 W, scanning speed is 1600 mm/s, beam offset is 0,06 mm and 45-degree of built angle.



Response Table for Signal to Noise Ratios
Smaller is better

Level	Laser Power (W)	Scanning Speed (mm/s)	Beam Offset (mm)	Scanning Angle
1	20,029	13,984	15,674	9,900
2	15,274	15,855	15,182	15,369
3	14,655	20,118	19,101	24,689
Delta	5,375	6,134	3,919	14,789
Rank	3	2	4	1

Figure 3.12 Dimension-3 of nut Taguchi analysis

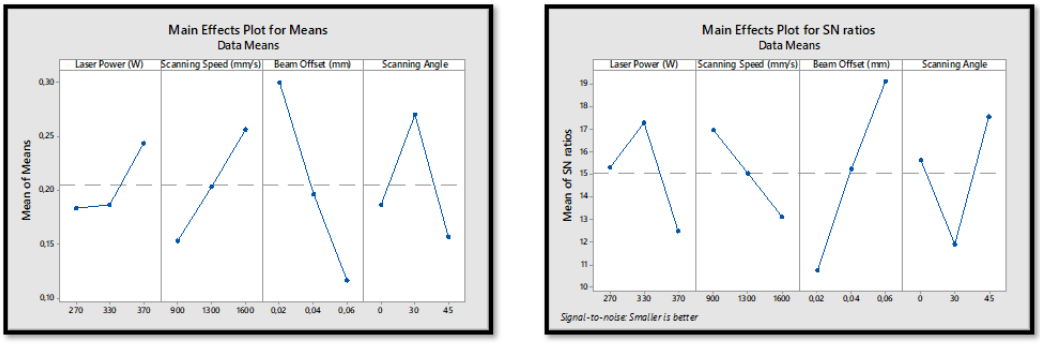
Finally, thread measurements of the nut sample were performed. While the average deviation amount of all measured samples was calculated as 0,20 mm, the minimum value was determined as 0,08 mm and the maximum value as 0,4 mm.

Looking at parameters set have been applied, the parameter that affects the process most is beam offset. Dimensional accuracy increased linearly with increasing beam offset values in the experimental samples produced by working at 0,02 mm, 0,04 mm and 0,06 mm beam offset levels. Average deviations were calculated as 0,03 mm, 0,19 mm and 0,11 mm, respectively.

Scanning angle is another significant parameter, while working at 0- and 45-degree scanning angles, lower deviation values were calculated than the samples produced with 30 degree scanning angles. When comparing the production at 0 and 45 degrees, the average deviation values were calculated as 0,18mm at 0 degree and 0,15 mm at 45-degrees.

The optimum process parameters for *dimension-thread*;

Where the laser power is 330 W, scanning speed is 900 mm/s, beam offset is 0,06 mm and 45-degree of built angle.



Response Table for Signal to Noise Ratios
Smaller is better

Level	Laser Power (W)	Scanning Speed (mm/s)	Beam Offset (mm)	Scanning Angle
1	15,32	16,96	10,76	15,62
2	17,28	15,03	15,24	11,92
3	12,51	13,11	19,11	17,56
Delta	4,77	3,85	8,35	5,65
Rank	3	4	1	2

Figure 3.13 Dimension of nut thread Taguchi analysis

3.3 Surface Measurements

Measurements taken by optical profilometer are given below and surface images could be seen. These measurements done with confocal method.

Table 3.6 Confocal measurements of nut

Sample No	Method	Average Sa (µm)	Average Sq (µm)	Average Sz (µm)
1	CF	16.76	20.8	147.37
2	CF	26.52	31.51	204.77
3	CF	19.37	24.67	246.46
4	CF	16.38	21.25	132.48
5	CF	17.56	21.18	138.28
6	CF	20.95	24.8	156.07
7	CF	20.94	25.29	173.35
8	CF	20.43	25.41	160.61
9	CF	12.03	15.02	123.86

Table 3.7 Focus variation measurements of nut

Sample No	Method	Sa (µm)	Sq (µm)	Sz (µm)
1	FV	16.95	20.74	132.65
2	FV	26.16	32.36	202.37
3	FV	20.94	26.68	155
4	FV	17.53	23.76	141.52
5	FV	11.34	14.01	81.45
6	FV	25.54	30	146.40
7	FV	15.75	19.45	123.38
8	FV	17.84	22.86	143.71
9	FV	9.15	11.94	71.45

While analyzing Sa values, repeated measurements were taken from 3 different points of each sample and the average Sa value was determined than Taguchi analyzes were performed. According from these measurements minimum value was calculated as 12,03 µm where the maximum was 26,52 µm.

