The Effect of Laser Power and Scan Speed on Melt Pool Characteristics of Pure Titanium and Ti-6Al-4V alloy for Selective Laser Melting

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering

By

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I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY Chandrakanth Kusuma ENTITLED The Effect of Laser Power and Scan Speed on Melt Pool Characteristics of Pure Titanium and Ti-6Al-4V alloy for Selective Laser Melting BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF Master of Science in Mechanical Engineering.

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ABSTRACT

Chandrakanth Kusuma. M.S.M.E., Department of Mechanical and Materials Engineering, Wright State University, 2016. The Effect of Laser Power and Scan Speed on Melt Pool Characteristics of Pure Titanium and Ti-6Al-4V alloy for Selective Laser Melting

Selective Laser Melting (SLM) is an additive manufacturing (AM) technique that creates complex parts by selectively melting metal powder layer-by-layer. In SLM, the process parameters decide the quality of the fabricated component. In this study, single beads of commercially pure titanium (CP-Ti) and Ti-6Al-4V alloy are melted on a substrate of the same material as powder using an in-house built SLM machine. Multiple combinations of laser power and scan speed are used for single bead fabrication while the laser beam diameter and powder layer thickness are kept constant. This experimental study investigates the influence of laser power, scan speed and laser energy density on the melt pool formation, surface morphology, geometry (width, depth, and height) and hardness of melt pools. The results show that the quality, geometry, and hardness of melt pool is significantly affected by laser power, scanning speed and laser energy density. In addition, the observed unfavorable effects such as inconsistent melt pool formation, balling, porosity are discussed in detail. At the end, suggestions are provided to use optimal parameters to avoid such unfavorable effects.
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Dedicated to my family
CHAPTER 1

INTRODUCTION

1.1 Overview

This chapter presents the theory and introduction to additive manufacturing (AM) and selective laser melting (SLM) to understand the work performed in this thesis. This chapter starts with a discussion on different manufacturing processes, followed by the detailed explanation of AM with its advantages and applications. Moreover, an elaborate discussion on SLM and its process parameters is also included.

1.2 Manufacturing Processes

Manufacturing is the backbone of all industrialized nations. Manufacturing and technical staff in the industry must know various manufacturing processes, materials being processed, tools and equipment to manufacture different products or components with optimal process plan, using proper safety rules and precautions specified to avoid accidents. Manufacturing is derived from the Latin word ‘manufactus’, means “made by hand.” The manufacturing process can be defined as “making industrially useful products from raw material by using the sequence of
processes, hand tools, machinery or even computers”. The process starts with the design aspects, followed by the series of manufacturing processes, like solidification, deformation, machining (metal removal), surface treatment, heat treatment, etc., and also involves the tests and investigations required for the purpose of quality assurance [1, 2]. The manufacturing processes can be classified into two categories:

1. Subtractive (conventional/traditional) manufacturing process.
2. Additive manufacturing process (AM)/3D printing.

![Subtractive Manufacturing and Additive Manufacturing](image)

Figure 1.1: The schematic illustration shows the main difference between additive manufacturing and subtractive (conventional) manufacturing [3].

1.2.1 Subtractive (Conventional or Traditional) Manufacturing Process

The subtractive (conventional/traditional) manufacturing process can be defined as a “process of removing undesired or excess material from the raw material to form a product with desired shape and size”. Examples are cutting, drilling, reaming, machining, turning and grinding, etc. This process involves significant material wastage, and this wastage may lead to environmental issues. In addition,
subtractive manufacturing process requires highly skilled operators, which may result in high production costs [2].

### 1.2.2 Additive Manufacturing Process/3D Printing

ASTM defines additive manufacturing (AM) as the “process of building three-dimensional objects by joining material layer-by-layer based on a CAD model, which is saved as a standard tessellation language (.STL) file”. .STL is a triangulated representation of the model and defines the shape and size of the component in the AM process. The fine triangulation results in good quality product. The software slices the data file into individual layers, which are sent as instructions to the AM device, in which the building process takes place [5].

![Triangulation](image)

Figure 1.2: Triangulation: (a) Course triangulation, (b) Fine triangulation, and (c) 3D model slicing into layers.

AM techniques require minimal or no tooling and use the material as powder form (except for fused deposition modeling (FDM), which uses the material as wire form). Once the part is built, a variety of finishing activities like sanding, polishing, filing, curing, metal fill, or painting may be required depending on the material type.
and the complexity of the object. This process does not require predetermined tool paths such as draft angles and undercuts [5].

1.2.3 Development History of Additive Manufacturing Technology

The additive manufacturing (AM) serves as a term for technologies that use the CAD based layer upon layer manufacturing process to build parts, which can be directly used as end-use products. So AM is also called digital manufacturing, solid freeform fabrication or direct manufacturing and recently, the term “3D printing” has been used to describe the AM technology. This technology is broadly utilized in the news media, which is hopefully taking into account as the driver of a “third industrial revolution” since it has the potential to revolutionize the way we make everything [6].

