

T.R.
GEBZE TECHNICAL UNIVERSITY
GRADUATE SCHOOL

INFULENCE OF HEAT TREATMENT PARAMETERS ON THE
TRIBOLOGICAL PERFORMANCE OF TI6AL4V
COMPONENTS PRODUCED BY LASER POWDER BED
FUSION

TANKUT TAŞDELEN

A THESIS OF MASTER OF SCIENCE
DEPARTMENT OF MECHANICAL ENGINEERING

ADVISOR: ASSIST. PROF. DR. RECEP ÖNLER

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LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

LAZER TOZ YATAK FÜZYONU İLE ÜRETİLEN Ti6Al4V
BİLEŞENLERİNİN TRİBOLOJİK PERFORMANSINA ISIL
İŞLEM PARAMETRELERİNİN ETKİSİ

TANKUT TAŞDELEN

YÜKSEK LİSANS TEZİ
MAKİNE MÜHENDİSLİĞİ ANABİLİM DALI

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MAYIS 2025



MASTER of SCIENCE JURY APPROVAL FORM

A thesis submitted by Tankut TAŞDELEN, defended on 13/05/2025 before the jury formed with the 03/02/2025 date and 2025/08 numbered decision of the GTU Graduate Administration Board, has been accepted as a MASTER of SCIENCE thesis in the Department of Mechanical Engineering.

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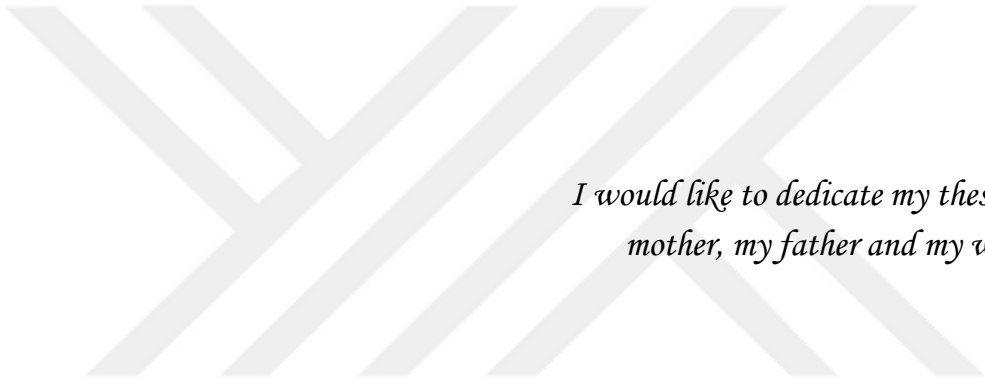
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*I would like to dedicate my thesis to my
mother, my father and my wife.*

ABSTRACT

The additive manufacturing method allows us to produce cheaper and easier designs that are too difficult or too expensive to build using traditional methods such as machining, molding or casting methods. Thanks to this method, the production of much more complex parts is made possible, and at the same time, lighter and more functional parts can be produced with new design methods that have entered our lives with additive manufacturing.

There are many metal and polymer-based additive manufacturing methods. SLM technology, one of the metal additive manufacturing methods, has found use in many different sectors in recent years. Selective laser melting technology is advantageous due to its low waste amount, faster production benefits, as well as its complex geometric capabilities. Recently, with the rapid development of additive manufacturing technology, Ti6Al4V alloy has found applications in many fields such as biomaterial, military industry, automobile, marine, chemical industries, aviation and space industry due to its high specific strength, bending resistance and biocompatibility. However, their tribological properties are poor because of high COF and catastrophic wear under sliding and fretting conditions. This may diminish the reliability of Ti-based components such as joints, etc., in biological systems where tribological properties are important. In this thesis, Ti6Al4V alloy experimental samples will be produced with additive manufacturing technology. While some parameters of the parts during production will be constant, the parts will be heat treated with different heat treatment parameters. As a result of this experiment, the effects of various heat treatment parameters on the microstructure and tribological properties of manufactured parts will be experimentally examined.

Keywords: Additive Manufacturing, Ti6Al4V Alloys, Heat Treatment, Selective Laser Melting, Tribology, Mechanical Properties.

ÖZET

Eklemeli imalat yöntemi, işleme, kalıplama veya döküm yöntemleri gibi geleneksel yöntemleri kullanarak inşa edilmesi çok zor veya çok pahalı olan tasarımları daha ucuz ve daha kolay üretmemize olanak tanır. Bu yöntem sayesinde çok daha karmaşık parçaların üretimi mümkün kılındığı gibi aynı zamanda eklemeli imalatla hayatımıza giren yeni tasarım yöntemleriyle daha hafif ve daha fonksiyonel parçalar da üretilebilmektedir.

Birçok metal ve polimer bazlı eklemeli imalat yöntemi vardır. Metal eklemeli imalat yöntemlerinden biri olan SLM teknolojisi son yıllarda pek çok farklı sektörde kullanım alanı bulmuştur. Seçici lazer eritme teknolojisi, düşük atık miktarı, daha hızlı üretim avantajları ve karmaşık geometrik yetenekleri nedeniyle avantajlıdır. Son zamanlarda eklemeli imalat teknolojisinin hızla gelişmesiyle birlikte Ti6Al4V alaşımı, yüksek özgül mukavemeti, bükülme direnci ve biyouyumluluk nedeniyle biyomalzeme, askeri sanayi, otomobil, denizcilik, kimya sanayi, havacılık ve uzay sanayi gibi birçok alanda uygulama alanı bulmuştur. Bununla birlikte, yüksek sürtünme katsayısı (COF) ve kayma ve aşındırma koşulları altında yıkıcı aşınma nedeniyle tribolojik özellikleri zayıftır. Bu, tribolojik özelliklerin önemli olduğu biyolojik sistemlerde eklemeler vb. gibi Ti bazlı bileşenlerin güvenilirliğini azaltabilir. Bu tezde, eklemeli imalat teknolojisi ile Ti6Al4V alaşımı deneysel numuneleri üretilecektir. Parçaların üretim esnasındaki bazı parametreleri sabit olurken, farklı ısıtım parametreleri ile parçalar ısıtım işlemi sokulacaklar. Bu deney sonucunda, çeşitli ısıtım parametrelerinin üretilen parçaların mikroyapı ve tribolojik özellikleri üzerine etkisi incelenecektir.

Anahtar Kelimeler: Eklemeli İmalat, Ti6Al4v Alaşımları, Isıtım İşlem, Seçici Lazer Ergitme, Triboloji, Mekanik Özellikler

ACKNOWLEDGEMENTS

I would like to express my deepest gratitude to several individuals and institutions whose support and contributions were invaluable in the completion of this thesis.

First and foremost, I would like to thank my esteemed advisor, Assist. Prof. Dr. Recep ÖNLER. His guidance, wisdom, and unwavering support have been instrumental throughout this journey. Without his insightful feedback, constructive criticism, and continuous encouragement, this thesis would not have been possible.

I would also like to extend my heartfelt thanks to my family, friends, and other professors for their constant support and encouragement. Their belief in me and their unwavering support have been a source of strength throughout this process. Finally, I am grateful to everyone who has contributed to this thesis, whether directly or indirectly.



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LIST OF SYMBOLS AND ABBREVIATIONS

SLM	: Selective Laser Melting
3D	: Three-Dimensional
SLA	: Stereolithography
AM	: Additive Manufacturing
CAD	: Computer-Aided Design
STL	: Standard Triangle Language
FDM	: Fused Deposition Modeling
SLS	: Selective Laser Sintering
DED	: Directed Energy Deposition
DLP	: Digital Light Processing
DMD	: Digital Micro Mirrors
FFF	: Fused Filament Fabrication
MJ	: Material Jetting
BJ	: Binder jetting
PBF	: Powder Bed Fusion
EBM	: Electron Beam Melting
DFAM	: Design of Additive Manufacturing
DLC	: Diamond-Like Carbon
TiN	: Titanium Nitride

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1. INTRODUCTION

Additive manufacturing, one of the new production methods that has become widespread recently, continues to rapidly enter our lives. It emerged at a point where traditional manufacturing methods fell short or became stagnant. It can be said that it is a production method that fills the gaps of traditional production methods and completes them.

In a digitalizing world, it is actually a manufacturing method that is needed. Digitalization, encountered everywhere in life, has also entered the industry, especially with Industry 4.0. It is known that there is a need for digitalization in production methods, and AM is a technology that can lead the industry in this regard.

Particularly in the healthcare and aerospace industries, titanium, which has become a sought-after material, has started to be produced in complex geometric designs using additive manufacturing. This has enabled both the opportunity to work with lattice structures and the production of complex geometric models, achieving the desired weight reduction in aviation.

In the production of hip cups, the Ti6Al4V material is particularly used with Selective Laser Melting (SLM) or Electron Beam methods. One of the important issues here is that one of the requirements of the SLM production method is heat treatment at the end of production. This is necessary because residual stresses form in parts produced by this method, and these need to be relieved through heat treatment. Different heat treatment parameters have an impact on the microstructure of the parts. Additionally, there is a need to observe the tribological changes that occur. Especially in the production of implants, the tribological properties of the material are important and need to be examined.

2. LITERATURE REVIEW

2.1. Additive Manufacturing Technology

Additive manufacturing is a constantly developing technology that allows the production of simple and complex models with 3D data. Additive manufacturing is the process of converting 3D data into a final product by adding materials layer by layer. This technology was discovered by Charles Hull in 1986. It first appeared with the SLA method. Today, there are many different technologies and production methods according to demand[1].

Additive manufacturing is seen as one of the most important industrial developments and is thought to cause a revolutionary change process in production for a long time. This production method covers different production methods from simple machines to much more advanced high-tech machines and offers a wide range of usage areas in many different sectors with different material availability[2].

The additive manufacturing process basically consists of 8 steps, and although many different AM technologies contain some different processes, there are similar processes. These steps can be defined in the following order[3]:

- Creating CAD data.
- Converting CAD data to STL data
- Transferring data to the machine
- Machine arrangements
- Production/Build
- Removing the produced part from the machine
- Applying post-process to the produced part
- Final product

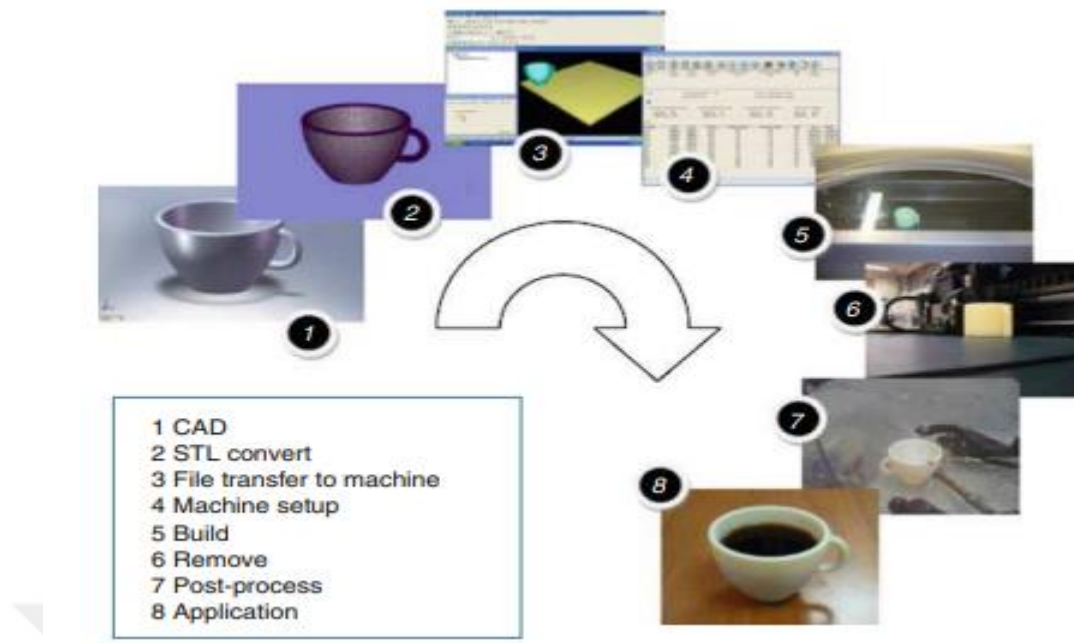


Figure 2.1: The basic 8 steps of the additive manufacturing process.

As the first step, the 3D design of the part is made. Then, the Cad model is converted to the stl format that almost all machines work with. In this way, the Cad model is converted to a format that defines its external surfaces and can be used for the slicing process. The data converted to stl format is prepared before being sent to the machine. For example, operations such as orientation or creation of supports are performed at this stage. Then the model is sliced.

The fourth step is to set the machine parameters before production. Each technology has its own parameters, and these parameters need to be set before each production. The next step is to perform production.

The finished part now becomes a real product and the processes of separating it from the machine are executed. An example of this process is the process of separating the part from the substrate in productions that require support. Post-processing is applied to the part separated from the table and surface improvements are performed on the part and it is made ready for the end user. And the produced product is used in a way that is suitable for the purpose. It can be used both as a prototype and at the same time, with the developing technologies today, it can now be used as a final product.

2.1.1. AM Methods

Additive manufacturing methods continue to be developed in order to produce difficult and complex structures at higher resolution, to produce larger models, to have a faster production process and to produce products with better mechanical properties. As a result, different production methods have been developed.

Some of the most important features that distinguish these methods are that they can produce different materials, produce parts with different mechanical properties, have different budgets, produce at different speeds, etc. Thus, the AM method suitable for the features of the requested part can be selected. Although the most well-known method is FDM, there are many well-known production methods such as selective laser melting (SLM), selective laser sintering (SLS) in powder bed fusion systems, and stereolithography (SLA) as well as direct energy deposition (DED) which performs resin-based production[4].

These AM methods can be examined under 7 headings according to ““The American Society for Testing and Materials (ASTM) Committee F42 on Additive Manufacturing Technologies”[5]:

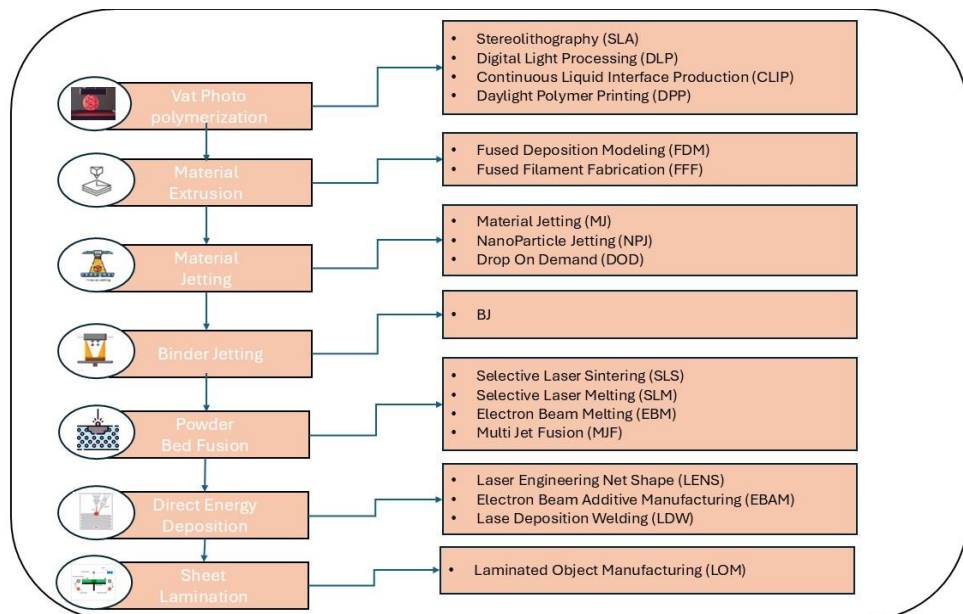


Figure 2.2: Classification of additive manufacturing according to ASTM F-42.