When the results are examined under the effects of parameters, it is seen that the parameter affecting the surface roughness the most was the scanning angle. The minimum mean Sa result was determined as 15,44 µm at 0 degree scanning angle. Also, when the scanning angle was 30 and 45 degrees, the average Sa values were calculated as 22,80 µm and 18,72 µm, respectively.

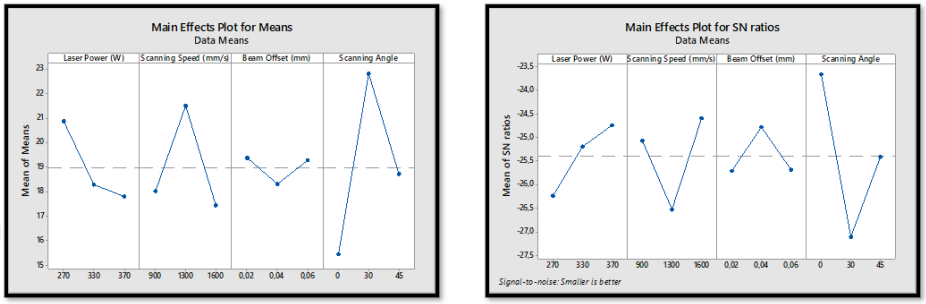
From the analysis results, scanning speed shows a significant effect on surface roughness. Scanning speed affected the surface roughness with a parabolic

distribution. The mean Sa values were reported as 18,03 µm at 900 mm/s scanning speed, 21,50 µm at 1300 mm/s scanning speed and 17,45 µm 1600 mm/s scanning speed.

According to the results obtained, it cannot be denied that the laser power is also effective on the surface quality. It was determined from the measurement results that the roughness value decreased with increasing laser power. 270 W, 330 W and 370 W laser power were applied on specimens and mean roughness values measured as respectively 20,89 µm , 18,30 µm and 17,80 µm

The optimum process parameters for *dimension-thread*;

Where the laser power is 370 W, scanning speed is 1600 mm/s, beam offset is 0,04 mm and 0-degree of built angle. Which is the same parameter set with sample-9 and it is clearly seen that minimum Sa values calculated for sample 9.



Response Table for Signal to Noise Ratios
Smaller is better

Level	Laser Power (W)	Scanning Speed (mm/s)	Beam Offset (mm)	Scanning Angle
1	-26,23	-25,06	-25,71	-23,66
2	-25,20	-26,52	-24,79	-27,11
3	-24,74	-24,59	-25,68	-25,41
Delta	1,49	1,93	0,92	3,45
Rank	3	2	4	1

Figure 3.14 Average Sa of nut Taguchi analysis

Yang et al. investigated the influence of linear energy density, which effected by process parameters, on surface quality. According to their research, LED and surface quality tends linearly at the beginning. However, as the LED continues to be increased, the surface roughness also starts to increase. They also focused on the adequacy of energy density. It is reported that, lack of LED causes rough surface. This is because the powder grains cannot be melted completely. Shorter solidification time also leads to the same result. Finally, excessive LED application negatively affects the surface roughness [38].

Another research on surface quality done by Maamuon et al. They noted energy density and surface roughness regression in literature. Increasing energy density causes improvement of surface quality to some specific point. Surface roughness measured where the energy density at 27 J/mm^3, 40,5 J/mm^3 and 65 J/mm^3. Results are respectively given 15 µm, 10 µm and 4,5 µm. At the same time, while laser power affects the surface quality linearly, scanning speed shows negative linear distribution [18].

