MECHANICAL CHARACTERIZATIONS OF Ti6Al4V MANUFACTURED BY LASER METAL DEPOSITION PROCESS (LMD)

A PROJECT REPORT

Submitted by

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in partial fulfillment for the award of the degree

of

BACHELOR OF ENGINEERING

in

MECHANICAL ENGINEERING

PANIMALAR ENGINEERING COLLEGE

(An Autonomous Institution, Affiliated to Anna University, Chennai)

APRIL 2023

PANIMALAR ENGINEERING COLLEGE

(An Autonomous Institution, Affiliated to Anna University, Chennai)

BONAFIDE CERTIFICATE

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This project report was submitted for Panimalar Engineering College Viva- Voce held on____________________ during the academic year 2022 – 2023

INTERNAL EXAMINER **EXTERNAL EXAMINER**

ACKNOWLEDGEMENT

At the outset we would like to express our gratitude to our beloved respected **Late Chairman, Dr. Jeppiaar, M.A., B.L., Ph.D.,** Our beloved correspondent and Secretary **Dr. P.Chinnadurai M.A., M.Phil., Ph.D.,** and our esteemed director for their support.

We would like to express thanks to our Principal, **Dr. K. Mani M.E., Ph.D.,** for having extended his guidance and cooperation.

We would also like to thank our **Head of the Department**, **Dr.L.Karthikeyan M.E., Ph.D., Professor, Department of Mechanical Engineering** for his encouragement.

Personally, we thank **Mr. I. John Solomon M.E. Assistant Professor in the Department of Mechanical Engineering** for the persistent motivation and support for this project, who always was the mentor of germination of the project from a small idea.

We express our thanks to the project co-ordinators **Mr. J. Srinivas M.E., and Mr. J. Gunasekaran M.E, Assistant professors in the Department of Mechanical Engineering** for their valuable suggestions from time to time at every stage of our project.

Finally, we would like to take this opportunity to thank our family members, friends, well-wishers who have helped us for the successful completion of our project. We also take the opportunity to thanks all faculty and non-teaching staff members to our department for their timely guidance to complete our project.

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CHAPTER 1- ABSTRACT

The aerospace and medical industries frequently utilise Titanium Grade 5 (Ti6Al4V) due to its high strength-to-weight ratio, good corrosion resistance, and biocompatibility. This alloy is typically manufactured using subtractive techniques, such as machining, which result in material waste and longer manufacturing times. A possible alternative to conventional manufacturing techniques has developed in the form of additive manufacturing, notably laser metal deposition (LMD). This study used laser metal deposition to compare the characteristics of Titanium Grade 5 produced conventionally and additively. On both materials, tests for Vickers hardness, tensile strength, and microstructure were performed. The findings indicated that Titanium Grade 5 produced using additive manufacturing had a higher Vickers hardness and, in comparison to material produced using conventional manufacturing methods, a relatively lower tensile strength. After microstructure analysis, a fine, equiaxed grain structure in the additive manufactured material, while the conventionally manufactured material exhibited elongated and irregular grains. The findings of this study suggest that additive manufactured Titanium Grade 5 using laser metal deposition can offer improved mechanical properties and microstructure over conventionally manufactured material. This has significant implications for the aerospace and medical industries, where the adoption of additive manufacturing can result in reduced material waste and increased manufacturing efficiency.

CHAPTER 2 - INTRODUCTION TO ADDITIVE MANUFACTURING (AM)

CHAPTER 2.1- HISTORY OF ADDITIVE MANUFACTURING

The first idea of 3D printing started to root in the early 1950s, the general concept of and procedure to be used in 3D printing was first described by Murray Leinester in 1945. He theorized that "This constructor is both efficient and flexible, I feed magnetron particles of plastics into a moving arm and it builds objects that desire". This derives the term in the later days as Rapid Prototyping (RP), and now popularly known as Additive Manufacturing (AM).

In the year 1971, Johannes F Gottwald patented a Liquid Metal Recorder which was filed by Teletype Corp. He states that a "continuous inkjet metal material device to form a removable metal fabrication on a reusable surface for immediate use or is salvaged for printing again by remelting". This was the first ever patent that has been filed in the field of ADM.

In the year 1980, the real development of additive manufacturing has begun and started to root in the manufacturing process and also made an impact in modern-day industrial manufacturing. In 1980, Dr. Hideo Kodama filed the first additive manufacturing patent. The researcher at the Nagoya Municipal Industrial Research Institute was looking for a system to create photopolymer prototypes. Kodama wanted to use a container of photopolymer material, exposed to ultraviolet light, to harden a part. His idea never materialized due to a lack of funds, but it did serve to lay the foundation for 3D printing. However, the patent filed by Hideo Kodama was failed and abandoned.

From that onwards, the development and newest kind of inventions in additive manufacturing has started to begun in the and it has significantly revolutionize the manufacturing industry.

In 1983-86, Chuck Hull invented the first Stereolithography (SLA) device. Through the use of lasers, the first solidified layer was achieved. A year later, Carl Deckard of the University of Texas invented a new technique in which a laser was used to bind the powder as a solid (SLS). However, until 2006, the first commercial SLS printers were not viable. He was the first person to invent the SLA machine (3D printer). This was the first ever device of its kind to print a real physical part from a digital (computer-generated) file. Hull later went on to co-found DTM Inc., which 3D Systems Corporation later acquired.

In 1986 Charles Chuck Hull was granted a patent for his system and also for his company's 3D systems. The 3D Systems Corporation released the first commercial 3D printer system SLA-1 in the year of 1987.

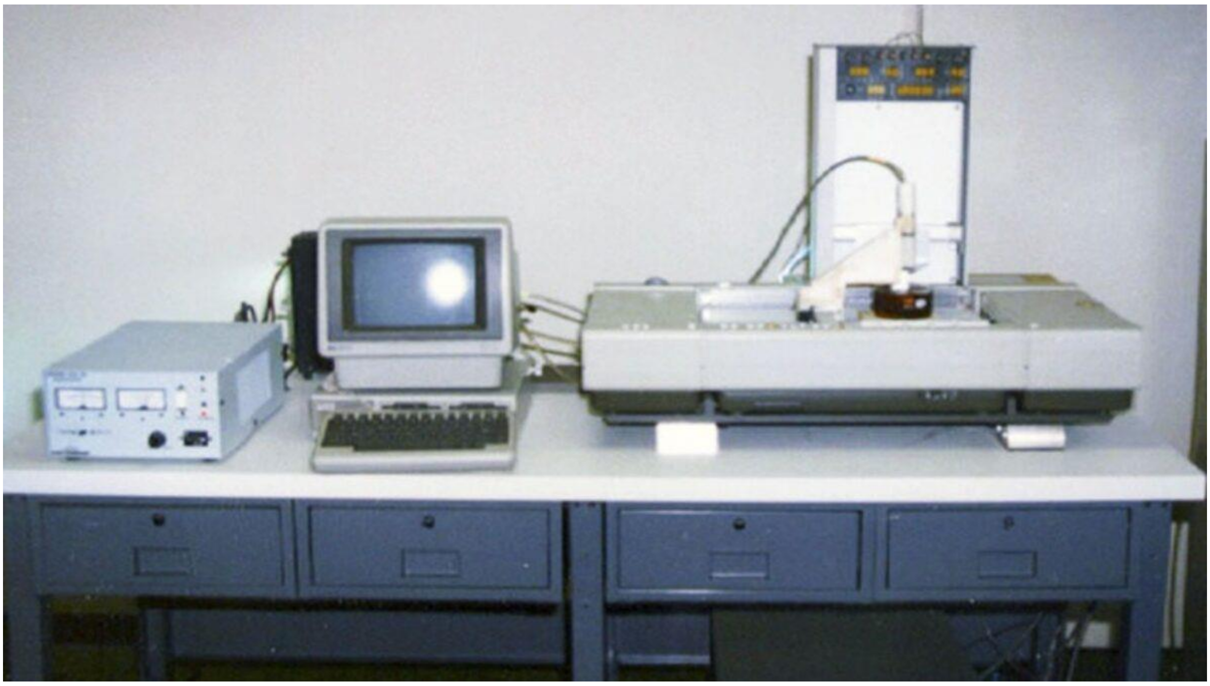


Figure 2.1. 1 The First 3D SLA Printer by Charles Chuck Hull in 1985

CHAPTER 2.2- WORKING OF ADDITIVE MANUFACTURING

The term Additive Manufacturing is defined as, also known as 3D printing, it is a process of creating three-dimensional objects by layering materials one on top of the other. Unlike traditional manufacturing processes that remove the extra material to create a final product, additive manufacturing builds up a product layer by layer.

Additive manufacturing allows for the creation of complex and intricate designs that may be difficult or impossible to create using traditional manufacturing processes. It also allows for the production of customized products, as each layer can be designed to meet specific requirements.

Additive Manufacturing operates and produces a part in a few simple steps and it follows for every additive manufacturing process those steps are as:

1. **Design:**

   The first step in 3D printing is to create a digital model of the object you want to print. This can be done using CAD (computer-aided design) software, or by using a 3D scanner to create a digital model of an existing object.

2. **Slicing:**

   Once you have your digital model, the next step is to prepare it for printing. This involves using software to "slice" the 3D model into thin layers, which the printer will then use to build up the final object. The slicing software generates instructions for the printer, telling it how to create each layer.

3. **Printing:**

   The 3D printer then begins the printing process. Depending on the type of printer, it may use different materials such as plastic, metal, or even food. The printer heats the material to a specific temperature and then deposits it layer by layer, following the instructions generated by the slicing software.

4. **Cooling and Finishing:**

Once the printing is complete, the object must be allowed to cool and harden before it can be removed from the printer. Depending on the material used, additional post-processing steps may be required, such as sanding, support structure removal, processing, polishing, or painting.

5. **Object removal:**

Once the object has cooled, it can be removed from the printer. This is typically done by carefully lifting it off the printer bed or by using a tool to separate it from the support structures.

Additive manufacturing has many applications, including prototyping, manufacturing, tooling repair, product development, and production. It is used in a wide range of industries, including aerospace, automotive, medical, and consumer products, among others.

This is the process of the working of each additive manufacturing, which is a powerful technology that allows for the creation of complex and intricate designs with high levels of precision and accuracy. It is more accessible and user-friendly than ever before.

CHAPTER 3- THE TYPES OF ADDITIVE MANUFACTURING PROCESS

There are different types of additive manufacturing processes are available, and a set of standards were created that categorize the different processes. Individual processes will differ depending on the material and machine technology used. Hence, in 2010, the American Society for Testing and Materials (ASTM) group "ASTM F42 – Additive Manufacturing", formulated a set of standards that classify the range of Additive Manufacturing processes into 7 categories (Standard Terminology for Additive Manufacturing Technologies, 2012). There are pros and cons for each of the seven main types of additive manufacturing. It's essential to know the differences so that we can classify the usage and the necessary process that we are required to use or suitable for a particular set of processes that is used in manufacturing.

I. Stereolithography (SLA),
II. Material Jetting (MJ),
III. Binder Jetting (BJ),
IV. Material Extrusion (MEX),
V. Sheet Lamination (SL),
VI. Powder Bed Fusion (PBF),
VII. Direct Energy Deposition (DED).

These are the seven processes that are available in additive manufacturing. However, all of the processes possess the same functionality rule on how an ADM works, but each of the processes has its unique features and its process parameters, advantages, materials, and method of working in the creation of a part in manufacturing.

CHAPTER 3.1- STEREOLITHOGRAPHY (SLA)

I. **History**:

Stereolithography (SLA) was invented in the mid-1980s by Chuck Hull, who co-founded 3D Systems Corporation.

II. **Definition**:

Stereolithography is an additive manufacturing process that uses a laser to cure a liquid photopolymer resin, creating a solid part.

III. **Working principle:**

In SLA, a laser is used to selectively cure a liquid photopolymer resin, solidifying it into a layer. The build platform is then lowered slightly, and the process is repeated to build up the part layer by layer.

IV. **Materials used:**

SLA is typically used with photopolymer resins, which can be formulated to have a wide range of mechanical and aesthetic properties.

V. **Process parameters:**

Important process parameters in SLA include the laser power and scan speed, the layer thickness, the exposure time of each layer, and the build platform movement speed.

VI. **Surface finish and Mechanical properties:**

Excellent Surface finish will be achieved (around 85-90%), but the mechanical properties will be still at average/satisfactory.

VII. **Requirement of Support structure:**

Yes, always required. It is essential to get a accurate part produced.

VIII. Advantages:

SLA can produce high-resolution parts with excellent surface finish and accuracy. It is also capable of printing fine details and intricate geometries.

IX. Disadvantages:

SLA is generally slower than other additive manufacturing processes, and is limited by the size of the build platform. The materials used in SLA may be brittle and prone to cracking over time, and the process can produce hazardous fumes.

X. Diagram and Image:

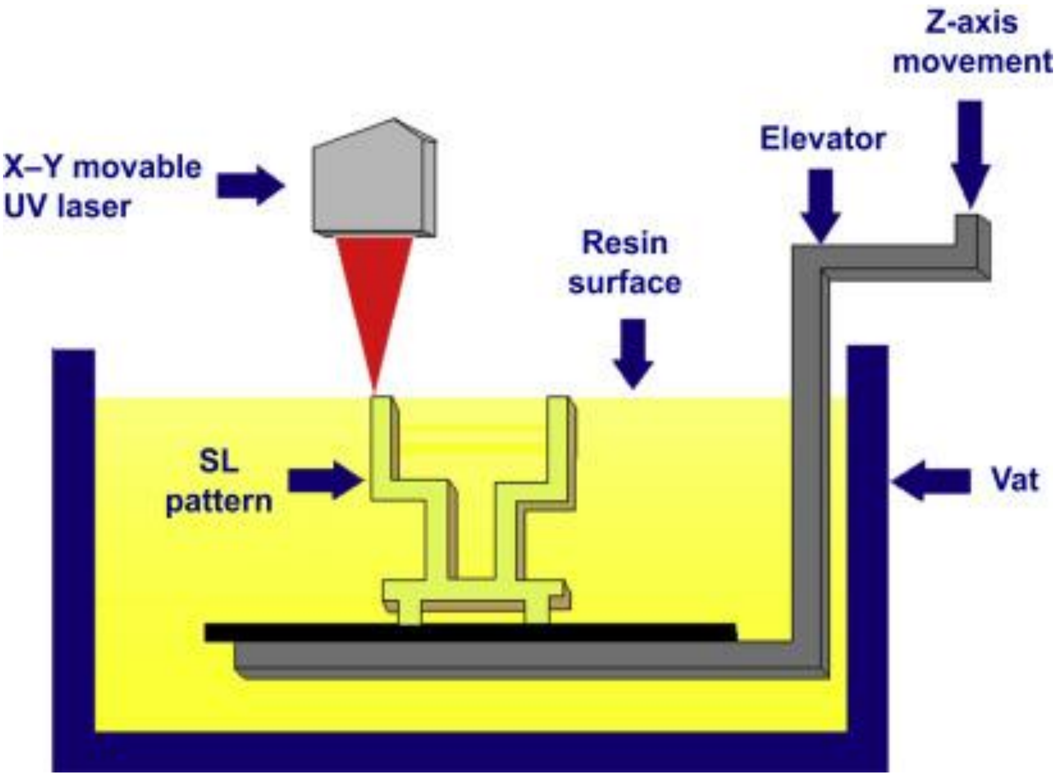


Figure 3.1. 1 Working diagram of SLA

CHAPTER 3.2- MATERIAL JETTING (MJ)

I. History:

Material jetting is a relatively new additive manufacturing process that emerged in the 1990s.

II. Definition:

Material jetting is an additive manufacturing process that uses a print head to deposit small droplets of a liquid material onto a build platform to create a solid part.

III. Working:

Material jetting works by using a print head to deposit small droplets of a liquid material onto a build platform. The material is cured with UV light, forming a solid layer. This process is repeated, building up the part layer by layer until it is complete.

IV. Materials used:

Material jetting can be used with a variety of liquid materials, including photopolymers, waxes, and ceramics.

V. Process parameters:

Important process parameters in material jetting include the viscosity and surface tension of the material, nozzle size and spacing, print head distance from the build platform, UV light intensity and wavelength, layer thickness, and print speed.

VI. Surface finish and Mechanical properties:

Excellent Surface finish will be achieved (around 90%) and offers a good mechanical property.

VII. **Requirement of Support Structure:**

Yes, it is always required to achieve good properties. Printed using dissolvable material.

VIII. **Advantages:**

Material jetting can produce highly detailed and accurate parts, with smooth surface finishes. It is also capable of printing multiple materials simultaneously, allowing for the creation of complex parts with varying properties. Also offers the user for multicolour materials and options. The wastage will be low.

IX. **Disadvantages:**

Material jetting can be a slow process, and is generally not suitable for large parts. It is also relatively expensive, and the materials used may be prone to shrinkage or warping.