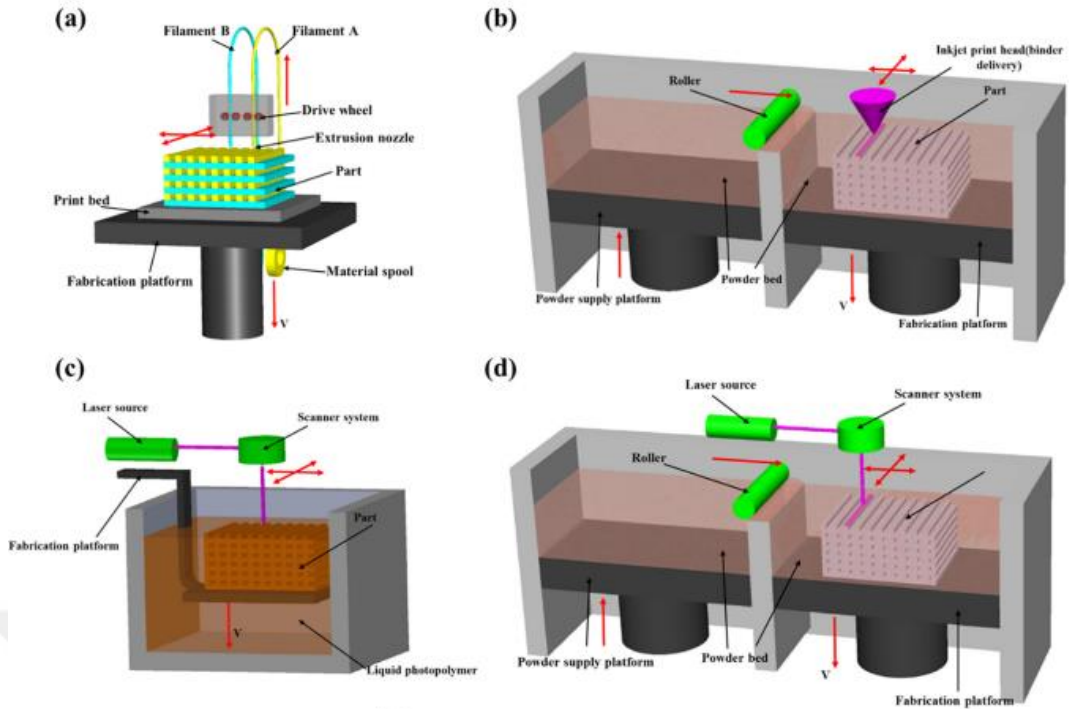


Figure 2.3: Some commonly used AM methods; (a) FDM; (b) inkjet printing; (c) stereolithography; (d) powder bed fusion [6].

2.1.1.1. Vat Photopolymerization

Vat Photopolymerization is the first method in which additive manufacturing was used. It can be said that it is the AM method with the oldest history.

This technology, which provides production with photopolymer-based material, hardens the liquid photopolymer resin by exposing it to light energy. X-rays, gamma rays, electron beams, UV rays and similar radiation sources can be used to solidify and shape the liquid resin. Thanks to this method, liquid resin can be cured with the help of a laser and shaped layer by layer and the desired design is produced [7].

In the photopolymerization process, the resin material is filled into a deep tray and cured with a UV light. In this curing process, the polymers exposed to the UV light cross-link and turn into a solid body. As can be seen from the **Figure2.4**, the photopolymer mixture consists of monomers, oligomers, and photo initiators. During curing, the photo initiators release the catalysts that form the chain between the monomers and oligomers, allowing the formation of the chain between the polymers. Thus, the resin that turns from liquid to solid form during curing cannot return to liquid form again [8].

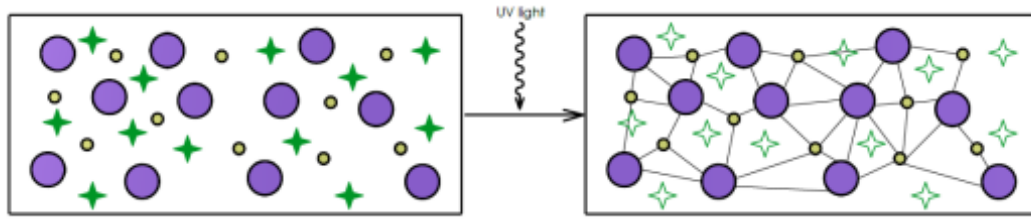


Figure 2.4: Curing process of liquid photopolymer (small circle; monomer, large circle; oligomer, star; photo initiators)[8].

One of the Vat Photopolymerization methods, Stereolithography (SLA), provides the polymerization reaction using a laser source. The movement of the laser is provided with Galvano scanners and provides high-accuracy production. Although it provides slower production compared to methods such as DLP, it allows high-resolution part production. The SLA method is widely used in many different sectors and areas. Some of these are; jewelry, footwear, mechanical applications, biomedical and dental applications, and in addition to these, this technology is used in electrical applications such as sensors and transducers. It can also be produced with high resolution in lattice structures that are difficult to produce with traditional methods. Another method, digital light processing (DLP), is very similar to the SLA method, but unlike SLA, it does not scan the cross-sectional area of the part to be produced point-to-point with a laser beam, thus providing a much faster production opportunity. In this method, digital micro mirrors (DMD) technology is used to scan the cross-sectional area and thus provides very fast curing [9], [10].

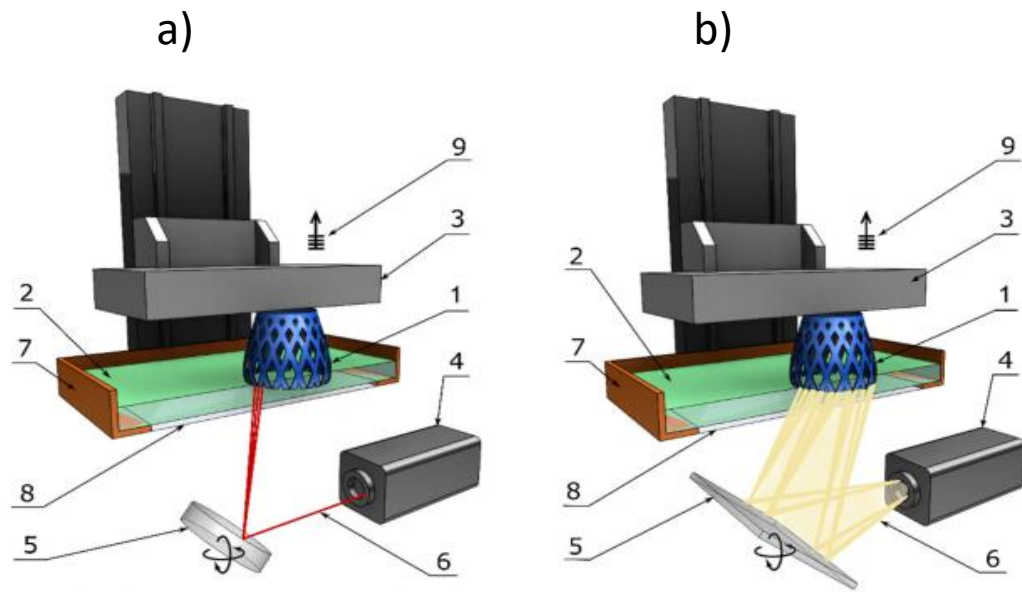


Figure 2.5: a) Stereolithography technology (SLA) and b) Digital Light Processing (DLP) [8].

2.1.1.2. Material Extrusion

The most well-known method of Material Extrusion is also known as FDM or FFF. This method uses various materials called filaments as raw material for production. It produces by melting the filament in an extruder system and sticking it layer by layer to the plate. This technology, which converts digital 3D data into physical data, provides fast production and allows the production of even parts with complex models [11], [12].

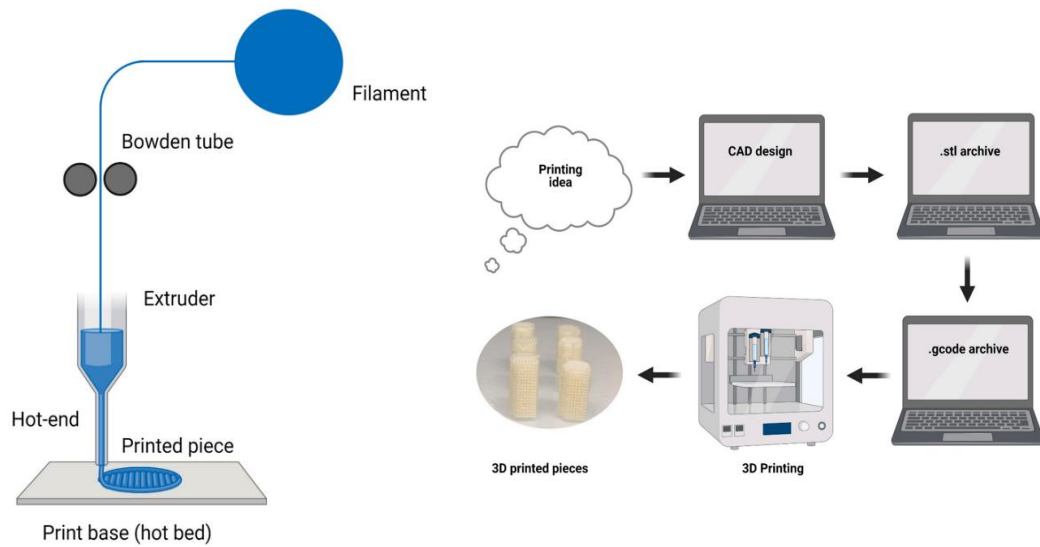


Figure 2.6: FDM method working principle [13].

This technology, which is widely used especially for the prototype production of thermoplastics, has produced many new machines that can also use metal and composite materials in recent years. Thermoplastic, composite materials and bioplastic materials can now be produced widely with this method. Especially recently, parts can be produced with the FDM method, also known as FFF, with reinforced composites with high mechanical properties. They can be used in many areas thanks to the wide range of producible materials and machines with high dimensions. It can be said that this 3D method, which attracts high interest, is also the most easily accessible technology in terms of price [14], [15], [16], [17].

The types of materials used in FDM printers can be seen schematically in **Figure 2.7** below. As can be seen from here, it has many different uses in many different sectors thanks to its different material variety.

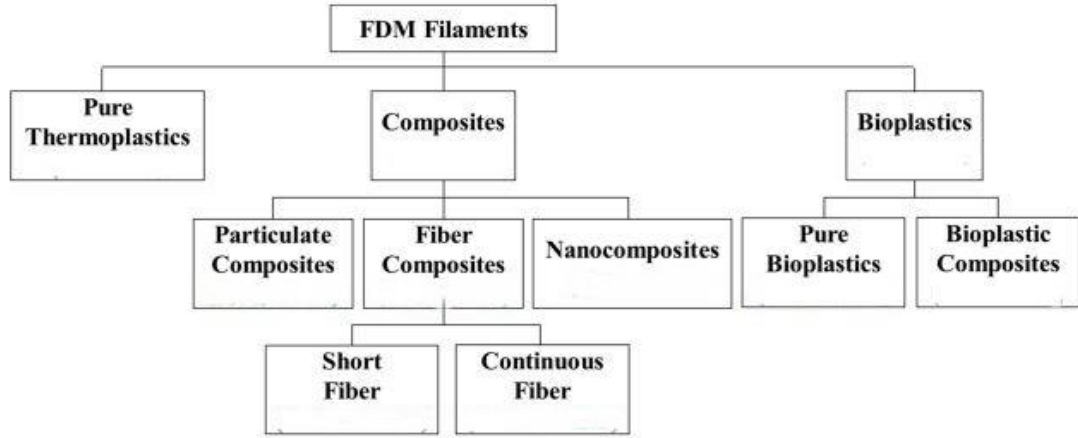


Figure 2.7: Filament categorization used with FDM technology [18].

In addition, FDM method can be used to produce recycled thermoplastics and provides a sustainable production opportunity by reducing the amount of waste. In this way, plastics that are considered garbage can be recycled and turned into products again. Some studies show that there are decreases in the mechanical properties of recycled thermoplastic materials. Various additives can be used to increase their mechanical properties. Thus, recycled thermoplastics with the desired mechanical properties can be produced with this technology [19].

With such developments, this technology, which has found its use in many different sectors with many materials today, continues to develop every day. Thanks to its easy accessibility, anyone who wants can use these devices at home and produce the designs they want and turn them into a real model [20].

2.1.1.3. Material Jetting

Material Jetting (MJ), one of the AM methods, is a production technology based on the principle of spraying photopolymer materials onto the platform in thin layers by heating. The photopolymer material in air-free storage tanks is selectively deposited on the platform as droplets forming a very thin layer with the help of a nozzle after being heated. Each layer is cured with UV light and the layers are combined in order and finally the desired part is produced. Thanks to this method, complex models can be easily produced and at the same time models with thimble surface quality can be produced compared to other technologies. Support structures are generally used and these support structures are cleaned in the final process with sodium hydroxide bath,

heating or high-pressure water jet [21]. At the same time, this different finishing process selection is important and affects the mechanical properties of the part [22].