Bhaduri et al. reports that laser power shows significant effect rather than scanning speed and hatch spacing [38]. Also, Khorasani et al.'s study shows that optimum surface quality achieved when the laser power higher and scanning speed at low values [40]. Sanaei et al. have reported in the literature that there is an inverse linear relationship between laser power and roughness. [41]

In the study of Artzt et al., the results obtained with high scanning speed have low surface roughness. [42] In addition, in the study of Louw et al., the surface roughness decreased with the increase of scanning speed. [43]

In this thesis, the effects of scanning speed and laser power on roughness are shown as summarized in the literature. In addition, it has been reported that the scanning angle is the most~~a more~~ important parameter. Yang et al. have studied effect of scanning angle on surface quality. According from their paper, the reason for the surface roughness is due to the overhang length that occurs in terms of scanning. In addition, the overhang length is defined as layer thickness multiple by the tangent value of the scanning angle. When increasing the build angle, overhang length fundamentally decreases, and it causes lower surface roughness. 30, 45 and 60 degrees of scanning angle have been studied and best surface reported from 60 degrees produced samples. [44] Another study has been caried out by Tarakci et al., The samples were produced with scanning angles of 0, 15, 30, 45, 60, 75 degrees. According to the analysis results obtained, scanning angles of 0, 60 and 75 degrees resulted with better surface quality than 15, 30 and 45 degrees. The lack of remelting in the layers explains the high surface defects. [45] Hatos performed surface roughness measurements with scanning angles between 0 and 90 degrees in increments of 10. According to the measurements of the lower and upper surface

roughness, the best surface qualities were recorded at 0 degrees and above 60 degrees. [46]

Optical and SEM images were taken for each sample. These images are examined and given in figure-15 to 22. Particular attention should be paid on; Optical and SEM images of sample-9 with the lowest surface roughness and sample-2 with the highest roughness value are given in Figure 3.22 and Figure 3.16, respectively. These images are proof of profilometer measurements and Sa values. While the surface topography of sample 9 is quite smooth, surface irregularities are observed for sample 2. The reason for this is that irregularities occur during the melting and solidification of the powder particles.