X. **Diagram and Image:**

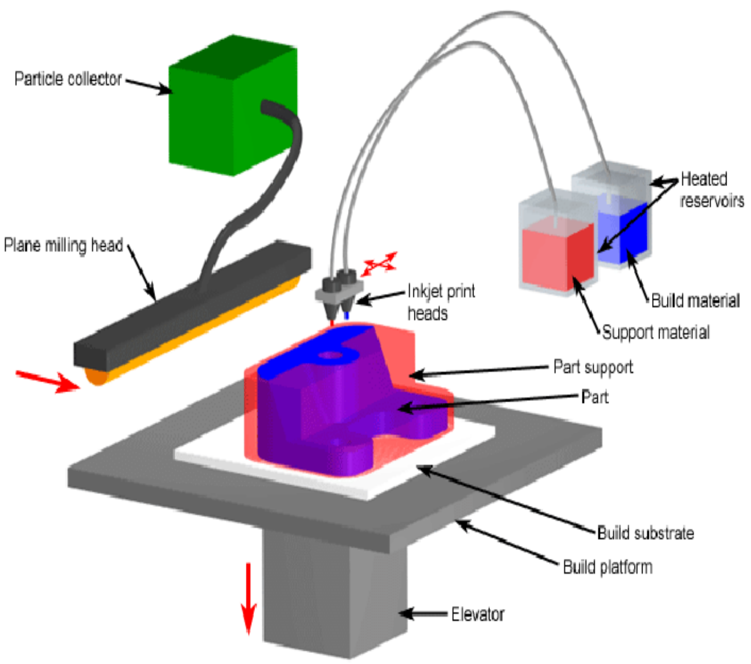


Figure 3.2. 1 Material Jetting Working Diagram

CHAPTER 3.3- BINDER JETTING (BJ)

I. History:

Binder jetting is a relatively new additive manufacturing process that emerged in the late 1990s.

II. Definition:

Binder jetting is an additive manufacturing process that uses a liquid binder to selectively bond powder particles together to form a solid part.

III. Working:

In binder jetting, a print head selectively deposits a liquid binder onto a bed of powder material. The binder bonds the powder particles together in the desired pattern to form a solid layer. The process is repeated layer by layer until the final part is complete.

IV. Materials used:

Uses polymers, metals, ceramics, and plastics. The binder is typically a liquid resin or polymer.

V. Process parameters:

Important process parameters in binder jetting include the size of the powder particles, the thickness of each layer, the print head resolution, the binder saturation level, and the post-processing steps.

VI. Surface finish and Mechanical properties:

Average Surface finish will be achieved (around 50%) and offers a poor mechanical property.

VII. **Requirement of Support structure:**

Not required for Support structure.

VIII. **Advantages:**

Binder jetting can produce parts with high accuracy and resolution, and is capable of producing parts in a range of materials. It is also a fast process and can produce large parts.

IX. **Disadvantages:**

Parts produced with binder jetting may have lower mechanical properties than those produced with other additive manufacturing processes. The process can also be messy and may require post-processing steps to remove excess powder material.

X. **Diagram and Image:**

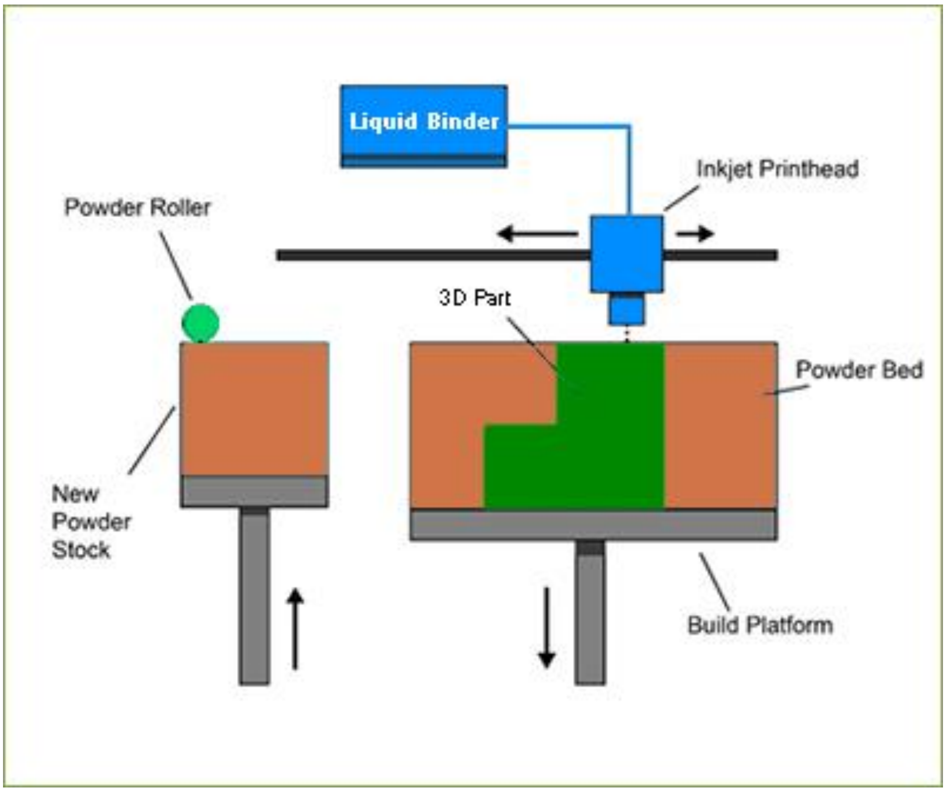


Figure 3.3. 1 Working Diagram of Binder Jetting Machine

CHAPTER 3.4- MATERIAL EXTRUSION (MEX)

I. History:

Material extrusion, also known as Fused Deposition Modeling (FDM), was invented in the late 1980s by Scott Crump, who co-founded Stratasys.

II. Definition:

Material extrusion is an additive manufacturing process that uses a melted material, is selectively dispensed through a nozzle or orifice. Typically, a thermoplastic material, used to build up a part layer by layer.

III. Working:

In material extrusion, a print head melts the thermoplastic material and extrudes it through a nozzle onto a build platform. The print head moves in the X and Y directions, while the build platform moves in the Z direction to build up the part layer by layer.

IV. Materials used:

Material extrusion can be used with a variety of thermoplastic materials, including ABS, PLA, PETG, and nylon.

V. Process parameters:

Important process parameters in material extrusion include the print speed, the layer thickness, the extrusion temperature, the bed temperature, and the nozzle diameter.

VI. Surface finish and Mechanical properties:

Low quality of Surface finish will be obtained (around 25%), and mechanical properties will be good.

VII. Requirement of Support structure:

Requires to achieve a good quality part, sometimes not needed for part overhanging less than 45 degrees.

VIII. Advantages:

Material extrusion is a widely used and accessible process, capable of producing parts with reasonable accuracy and strength. It is also relatively fast and has a low barrier to entry. Can be able to build a fully functional part and offers a widespread variety of process availability. Widely used process.

IX. Disadvantages:

Parts produced with material extrusion may have lower accuracy and resolution compared to other additive manufacturing processes. The process can also result in visible layer lines and may require post-processing steps to achieve a smoother surface finish.

X. Diagram and Image:

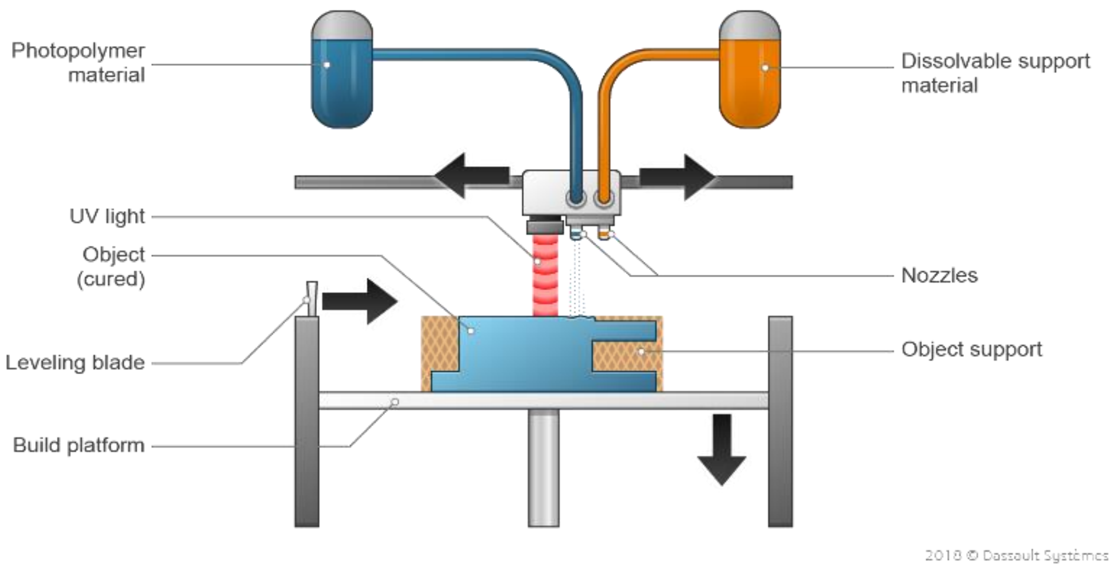


Figure 3.4. 1 Material Extrusion Working Diagram

CHAPTER 3.5- SHEET LAMINATION (SL)

I. History:

Sheet metal lamination is a relatively new process that is invented in the year of 1991

II. Definition:

Sheet metal lamination is a manufacturing process that is, an AM process in which sheets of material are bonded to form an object

III. Working:

In sheet metal lamination, thin sheets of metal are stacked and bonded together using an adhesive, typically a heat-activated film, to create a thicker, more complex part.

IV. Materials used:

Sheet metal lamination can be used with a variety of metals, including steel, aluminium, copper and, also paper and plastics are used in sheets.

V. Process parameters:

Important process parameters in sheet metal lamination include the thickness and composition of the individual metal sheets, the type of adhesive used, and the temperature and pressure of the lamination process.

VI. Surface finish and Mechanical properties:

Low quality Surface finish (around 15%), and very poor Mechanical property will be obtained.

VII. Requirement of Support structure:

Not required in any case.

VIII. Advantages:

Sheet metal lamination can produce complex parts with high precision and accuracy, without the need for expensive tooling. It can also reduce waste and lower production costs compared to traditional stamping and welding processes. High speed process and also low cost with a ease of material handling.

IX. Disadvantages:

Sheet metal lamination can be a time-consuming process, and may require specialized equipment and expertise. The adhesive used in the process may also be vulnerable to delamination or failure over time.

X. Diagram and Image:

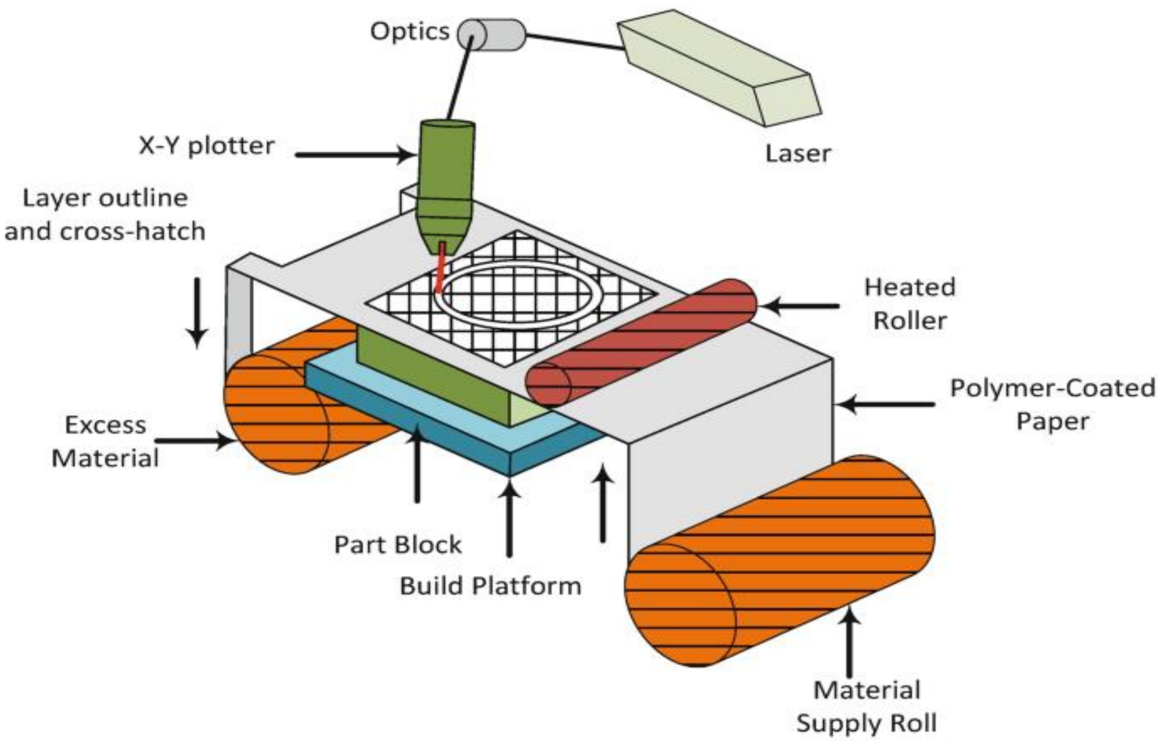


Figure 3.5. 1 Sheet Lamination Working Diagram

CHAPTER 3.6- POWDER BED FUSION (PBF)

I. History:

Powder bed fusion, also known as selective laser sintering (SLS), was first developed in the mid-1980s by Carl Deckard and Joe Beaman at the University of Texas at Austin, and started to use in 1992.

II. Definition:

It is a subset of AM whereby a heat source is used to consolidate material in powder form to form three-dimensional objects.

III. Working:

In powder bed fusion, a thin layer of powdered material is spread evenly over a build platform. A laser then selectively fuses the particles of the material in a pattern corresponding to the cross-section of the part being produced. The platform is then lowered, and the process is repeated with a new layer of powder until the part is complete.

IV. Materials used:

Powder bed fusion can be used with a variety of powdered materials, including plastics, metals, and ceramics.

V. Process parameters:

Important process parameters in powder bed fusion include the laser power, the scan speed, the layer thickness, the bed temperature, and the powder particle size and distribution.

VI. Surface finish and Mechanical properties:

An average Surface finish will be achieved (around 50-60%), and posses a excellent mechanical property in the produced part.

VII. **Requirement of Support structure:**

Support structure for SLS not required but, SLM and DLMS always required of support structure

VIII. **Advantages:**

Powder bed fusion can produce highly complex parts with excellent accuracy and surface finish. It can also produce parts with a high level of detail and intricate internal structures.

IX. **Disadvantages:**

Powder bed fusion can be a slow process, and may require post-processing steps to remove excess powder and achieve the desired surface finish.

X. **Diagram and Image:**

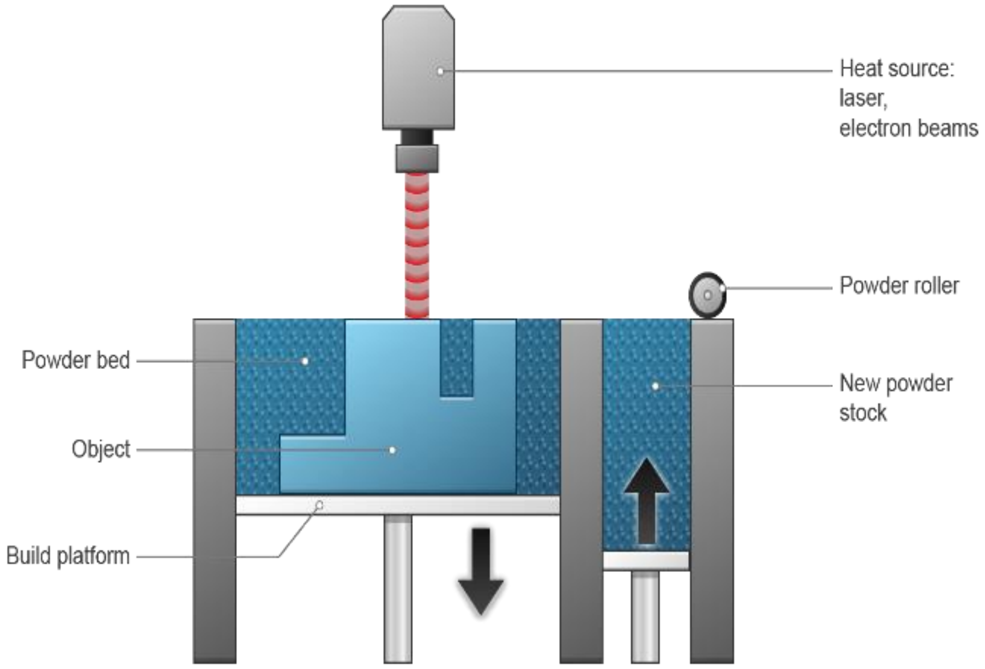


Figure 3.6. 1 Powder Bed Fusion Working Diagram

CHAPTER 3.7- DIRECT ENERGY DEPOSITION (DED)

I. History:

Direct energy deposition (DED) has been in use since the 1990s, and has its roots in traditional welding processes.

II. Definition:

Direct energy deposition is an additive manufacturing process that uses a focused energy source, such as a laser or electron beam, to melt and fuse a powdered or wire feedstock material onto a substrate.

III. Working:

In direct energy deposition, a feedstock material is introduced to a focused energy source, such as a laser or electron beam, which melts and fuses the material onto a substrate. The process is repeated layer by layer to build up a three-dimensional object.