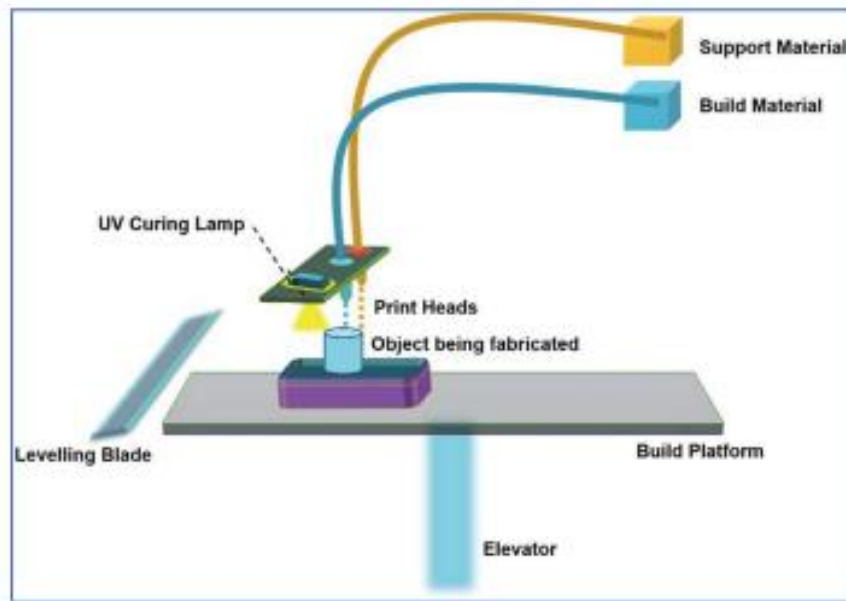


Figure 2.8: Production scheme of Material Jetting (MJ) [23].

One of the most important features of this method is that it can produce hybrid products by using different materials on the same product. It offers a hybrid production opportunity by using hard, flexible, transparent photopolymer materials in the same production. In this way, the overall performance of the material can be improved by using materials of different hardness together in different areas. This means that the material properties can be optimized according to a specific design or application [24].



Figure 2.9: Examples of hybrid models produced with Polyjet.

MJ technology is considered one of the most useful methods in terms of precision and speed among existing methods. Offering production with 0.015 mm precision, this printer is widely used in the production of high-accuracy and high-visual models[25].

2.1.1.4. Binder Jetting

Binder jetting is a powder bed additive manufacturing process that works by depositing a thin layer of powdered material and selectively bonding it to the desired shape with a binder fluid (usually polymeric). As the layers coalesce, a powder box is created that matches the geometry of the 3D model. If necessary, the binder is cured or set, and then the parts are removed from the powder bed in a process called depowdering. At this stage, the parts are usually in a “green” state, unsuitable for end use, and are subjected to a process such as sintering or infiltration to achieve the desired mechanical properties. All these processes can be seen in **Figure 2.10** [26].

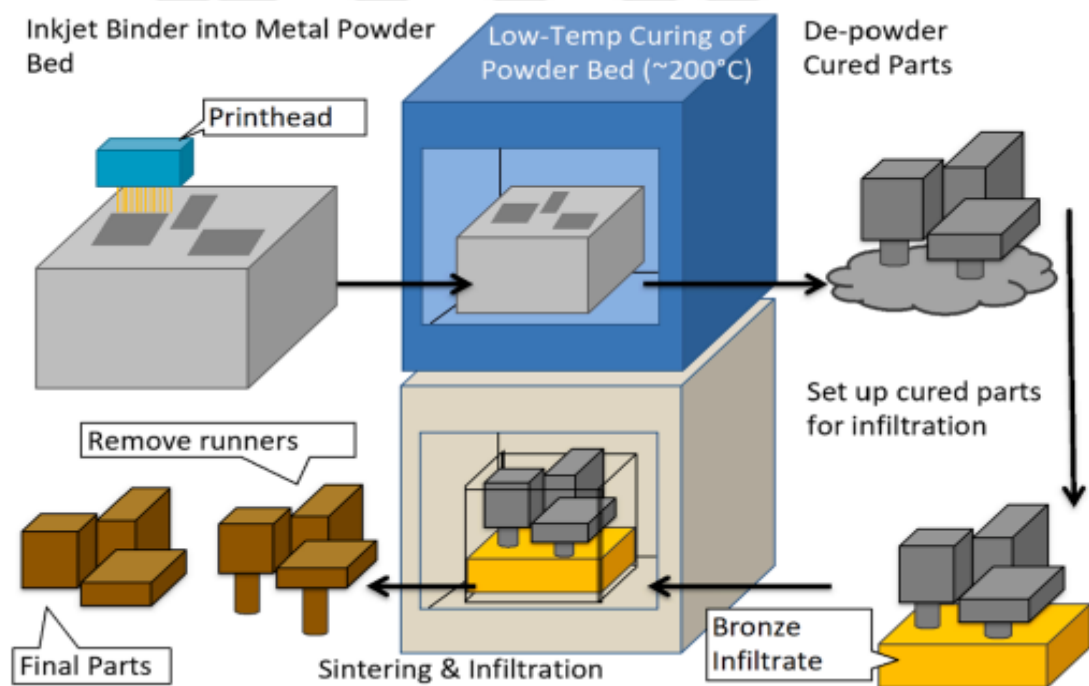


Figure 2.10: Production and post-production processes of the part produced with binder jetting.

This technology was first developed and patented by Emanuel Sachs at the Massachusetts Institute of Technology (MIT) in 1993. Z Corporation (Z Corp.)

commercialized the technology, adding full-color printing capabilities and popularizing the term "3D printing" [27].

As can be seen in **Figure 2.11**, the basic components of a binder jet 3D printer are the powder stock, build platform, roller, binder cartridge, and print head. The build process proceeds in a cycle that builds each layer step by step. First, the spreader spreads a thin layer of powder evenly across the build platform, preparing the powder bed. Then, the print head selectively fuses the powder particles by spraying binder into areas specified by the 3D model. As each layer is completed, the build platform is lowered for the next layer, and a new layer of powder is added on top. This process is repeated until the model is completely built. Once the build is complete, the printed part is cured and freed from the surrounding loose powder, reaching its final form [28].

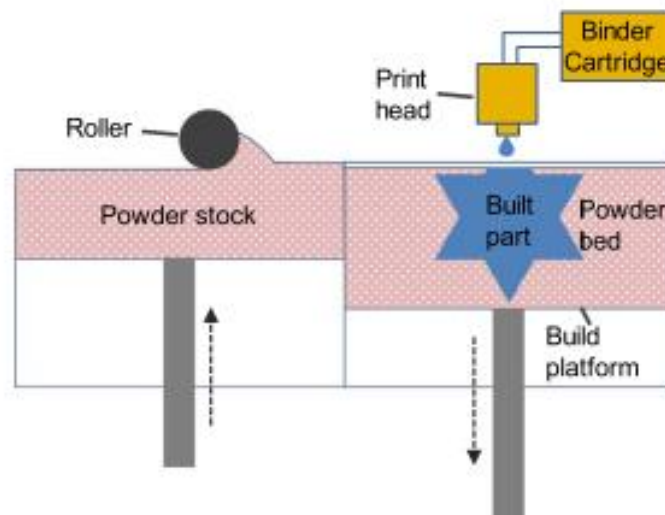


Figure 2.11: Basic components of a binder jet 3D printer.

Binder jetting has emerged in the additive manufacturing community as an easy method for creating porous structures. Unlike energy-based technologies such as powder bed fusion, binder jetting operates at ambient conditions and does not require support structures. This technology offers a convenient manufacturing solution for producing complex shaped porous metal structures without requiring mold and tooling costs. Literature review shows that porous metal parts produced by BJ method are mainly developed for biomedical applications[29].

BJ is also widely used for ceramic materials. This technology has the potential to solve the difficulties encountered in the production of complex-shaped ceramic parts and the shrinkage problem that occurs during sintering. If the current problems such as accuracy and durability can be resolved, it is expected that this method will become a standard process in ceramic production. Currently, this technology is used in the production of bio ceramics, structural ceramics and functional ceramics. The ceramic production process in BJ technology can be seen in **Figure 2.12** [30].

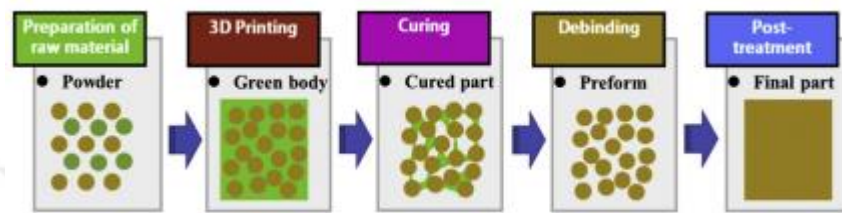


Figure 2.12: BJ printing process for ceramic production.

2.1.1.5. Powder Bed Fusion

It is one of the most used AM methods. Since the PBF process is based on the principle of production with powder particles, it acts as a powder support structure during production and in some productions, support is not required or little support is needed. This technology offers the production of many different materials. Plastic, glass, metals, alloys can be produced with this production method. It is also a very useful method in terms of sustainability. Because the powder that is not used during production can be reused. In this way, very little waste is provided. The PBF method is based on fusing powder with a heat source for part production. These heat sources include thermal energy, electron beams and lasers. The laser fusing method is divided into two as Selective Laser Sintering and Selective Laser Melting. While SLS generally works on plastic materials, SLM is used in the production of metal parts and is also known as Direct Metal Laser Sintering. In this process, heat is applied directly to the bed of powder material and is applied to the cross-sectional area of the part in that layer. In the layered manufacturing cycle, after each layer is completed, a thin layer of powder is laid on the bed and a new layer is built. Thanks to these continuously repetitive steps, complex 3D structures are created [31].

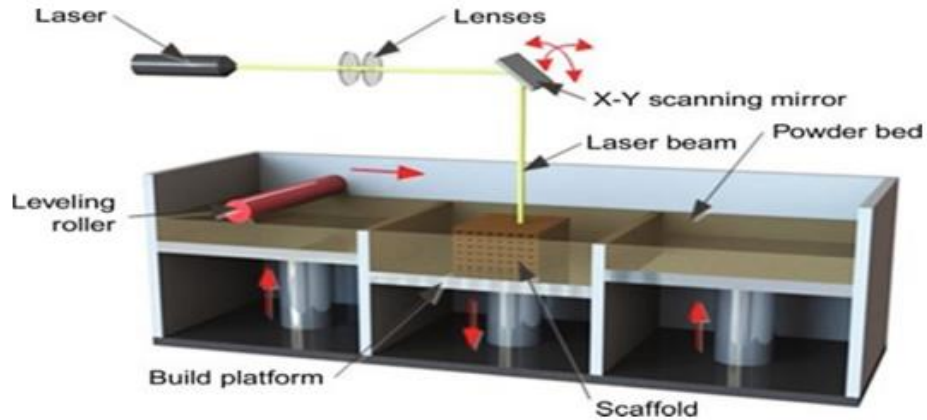


Figure 2.13: Production method of PBF technology [32].

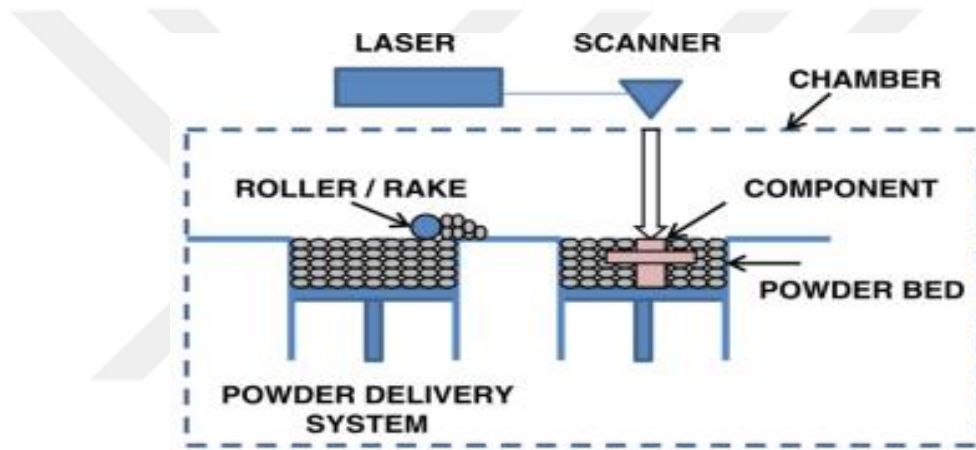


Figure 2.14: Selective Laser Sintering process [33].

The Selective Laser Sintering process is as follows: Using a spreader mechanism in conjunction with the upward movement of the transport piston, the powder material is spread onto the build platform in a thin layer. The laser beam selectively scans the powder surface and forms the first layer through the sintering process. The build platform then descends by the specified layer thickness and the next powder layer is spread over the existing sintered layer. The laser beam continues the build process by bonding the new layer to the previous one. These steps are repeated until the model is complete. After production, the part is cleaned and additional processes are applied if necessary. A CO₂ laser beam can be preferred as the laser source [34].

With this method, mostly polymer materials are used. These are: Polyamide (PA), Polypropylene (PP), TPU (Thermoplastic Polyurethane), Glass and carbon filled polyamides. In addition, the SLS method is used with ceramic and composite

materials. Thanks to its unsupported production, assembled parts can be produced as a single piece and at the same time, very complex parts can be easily produced. In addition, it can be used both as a prototype and as a final product by producing high precision parts.

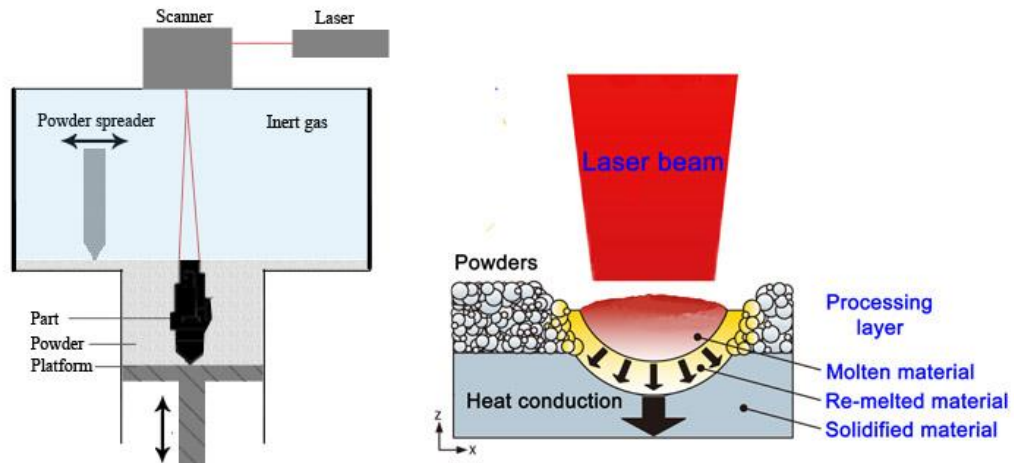


Figure 2.15: SLM 3d production process.