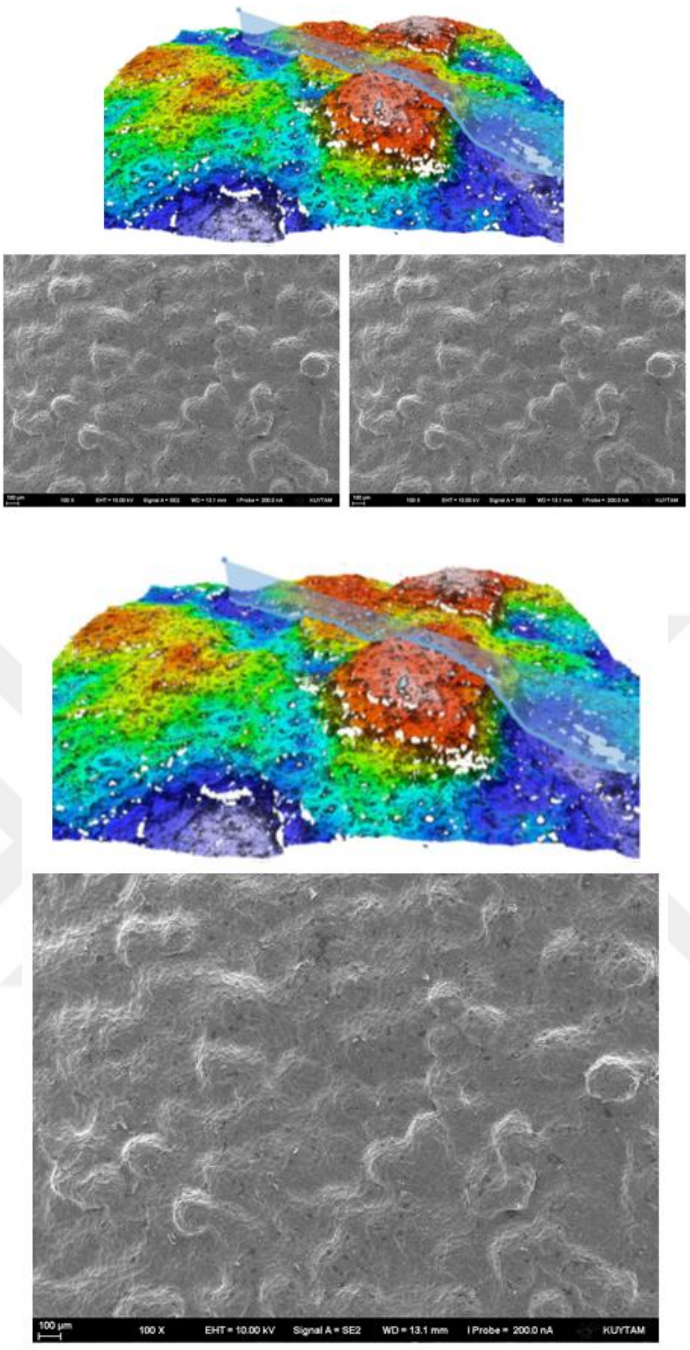


Figure 3.15. Confocal optical profilometer and SEM images of nut sample-1

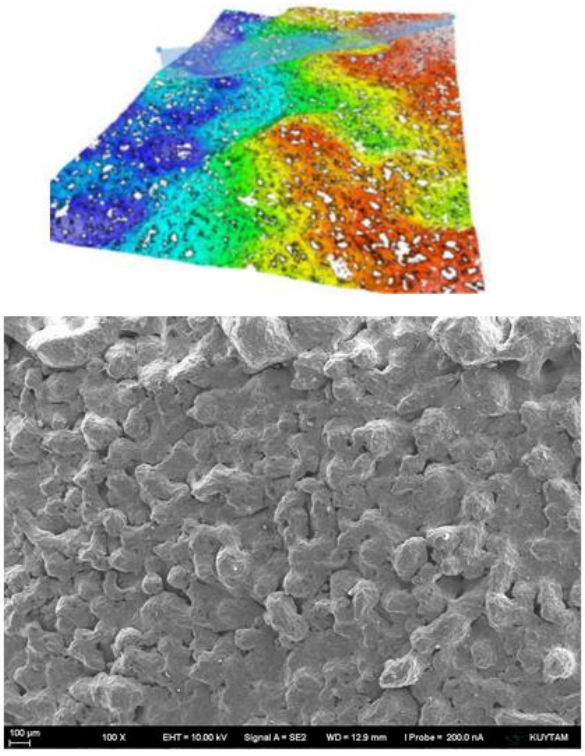


Figure 3.16. Confocal optical profilometer and SEM images of nut sample-2

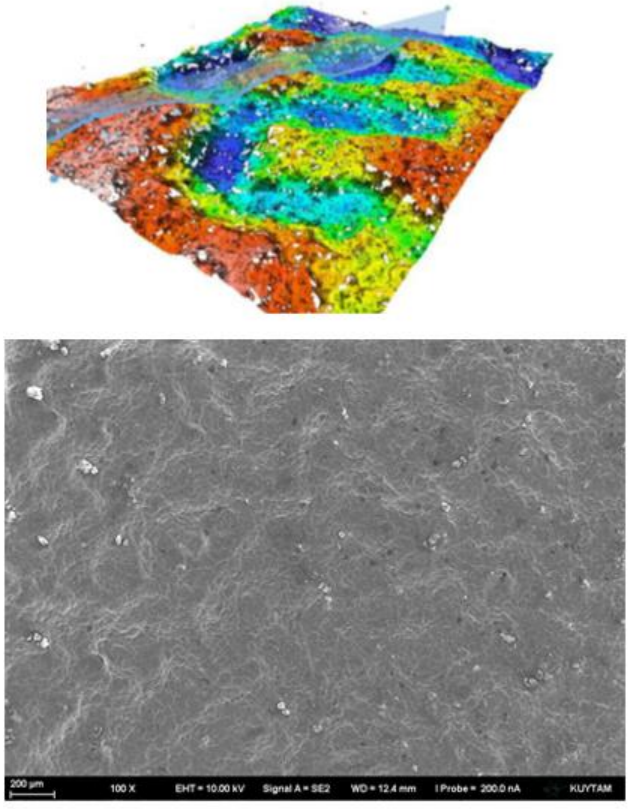