IV. Materials used:

Direct energy deposition can be used with a variety of materials, including metals, it contains stainless steel, Inconel, Tungsten carbide, Stellite, Hastelloy and, Tool steel and other materials like the polymers and ceramics.

V. Requirement for Support structure:

Support structure is not required at any case.

VI. Process parameters:

Important process parameters in direct energy deposition include the energy source power, the feedstock material and size, the deposition rate, and the travel speed.

VII. Surface finish and Mechanical properties:

Very low Surface finish will be achieved (around 18%), and posses an excellent/ fantastic mechanical property in the finished part.

VIII. Advantages:

Direct energy deposition can produce large and complex parts with high precision and accuracy. It can also be used to repair or add material to existing parts. DED can be used with a wide range of materials and can produce parts with unique material properties that cannot be achieved with other manufacturing processes.

IX. Disadvantages:

Direct energy deposition can be a relatively slow process, and may require post-processing steps to achieve the desired surface finish.

X. Diagram and Image:

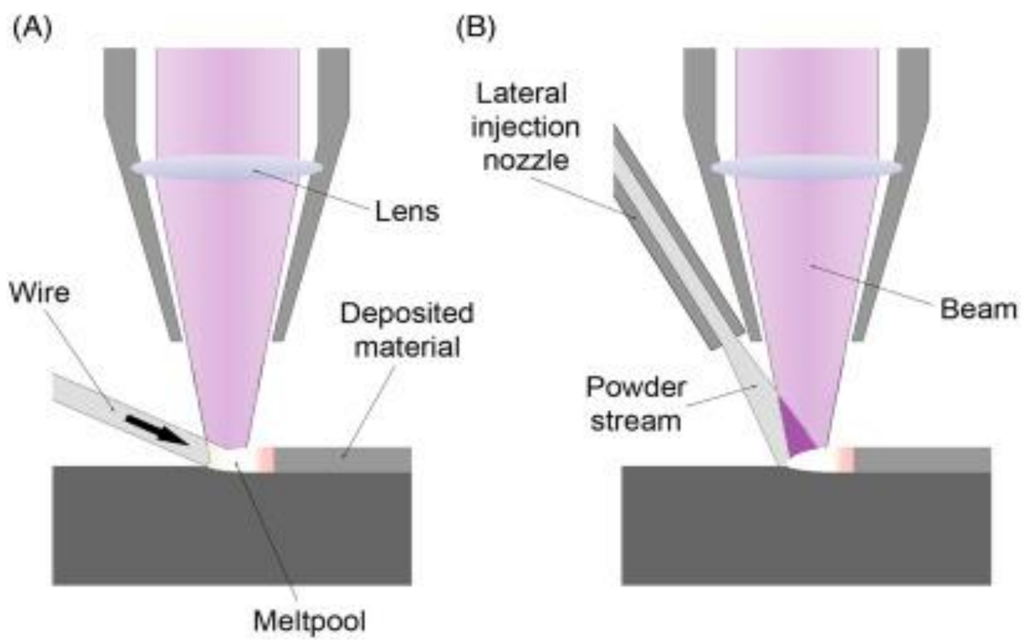


Figure 3.7. 1 DED Working Diagram

CHAPTER 4- LITERATURE SURVEY

Due to its capacity to generate complicated shapes with high precision and exceptional mechanical qualities, laser metal deposition (LMD) is a potential additive manufacturing process that has attracted growing attention in recent years. Due to its exceptional mix of mechanical qualities and biocompatibility, Ti-6Al-4V (Grade 5) is the most widely used grade of titanium alloy in the aerospace and biomedical industries.

In this literature survey, we will review recent research articles on LMD of Ti-6Al-4V alloy with a focus on the microstructure and mechanical properties of the produced parts. This survey will cover various aspects of LMD process optimization, microstructural characterization, and mechanical properties evaluation of Ti-6Al-4V parts produced by LMD.

The study by M. S., et al 2012, Han on Microstructure and mechanical properties of Ti-6Al-4V alloy produced by laser metal deposition [1]. The authors investigated the micro structure of Ti-6Al-4V alloy produced by laser metal deposition (LMD) and found that the material had a fine-grained microstructure with an average grain size of 4-8 micro metre. The microstructure was affected by process parameters such as laser power and scanning speed, with higher laser power resulting in larger grains.

The study by S. S. Park, et al 2009, [2] examined the effect of laser metal deposition (LMD) process parameters on the microstructure and mechanical properties of Ti-6Al-4V alloy. The researchers found that optimizing the process parameters produced a fine-grained microstructure with an average grain size of 2-3 micro metres, and that post-processing techniques such as heat treatment and shot peening could further refine the microstructure and improve the mechanical properties of the material.

The review by P. Gao [3] et al, 2017, provided an overview of the recent advances in additive manufacturing of titanium alloys using laser metal deposition (LMD). The authors found that the mechanical properties of LMD-produced titanium were dependent on factors such as the microstructure, process parameters, and post-processing techniques. The review highlights the potential of LMD as a promising technique for producing high-quality titanium components with complex geometries and improved mechanical properties.

The study by S. H. Jeon et al, 2012, [4] characterized the microstructure and mechanical properties of laser metal deposited Ti-6Al-4V alloy. The researchers found that optimizing the LMD process parameters produced a microstructure with an average grain size of 3-5 micro metres, and that the mechanical properties of the material were improved compared to conventionally manufactured components. The study highlights the potential of LMD for producing Ti-6Al-4V components with improved mechanical properties.

The study by Di Wang et al, 2022, [5] investigated the densification, microstructure, and mechanical properties of selective laser melted Ti-6Al-4V alloy through annealing heat treatment. The results showed that the annealing heat treatment resulted in a denser microstructure and improved mechanical properties of the alloy. The researchers found that the microstructure was dependent on the annealing temperature, and the highest tensile strength was obtained at an annealing temperature of 750°C. The study highlights the potential of annealing heat treatment to tailor the microstructure and mechanical properties of selective laser melted Ti-6Al-4V alloy.

The study by Hao Deng et al, 2019, [6] investigated the microstructure and mechanical properties of as-deposited and heat-treated Near β- Titanium alloys ((Tie5Ale5Moe5Ve3Cre1Zr);{Ti-55531}) alloy fabricated by laser melting deposition. The researchers found that the as-deposited alloy had a complex microstructure, consisting of primary α phase and fine β phase. After heat treatment, the alloy showed a refined microstructure with an average grain size of 2-3 micro metres and improved mechanical properties. The study highlights the potential of heat treatment for refining the microstructure and improving the mechanical properties of Ti-55531 alloy produced by laser melting deposition.

The study by Rasheedat M. Mahamood et al, 2015, [7] optimized the processing parameters to improve the material deposition efficiency in laser metal deposited titanium alloy. The researchers found that optimizing the laser power and scan speed improved the material deposition efficiency, while the powder feed rate had a minimal effect on the efficiency. The study also found that increasing the laser power and scan speed resulted in a coarser microstructure with larger grain sizes, which could potentially affect the mechanical properties of the alloy. The study highlights on achieving high material deposition efficiency and maintaining desirable microstructure and mechanical properties in laser metal deposited titanium alloy.

The study by Abolfazl Azarniya et al, 2019, [8] investigated the additive manufacturing of Ti-6Al-4V parts through laser metal deposition (LMD). The researchers found that the LMD process parameters affected the microstructure and mechanical properties of the material. They optimized the parameters to produce a fine-grained microstructure with an average grain size of 3-5 micro metres, and the tensile and yield strengths were found to be comparable to conventionally manufactured Ti-6Al-4V alloy. The study highlights the potential of LMD as a promising technique for producing high-quality Ti-6Al-4V components with complex geometries and improved mechanical properties.

The research review by Esther Akinlabi et al, 2020, [9] provides an overview of the recent developments in laser metal deposition (LMD) of titanium composites. This review covers various aspects of LMD such as process parameters, microstructure, and mechanical properties. The researchers found that LMD of titanium composites can result in improved mechanical properties, such as higher strength and ductility, compared to conventionally manufactured titanium composites. Additionally, the study highlighted the importance of optimizing the LMD process parameters for achieving desirable microstructure and mechanical properties of the material. The review provides valuable insights into the current state-of-the-art in LMD of titanium composites and highlights the potential for future research in this area.

The study by H.P. Qu et al, 2010, [10] investigated the microstructure and mechanical properties of a laser melting deposition (LMD) Ti/ TiAl structural gradient material. The researchers found that the LMD process parameters affected the microstructure and mechanical properties of the material. The gradient material had a graded microstructure with different phases and grain sizes across the thickness, resulting in improved mechanical properties. The study highlights the potential of LMD for producing gradient materials with improved mechanical properties and the importance of optimizing the processing parameters for achieving desirable microstructure and mechanical properties.

The project research review by Shunyu Liu and Yung C. Shin et al, 2018, [11] provides a comprehensive overview of additive manufacturing (AM) of Ti6Al4V alloy, a commonly used titanium alloy. The researchers discuss various AM technologies, including laser metal deposition, selective laser melting, and electron beam melting, and compare their advantages and disadvantages. The review covers aspects of AM such as process parameters, microstructure, and mechanical properties. The researchers found that AM of Ti6Al4V can result in improved mechanical properties compared to conventional manufacturing techniques. Additionally, the review highlights the importance of optimizing the AM process parameters for achieving desirable microstructure and mechanical properties of the material. The review provides valuable insights into the current state-of-the-art in AM of Ti6Al4V and highlights the potential for future research in this area.

Peter Omoniyi and Esther Akinlabi et al, 2021, [12] provides an overview of the microstructural and mechanical properties of laser-deposited Ti-6Al-4V alloy. The researchers discuss the effects of various laser deposition parameters, such as laser power, scanning speed, and powder feed rate, on the microstructure and mechanical properties of the material. The review covers various microstructural features observed in laser-deposited Ti-6Al-4V alloy, including columnar grains, equiaxed grains, and microcracks. The review also discusses the mechanical properties of the material, including tensile strength, fatigue behavior, and wear resistance. The researchers found that the microstructure and mechanical properties of laser-deposited Ti-6Al-4V alloy were strongly influenced by the processing parameters and post-processing treatments.

The brief review by Chongliang Zhong et al, 2021, [13] provides an overview of the laser metal deposition (LMD) process for Ti6Al4V alloy. The review discusses the advantages of the LMD process, including its ability to produce near-net shape parts and the potential for high production efficiency. The researcher also describes the factors affecting the LMD process, including laser power, scanning speed, powder feed rate, and shielding gas. The review provides an overview of the microstructure and mechanical properties of Ti6Al4V alloy produced by LMD and discusses the effect of process parameters on these properties. The review concludes that the LMD process is a promising method for producing Ti6Al4V alloy components with desirable microstructure and mechanical properties.

The research article by Nanda Kumar Dey et al, 2014, [14] investigates the use of additive manufacturing (AM) laser deposition to repair aerospace components made of Ti-6Al-4V alloy. The researcher discusses the challenges associated with repairing aerospace components and how AM can be a suitable solution due to its ability to repair complex geometries and restore components to their original condition. The study analyzes the microstructure and mechanical properties of the repaired Ti-6Al-4V alloy components produced by the AM laser deposition process. The research also examines the effect of various process parameters such as laser power, scanning speed, and powder feed rate on the microstructure and mechanical properties of the repaired components.

The research article by Markus Heilemann et al, 2017, [15] discusses a new building strategy for laser metal deposition (LMD) of titanium structures that can result in a decreased shape deviation and improved microstructure and mechanical properties. The study investigates the effect of process parameters, such as laser power, scanning speed, and powder feed rate, on the LMD process and the resulting properties of the Ti-6Al-4V parts. The article presents a detailed analysis of the microstructure of the LMD-fabricated parts, including the formation of columnar grains and the presence of porosity, and evaluates their effect on the mechanical properties, such as tensile strength and ductility. The results show that the new building strategy can significantly reduce shape deviation and improve the microstructure and mechanical properties of the LMD-fabricated Ti-6Al-4V parts. The study also discusses the challenges and limitations of the LMD process, such as the need for careful optimization of process parameters to achieve the desired properties and the potential for residual stress and distortion. Overall, the article provides valuable insights into the optimization of the LMD process for titanium structures and the potential for future improvements in the field components and highlights the potential for future research in this area.

CHAPTER 5- PROCESS USED: LASER METAL DEPOSITION PROCESS (LMD)

CHAPTER 5.1- INTRODUCTION AND WORKING OF LMD

Laser Metal Deposition (LMD), also known as Directed Energy Deposition (DED), is a modern additive manufacturing process that utilizes a high-powered laser beam to melt and fuse metallic powders or wires onto a substrate to build complex 3D structures. This process offers unique advantages over traditional manufacturing methods, such as the ability to produce complex geometries, repair damaged parts, and create near-net-shape components. Additionally, LMD can be used with a wide range of materials, including titanium, aluminium, stainless steel, and nickel alloys. As a result, LMD has found numerous applications in industries such as aerospace, automotive, medical, and energy.

In LMD process, a laser beam continuously irradiates the metal wire or powder preforms for their localized deposition. The substrate shifts suitably in the Z-direction to enable the creation of the entire 3D part from zero medium. In these systems, a focused laser beam is oriented along with a deposition head that may consist of either one or many nozzles. As soon as the deposition of the model material particles take place along the deposition profile, an ample quantum of thermal energy is supplied by the laser to accomplish their melting, leading to the creation of melt pool. A heat-affected zone of variable penetration depth thus develops. Movement of the build plate with the help of CNC with respect to the deposition head takes place on a complete deposition of the first layer to accommodate deposition of the subsequent layers and thus the creation of the complete part. The process can be thermally monitored via different devices like infrared cameras and pyrometers and the data obtained can be further utilized for feedback or collection. Fixed build plates with a material composition identical to that of the preform are typically used in LMD. The substrate can be thought of as the stage for the process. Shearing off the parts from the substrate is required for their removal. These systems have CNC operated X and Y for carrying out raster scanning and a set-up for delivering laser and model material. The schematic diagram of DLMD process is reproduced below Figure 5.1 [16]

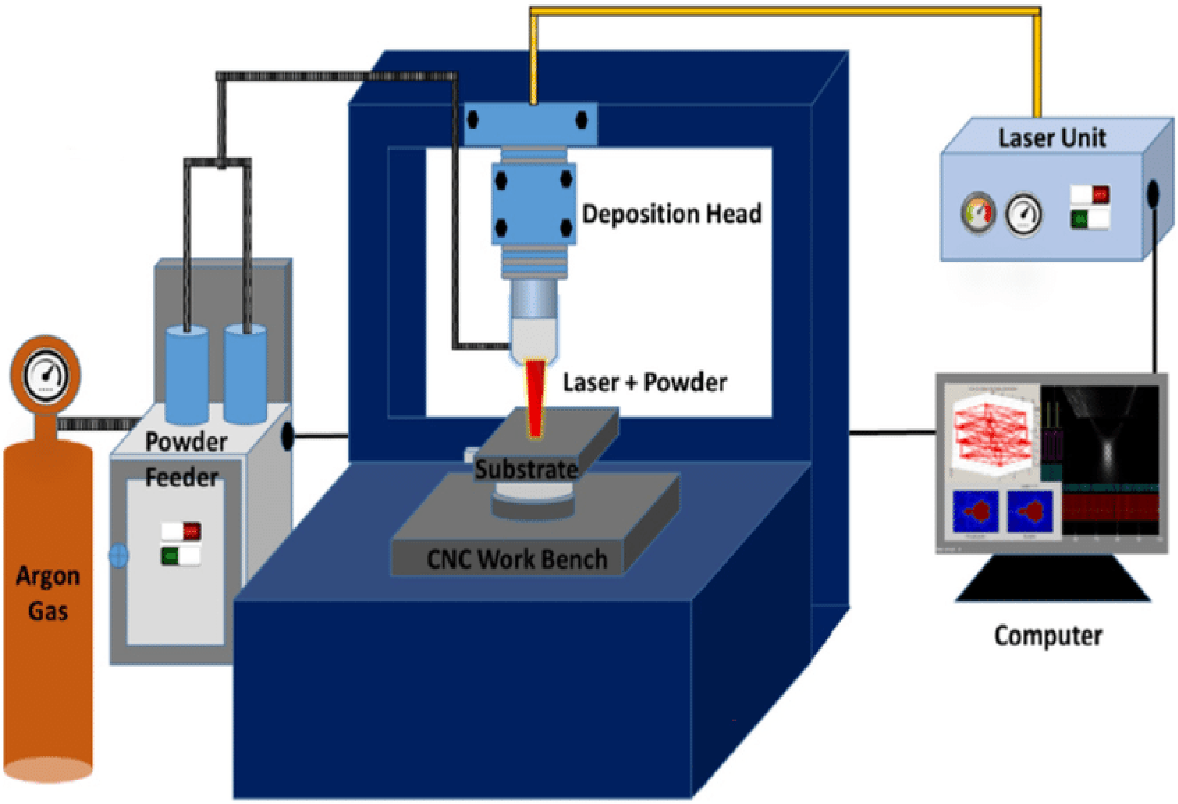


Figure 5.1 Schematic working of DLMD process

CHAPTER 5.2- PROCESS PARAMETERS ON LMD

The process parameters for Laser Metal Deposition (LMD) can vary depending on the specific application and materials being used. The key process parameters that are typically considered when setting up an LMD process for an effective DLMD system consists of:

I. **Laser power:**

Determines the amount of energy delivered to the material, affects the melt pool size and depth.