The working principle of selective laser melting is quite similar to SLS. It works mostly with metals and their alloys as materials. High residual stress occurs due to uneven expansion/contraction during production. Therefore, support structures are needed in parts produced with SLM. After production, stress relief is applied and then the support structures are cleaned and the final processes are performed to bring the part to its final state. The environment must be inert during production. Production usually takes place in argon or nitrogen environment. Production is prepared depending on many parameters. Some basic parameters to be considered: laser power, layer thickness, laser scanning speed, distance between consecutive laser passes (also known as scanning distance) and scanning strategies. It is necessary to work on these parameters according to the material to be produced and the layer thickness. The most commonly used materials in the market: titanium alloy (usually Ti-6Al-4V), nickel (Inconel 625 and 718), stainless steels (304, 316/316L), aluminum alloys (AlSi10Mg). This production method is mostly used in the defense industry, energy industry, aviation, biomedical and detail industries [35], [36], [37].

Parts with complex geometry that cannot be produced with traditional methods can be produced with this method. Although it is a very costly technology for mass-produced

parts, it is a very useful method for personalized products. It is widely used especially in the biomedical and dental fields. It attracts manufacturers because it allows lighter production of parts in areas where product weight is important, such as aviation and automotive industry. In addition to complex parts, produce assembled parts can be also produced as a single piece with this technology. Thanks to such capabilities, it has many areas of use today.

Although it has a disadvantage due to being a high-cost production method, it is predicted that powder and machine prices will decrease to acceptable levels with the increase in competition recently.

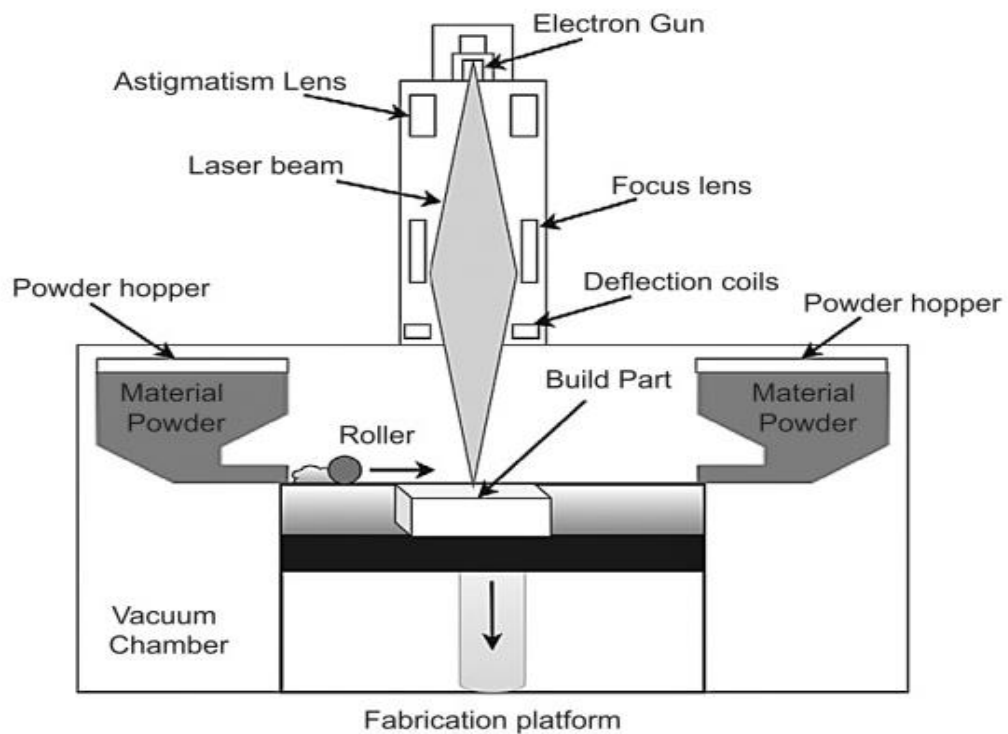


Figure 2.16: Electron beam melting working principle [38].

Electron Beam Melting technology is another powder bed fusion method that produces parts with high precision by melting metal powders layer by layer using high-energy electron beams. This process takes place in a vacuum environment, unlike SLM and SLS production. The risk of oxidation is eliminated in production in a vacuum environment. The EBM production process is carried out at high temperatures in a vacuum environment and these temperatures are maintained in a controlled manner during production, providing better sintering and stress-reducing effect between the

material layers. Thus, unlike SLM, much less internal stress occurs in the parts produced with this method and better mechanical properties are obtained. EBM is ideal for working with durable metals, especially titanium and nickel alloys, and has a wide range of applications from medical implants to lightweight parts in the aviation sector. The ability to produce complex designs quickly and effectively makes this method indispensable in sectors requiring high performance [39], [40].

After the production is complete, a long cooling phase is required to cool the powder bed. The process requires precise optimization of numerous parameters such as beam power, scanning speed, focusing, preheat temperature, and scanning strategies. For this reason, EBM is often applied to limited materials. Costs can be high due to the slow production process and limited material options. In addition, there are certain limitations in terms of structure dimensions and design complexity. Despite this, the high temperature advantage and low oxidation risk of EBM make it an important method for producing precise and durable parts [41].

In summary, PBF systems are advanced technology-based production methods that are frequently preferred in the production of parts with complex geometries, as well as in custom designs that require high precision. These systems play an important role in the production of parts that offer high mechanical properties. Today, it is used both as an auxiliary and main production technique in the production of parts that are difficult to obtain with traditional production methods. PBF technology has become an indispensable AM method in modern production processes with the advantages it provides for complex structures and customized designs.

2.1.1.6. Direct Energy Deposition

DED (Directed Energy Deposition) systems are advanced production technologies that enable the production of complex metal parts with various energy sources and material feeding methods. The basic principle of these systems is to melt the raw material by focusing the energy density at a point and to create a physical structure by combining it layer by layer. As can be seen in **Figure 2.17**, DED systems are divided into different subcategories as powder-based and wire-based according to the type of material feeding used; and laser, electron beam, plasma or electric arc-based according to the energy source. While different energy sources and material forms expand the

application areas of the systems, each technology has its own advantages and disadvantages. While powder-based DED systems provide superiority in terms of precision, wire-based DED offers a faster production process and is suitable to produce large-scale structures. High-energy sources such as electron beam allow the processing of almost all metals, while methods such as plasma and electric arc can provide more efficient results in certain materials. Kinetic energy-based methods differ from other methods by bonding the material without melting it and offer an innovative solution for different applications [42].

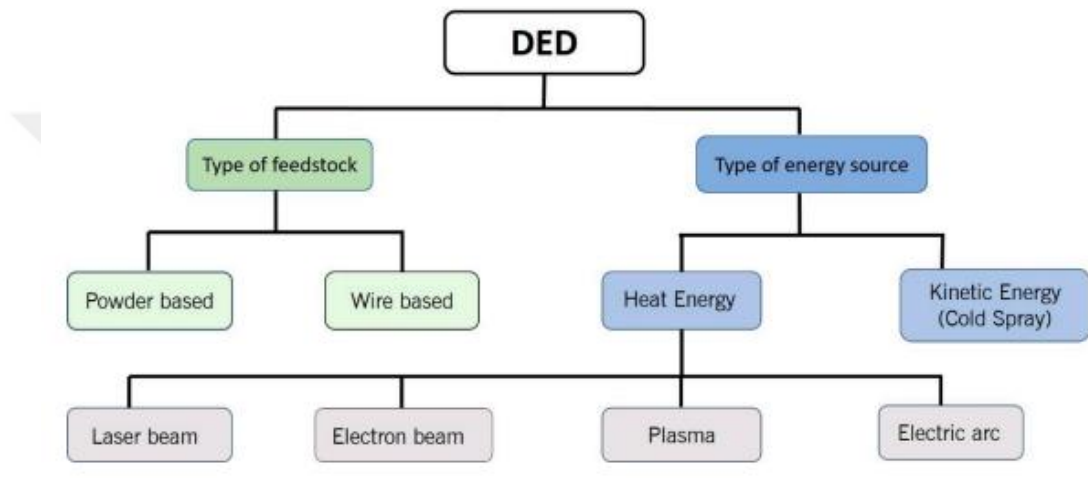


Figure 2.17: Classification of DED.

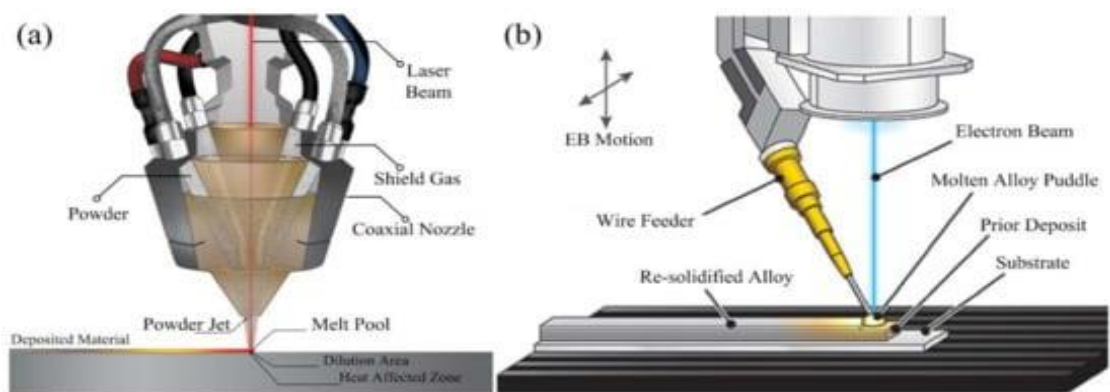


Figure 2.18: a) Powder based LENS and b) Wire based EBAM [43].

DED offers flexible solutions depending on the energy source, feed type and process environment, but defects such as internal stress, cracks and porosity may occur due to rapid thermal cycles. These problems can be minimized with process optimization and

advanced monitoring systems. DED has made significant progress in areas such as alloy design, multi-material structures and repair of critical structures and is expected to become more widespread with a wide range of applications in the future. These technologies have significant potential to meet the needs of high precision, low material waste and customized production in sectors such as aerospace, automotive and medical. However, optimization studies in areas such as control of energy sources, process times and material diversity still maintain their importance [44].

DED technology exhibits superior performance in metal part repair. In particular, by adding material to damaged components such as turbine blades, this technology offers a unique solution for extending the life of existing parts. However, DED's application areas are not limited to repair; it is also widely used in the aerospace and defense sectors, in the production of complex and critical parts such as titanium fuel tanks in satellites or structural titanium components in Boeing 787 aircraft. In addition, thanks to DED's high deposition rate, it stands out as the most efficient metal additive manufacturing method in terms of both speed and cost in the production of large-volume and high-quality metal parts. These features make DED an ideal solution for large-scale industrial applications [45].

2.1.2. Advantages and Disadvantages

As can be seen in **Figure 2.19**, since the mold cost in formative manufacturing is not present in additive manufacturing, the mold cost are eliminated for each part to be produced [46]. In addition, in subtractive manufacturing, a lot of chips are formed during production and these are waste. However, in additive manufacturing, very little waste is formed. This provides benefits both in terms of sustainability and in terms of saving raw materials.

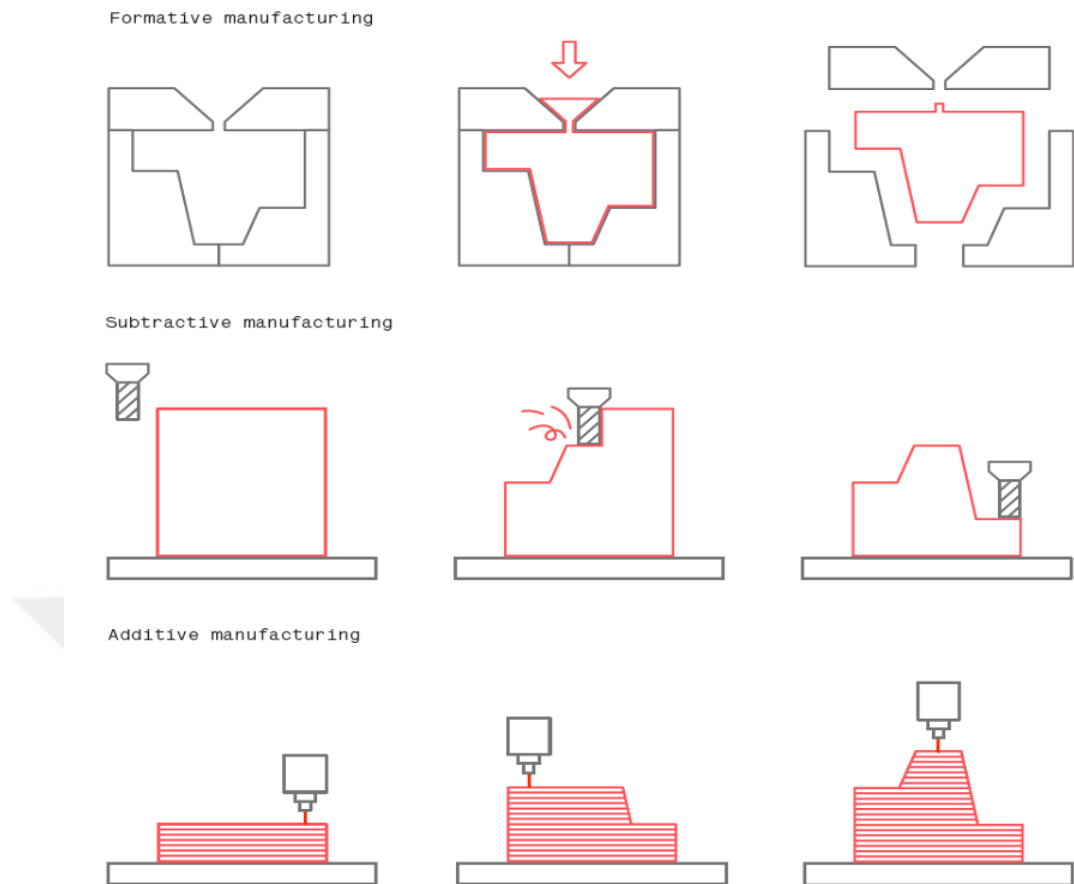


Figure 2.19: Visual of traditional manufacturing and additive manufacturing working principles.

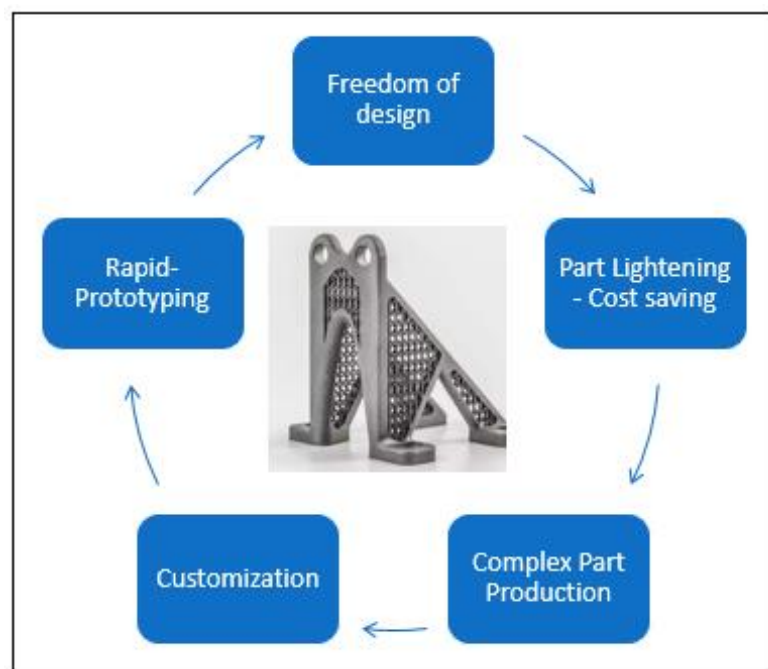


Figure 2.20: Advantages of AM.