Figure 3.17. Confocal optical profilometer and SEM images of nut sample-3

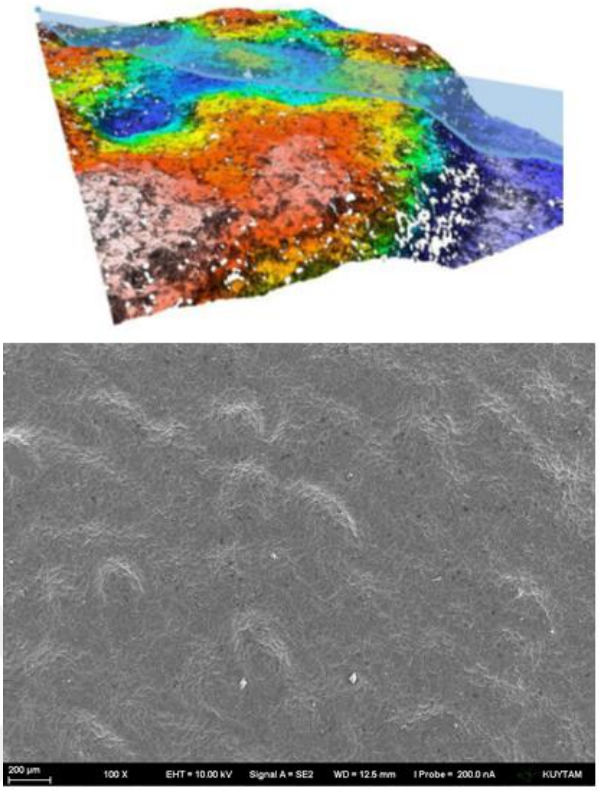


Figure 3.18. Confocal optical profilometer and SEM images of nut sample-4

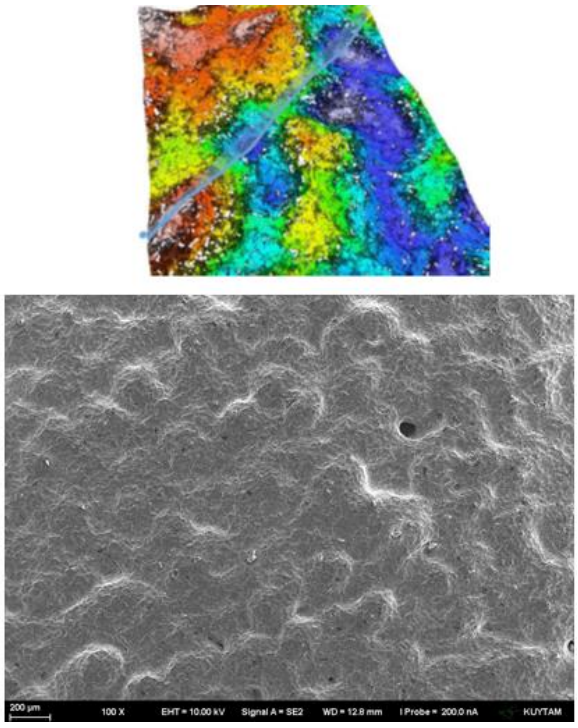


Figure 3.19. Confocal optical profilometer and SEM images of nut sample-5