II. **Scan speed:**

Controls the rate of material deposition and cooling, impacts the microstructure and properties.

III. **Powder feed rate:**

Controls the amount of powder delivered to the melt pool, affects the composition and quality of the deposit.

IV. **Layer thickness:**

Determines the height of each layer, affects the accuracy and resolution of the part.

V. **Hatch spacing:**

Controls the distance between adjacent laser tracks, affects the surface finish and mechanical properties.

VI. **Laser spot size:**

Determines the size of the melt pool, affects the accuracy and resolution of the part.

VII. **Traverse speed:**

The traverse speed is the speed at which the laser moves across the workpiece. This parameter is typically measured in milli-meters per second (mm/s) and can be adjusted using the CNC system.

VIII. **Gas flow rate:**

The gas flow rate is the rate at which the inert gas is delivered to the melt pool to protect it from oxidation and contamination.

IX. **Beam focus position:**

The beam focus position is the distance between the laser lens and the metal powder or wire. This parameter is typically adjusted to optimize the melt pool size and shape.

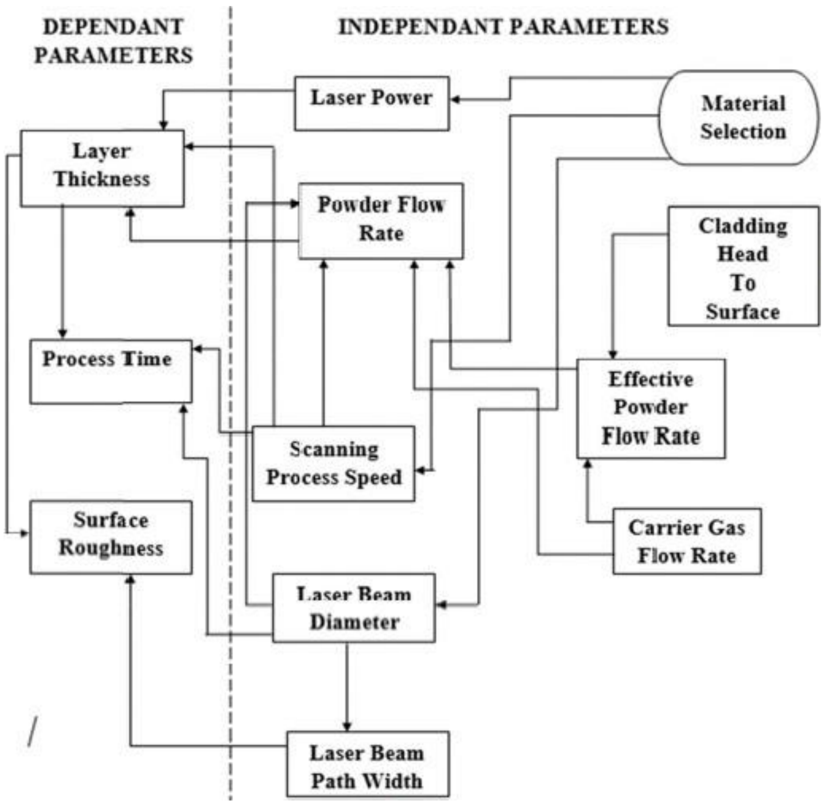


Figure 5. 1 Flowchart representing the LMD Process Parameters

CHAPTER 6- MATERIAL USED: TITANIUM ALLOY (Ti-6Al-4V)

CHAPTER 6.1- INTRODUCTION

Ti-6Al-4V (UNS designation R56400), also sometimes called TC4, or ASTM GRADE-5, is an alpha-beta titanium alloy with a high specific strength and excellent corrosion resistance.

Titanium is a chemical element with the symbol Ti and atomic number 22. It is a strong, lightweight, corrosion-resistant, and biocompatible metal that has numerous industrial, aerospace, medical, and consumer applications.

Titanium was first discovered in 1791 by William Gregor, an English clergyman, and independently by Martin Heinrich Klaproth, a German chemist. It is the ninth most abundant element in the Earth's crust and is found in minerals such as ilmenite, rutile, and anatase.

Pure titanium is a lustrous, silver-white metal that has a low density and high strength-to-weight ratio. It is highly resistant to corrosion by water, seawater, and chlorine, making it an ideal material for use in marine and chemical processing applications. It is also resistant to high temperatures, making it useful in aerospace and military applications.

Titanium is commonly alloyed with other metals, such as aluminium, vanadium, and iron, to improve its mechanical properties and increase its usefulness in various applications. These alloys have high strength, excellent corrosion resistance, and good biocompatibility, making them suitable for use in medical implants and prosthetics.

CHAPTER 6.2- PROPERTIES OF TITANIUM

Chemical Properties of Ti-6Al-4V

Element presented	Percentage by Weight	
	Minimum	Maximum
Ti- Titanium	90.00%	90.00%
Al- Aluminium	5.5%	6.75%
V- Vanadium	3.5%	4-4.5%
C- Carbon	0.1%	0.8%
O- Oxygen	0.2%	0.3%
N- Nitrogen	---	0.05%
H- Hydrogen	---	0.0125%
Fe- Iron	0.1%	0.3%

Table 6.2.1 Chemical properties of Ti-6Al-4V (Grade 5)

Some characteristic chemical properties are:

I. **Corrosion resistance:** Ti6Al4V has excellent corrosion resistance in a variety of environments, including seawater and chloride solutions.

II. **Biocompatibility:** Ti6Al4V is biocompatible and is suitable for use in medical implants and prosthetics.

III. **High melting point:** Ti6Al4V has a high melting point of 1,680°C (3,056°F), which makes it suitable for high-temperature applications.

IV. **Low thermal conductivity:** Ti6Al4V has a low thermal conductivity, which means that it is an excellent insulator and is useful in applications where thermal insulation is needed.

Physical Properties of Ti-6Al-4V

Examined Properties	Readings
Density	0.16lbs./in^3
Specific Heat	0.135(Btu/lb./◦F (32-212)
Electrical Resistivity	171(Microhm-cm at 68◦F)
Melting Point	3200◦F
Thermal Conductivity	3.9
Modulus of Elasticity Tension	16.5
Beta Transus	1830 (◦F +/- 25)

Table 6.2.2 Physical properties of Ti-6Al-4V

Some characteristic Physical properties are

I. **Density:** Ti6Al4V has a density of 4.43 g/cm³, which is approximately 60% of the density of steel.

II. **Melting point:** Ti6Al4V has a high melting point of 1,680°C (3,056°F).

III. **Thermal conductivity:** Ti6Al4V has a low thermal conductivity, which makes it an excellent insulator.

IV. **Electrical conductivity:** Ti6Al4V has a low electrical conductivity, which means that it is not suitable for use in electrical applications.

V. **Magnetic properties:** Ti6Al4V is non-magnetic, which makes it useful in applications where magnetic interference needs to be minimized.

VI. **Hardness:** Ti6Al4V has a hardness of approximately 36 HRC, which means that it is relatively hard and can withstand wear and tear.

Mechanical Properties of Ti-6Al-4V

Examined Properties	Readings
Hardness Brinell	**334**
Hardness Rockwell C	**36**
Ultimate Tensile Strength	**131000 psi**
Yield Strength	**120000 psi**
Machinability Rating	**22% of B 112**
Typical Stock Removal Rate	**30 surface ft./minute**

Table 6.2.3 Mechanical properties of Ti-6Al-4V

Some characteristic Mechanical properties are

I. **High strength-to-weight ratio:** Ti6Al4V has a high strength-to-weight ratio, which makes it ideal for applications where strength and low weight are important.

II. **High tensile strength:** Ti6Al4V has a tensile strength of up to 1,250 MPa (181 ksi), which makes it stronger than some steels.

III. **Good fatigue strength:** Ti6Al4V has good fatigue strength, which means that it can withstand repeated loading cycles without failure.

IV. **Good toughness:** Ti6Al4V has good toughness, which means that it can absorb energy without fracturing.

V. **Good ductility:** Ti6Al4V has good ductility, which means that it can be deformed without fracturing.

CHAPTER 7- TESTING USED AND ITS SIGNIFICANT ROLE

Testing of an additive manufactured material in comparison with a normal conventionally processed forged material will exhibit its most notable changes in the ways of chemical, microstructure and mechanical ways. To analyse and interpret the results four different methods that undertook. Those testing methods are:

I. **Vickers Hardness Test,**
II. **Tensile Test,**
III. **Scanning Electron Microscopy (SEM) Analysis,**
IV. **X-Ray Diffraction (XRD) Analysis.**

To analyse the microstructural and mechanical properties of the both unconventional and additive manufactured Ti-6Al-4V material, and its significant changes in properties can be found out. Role of each test in ADM is

I. In additive manufacturing, Vickers hardness testing can provide valuable information about the mechanical properties of the material, including its hardness, strength, and resistance to deformation.
II. In additive manufacturing, tensile testing can provide valuable information about the strength, stiffness, ductility, and other mechanical properties of the material.
III. In additive manufacturing, SEM can be used to examine the morphology of the individual layers, the distribution and size of pores or defects. It provides valuable information of the mechanisms of failure, deformation, and other performance-limiting factors of additively manufactured parts.
IV. XRD can provide the valuable information about the degree of crystallinity, the texture of the material, and mechanical properties.

CHAPTER 7.1- VICKERS HARDNESS TEST

I. **Principle:** The Vickers hardness test is based on the principle of plastic deformation of a material caused by the application of a static load. The load is applied to the surface of the material using a diamond indenter with a square-based pyramid shape. The size of the indentation produced by the indenter is proportional to the hardness of the material. By measuring the size of the indentation, the Vickers hardness number (HV) can be calculated.

II. **Role of this test in additive manufacturing:** It provides information about the mechanical properties of materials used in additive manufacturing, including their strength, hardness, and resistance to deformation. This information can be used to optimize processing conditions and improve the quality and performance of the final product. The test can also assess the consistency and uniformity of the material's properties across different regions of the additively manufactured part.

III. Diagram and Image:

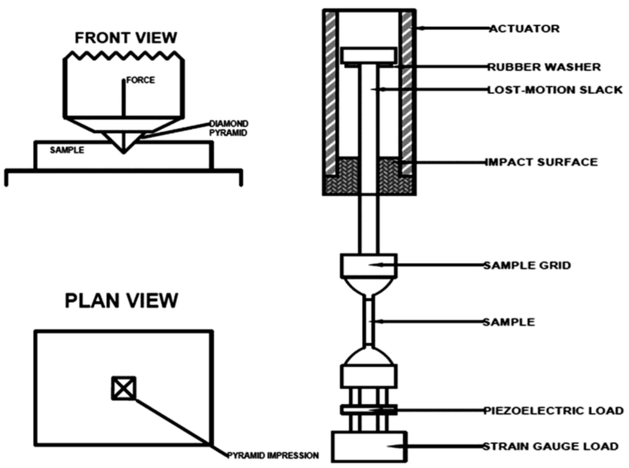


Figure 7.1.1 Schematic diagram of Vickers Hardness

Figure 7.1. 2 Vickers Hardness Testing Machine

CHAPTER 7.2- TENSILE TEST

I. **Principle:** The tensile test is based on the principle of measuring the resistance of a material to a tensile load. A test specimen of known dimensions is subjected to an increasing tensile load until it breaks. The deformation and force are measured throughout the test, and the mechanical properties of the material are calculated from the resulting stress-strain curve.

II. **Role of this test in additive manufacturing:** The tensile test is an important tool in additive manufacturing, as it can be used to measure the mechanical properties of 3D-printed parts. This information can be used to optimize the printing process, ensure the quality of the finished part, and validate the performance of the material.

III. **Diagram and Image:**

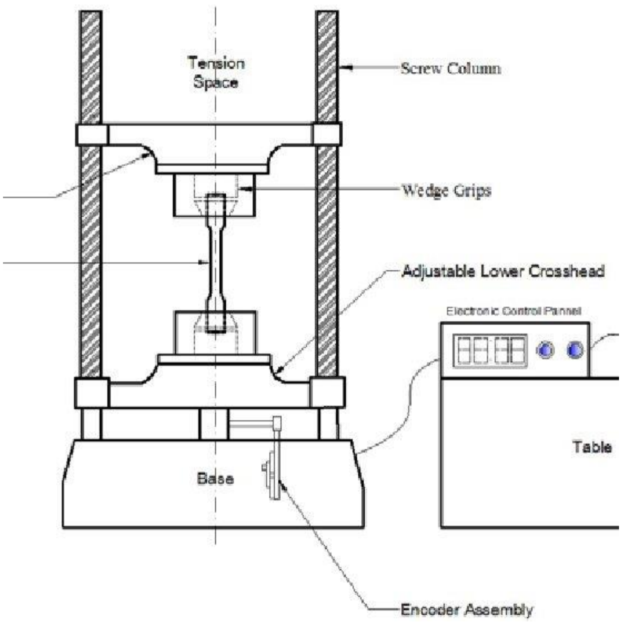


Figure 7.2. 1 Schematic diagram of Tensile Test

Figure 7.2. 2 Tensile Test Machine

CHAPTER 7.4- SCANNING ELECTRON MICROSCOPY (SEM)

I. **Principle:** SEM is based on the principle of using a focused electron beam to scan the surface of a material and generate signals that are used to produce an image. The electrons in the beam interact with the atoms in the material, producing secondary and backscattered electrons that are detected by a detector and used to create an image of the surface.

II. **Role of this test in additive manufacturing:** SEM is used in ADM, as it can be used to analyse the microstructure and surface morphology of 3D-printed parts. This information can be used to optimize the printing process, ensure the quality of the finished part, and validate the performance of the material.

III. **Diagram and Image:**

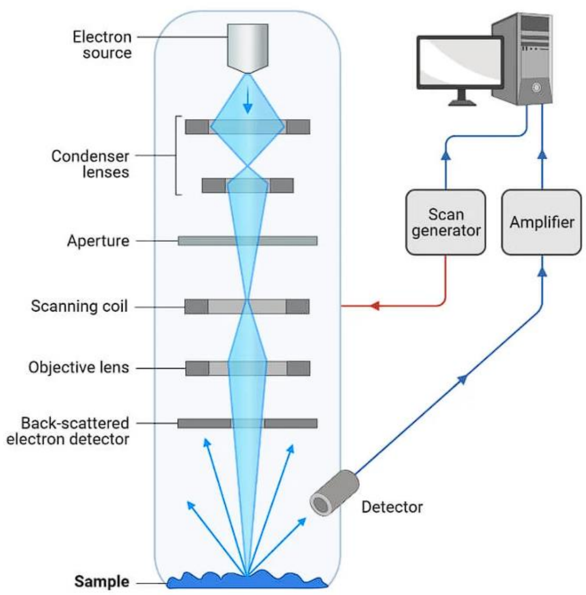


Figure 7.3. 1 Schematic Working of SEM Analysis

Figure 7.3. 2 SEM analysis Machine

CHAPTER 7.5 X-RAY DIFFRACTION (XRD)

I. **Principle:** XRD is based on the principle of diffraction, which occurs when X-rays are scattered by the atoms in a crystal lattice. The scattering produces a pattern of constructive and destructive interference that is related to the crystal structure of the material.

II. **Role of this test in additive manufacturing:** XRD is an important tool in additive manufacturing, as it can be used to analyse the crystal structure and composition of 3D-printed parts. This information can be used to optimize the printing process, ensure the quality of the finished part, and validate the performance of the material.

III. **Diagram and Image:**

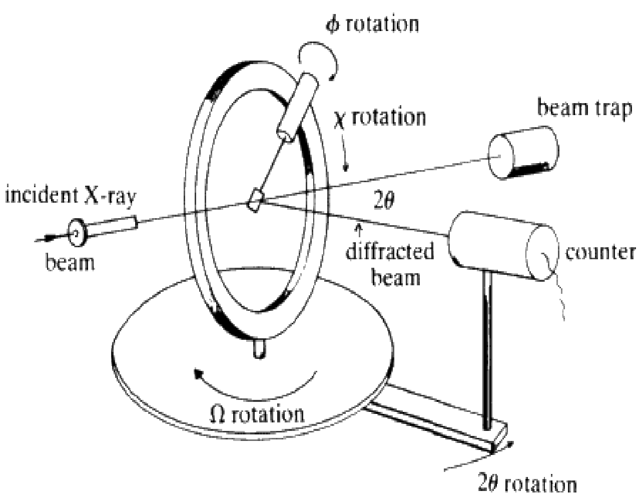


Figure 7.4. 1 X Ray Diffraction Working Diagram

Figure 7.4. 2 XRD Machine

CHAPTER 8 - EXPERIMENT AND TESTING

Testing of an additive manufactured material in comparison with a normal conventionally processed forged material will exhibit its most notable changes in the ways of chemical, microstructure and mechanical ways. The properties of the conventionally manufactured material and LMD processed additively manufactured material properties are mentioned.

CHAPTER 8.1 CONVETIONAL PROCESS:

Material used: Ti6Al4V

Physical properties: Refer table 6.2.2

Chemical properties: Refer table 6.2.1

Dimensions of the base plate: 100x60 mm; Thickness- 6mm.