Some advantages of Am technology can be seen in **Figure 2.20**. AM allows the creation of lighter, more complex designs that are very difficult or expensive to build using traditional molds, milling and machining.

Another advantage it provides us is the freedom of design. Many design techniques such as lattice structures, topology optimization, generative design, etc. are widely used with AM. Lighter parts can be produced with DFAM (design of additive manufacturing). Lighter parts with the desired strength can be manufactured and these difficult geometric parts can be produced with the AM method. Producing these difficult geometries with traditional production methods is both very costly and time-consuming. Producing small quantities of difficult geometric parts with AM is much more effective.

The AM method offers a rapid prototyping process before moving to mass production. Thus, it helps us to move to mass production in a short time by repeatedly testing the designed part and obtaining the desired final model.

In addition, using this method as a direct production method in low volume production and small batch production is very useful. Because it provides fast production by eliminating time losses such as mold processes. In addition, there is no need to manage a separate mold process for each different model.

In addition to these advantages, there are also some disadvantages. Some of these are;

- High tolerance errors in the parts produced,
- High machinery investment and high manufacturing costs.
- Not yet providing production at the desired speed,
- Surface roughness,
- Shortage of raw material options,
- Negative reception in terms of speed and price in high-volume mass production,
- Still needing development,

2.2. Ti6Al4V Alloy

Ti6Al4V alloy, as a typical $\alpha+\beta$ alloy, has important application areas such as aviation, biomedical, automotive and sports equipment [47]. The most important features of this

alloy are its high specific strength, good creep resistance and biocompatibility, and thus it is used in many areas. Its low density ($\sim 4.43 \text{ g/cm}^3$) significantly reduces weight in aircraft and automotive components while maintaining its superior strength, increasing fuel efficiency and reducing costs. With these features, Ti6Al4V is considered one of the most preferred materials in industrial areas among high strength and low weight alloy materials [48].

Ti6Al4V is considered one of the most widely used and preferred types among titanium alloys. This alloy, which has a content of 6.01% aluminum (Al) and 3.98% vanadium (V), is an $\alpha+\beta$ phase alloy, and aluminum stabilizes the α -phase while vanadium stabilizes the β -phase, providing excellent stability to the material. Dual phase ($\alpha+\beta$) titanium alloys are known for their high strength, corrosion resistance and high temperature resistance. The mechanical properties of Ti-6Al-4V alloy depend on microstructure elements, especially the size, distribution and orientation of α lamellae. Research shows that lamellae width and colony boundaries have significant effects on fatigue strength, fracture toughness and yield strength [49].

Due to its unique mechanical properties, it has application areas in many different sectors. Ti-6Al-4V alloy are widely used in fields requiring advanced technology such as aerospace, biomedical and energy thanks to their superior corrosion resistance, low density and high specific strength [50]. Aerospace Industry: Due to its lightness and strength, it is used in engine components such as aircraft interior components, landing gear, jet engine components. Ti6Al4V material has started to be used more thanks to the easier production of designs such as topology optimization with additive manufacturing.

Medical Sector: It is a preferred material in the biomedical sector such as human and animal prostheses, dental implants and surgical devices. Again, it is widely used in structures such as prostheses with its lattice structures that are easy to produce with additive manufacturing.

It is also seen to be used in vehicle components that emphasize features such as lightness and durability, and in sports equipment such as golf clubs, bicycle frames and rackets. On the other hand, it also finds its use in the Defense Industry, where armor materials, military vehicles and weapon components are located.

When looking at its advantages, it can be said that it increases fuel efficiency and reduces costs thanks to its lightness, while also providing energy savings and increasing carrying capacity. Since it is suitable for the production of complex geometries, it can be processed with additive manufacturing methods such as SLM and EBM. In addition, the Ti-6Al-4V alloy produced by the SLM method exhibits higher tensile strength compared to traditional production techniques; however, despite this advantage, a slight decrease in ductility is observed. For this reason, the applied HIP heat treatments increase the ductility of the material, but may cause a partial decrease in mechanical strength [51]. Furthermore, in Ti-6Al-4V alloy produced by SLM and EBM compared to traditional methods, correct adjustment of process parameters is required; otherwise, it may cause defects [52].

In addition to its many advantages, it is a disadvantage that it is difficult to process compared to other metals and therefore requires more energy. Due to its high cost, it is generally preferred for critical applications and a certain budget is required. Due to its weak tribological properties, it can cause problems in high friction conditions.

2.2.1. Heat Treatment

Ti-6Al-4V (Ti64) has become one of the most widely used titanium alloys, especially in the aerospace and biomedical industries, due to its excellent strength-to-weight ratio. However, its low thermal conductivity and chemical reactivity make it one of the most difficult materials to machine. Heat treatment plays a significant role in changing the microstructure of Ti64, which significantly affects its machinability. Therefore, the choice of heat treatment directly affects the mechanical behavior and efficiency of the alloy, making it an important factor in optimizing the performance of Ti64 components in demanding industrial applications [53].

Studies have shown that although heat treatment has positive effects on the microstructure, it requires careful optimization in terms of surface properties. Especially in biomedical applications, the balance between surface quality and mechanical strength is vital for long-lasting and durable implants [54].

In addition, research shows that heat treatment applied to Ti-64 alloy produced by DMLS method increases both mechanical strength and workability by transforming thin α phases into thick and elongated structures in the microstructure. Significant

improvements are observed especially for biomedical and high-performance engineering applications after heat treatment. This shows the importance of heat treatment [55].

2.2.2. Microstructure and Residual Stress

Ti-6Al-4V alloy is widely used in aerospace and critical structural parts due to its high strength, fatigue resistance and corrosion resistance. Difficult and costly production difficulties with traditional processing methods have led to the emergence of additive manufacturing technologies such as SLM or WAAM. In Ti6Al4V parts produced with AM method, the microstructure varies along the layers. The microstructure diversity caused by these thermal cycles is seen. However, the residual stresses formed in Ti6Al4V parts produced with additive manufacturing are especially caused by rapid heating and cooling processes. These anisotropic parts, which exhibit direction-dependent mechanical properties, show higher strength in the longitudinal direction, while the residual stress distribution also affects the crack growth behavior. In some cases, it has been determined that residual compressive stresses can increase fatigue life by slowing down crack propagation. As a result, microstructure control and residual stress management in additive manufacturing processing of Ti6Al4V play a critical role in terms of structural safety and longevity [56].

Rapid heating and cooling in the heat-affected zone causes the previous grain boundaries to grow significantly, while in the weld zone, acicular and lamellar phases are formed after solidification. In cases where the cooling rate is high, a transition to martensitic phases is observed. Different welding methods directly affect the microstructure. For example, high cooling rates in electron beam welding trigger the formation of martensitic phases. In addition, it has been determined that post-weld heat treatments, especially when applied under vacuum, can eliminate a large portion of residual stresses (up to 90%) [57].

In addition, in contact with elements such as hydrogen, oxygen, nitrogen and carbon, pores and unwanted phases (e.g. inclusions) are formed in the material structure, causing adverse effects on mechanical properties. Therefore, protection with Argon gas is mandatory in melting methods [58].

2.2.3. Tribological Behavior Structures

Ti6Al4V (Ti64) alloy exhibits poor tribological behavior despite its superior properties such as high strength and biocompatibility. It has low wear resistance and high friction coefficient due to low thermal conductivity, low hardenability and loose oxide layers. Ti6Al4V has a high friction coefficient and is prone to adhesion-based wear mechanisms. In addition, low surface hardness and poor wear resistance reduce the long-term usability of the material, especially in load-bearing joint implants. Various surface modification techniques have been developed to eliminate these negativities. Although surface coatings (DLC, TiN, etc.) provide solutions to these problems by increasing surface hardness, they can cause new problems such as peeling in long-term use. Therefore, thermal treatment and structural modification techniques that target not only the surface but also the microstructure of the material are becoming more critical in improving tribological performance [59], [60].

2.3. Contribution to Literature

In this thesis, the effects of changes in heat treatment parameters (temperature and residence time) on tribology, microstructure and hardness of Ti6Al4V alloy produced with SLM technology were investigated systematically and comprehensively for the first time. In the literature, studies addressing the role of heat treatment on the properties of Ti6Al4V produced with SLM were limited. This thesis aimed to better elucidate the mechanisms affecting the temperature and time parameters by revealing how different heat treatment conditions affect the microstructure, hardness and tribological performance of the material.

Thus, the obtained results provide valuable information for process optimizations that will increase the usage properties and service life of Ti6Al4V parts produced with SLM.

3. METHODOLOGY

SLM additive manufacturing technology is based on the principle of shaping metal powders by melting them layer by layer as a production method. When metal powders are processed with a powerful laser in the SLM production process, a high temperature gradient is created, which causes microstructure instability and high residual stresses due to rapid melting and crystallization during production in each layer. This distorts the shape of the manufactured components and disrupts structural continuity. A heat treatment process can be applied to eliminate residual stresses [61].

Due to the residual stress created during production with SLM technology, distortion occurs in the part. In order to prevent this, a support structure is created between the part and the table. However, if stress relief is not applied to the part after production is completed, distortion will occur in the part as seen in **Figure 3.1**.

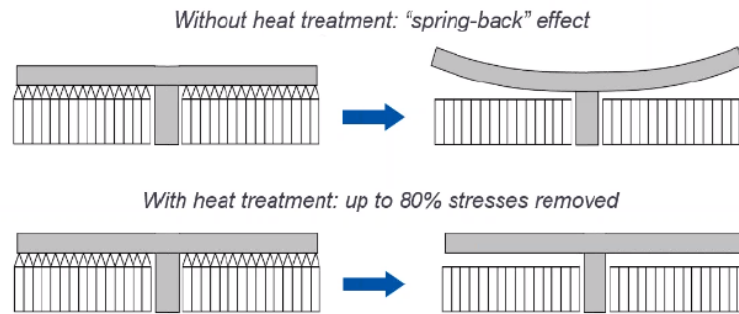


Figure 3.1: Image of stress relief after heat treatment.

In this research, the effects of changing the temperature and residence time parameters to be used in stress relief on the properties such as microstructure and hardness of the part produced with Ti6Al4V material will be investigated.

The tribological properties of the part to be produced with Ti6Al4V material are important in terms of usage areas. For this reason, the changes in the friction and wear properties of the part produced will be examined by changing the parameters to be used for stress relief.

3.1. LPBF Process Parameters

In this research, production was carried out with SLM technology. The brand and model of the device used: EP-M150 Pro. Sample printing was completed with this machine. As seen in **Figure 3.2**, the dimensions of the part to be used in the experiments were selected as: $x=16\text{mm}$, $y=14\text{mm}$, $z=12\text{mm}$.

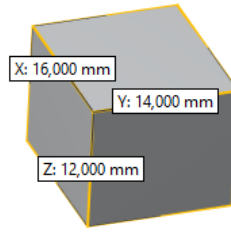


Figure 3.2: Dimension of the sample.

Since the material properties change according to the orientation of the parts in the SLM production method, all samples were produced with the same orientation and the same support. The orientation of the part is seen in **Figure 3.3**.

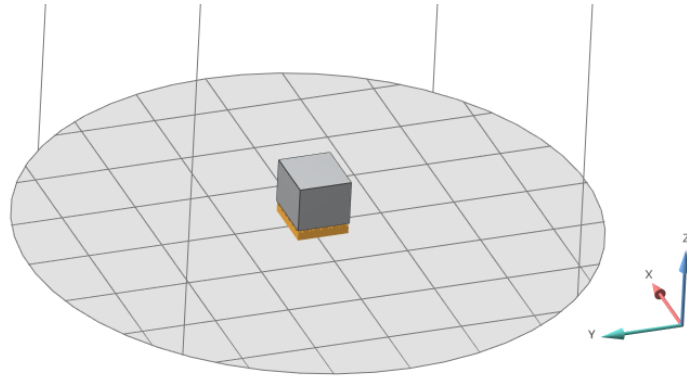


Figure 3.3: printing orientation of the sample.

There are some parameters that are important in SLM production. Some parameters used during production are as in the **Table 3.1**.

Sample production was carried out with Ti6Al4V grade 23 material with a layer thickness of 30 microns. The particle size range of the Ti6Al4V metal powder used is: 10-45 μm .

Table 3.1: SLM production parameters.

Layer Thickness	30 mikron
Laser Spot Size	70 mikron
Scan Pattern	Stripe Pattern
Atmosphere and Gas Flow	Inert Gas (Argon(Ar))
Build Plate Temperature	80 °C
Optical System	Fiber Laser 500W

Other important things are the laser power and speed of the machine. The parameters adjusted according to the regions during production are as in the **Table 3.2**.

Table 3.2: Laser power and speed parameters used in production of the machine.

Definition	Speed(mm/s)	Power(W)
InSkin	1000 mm/s	180 W
DownSkin	1500 mm/s	150 W
UpSkin	1000 mm/s	180 W
DownSkin Border	700 mm/s	180 W
Fill Border Speed	900 mm/s	160 W
Outer	1500 mm/s	150 W

Since all samples could not fit into a single production, they were produced in different productions. Production was made with the same parameters in each production. Thus, the produced samples were repeated in the same environment and conditions. In the production of the samples included in the research, the machine production parameters were kept constant. All samples were produced with the parameters in the above **Table 3.1** and **Table 3.2**.

After production, the parts were removed from the machine and no process was applied. After the unused dust was cleaned from the substrate, the parts were sent to the heat treatment furnace together with the substrate for stress relief.