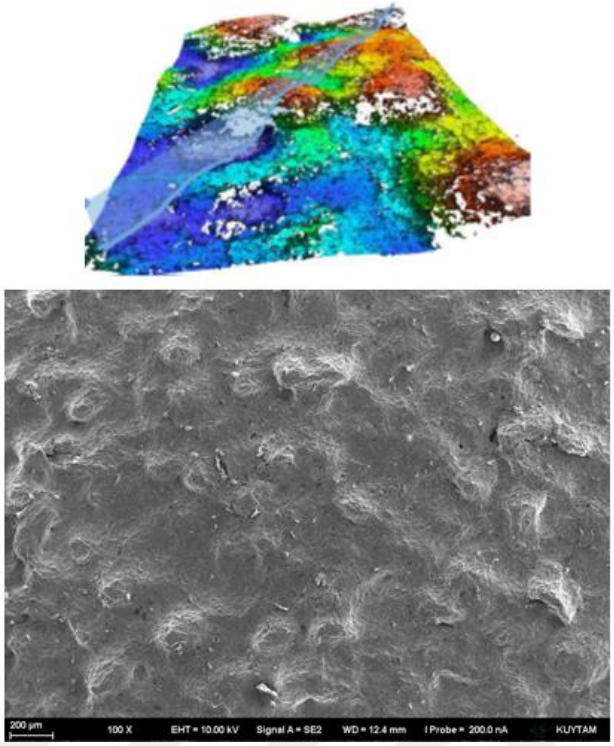


Figure 3.20. Confocal optical profilometer and SEM images of nut sample-7

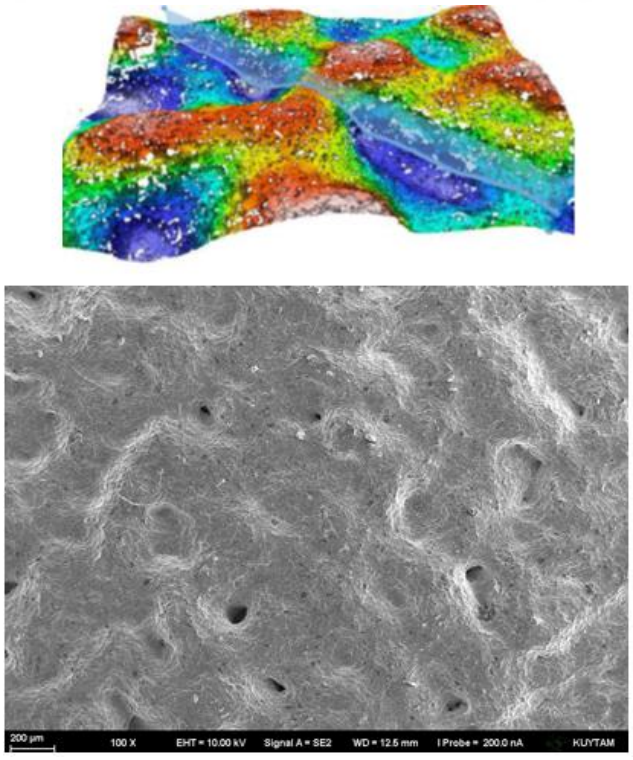


Figure 3.21. Confocal optical profilometer and SEM images of nut sample-8

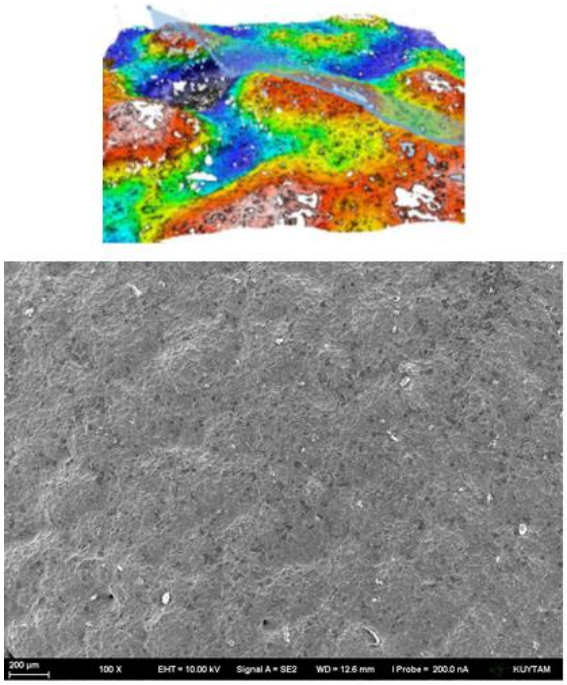
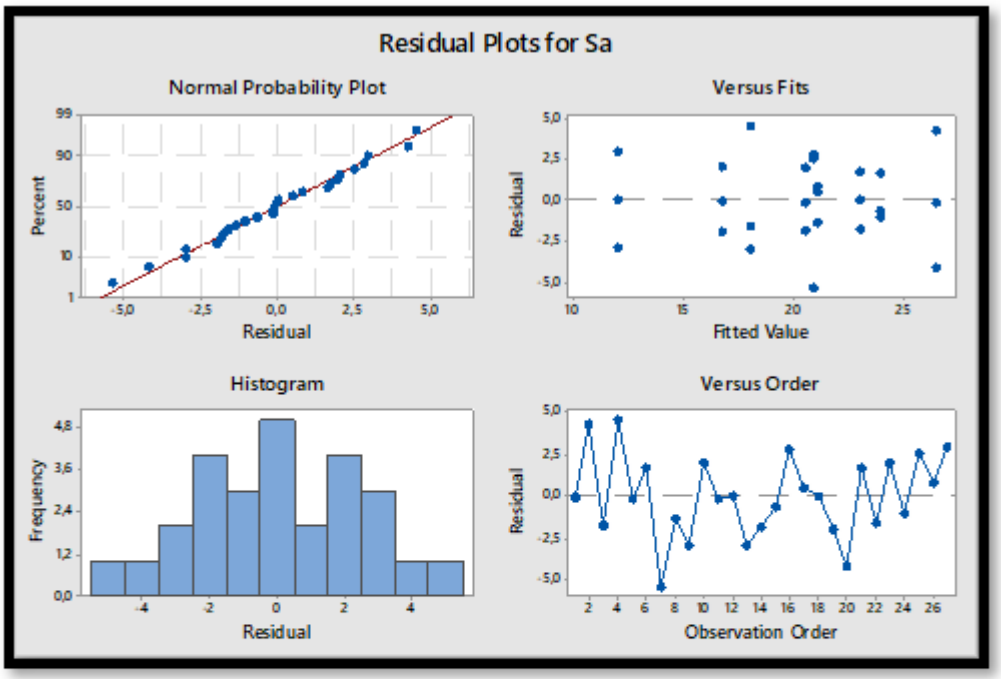