Tests done: Vickers Hardness, Tensile test, SEM analysis, and XRD analysis.

Image:

Figure 8. 1 Titanium base plate used (Conventional method)

CHAPTER 8.2 ADDITIVE MANUFACTURED MATERIAL:

ADM process used: Laser metal deposition (LMD).

Layers height: 0.9 mm.

Scanning speed:10 mm/s.

Laser power: 800W.

Build orientation: X=60; Y=100; Z=6.

Material used: Ti6Al4V.

Tests done: Vickers Hardness, Tensile test, SEM analysis, XRD analysis.

Image:

Figure 8. 2 LMD manufactured additive material used

By comparing these two different processes of materials we are going to compare the microstructural and mechanical properties of both different titanium materials.

CHAPTER 8.3- SPECIMEN PREPARATION

The specimen for the material testing are prepared from both the base plates of conventional and additively manufactured components of Ti6Al4V. The specimen preparation and the measurements with CAD model are used is given,

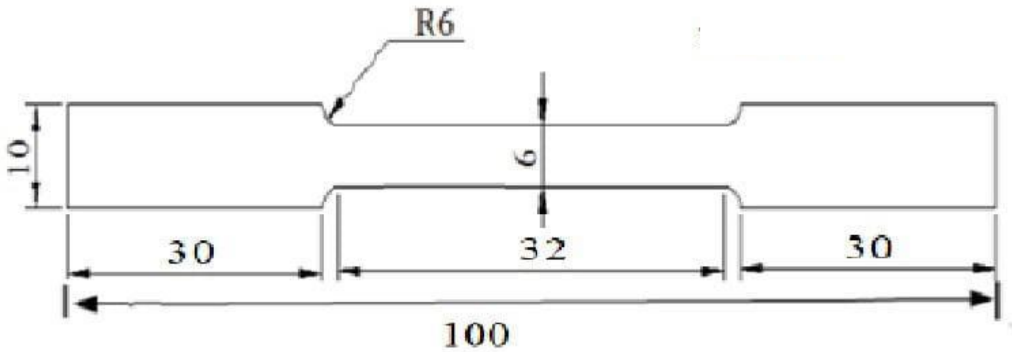


Figure 8. 3 .1The specimen measurements (All dimensions are in mm)

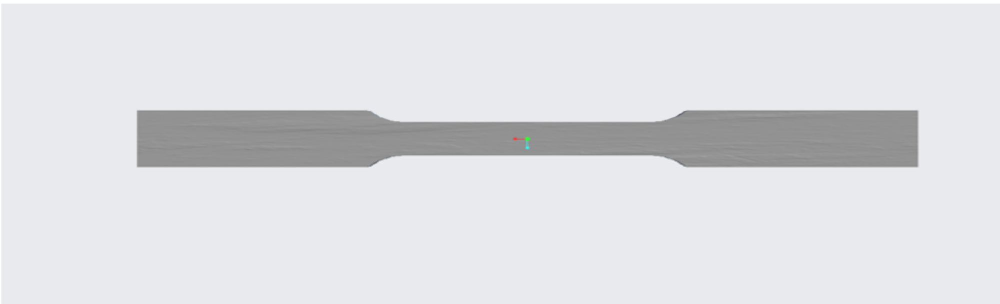


Figure 8. 3.2 CAD model of Specimen

The measurements which were depicted in the figure 8.3.1 were followed and used for 4 of the specimens for 4 different types of the tests.

Prepared 4 specimens of both additive and conventional processes are given.

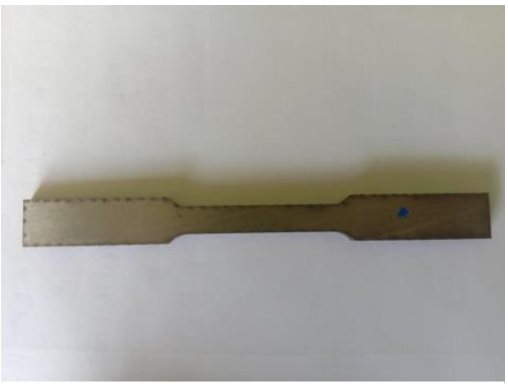


Figure 8.3. 3 ADM prepared specimen 1

Figure 8.3. 4 ADM prepared specimen 2

Figure 8.3. 5 ADM prepared specimen 3

Figure 8.3. 6 ADM prepared specimen 4

Figure 8.3. 7 Conventional specimen 1

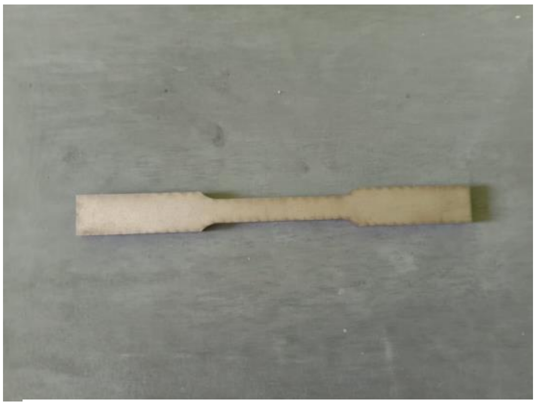


Figure 8.3. 8 Conventional specimen 2

Figure 8.3. 9 Conventional specimen 3

Figure 8.3. 10 Conventional specimen 4

Proper specimen preparation is crucial for accurate microstructure and mechanical properties testing, but it can be difficult to do well. Sampling, surface finish, orientation of the sample all these things must be considered when planning a test so that reliable results are obtained.

CHAPTER 9 - VICKERS HARDNESS TEST

Working:

The Vickers hardness test is used to assess material hardness and microstructure, optimise manufacturing processes, and ensure quality control. The test begins with the preparation of a specimen and the loading of a diamond pyramid-shaped indenter onto the testing machine. A load is applied to the indenter, causing it to penetrate the surface of the specimen for a predetermined amount of time. The resulting indentation is then measured with a microscope, and the Vickers hardness number is calculated by dividing the applied load by the indentation's surface area.

Specimen:

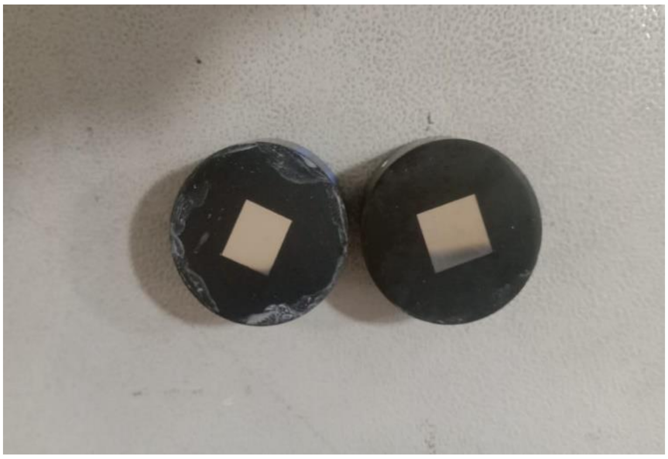


Figure 9.1. Hardness test specimen for

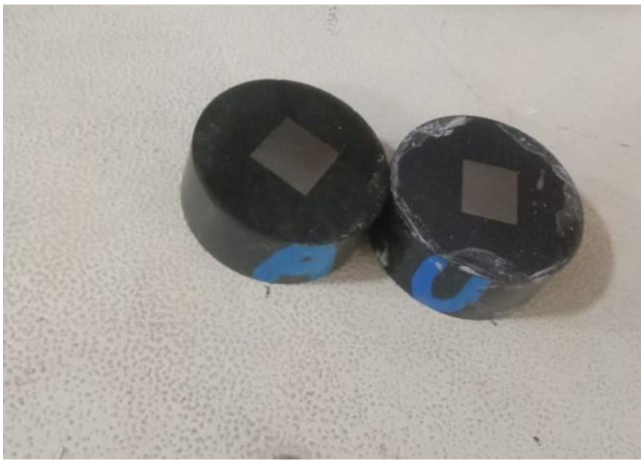


Figure 9.2 Hardness test specimen Additive (LMD)

Hardness Test properties:

Load	Dwell	Unit H.V	Scale
1.0 KGF	10 Seconds	0.5 KGF	Vickers Hardness

CONVENTIONAL MATERIAL RESULTS:

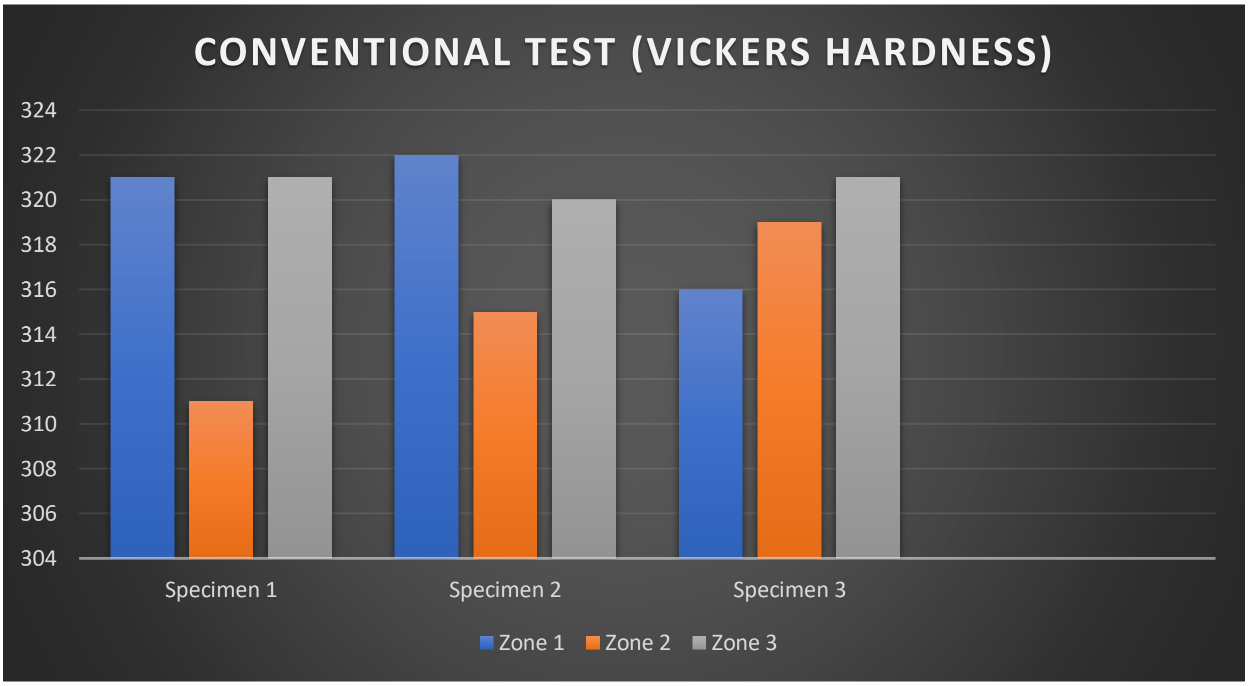


Chart 9.1 Vickers hardness Conventional 1

ADDITIVE MANUFACTURED MATERIAL RESULTS:

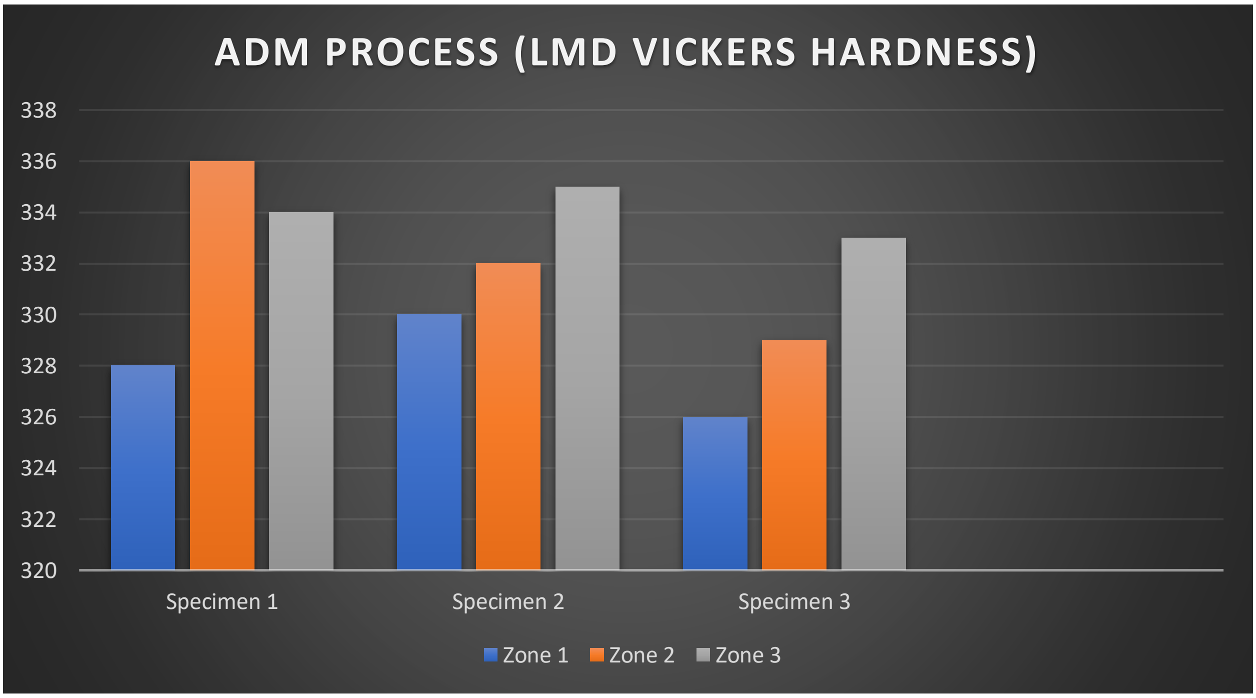


Chart 9.2 Vickers hardness ADM material 1

Results of this test:

When compared to Ti6Al4V produced conventionally, the additive manufacturing LMD have even higher hardness values. This is due to the Heat treatment of the titanium by layer-by-layer deposition process and the ability of LMD to create a fine microstructure with few residual stresses and imperfections, which raises the hardness values. The process also increases the amounts of alloying elements that are present in LMD Ti6Al4V. This reduces the chance of corrosion, which is especially important when working with medical-grade titanium and also for aerospace application.

CHAPTER 10- TENSILE TEST

Working:

The strength and deformation characteristics of materials are assessed using the mechanical testing technique known as tensile testing. The characteristics of both conventional and additive produced materials can be examined using this method. Tensile testing can offer important information about the material's strength, ductility, and fracture properties by measuring stress and strain while applying an increasing load to a sample.

Tensile testing is performed using a universal testing machine, which measures the load applied to a material sample as it is pulled apart under a controlled load. The resulting data can include measurements such as tensile strength, yield strength, elongation, and modulus of elasticity, which can be used to evaluate the mechanical properties of the material. The test is performed on samples that are usually 10-15mm wide and 100-400mm long, depending on the size of the material being tested.