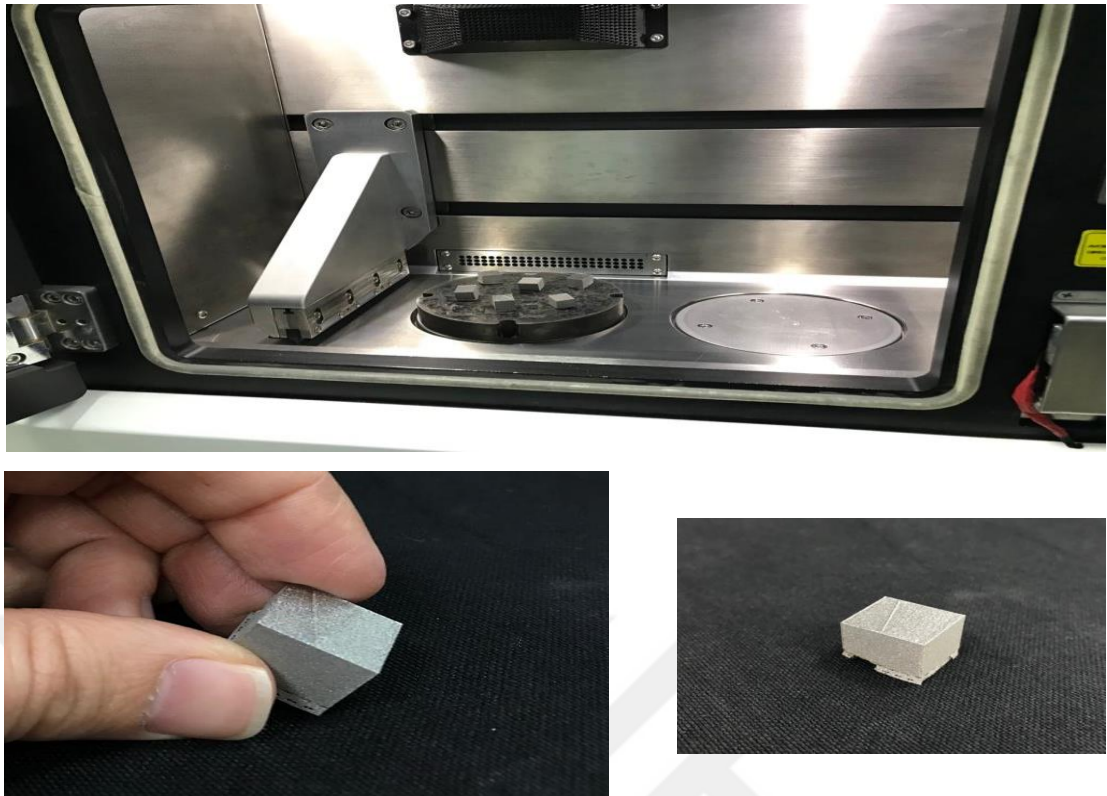


Figure 3.4: The visual of the completed samples in the substrate.

3.2. Heat Treatment Parameters

Heat treatment will be applied to Ti6Al4V based samples produced with SLM technology to relieve stress.

The effect of temperature and residence time will be used as heat treatment parameters. The cooling parameter will be kept constant with furnace cooling.

600, 700, 800 °C will be used as temperature parameters. 90, 120, 150, 180 minutes will be used as residence time parameters.

The heat treatment furnace operates in a vacuum environment. Other parameters in the heat treatment process are constant and the experiment will be carried out by changing only the temperature and residence times.

For example, the temperature will increase from 0 degrees to 600 degrees at a constant rate and then heat treatment will be applied at 600 degrees until the residence time in the experiment and at the end of this period it will be left to cool down automatically in the furnace. A heat treatment cycle is seen in the visual in **Figure 3.5**.

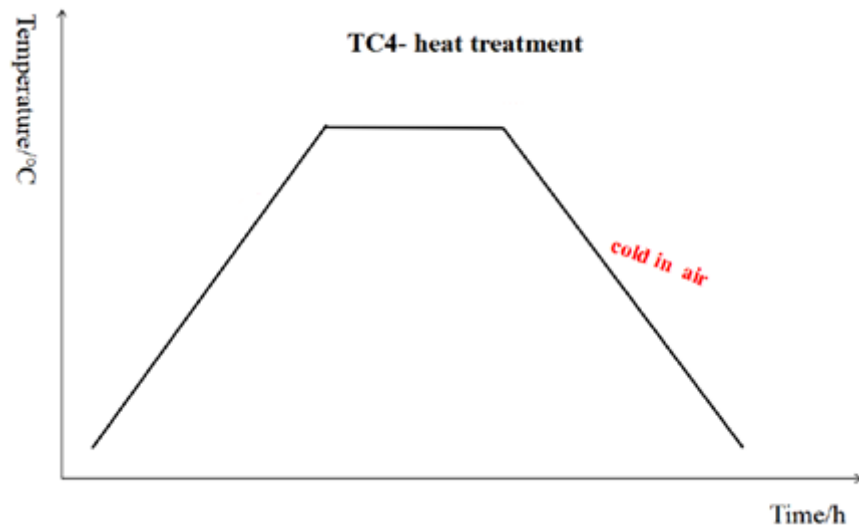


Figure 3.5: Graph of heat treatment process for Ti6AL4V.

3.3. Experimental Design

12 different situations will be examined in this study. There are 2 factors, one is temperature and the other is residence time. The temperature consists of 3 levels, they are 600-700-800 °C. The residence time consists of 4 levels, these are 90-120-150-180 minutes.

Table 3.3: Table of sample and heat treatment variables.

Sample No	Temperature	Residence Time
1	600 °C	90 minutes
2	600 °C	120 minutes
3	600 °C	150 minutes
4	600 °C	180 minutes
5	700 °C	90 minutes
6	700 °C	120 minutes
7	700 °C	150 minutes
8	700 °C	180 minutes
9	800 °C	90 minutes
10	800 °C	120 minutes
11	800 °C	150 minutes
12	800 °C	180 minutes

It will examine 12 different situations and for this, 3 prints will be taken for each sample. The total number of samples to be printed will be 36. In addition, a sample print will be taken as an as-build and used for comparison in tests.

Before examining the microstructure of the parts, the samples were pre-prepared to obtain accurate and reliable results. First, the samples were fixed in a mold with resin and the surface to be examined was kept fixed under the microscope.

Then, the surface to be examined was prepared. First, the surface was sanded with numbers 80-220-400-800-1000-2000 from thick to thin. Finally, the surface was polished with a Forcipol 202 metallography machine rotating at 450 rpm. To reach its final state, the surface was polished with 6-micron, 2-micron and finally 1-micron diamond solution. An example of a polished sample is shown in the **Figure 3.6 c**. Finally, an etching process is performed on the surface whose microstructure will be examined. Kroll's Reagent Titanium Etching Solution, which is suitable for Ti6Al4V, was used. The surface of the part to be etched was kept in this solution for 50 seconds and the etching was performed.

"Zeiss Axio Imager 2" microscope was used to examine the microstructure of the samples. Images were taken at a measurement range of 100 micrometers to perform microstructure analysis of each sample.

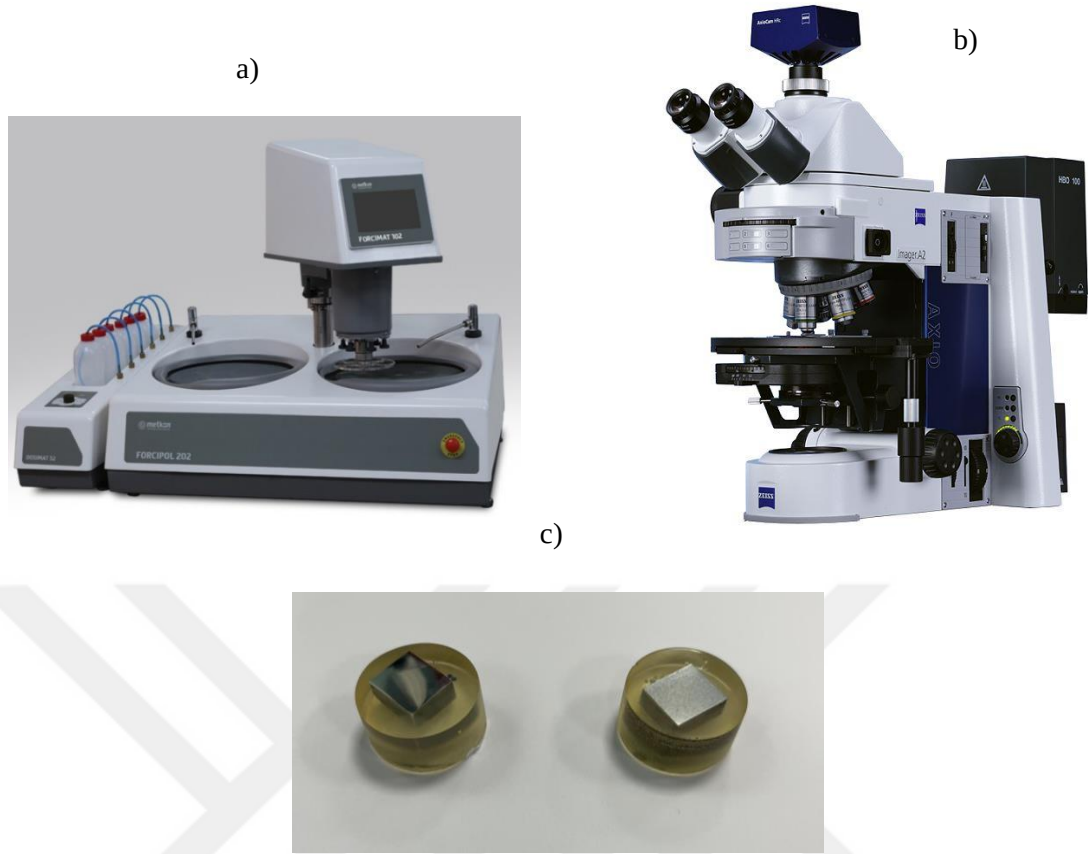


Figure 3.6: a) Forcipol 202 metallography machine, b) Zeiss Axio Imager 2 microscope, c) Images of polished and etched samples before microstructure examination.

Hardness tests were performed on 13 different samples. In this study, the hardness measurements of the material were carried out using the Vickers hardness measurement method. The measurements were made using the DuranScan G5 model device with an HV 0.3 load and a 50x lens. The Vickers method was preferred to obtain precise results on small samples and thin surfaces. An image of the device and a measured sample is shown in **Figure 3.7**.

4. RESULTS AND DISCUSSION

This research analyzes microstructures, hardness measurements, and tribological test results such as wear observed on as-built and heat-treated Ti64 samples subjected to various stress-relieving conditions. The aim is to observe the different results produced by temperature and residence time.

4.1. Effect of Heat Treatment on Microstructure

Selective Laser Melting (SLM) is an additive manufacturing method capable of producing complex geometries with high precision. The microstructure of SLM-produced Ti6Al4V is strongly influenced by the rapid cooling rates inherent to the process and subsequent post-processing treatments such as stress relief annealing. Martensitic α' phase (acicular structure) is formed in Ti6Al4V produced by this method due to the high cooling rate it undergoes during the production phase [62].

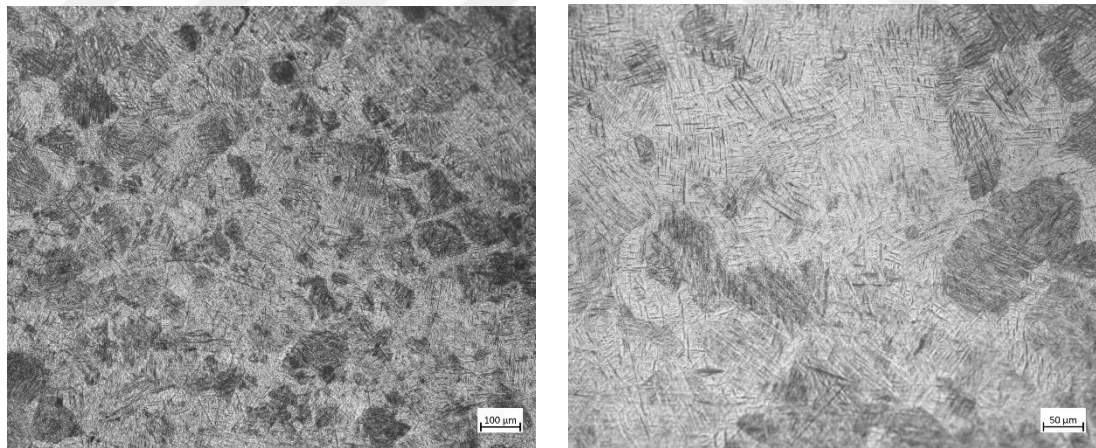


Figure 4.1: Microstructure image of the sample produced as-built at different scales.

The microstructure of the as-built Ti64 specimen, shown in the first image **Figure 4.1**, reveals a typical martensitic α' -phase structure. This is characterized by fine acicular (needle-like) features distributed throughout the prior β -grain boundaries. It can be seen that the needles are randomly oriented due to the effect of the laser path and cooling conditions. It is seen that the rapid cooling that occurs during SLM prevents

the formation of equilibrium α and β phases and causes the formation of non-equilibrium microstructure.

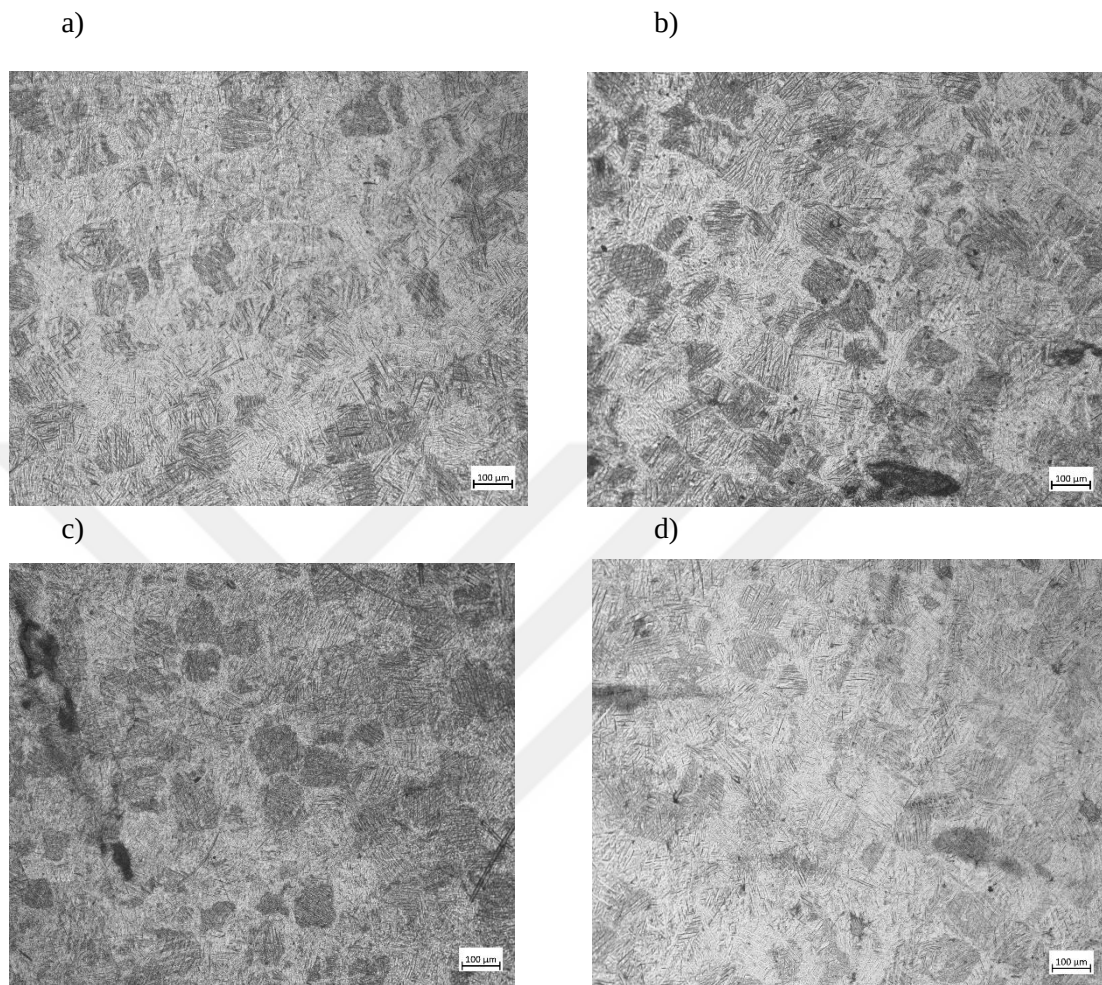


Figure 4.2: Microstructure images of the material heat treated at 600°C for different times, a) 600°C for 90 min, b) 600°C for 120 min, c) 600°C for 150 min, d) 600°C for 180 min.