Figure 3.22. Confocal optical profilometer and SEM images of nut sample-9

3.4 ANOVA Analysis

The ANOVA analysis, which is performed to evaluate the contribution of each factor on the results, is shown in figure 3.16. Where the degree of freedom is 2 for the factor levels and the degree of freedom of error is 18, the critical F value read from the F-table is 3.55. From the ANOVA table, it is seen that the F values of the laser power, scanning speed and build angle parameters are higher than the critical F value, while beam offset is less than the critical F value. In this case, the hypothesis that laser power, scanning speed and scanning angle parameters have a significant effect on surface roughness is confirmed. These results are compatible with the literature studies in the previous chapters.



Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Lazer Power	2	79,12	39,559	4,52	0,026
Scan Speed	2	82,50	41,250	4,71	0,023
Beam Offset	2	32,18	16,089	1,84	0,188
Build Angle	2	245,81	122,904	14,04	0,000
Error	18	157,61	8,756		
Total	26	597,22			

Figure 3.23 ANOVA analysis of nut, surface measurements

4
CONCLUSION

- It is possible to mention about a relationship between energy density and relative density. When the results obtained in this study and literature studies were compared, increasing the energy density up to a certain critical point increased the relative density. However, after this critical value, relative density tends to decrease. In this study, critical ED value calculated as 48,78 J/mm^3.
- Scanning speed and built angle were determined as two important factors affecting the dimensional accuracy of the bolt head diameter. Built angle affects the dimensional accuracy linearly in the negative direction.
- Laser power, scanning speed, beam offset and scanning angle effects dimensional accuracy of DMLS produced AlSi10Mg parts. In this study, it's revealed that scanning speed is a key parameter for linear dimension of a bolt. Also, it is possible to reduce dimensional errors with scanning speed.
- Thread geometry have been mostly affected by beam offset. Moreover, samples produced with 0.04 mm offset gave the best dimensional results. The defined optimal conditions for the distance between two teeth was the same as 9th parameter set in which deviation was at the minimum value. So, the results were in accordance with each other which confirms that defined optimum parameter set is sensible.
- Since the inner diameter of the nut is the surface to be used in assembly, it is extremely important to ensure its dimensional accuracy. However, according to the results obtained in this study, it was determined that the dimensional deviations were above 1 mm. Studies need to continue to increase the internal diameter dimensional accuracy.
- Finally, when the effect of the process parameters on the surface roughness was examined, it was revealed that the scanning angle was dramatically effective. The samples produced at 0-degree angle gave the best surface quality. Besides, when ANOVA analysis was performed for surface roughness results, it was confirmed that laser power, scanning speed and scanning angle were effective on the process. Beam offset has not significant effect on surface roughness.

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PUBLICATIONS FROM THE THESIS

Books

1. Bagci, H. B., Sagbas, B., & Durakbasa, M. N. (2020). EFFECT OF DIRECT METAL LASER SINTERING PROCESS PARAMETERS ON DIMENSIONAL ACCURACY OF ALSI10MG PARTS. *DAAAM International Scientific Book*.