Test Specimen:

Figure 10. 1 ADM tensile test specimen

Figure 10. 2 Conventional tensile test specimen

Additive LMD Results

Test properties for Additive (LMD):

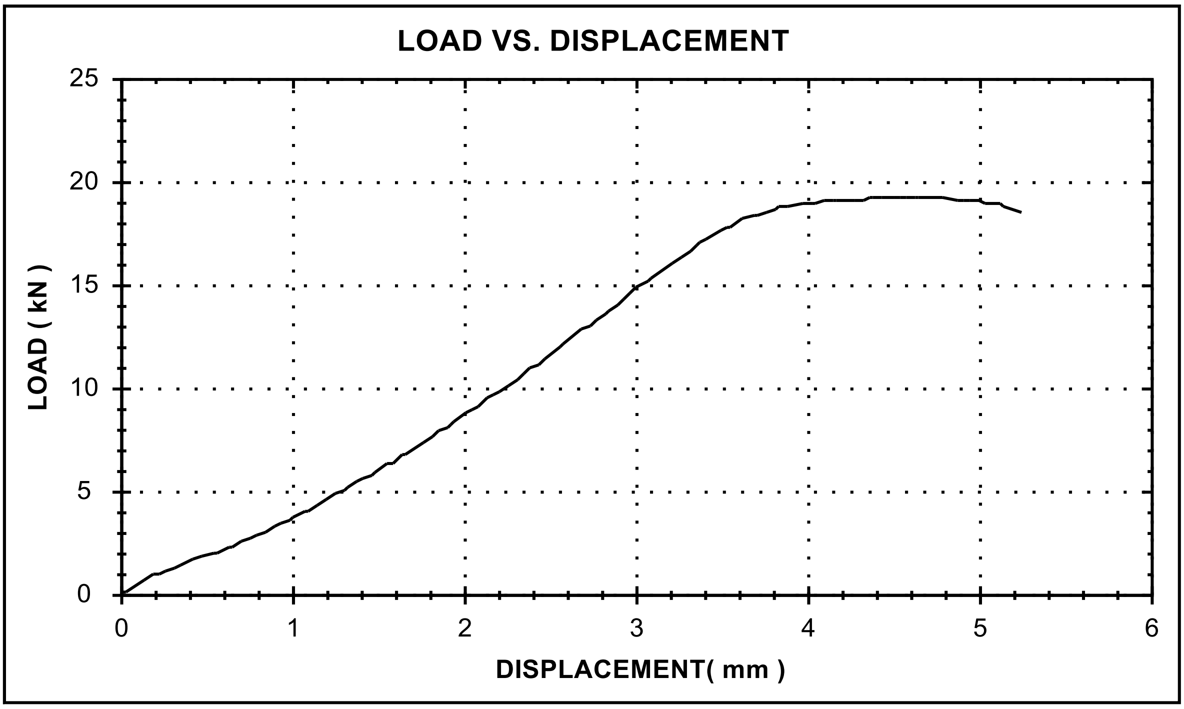
S/N	1	2	3
Test Name	S-ADD-1	S-ADD- 2	S-ADD-3
Initial Area (mm^2)	36.48	36.48	36.48
Ultimate Load in kN	19.18	19.23	19.21
Ultimate Stress in kN/mm^2	0.53	0.54	0.53
Breaking Load in kN	18.27	18.37	18.34
Yield Stress in kN/mm^2	0.52	0.53	0.52
Max. Displacement in mm	5.33	5.39	5.41
Final Gauge Length in mm	29.13	29.15	29.19
Final Dimension (W X T) in mm	5.64 X 3.7	5.65 x 3.71	5.68 x 3.73
YS / UTS Ratio	0.98	0.98	0.97
% of Elongation	16.52	16.53	16.54
% of Reduction of Area	12.81	12.81	12.81
Load Unit	kN	kN	kN
Displacement Unit	mm	mm	mm
Time Unit	sec	sec	sec

Table 10.1 Additive (LMD) test properties

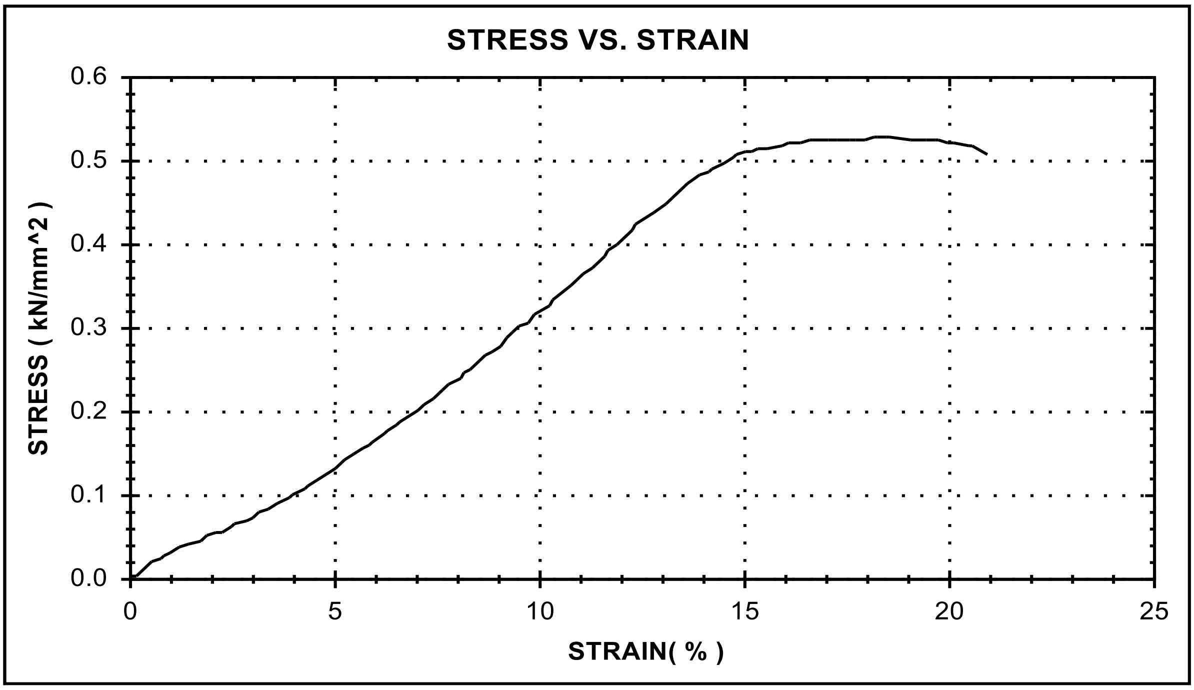
Specimen 1		Specimen 2		Specimen 3	
Load	**Displacement**	**Load**	**Displacement**	**Load**	**Displacement**
23.3	0.01	26.5	0.01	25.32	0.01
89.07	0.04	95.62	0.05	92.31	0.05
898.27	0.19	930.24	0.23	934.28	0.2
1432.71	0.36	1450.88	0.37	1452.39	0.41
2148.04	0.6	2165.32	0.6	2147.05	0.65
2814.04	0.8	2803.54	0.85	2822.87	0.8
3837.7	1.04	3862.31	1.1	3865.58	1.08
4918.8	1.28	4965.57	1.25	4941.74	1.3
5800.6	1.46	5822.91	1.5	5830.59	1.5
6815.49	1.66	6833.74	1.7	6849.27	1.72
8159.82	1.91	8188.24	1.9	8155.42	2
9400.12	2.13	9433.49	2.1	9450.81	2.18
10534.56	2.33	10530.41	2.25	10558.08	2.2
11787.85	2.53	11818.7	2.5	11803.29	2.5
13165.75	2.76	13198.65	2.75	13212.55	2.8
14454.86	2.96	14470.34	3	14450.88	2.9
15366.55	3.1	15370.59	3.13	15380.9	3.2
17616	3.5	17643.88	3.5	17656.55	3.54
18576.62	3.78	18612.21	3.75	18622.69	3.71
18917.16	4.01	18929.74	4	18919.41	4
19057.62	4.17	19070.09	4.2	19077.19	4.19
19183.01	4.54	19231.11	4.5	19217.64	4.4
19011.71	5.02	19085.85	5.04	19105.54	5.05
18989.1	5.04	19021.14	5.07	19000.9	5.1
18268.98	5.33	18372.49	5.39	18348.38	5.41

Table 10.2 Load vs. Displacement values for additive material (LMD)

Graph Results for Additive manufactured (LMD) material:



Graph 10. 1 Load vs Displacement Additive process (LMD)



Graph 10. 2 Stress vs Strain Additive process (LMD)

Conventional Results

Test properties for Conventional material:

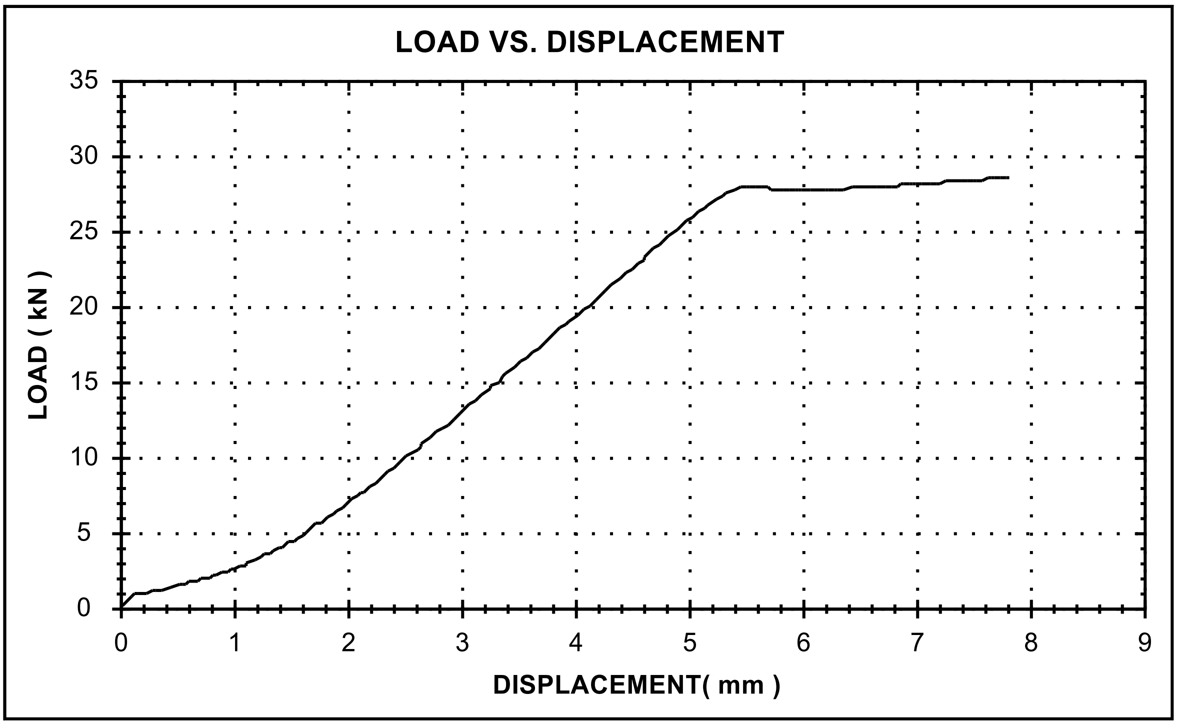
S/N (specimen)	1	2	3
Test Name	S-CON-1	S-CON-2	S-CON-3
Initial Area (mm^2)	36.48	36.48	36.48
Ultimate Load in kN	28.52	28.53	28.52
Ultimate Stress in kN/mm^2	0.78	0.8	0.79
Breaking Load in kN	28.52	28.61	28.6
Yield Stress in kN/mm^2	0.76	0.81	0.85
Max. Displacement in mm	7.82	7.85	7.91
Final Gauge Length in mm	28.88	28.95	28.91
Final Dimension (W X T) in mm	5.84 X 3.72	5.84 x 3.79	5.85 x 3.7
YS / UTS Ratio	0.97	0.97	0.98
% of Elongation	15.52	15.54	15.53
% of Reduction of Area	6.51	6.51	6.51
Load Unit	kN	KN	KN
Displacement Unit	mm	mm	mm
Time Unit	sec	sec	sec

Table 10.3 Conventional material test properties

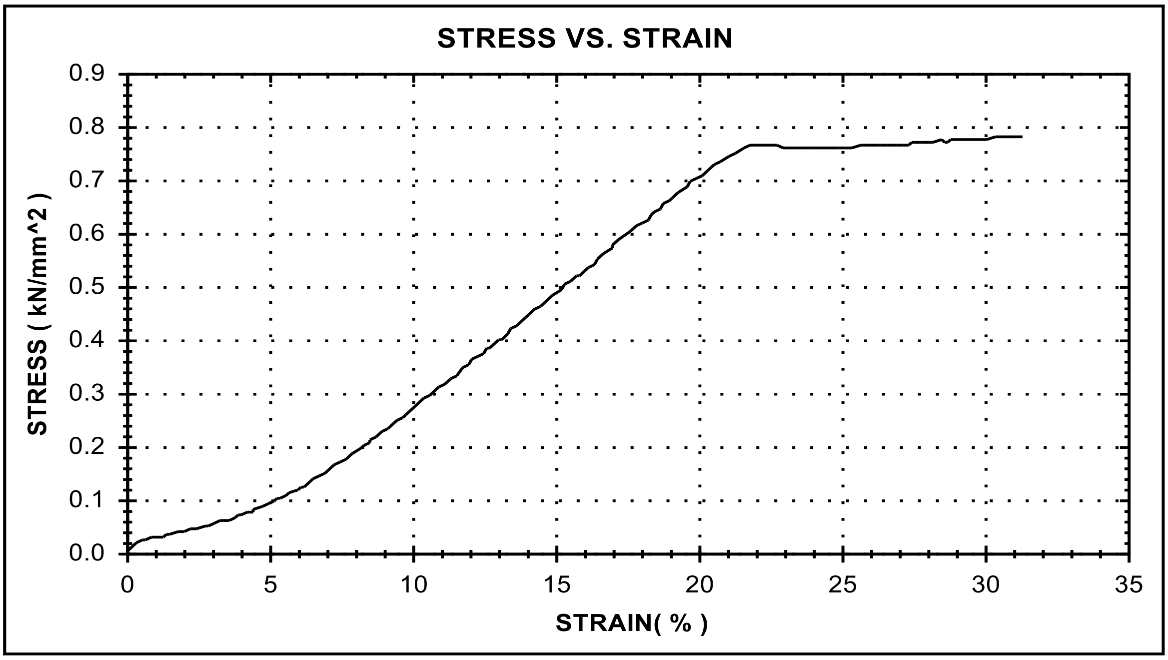
Specimen 1		Specimen 2		Specimen 3	
Load	**Displacement**	**Load**	**Displacement**	**Load**	**Displacement**
56.87	0.01	65.41	0.01	64.9	0.01
637.9	0.1	650.7	0.11	653.47	0.15
1495.06	0.5	1511.08	0.52	1499.51	0.5
1983.6	0.76	2018.21	0.75	2002.28	0.8
2612.59	1.01	2644.29	1	2650.49	1.1
4584.54	1.55	4608.74	1.5	4598.28	1.51
6787.4	1.98	6821.89	2.01	6811.29	2
8181.74	2.22	8207.56	2.2	8180.47	2.29
9993.36	2.52	10024.46	2.6	10030.87	2.55
12692.97	2.99	12705.22	3	12721.96	2.95
15019.85	3.33	15200.9	3.35	15128.74	3.4
17142.54	3.71	17183.44	3.7	17141.68	3.7
19371.43	4.01	19397.68	4.05	19418.76	4.1
21342.7	4.31	21388.55	4.33	21397.52	4.3
22499.97	4.55	22536.7	4.5	22525.88	4.8
25035.82	4.9	25077.19	5	25083.48	5.01
26180.07	5.08	26227.5	5.1	26230.47	5.2
27734.06	5.4	27755.78	5.44	27809.39	5.5
27881.38	5.55	27912.43	5.6	27920.88	5.68
27750.51	6.07	27779.8	6.15	27801.11	6.11
27823.82	6.44	27841.17	6.4	27833.75	6.5
28063.63	6.95	28086.22	6.9	28109.59	6.99
28212.32	7.25	28225.47	7.22	28244.9	7.21
28408.28	7.6	28419.56	7.63	28458.49	7.7
28522.71	7.82	28613.28	7.85	28606.15	7.91

Table 10.4 Conventional material Load vs. Displacement values

Graph Results for Conventional material:



Graph 10. 3 Load vs Displacement Conventional material



Graph 10. 4 Stress vs. Strain Conventional Material

Results of this test:

The tensile strength of Ti6Al4V produced using conventional manufacturing techniques, will be greater than that of components created using additive manufacturing techniques, LMD (Laser Metal Deposition). This is due to the fact that traditional production techniques frequently produce a more uniform microstructure and fewer flaws or imperfections, which can result in greater strength and better mechanical qualities. The Scanning Electron Microscopy test proves this result by analysing the microstructure. Due to layer-by-layer manufacturing of the material, it creates a void or gap between the bonds and makes it low potential for use. Contrarily, the procedures used in additive manufacturing have the potential to produce a number of flaws, including porosity and residual stresses, which could impair the material qualities.

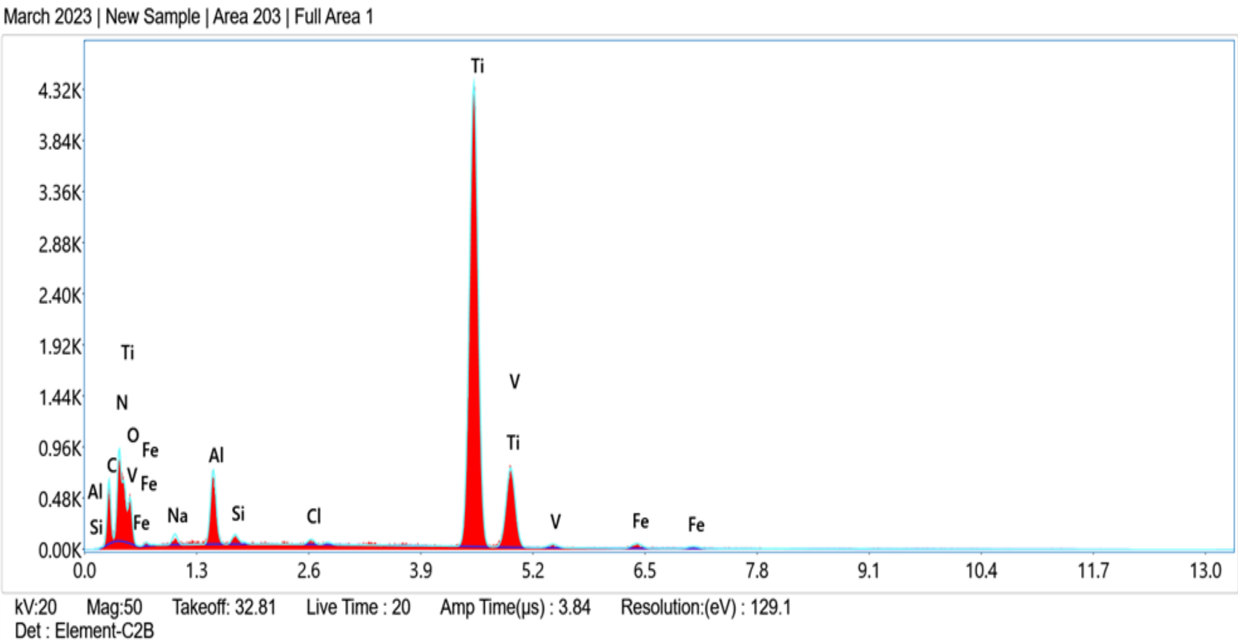
CHAPTER 11 - SCANNING ELECTRON MICROSCOPY ANALYSIS (SEM)

Working:

SEM analysis is a potent tool used in both traditional and additive manufacturing processes to evaluate the microstructure and surface morphology of materials. SEM examination can disclose crucial details about a material's microstructure and spot flaws or faults that could affect the material's qualities in conventional manufacturing processes. SEM examination can shed light on the distinctive microstructure and surface morphology of materials produced through additive manufacturing by revealing how the method was used to create them. These details can be used to assess the material's characteristics, such as its ductility and strength. The impact of elements like porosity, layering, and thermal gradients on the material's properties can also be determined with the aid of SEM examination.