As the microstructures are examined sequentially, in **Figure 4.2a**, it can be observed that the transformation of α' -martensite into $\alpha + \beta$ phases has begun. In **Figure 4.2b**, it is evident that α laths have further thickened, and the β -phase has become more pronounced, particularly at grain boundaries. From this, it can be inferred that ductility increases while strength is largely maintained. As the heating duration increases to 150 minutes and 180 minutes, it is observed that α laths further thicken, forming a lamellar structure. The β -phase at the grain boundaries has significantly thickened, and diffusion-driven transformations are noticeable. It can be inferred that toughness increases, and brittleness decreases due to homogenization and stress relief.

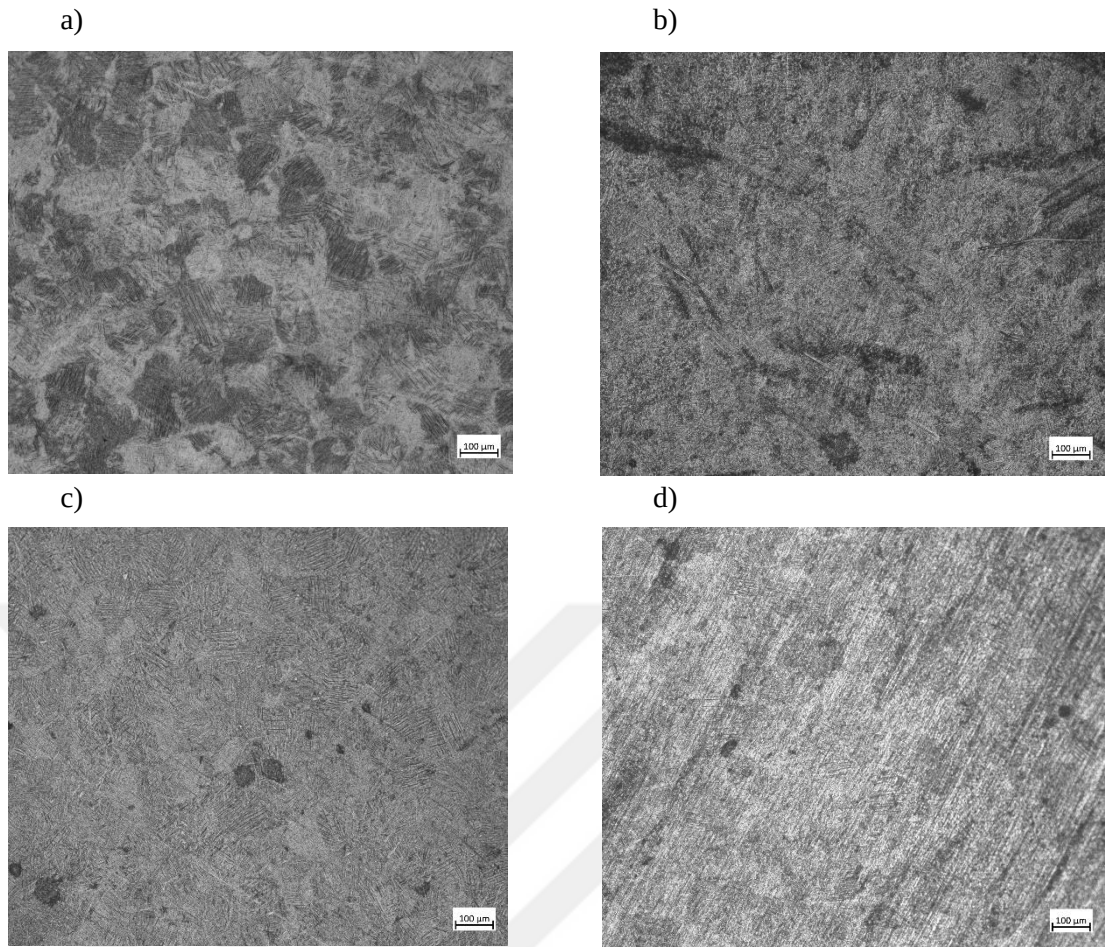


Figure 4.3: Microstructure images of the material heat treated at 700°C for different times, a) 700°C for 90 min, b) 700°C for 120 min, c) 700°C for 150 min, d) 700°C for 180 min.

At 600°C, the β -phase was seen to start to form along grain boundaries, but the α -phase still constituted the majority of the microstructure. In contrast, when looking at **Figure 4.3**, it is observed that the β -phase becomes dominant at the grain boundaries and even forms a connected structure.

At 600°C, the lamellae remain thinner and more homogeneous, but as the duration increases, the α lamellae were observed to thicken. On the other hand, in the material subjected to heat treatment at 700°C, the lamellae thicken more rapidly and intensively.

In **Figure 4.3b**, it is observed that primary α colonies become more distinct. In **Figure 4.3c**, α and β phases are seen to reach a balanced lamellar structure. Finally, in **Figure 4.3d**, excessive coarsening is observed.

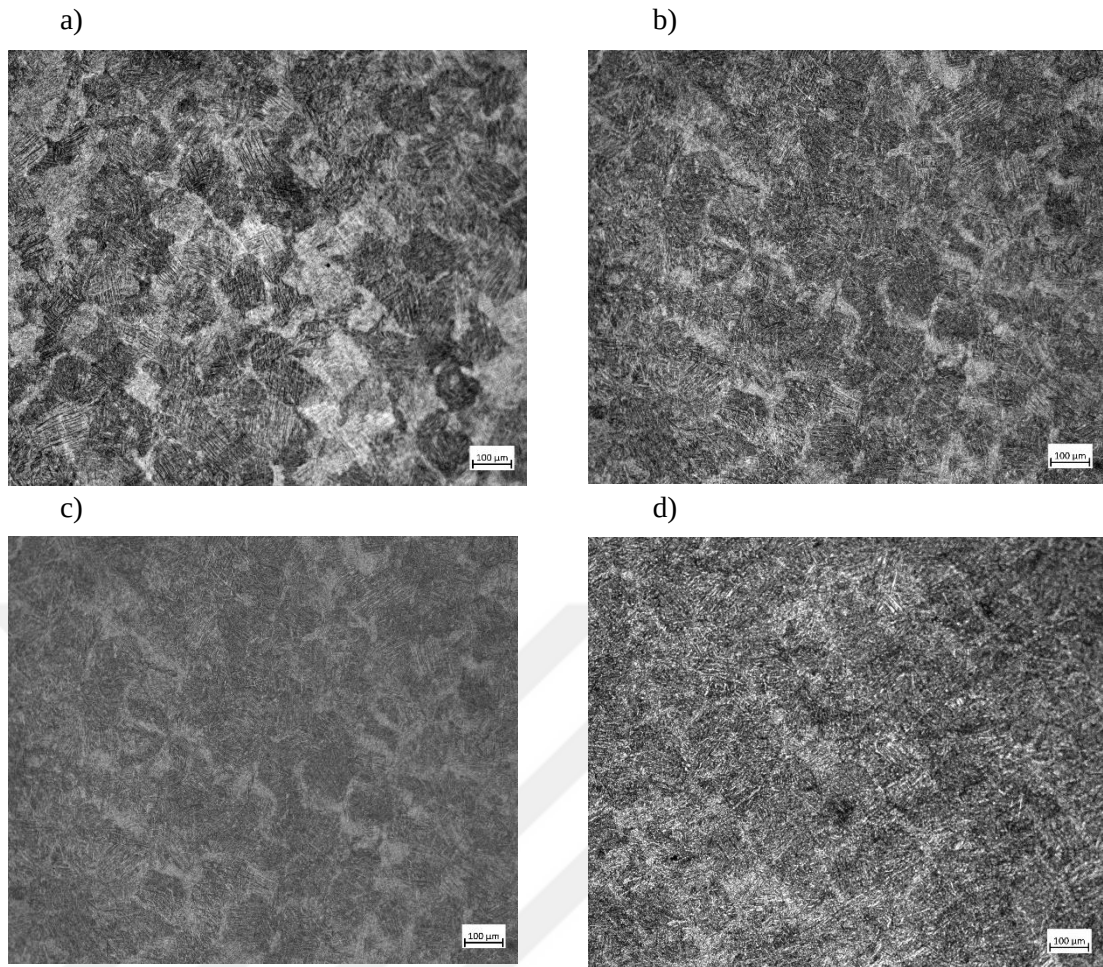


Figure 4.4: Microstructure images of the material heat treated at 800°C for different times, a) 800°C for 90 min, b) 800°C for 120 min, c) 800°C for 150 min, d) 800°C for 180 min.

When the temperature rises to 800°C, it is observed that the diffusion processes accelerate, and the material undergoes a more pronounced transformation toward equilibrium phases. At this temperature, the β -phase becomes dominant, and the α -phase lamellae are observed to thin or diminish.

When looking at **Figure 4.4**, it is understood that the prolongation of the heat treatment time increases the proportion of the β -phase and the α -phase lamellae become thicker and less distinct.

When looking at **Figure 4.4c**, it is seen that the β -phase continues to grow and the α -phase lamellae become more sparse, while in **Figure 4.4d**, it is seen that the microstructure almost completely turns into an $\alpha + \beta$ equilibrium structure and the α -phase lamellae decrease significantly and the β -phase becomes dominant in the grain structure.

4.2. Effect of Heat Treatment on Hardness

Figure 4.5 shows the hardness measurements obtained after heat treatment. It is seen that the hardness value of the material produced as-built, that is, not heat treated, is lower than the heat treated materials.

The highest hardness was obtained at the end of the heat treatment applied at 600 degrees. An average hardness of 400 HV is seen. **Figure 4.6** shows a tendency for hardness to decrease as the temperature applied in the heat treatment increases.

The martensitic α' -phase in the as-built microstructure transforms into a mixture of α and β phases during heat treatment. It is understood that the hardness value of the material is higher since the increasing β -phase ratio, especially in the 600°C and 700°C processes, contributes to the formation of a harder and more stable microstructure.

It is seen that long-term heat treatment at 800°C causes the microstructure to become extremely coarse-grained and the β -phase to become dominant. It is understood that the hardness decreases at the temperature of 800°C due to these factors.

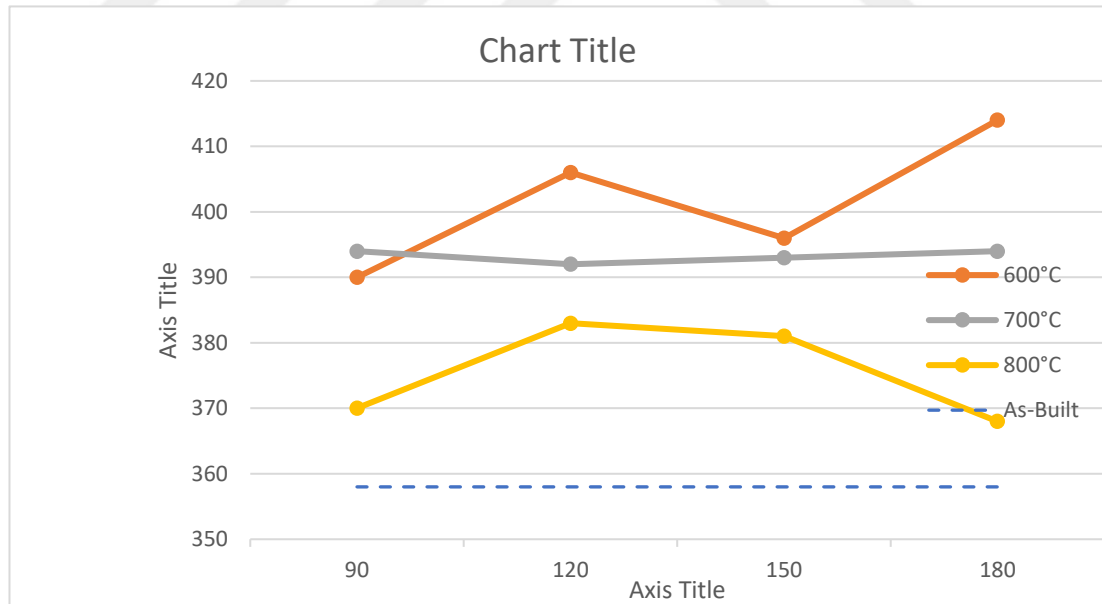


Figure 4.5: Line graph visualization of hardness as a function of temperature and time.