Before the use of nomenclature “additive manufacturing (AM)”, rapid prototyping (RP) and rapid manufacturing (RM) are two widely recognized nomenclatures for the description of AM technology. A series of processes for RP was established primarily in the historical subsequence. Then significant research efforts proved that some of these processes could also be used for manufacturing, especially for small runs. So that, “rapid prototyping” was combined with “manufacturing” to give nomenclature “rapid manufacturing”. When compared to the phrases RP and RM, AM is considered as a general designation, which reflects the processing strategy of this advanced manufacturing technology [7].
Since the first technique for AM became available in the late 1980s and was used to fabricate models and prototypes, AM technology has the development of more than 20 years and now present it is one of the rapidly developing advanced manufacturing techniques in the world. Contrary to the material removal method in traditional or conventional machining processes, AM is material incremental manufacturing (MIM) that uses materials involving liquid, powder, and wire, etc. AM involves layer-by-layer shaping and consolidation of feedstock to random configurations. A wide-ranging feedstock can be applied to AM technology, from the low melting point polymer materials like acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA) to the high melting point metals like titanium, steel and ceramics. The initially developed AM techniques include stereolithography apparatus (SLA), laminated object manufacturing (LOM), fused deposition modeling (FDM), and selective laser sintering (SLS). These mentioned AM processes are usually applied for the fabrication of prototypes made from low melting point polymers as inspection or communication tools. The ability to produce physical objects in a short period directly from CAD models helps to reduce the production development steps [7, 8].

In 1994, the first European laser sintering system to manufacture plastic prototypes, i.e., the EOS machine EOSINT P350 was launched by EOS GmbH Electro Optical Systems. The EOSINT M 250 direct metal laser sintering (DMLS) system for AM of metal tools for plastics injection molding was launched in 1995. In 2004, EOS GmbH picked up the right to all the relevant patents of DTM, University of Texas and 3D Systems related to laser sintering [7, 9].
In 1995, selective laser melting (SLM) started at the Institute for Laser Technology (ILT), Aachen, Germany. Dr. Matthias Fockele and Dr. Dieter Schwarze from the Fockele & Schwarze (F&S) Stereolithographietechnik GmbH, worked together with the ILT researchers Dr. Konrad Wissenbach and Dr. Wilhelm Meiners on this technology. In the early 2000s, Fockele & Schwarze come into a commercial partnership with MCP HEK GmbH Germany. In 2007, MCP HEK Tooling GmbH was initiated to promote SLM technology. In 2008, MCP became MTT Technologies group to support the approach in AM. It was renamed into SLM Solutions GmbH in 2010 [7, 10-11].

The similar and parallel development was going on at the Westinghouse Electric Corporation in a patent application in 1988 and the middle of the 1990s by Sandia National Laboratories. AeroMet was founded as a subsidiary of MTS Systems Corporation in 1997. This company developed laser additive manufacturing (LAM) that used powdered titanium alloys and a high-power laser. AeroMet manufactured objects for the aerospace industry as a service provider until it shut down in December 2005. In 1997, based on the laser engineering net shaping (LENS) technology developed at Sandia National Laboratories, Optomec introduced its first commercial AM system. Optomec has now installed systems at 150 customer sites in 15 countries [7, 12].

1.2.4 Advantages and Benefits of Additive Manufacturing Technology

Additive manufacturing (AM) and traditional (conventional) manufacturing face different trade-offs, with each process likely to play a significant role in the
deployment of manufacturing capabilities. AM technology has the potential to accelerate innovation, compress supply chains, minimize materials and energy usage, and reduce waste. The significant advantages and benefits of AM technology are highlighted as follows [4, 13-17]:

- **Waste Reduction:** AM is a more efficient process as it uses the less extraneous material to manufacture parts, thus significantly reducing or eliminating waste and scrap during production as shown in the Figure 1.3.

![Conventional/subtractive manufacturing process](image)

![Additive manufacturing process](image)

Figure 1.3: Material wastage in conventional and additive manufacturing [18].

- **Lower Energy Consumption:** AM technology reduces production steps by using substantially less material and saves energy.
• **Environment-friendly:** AM is an environment-friendly process and energy efficient process as it involves minimal wastage of materials during production.

• **No Assembly is required:** AM prints moving parts such as bicycle chains and hinges directly into the product, which can reduce the effort of assembly.

![Breakeven Analysis](image)

Figure 1.4: Breakeven analysis compares conventional and additive manufacturing [16].

• **The Speed of Production and Market:** Without using molds and dies, the AM technology allows the manufacturer to build prototypes and parts on demand and
save time during product design, development, and enabling on-demand manufacturing and use little or no tooling.

- **Cost Saving:** Since no highly skilled operators, molds, dies and tools required, results in a reduced production cost. Additionally, AM allows for real-time visibility of production, which further increases time and cost savings for the part and original equipment manufacturer.

- **Design Freedom:** The AM technology brings the design innovation to the forefront. In AM, the design process has an extra degree of freedom and the design changes can be easily modified at any time with minimum or no additional costs, is the ultimate advantage of AM over conventional manufacturing.

- **Design Complexity:** The objects with complexity in design, which are difficult or impossible to manufacture using traditional methods can be easily build using AM techniques.