A high-energy electron beam is used in SEM analysis to bombard a prepared sample. This produces secondary electrons and other signals, which are gathered by detectors and transformed into images that are presented on a monitor. The material's microstructure, surface morphology, and any flaws or blemishes can subsequently be assessed using the photographs. To examine the material's elemental makeup, further methods can be applied, such as energy dispersive spectroscopy (EDS).

Conventional Ti6Al4V SEM analysis results:



Graph 11. 1 Conventional EDS analysis graph

Element	Weight %	Atomic %	Error %	Net Int.	R	A	F
C K	12.84	26.69	12.69	157.18	0.8624	0.0914	1.0000
N K	8.02	14.30	14.00	116.24	0.8697	0.1064	1.0000
O K	14.70	22.95	14.85	103.28	0.8757	0.0412	1.0000
Na K	1.28	1.39	17.48	33.38	0.8912	0.1875	1.0037
Al K	4.15	3.84	8.56	275.08	0.9005	0.4328	1.0100
Si K	0.48	0.42	16.20	37.66	0.9049	0.5325	1.0164
Cl K	0.30	0.21	27.87	23.56	0.9167	0.8022	1.0684
Ti K	54.01	28.17	2.16	2666.76	0.9344	0.9538	1.0166
V K	3.08	1.51	6.99	127.07	0.9377	0.9499	1.0204
Fe K	1.14	0.51	14.59	32.10	0.9476	0.9084	1.0358

Table 11.1 Conventional SEM analysis results

SEM analysis Conventional Ti6Al4V images:

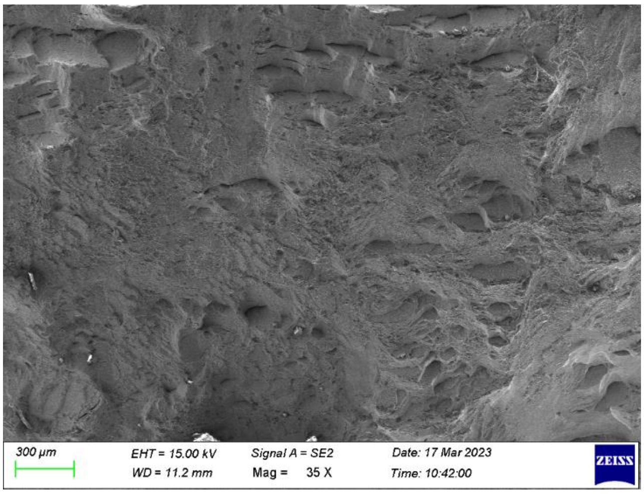


Figure 11. 1 Conventional SEM 300 micro metre

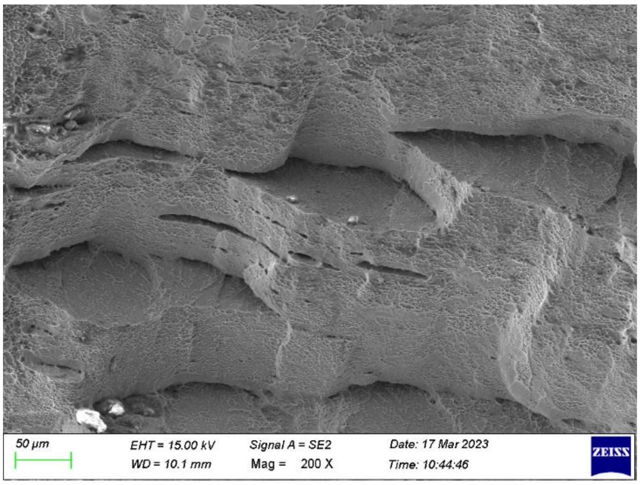


Figure 11. 2 Conventional SEM 100 micro metre

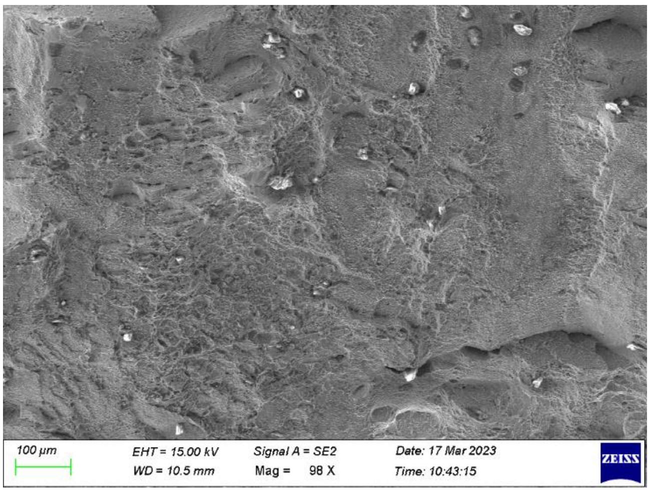


Figure 11. 3 Conventional SEM 50 micro metre

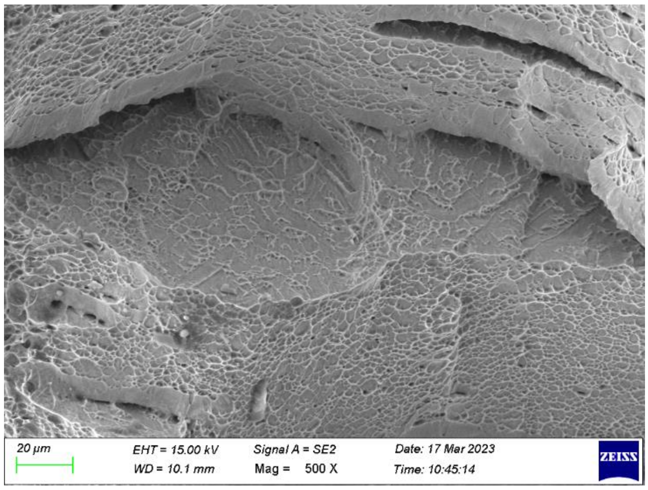


Figure 11. 4 Conventional SEM 40 micro metre

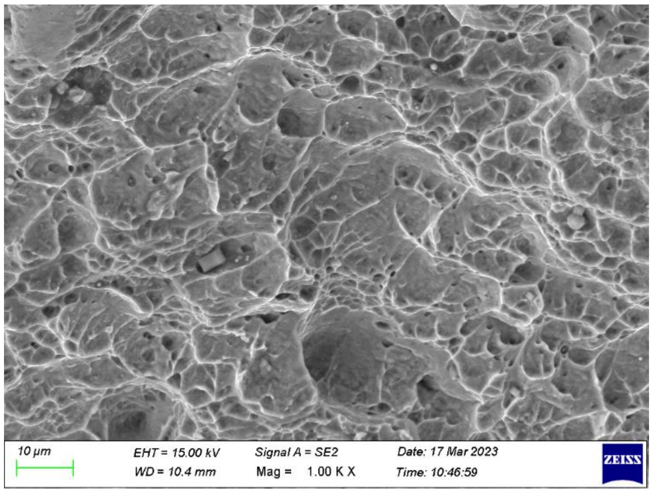


Figure 11. 5 Conventional SEM 10 micro metre

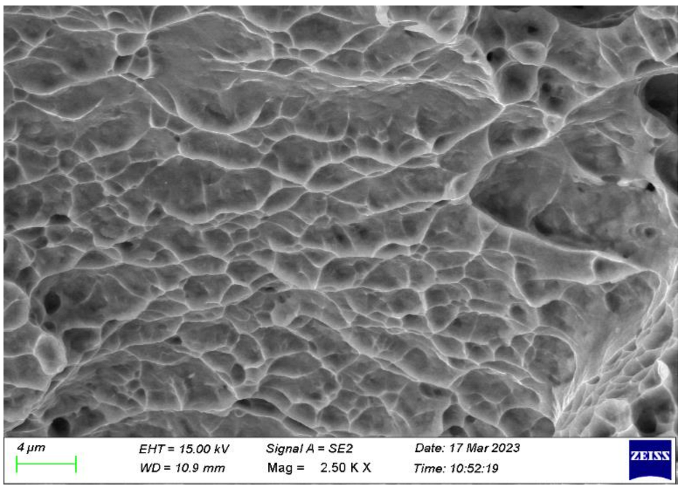
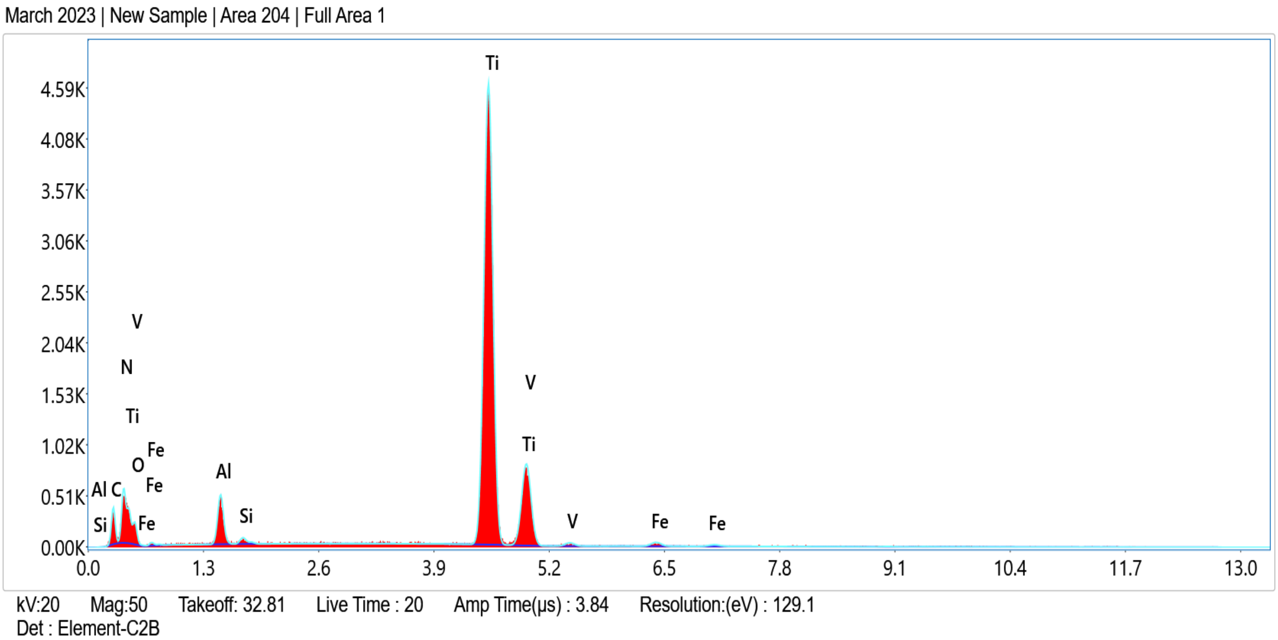


Figure 11. 6 Conventional SEM 4 micro metre

Additive (LMD) Ti6Al4V SEM analysis results:



Graph 11. 2 Additive (LMD) EDS analysis graph

Element	Weight %	Atomic %	Error %	Net Int.	R	A	F
C K	9.34	23.58	13.21	96.62	0.8443	0.0930	1.0000
N K	6.58	14.24	14.02	91.51	0.8519	0.1230	1.0000
O K	5.69	10.79	21.40	28.52	0.8582	0.0353	1.0000
Al K	3.68	4.14	9.05	195.19	0.8849	0.4155	1.0112
Si K	0.41	0.44	16.54	26.20	0.8896	0.5190	1.0185
Ti K	68.96	43.69	2.17	2827.49	0.9222	0.9510	1.0154
V K	4.17	2.48	6.45	142.19	0.9259	0.9439	1.0187
Fe K	1.18	0.64	18.48	27.10	0.9372	0.8865	1.0331

Table 11.2 Additive (LMD) SEM analysis results

SEM analysis Additive (LMD) Ti6Al4V images:

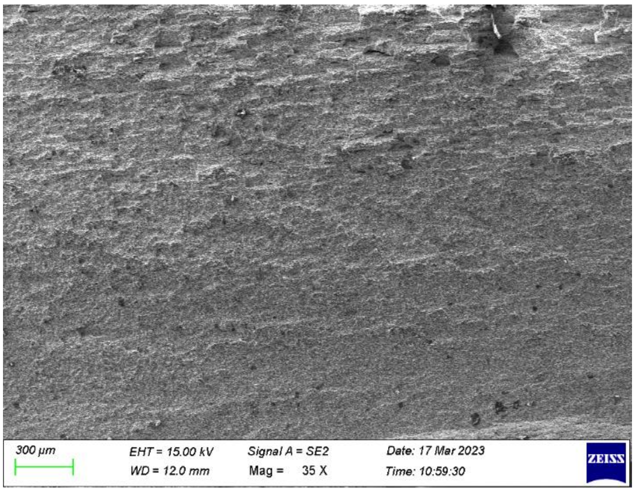


Figure 11. 7 Additive LMD SEM 300 micro meter

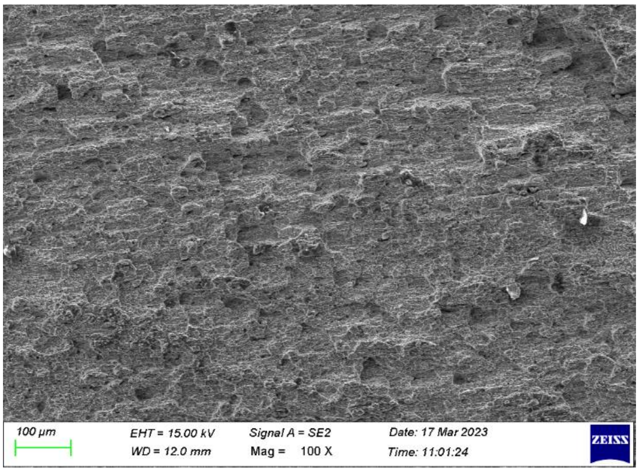


Figure 11. 8 Additive LMD SEM 100 micro meter

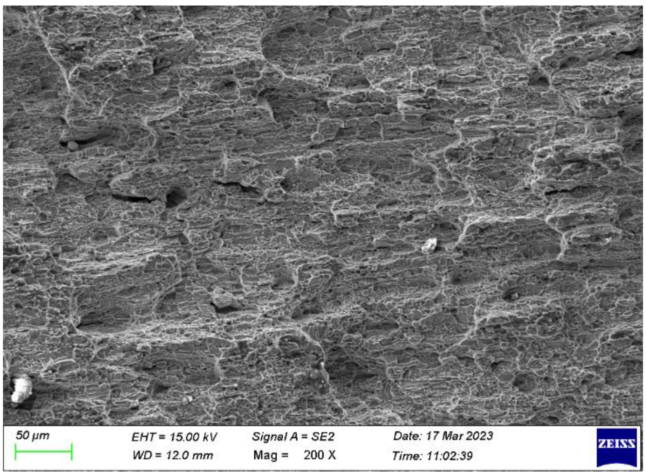


Figure 11. 9 Additive LMD SEM 50 micro meter

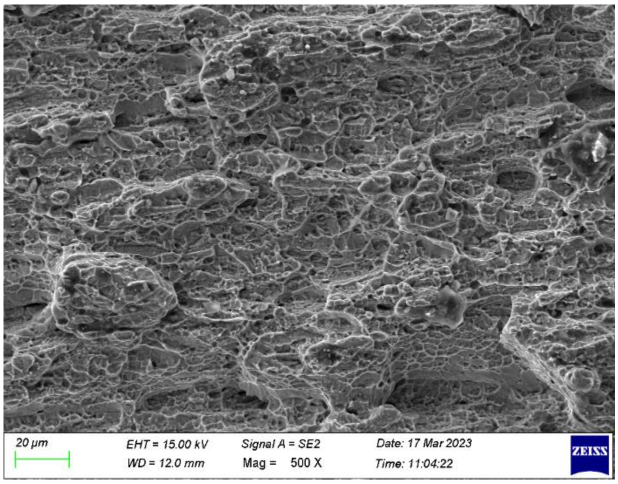


Figure 11. 10 Additive LMD SEM 20 micro meter

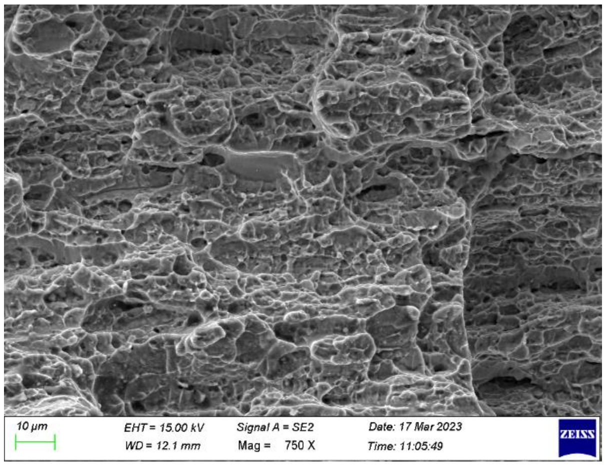


Figure 11. 11 Additive LMD SEM 10 micro meter

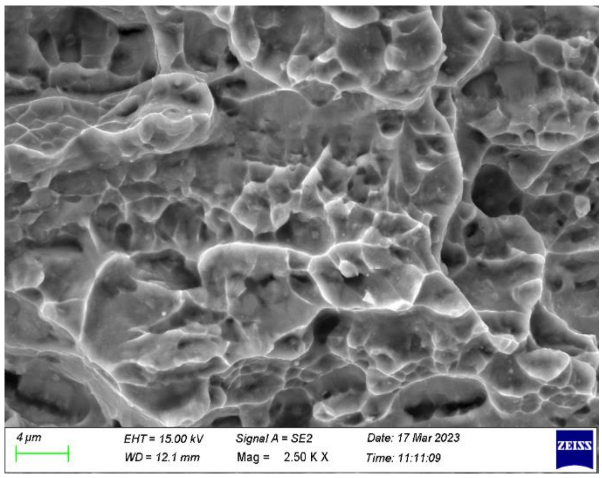


Figure 11. 12 Additive LMD SEM 4 micro meter

Results of this test:

Ti6Al4V materials have distinctive surface morphologies and microstructures, making SEM analysis a useful method for analysing the characteristics of both kinds of materials. SEM examination can reveal details about the material microstructure and reveal any flaws or inconsistencies in conventional manufacture. SEM analysis in additive manufacturing can show the distinctive microstructure that results from the particular additive manufacturing process that was utilised. To compare, in conventional SEM analysis the material shows very less flaws and pores in the material microstructure. Whereas, the additively manufactured material shows its grain structure and flaws in the layers, it is because of the layer-by-layer manufacturing process leaves improper bind and creates a void among the layers. In this case, the conventional part shows a smoother surface with fewer pores or voids than the additively manufactured part.