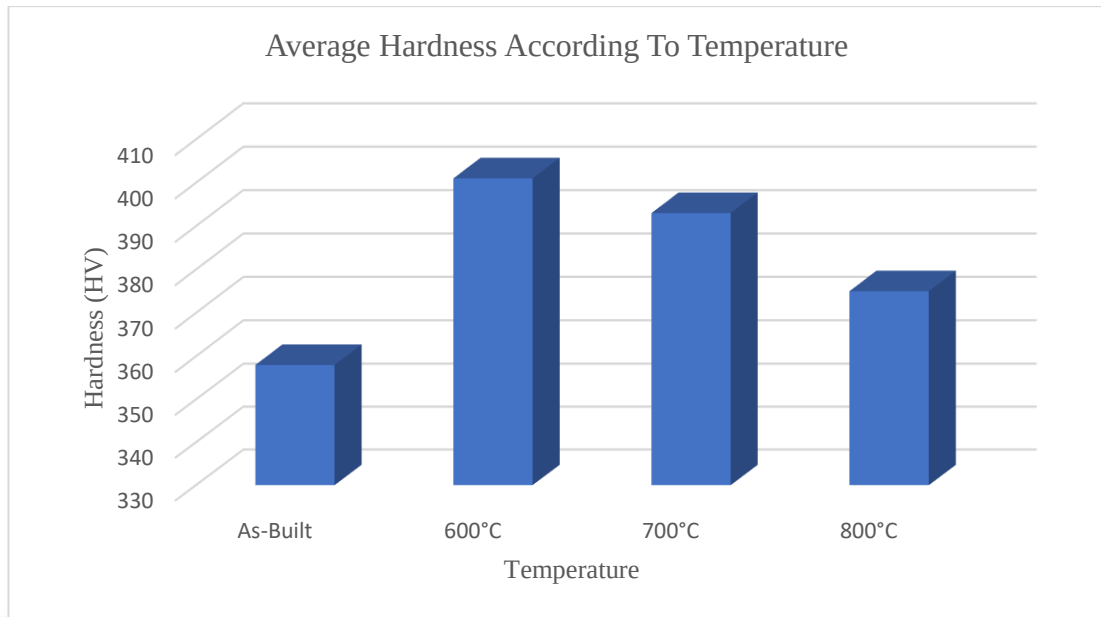


Figure 4.6: Visualization of average hardness according to temperature in a histogram.

4.3. Analysis of Tribological Performance

Figure 4.7 shows the change in wear values depending on temperature and time. It is seen that the wear amounts are generally low and stable.

A significant increase in the wear amount is seen in 180 minutes at 600°C. This may be a result of excessive growth in phases or a decrease in phase stability.

The lowest wear amount was observed in 120 minutes at 700°C. This is the situation where the microstructure is best balanced and an optimum balance is achieved between hardness and strength.

At 800°C, an increase in wear values depending on temperature and time was observed.

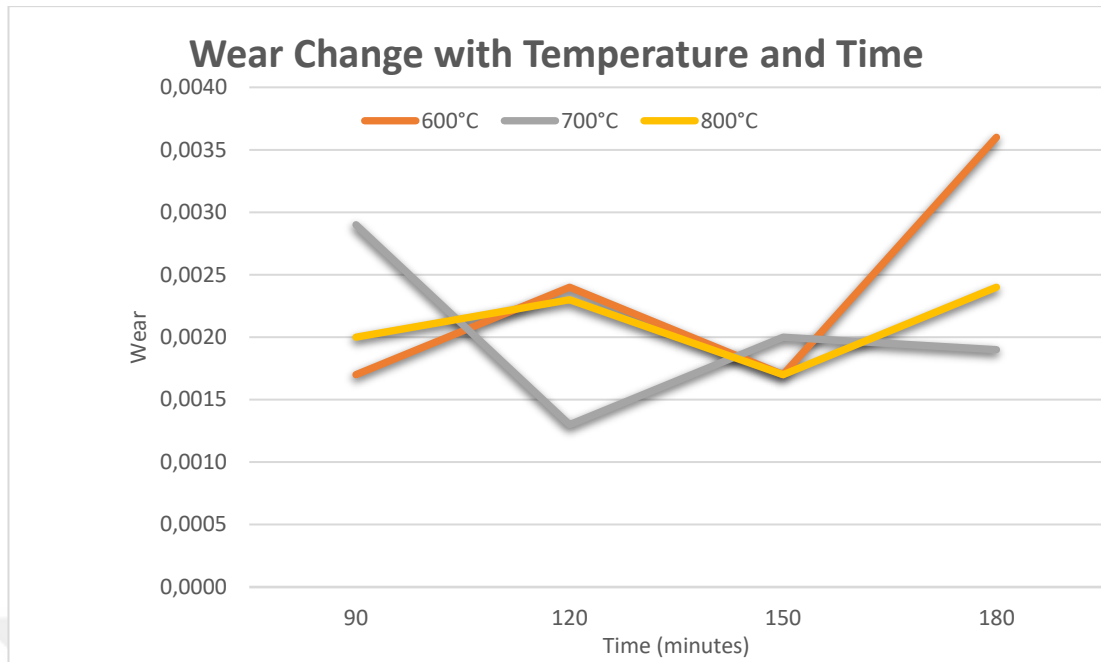


Figure 4.7: Line graph visualization of wear as a function of temperature and time.

4.4. Discussion

In the studies in the literature, it is seen that the microstructure of Ti6Al4V produced by SLM method consists mainly of α' lath martensite and β phase. In addition, it is understood that as the heat temperature increases to 800°C, the amount of β phase increases and the α' lath martensite structure becomes coarser [63]. Complete dissociation of the α' -martensitic phase in the as-build sample leads to the formation of lamellar $\alpha + \beta$ structure with the application of heat treatment [64].

In the studies, it is seen that Ti-6Al-4V alloy initially contains acicular α' -martensite supersaturated with vanadium atoms after SLM and this structure provides high hardness and strength while decreasing ductility. As the applied heat treatment temperature increases, vanadium atoms diffuse from the α' phase to the β phase, increasing the β phase content, with inclusions transitioning from scattered points to needle-like and then lamellar structures. At higher temperatures, the structure becomes coarse-grained and acquires a basket weave morphology. The increase in annealing temperature reduces the alloy's strength and hardness while improving ductility due to changes in phase composition, morphology, and grain growth [65].

When looking at the microstructure, hardness and tribological effects in general, the wear and friction values of samples 1, 2, 3 at 600°C were generally low. Low wear values were recorded in samples at Residence 90 and 150 minutes. Here, it is seen that the lamellae are in a thin structure and the α -phase and β -phase balance of samples 2 and 3 is preserved. However, the holding time for 180 minutes (in sample 4) seems to have caused excessive phase growth and increased wear resistance. However, it is seen that the material hardness is high.

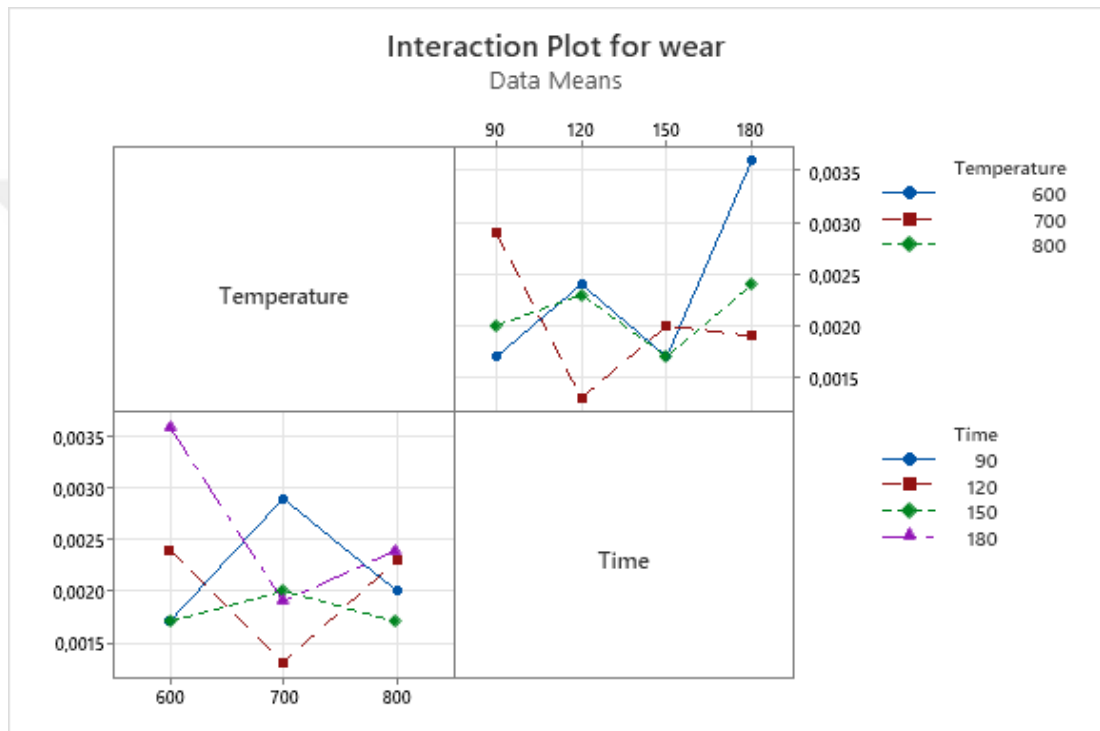


Figure 4.8: Interaction graph of temperature and residence time for wear.

If looking at the results with the heat treatment applied at 700°C, the best results in terms of wear were obtained at this temperature. The hardness and friction balance is due to the smooth formation of the lamellae in the microstructure, and friction stability and low wear were achieved at residence 120 minutes. This shows that the α -phase and β -phase phases in the microstructure are in optimum balance. A slight increase in wear values was observed at 90 and 180 minutes. This indicates fluctuation in phase stability depending on temperature and time.

At 800°C, wear values are relatively high and an increase is observed with time. Due to the high temperature, phase growth and β -phase dominance are caused. It is seen that lamellar structures grew at high temperature and the excessive dominance of β -

phase negatively affected the wear resistance and hardness. This situation caused fluctuations in COF values while decreasing the wear resistance and also caused the hardness of the material to decrease.

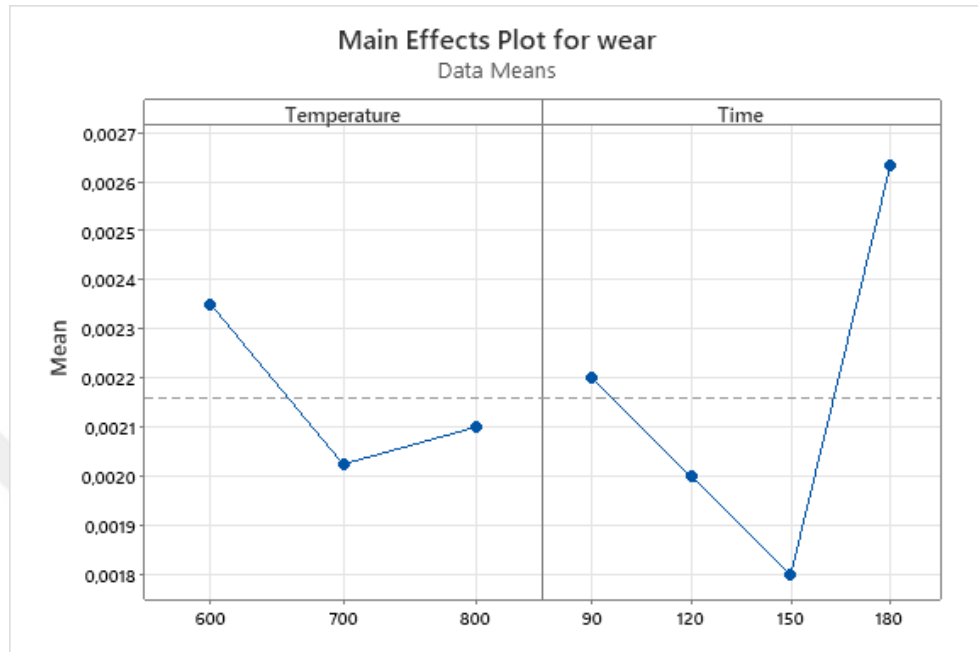


Figure 4.9: Main plot of the effect on wear for temperature and residence time separately.

Also, when looking at **Figure 4.8** and **Figure 4.9**, there is no clear trend in the changes in temperature and time for wear. As the temperature increases, wear does not always increase or decrease. When looking at these results, the same conclusion is valid for the residence time.

5. CONCLUSIONS

When looking at the tribological effects of phases and microstructure, low wear values are associated with cases where α -phase and β -phase phases are formed in a balanced manner. This is especially evident for 700°C/120 minutes. High temperatures and long times (800°C/180 minutes) increased wear due to hardness loss and β -phase dominance. In other words, it is inferred from here that while the homogeneous distribution of the equilibrium phases ($\alpha+\beta$) reduces friction, excessive phase growth (for example 600°C/180 minutes or 800°C/150 minutes) increases the amount of friction and wear.

It has been observed that the amount of wear is lower in cases where the microstructure is stable and the hardness is in optimum balance. In cases of excessive growth of the lamellae or imbalance in the phases, the friction coefficient increases and wear accelerates.

When looking at the optimum temperatures and times: At 600°C performance, at low temperatures, the fine structure of the microstructure stabilizes the wear and friction values. However, it is seen that wear increases at 180 minutes and microstructure deterioration begins as the time increases.

When looking at the 800°C Performance, an increase in wear and friction coefficient is observed at high temperatures. It can be said that this situation is due to the hardness loss and microstructure instability caused by the dominance of the β -phase.

When looking at the Optimum Tribological Performance, optimum hardness (393 HV) and low wear (0.0013) are achieved at 700°C/120 minutes. This situation shows that the microstructure has a balanced and stable phase structure. Low friction coefficients (COF1 and COF2) mean less energy loss and extended material life.

As a result of the tests performed on Ti6Al4V samples produced with SLM, it is seen that the temperature parameters to be applied for the most ideal stress relief are 700°C and 120 minutes. If concluding from this research, it can be seen that 700°C and 120 min is the point where the α -phase and β -phase balance is best optimized and the tribological performance is ideal.

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PUBLICATIONS AND PRESENTATIONS FROM THE THESIS

Taşdelen T., Önlér R., (2025), “Effects of Heat Treatment Parameters on Tribological Performance of Laser Powder Bed Fusion Additive Manufactured Ti6Al4V Components”, 2nd International Thales Congress on Life, Engineering, Architecture, and Mathematics, Cairo, Egypt, 25-26 January.



APPENDICES

APPENDIX-A: Wear Formula and Explanations

Different formulations of wear vary depending on the parameters used. The two basic formulas are:

1. Wear Coefficient Formula

$$w = \frac{v}{F \cdot d}$$

Explanations:

- W: Wear coefficient (mm³/N·m)
- v: Wear volume (mm³)
- F: Applied load (N)
- d: Sliding distance (m)

2. Wear Coefficient Formula

$$w = \frac{dw}{dt} = \frac{\Delta m}{s \cdot A \cdot p}$$

Explanations:

- W: Wear coefficient (mm³/N·m)
- Δm: weight loss(gr)
- A: contact area (mm²)
- s: sliding distance(mm)
- ρ: Density of wearing material (gr/mm³)

Wear volume (V) is expressed in terms of mass loss:

$$V = \frac{\Delta m}{P}$$

This value of V is inserted into the first formula:

$$w = \frac{\frac{\Delta m}{P}}{F \cdot d}$$

If the distribution of the load over the contact area is considered:

$$F = \sigma \cdot A$$