CHAPTER 12- X- RAY DIFFRACTION ANALYSIS (XRD)

In XRD analysis, a sample is exposed to an X-ray beam, and the diffraction pattern that results from the X-rays' interactions with the sample's atoms is measured. By comparing the diffraction pattern to recognised standards, it is possible to determine the material's crystal structure and phase composition. XRD analysis can be used in conventional production to determine the crystal structure and phases present in a material, giving crucial details about its qualities. For instance, XRD can be used to detect the existence of undesired phases such brittle inter-metallics or to determine how heat treatment has changed the characteristics of the material. XRD can be used in additive manufacturing to determine a material's distinct crystal structure and phase composition.

How the test is done:

An X-ray diffractometer, which emits an X-ray beam at the sample held in the sample holder, is used to do XRD analysis. A diffraction pattern is created as a result of the X-rays' interactions with the material's atoms; this pattern is caught by a detector and analysed by computer software. This method enables the quantification of numerous material properties as well as the identification of the material's crystal structure and phase composition.

Test Parameter used for Conventional XRD analysis:

Scan Axis= Gonio; Spinning = No

Start Position [°2Th.] = 10.0000

End Position [°2Th.] = 80.4800

Step Size [°2Th.] = 0.0400

Scan Step Time [s] = 13.4400

Scan Type = Pre-set time

Offset [°2Th.] = 0.0000

Divergence Slit Type = Fixed

Divergence Slit Size [°] = 10.5000

Specimen Length [mm] = 10.00

Receiving Slit Size [mm] = 0.1000

Measurement Temperature [°C] = 25.00

Anode Material =Cu

K-Alpha1 [Å] =1.54060

K-Alpha2 [Å] = 1.54443

K-Beta [Å]= 1.39225

K-A2 / K-A1 Ratio =0.50000

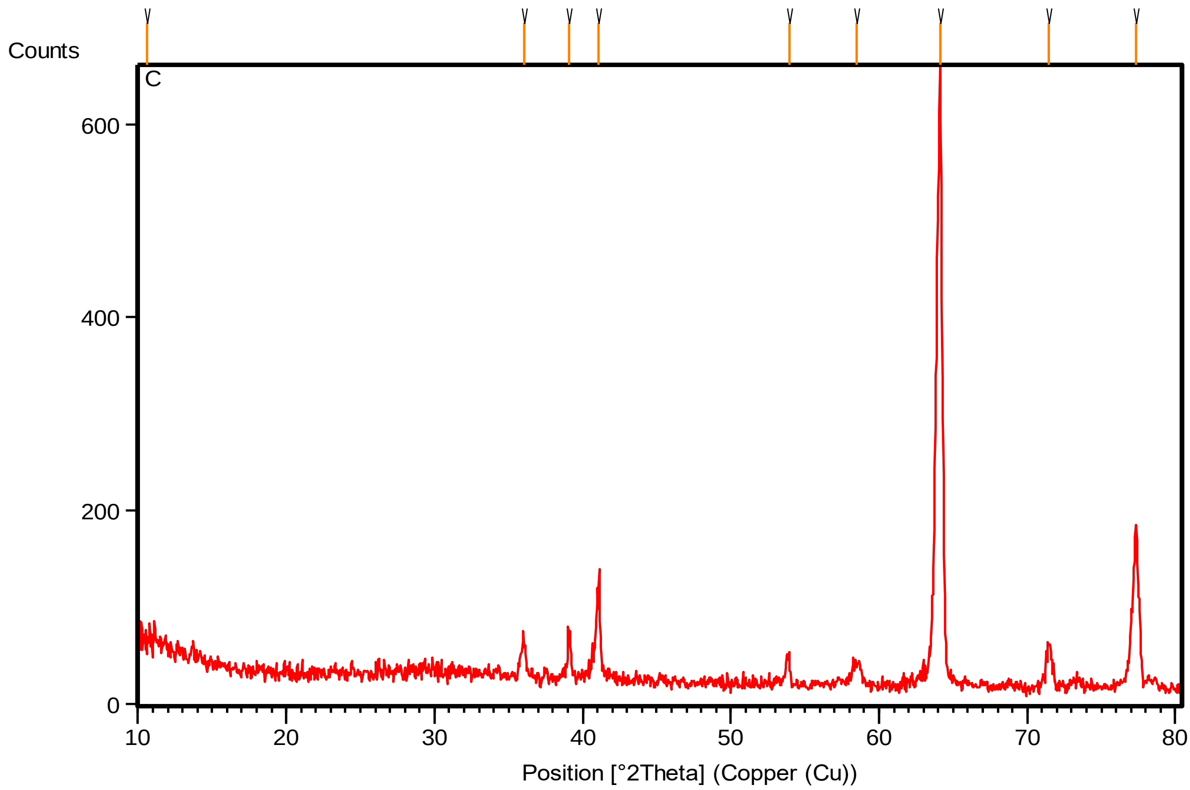
Generator Settings = 30 mA, 40 kV

Diffractometer Type =Theta/Theta; Incident Beam Monochromator = No

Diffractometer Number = 0; Dist. Focus-Diverg. Slit [mm]= 91.00

Goniometer Radius [mm] = 240.00; Dist. Focus-Diverg. Slit [mm]= 91.00.

Conventional Ti6Al4V XRD analysis results:



Graph 12. 1 XRD analysis Conventional material

Pos. [°2Th.]	Height [cts]	FWHM Left [°2Th.]	d-spacing [Å]	Rel. Int. [%]
10.6435	27.62	1.8893	8.31215	4.51
36.0283	35.20	0.2362	2.49291	5.75
39.0953	46.92	0.1968	2.30412	7.66
41.0879	99.49	0.1181	2.19686	16.25
53.9518	17.35	0.2755	1.69954	2.83
58.5068	22.77	0.6298	1.57761	3.72
64.1434	612.16	0.3542	1.45191	100.00
71.4567	44.24	0.3149	1.32023	7.23
77.3512	170.18	0.2362	1.23368	27.80

Table 12.1 XRD analysis results Conventional material

Test parameters used for ADM material XRD analysis:

Scan Axis= Gonio; Spinning = No

Start Position [°2Th.] = 10.0000

End Position [°2Th.] = 80.4800

Step Size [°2Th.] = 0.0400

Scan Step Time [s] = 13.4400

Scan Type = Pre-set time

Offset [°2Th.] = 0.0000

Divergence Slit Type = Fixed

Divergence Slit Size [°] = 10.5000

Specimen Length [mm] = 10.00

Receiving Slit Size [mm] = 0.1000

Measurement Temperature [°C] = 25.00

Anode Material =Cu

K-Alpha1 [Å] =1.54060

K-Alpha2 [Å] = 1.54443

K-Beta [Å]= 1.39225

K-A2 / K-A1 Ratio =0.50000

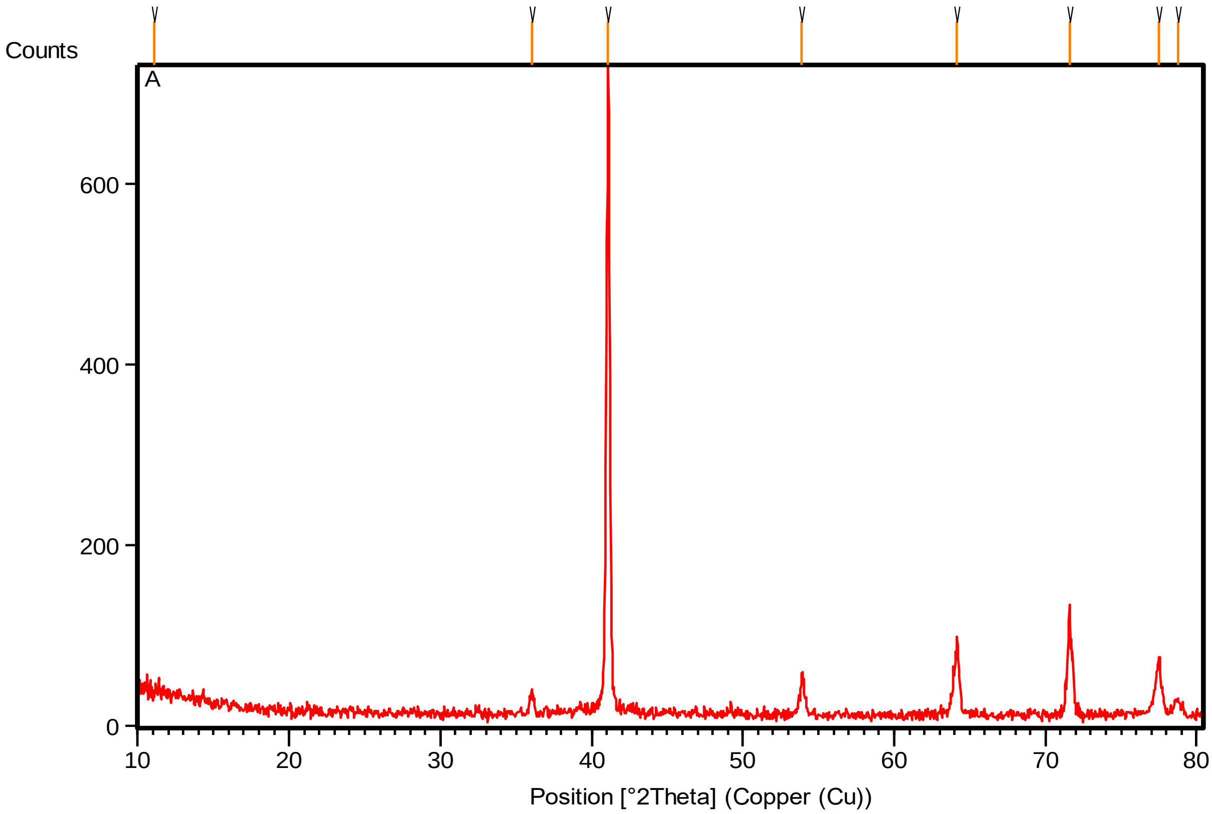
Generator Settings = 30 mA, 40 kV

Diffractometer Type =Theta/Theta; Incident Beam Monochromator = No

Diffractometer Number = 0; Dist. Focus-Diverg. Slit [mm]= 91.00

Goniometer Radius [mm] = 240.00; Dist. Focus-Diverg. Slit [mm]= 91.00.

Additive manufactured (LMD) Ti6Al4V XRD analysis results:



Graph 12. 2 XRD analysis Additive (LMD) material

Pos. [°2Th.]	Height [cts]	FWHM Left [°2Th.]	d-spacing [Å]	Rel. Int. [%]
11.0542	15.02	3.1488	8.00423	2.13
36.0614	27.06	0.3149	2.49070	3.84
41.1026	703.83	0.2755	2.19612	100.00
53.9131	48.16	0.1574	1.70067	6.84
64.1696	88.30	0.1574	1.45138	12.55
71.5824	119.07	0.1181	1.31822	16.92
77.5236	64.39	0.2755	1.23136	9.15
78.7799	16.02	0.4723	1.21485	2.28

Table 12.2 XRD analysis results Additive (LMD) material

Results of this test:

The XRD analysis determines the crystalline structure of the material and shows that the conventional Ti6Al4V material has a more well-defined crystal structure, while the additive manufactured LMD Ti6Al4V material shows more broad peaks, indicating a possible amorphous phase. However, the XRD results alone cannot determine the superiority of one material over the other, and further analysis is needed to determine the mechanical properties.

CHAPTER 13- RESULTS AND DISCUSSION

Vickers hardness test, tensile test, SEM analysis, and XRD analysis are the four tests discussed for examining the properties of conventional and additive-manufactured Ti6Al4V materials.

The findings of this study suggest that additive-manufactured Titanium Grade 5 using laser metal deposition can offer improved mechanical properties and microstructure over conventionally manufactured material. This has significant implications for the aerospace and medical industries, where the adoption of additive manufacturing can result in reduced material waste and increased manufacturing efficiency.

In the Vickers hardness test, we found that when compared to Ti6Al4V produced conventionally, the additive manufacturing LMD has even higher hardness values. This is due to the layer-by-layer deposition process and the ability of LMD to create a fine microstructure with few residual stresses and imperfections, which raises the hardness values. The process also increases the amounts of alloying elements that are present in LMD Ti6Al4V.

In the tensile test, we found that the tensile strength of Ti6Al4V produced using conventional manufacturing techniques, will be greater than that of components created using additive manufacturing techniques, LMD (Laser Metal Deposition). This is because traditional production techniques frequently produce a more uniform microstructure and fewer flaws or imperfections, which can result in greater strength and better mechanical qualities. The Scanning Electron Microscopy test proves this result by analyzing the microstructure. Due to layer-by-layer manufacturing of the material, it creates a void or gap between the bonds and makes it low potential for use.

In SEM analysis we found that in conventional SEM analysis, the material shows very less flaws and pores in the material microstructure. Whereas the additively manufactured material shows its grain structure and flaws in the layers, it is because the layer-by-layer manufacturing process leaves improper binding and creates a void among the layers. In this case, the conventional part shows a smoother surface with fewer pores or voids than the additively manufactured part.

In XRD analysis we found that, The XRD analysis determines the crystalline structure of the material and shows that the conventional Ti6Al4V material has a more well-defined crystal structure, while the additive manufactured LMD Ti6Al4V material shows more broad peaks, indicating a possible amorphous phase.

In the future, even further developments are to be made to find out the possible usage of additively manufactured material for wide usage. To be brief, further optimization of specimen preparation techniques to reduce surface artifacts and improve results accuracy and reproducibility. Integration of advanced imaging and spectroscopic techniques, to provide more detailed information about the material microstructure and chemical composition.

The effect of various processing parameters such as laser power, scanning speed, and powder feed rate on the microstructure and mechanical properties of the materials, can aid in optimizing the additive manufacturing process and improving the final product's quality and performance.

CHAPTER 14-CONCLUSION

A thorough examination of the microstructure, mechanical properties, and crystal structure of conventional and additively manufactured Ti6Al4V materials revealed significant differences. When compared to the additive-manufactured LMD material, the conventional material had a finer microstructure, lower Vickers hardness, and higher tensile strength. And the LMD manufactured material had a very fine structure with higher Vickers hardness and lower tensile strength. These findings could be attributed to various manufacturing processes and emphasize the importance of proper specimen preparation in material characterization. The SEM and XRD analysis helped us to look into the microstructural changes and the grain structure of both of the materials. The study findings may be useful in the design and selection of materials for a variety of engineering applications. Future research could look into the effect of different process parameters on the microstructure and properties of the material. According to the test results, the additively made titanium (LMD Ti6Al4V) has shown excellent potential for use in areas like aerospace and biomedicine where corrosion resistance is a crucial need. Further developments and possible tests and upgrades could be in the future.

CHAPTER 15- REFERENCES

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