### 1.2.5 Applications of Additive Manufacturing Technology

The following review is on AM applications in different fields such as aerospace, automobile, biomedical, electrical and other energy fields.

- **Aerospace Industry:** Usually, aerospace components have complex geometries and are made from advanced materials, such as nickel superalloys, titanium alloys, special steels or ultrahigh-temperature ceramics, which are costly, time-consuming and difficult to manufacture. Most of the industrial applications lie in
the production of jet engines, rib web structural components, turbine engine cases, engine blades, vanes, etc [17].

Figure 1.5: Aerospace elements manufactured by AM technology [19]: (a) Turbine blade, and (b) Blade integrated.

Figure 1.6: Aerospace elements manufactured by AM technology: (a) The flight crew rest compartment bracket [20], and (b) Engine housing produced by SLM [17].

- **Automotive Industry**: New product developments are critical for the automotive industry and developing new products are often a very costly and time-consuming process. The automotive industry has been using AM technology as an essential
tool in the design and development of automotive components and structural and functional parts, such as drive shafts, gearbox components, engine exhausts, pistons, wheels and drive shafts for vehicles [17].

![Automotive elements manufactured by AM technology](image)

**Figure 1.7:** Automotive elements manufactured by AM technology [17]: (a) Oil pump housing produced by electron beam melting (EBM), (b) Race car gearbox produced by EBM, and (c) Exhaust manifold produced by SLM.

- **Biomedical Applications:**

![Biomedical parts manufactured by AM technologies](image)

**Figure 1.8:** Biomedical parts manufactured by AM technologies: (a) Dental prosthesis built using SLM, (b) Hip stems fabricated using EBM, and (c) 3-unit dental bridge produced using SLM [17].

AM comes as a life-saving process in the medical sector. Recent developments in biomaterials, biomedicine, and biologic sciences have expanded
the application of AM techniques in the biomedical field to such products substantially as orthopedic implants, dental applications, artificial organs, tissue scaffolds, medical devices, artificial bladders, bio-printing, painted organs, microvasculature networks and biologic chips [12].

- **Electronics Industry:** Electronics industry covers applications from mobile phones and computers to cars. Electronics products are often small in size and requires highly precision tools for the manufacturing process. The production of embedded electronics represents another field of application. Furthermore, AM is already used for products such as Embedding Radio Frequency Identification (RFID) devices inside metallic objects, polymer based 3D microelectromechanical systems, microwave circuits and all kind of grippers [23].

![Figure 1.9: An operating circuit built by fused deposition method (FDM) [24].](image)

- **AM in Art:** AM technologies are a very powerful tool for the artist in the fashion, and furniture gave the possibility of virtually producing the most complex form
imaginable. Some companies can build furnishing complements and accessories including clothes using AM [21].

![Art products built by AM technologies](image)

**Figure 1-10**: Art products built by AM technologies [22].

### 1.2.6 Steps involved in Additive Manufacturing

![Additive manufacturing process flow](image)

**Figure 1.11**: Additive manufacturing process flow [25].
Additive manufacturing includes a number of steps that move from the basic CAD description to the resultant physical part as shown in the Figure 1.11. Small, relatively simple products only use AM for visualization models, while larger, more complex products with more engineering content involves AM during several stages and iterations throughout the development process. In general, a typical AM process involves the following steps [5, 7]:

- **Create CAD Model:** The general AM process starts with 3D CAD information. Firstly, the part to be built is modeled using any professional CAD solid software. Generally, a solid modeling (a solid modeler) can represent three-dimensional objects more accurately than a wire-frame model, thereby yielding better design results. The designer can use a preexisting CAD file or create one subjectively for prototyping purposes.

- **Convert CAD Model to STL Format:** The second step is to convert the CAD file into STL format. The different CAD software packages use some different algorithms to represent solid objects. However, the STL (stereolithography, known as the primarily developed AM technique) format has been adopted as the standard for the AM industry to maintain the consistency. The STL file is a triangular representation of a three-dimensional surface geometry. In the software, the surface of the part is tessellated logically into a set of oriented triangles, i.e., facets. Large and complex structures require more time to preprocess and build than simple ones. So to produce a useful STL file, the designer must balance accuracy with manageability. As the STL file format is universal, this process is similar for all of the AM technique.
• **Slice the STL File into Layers of Thin Cross-section:** In the third step, the STL file to be built will be prepared by a preprocessing program. There are several programs, which allow the user to adjust the orientation, size, and location of the model. Build orientation is necessary for several reasons. The properties of prototypes made by AM vary from one coordinate direction to another. For instance, AM-processed prototypes are usually less accurate and weaker in the Z (vertical) direction than in the X–Y (horizontal) plane.

Sometimes, part orientation determines the amount of time required to build the model. Printing the object by placing the shortest dimension in the Z direction reduces the number of layers, hopefully shortening the whole building time. The preprocessing software logically slices the STL model into a number of layers with the thickness from several µm to several hundred µm, based on the build technique. The software may also generate an auxiliary structure to support the model during the model building. Supports are useful for delicate parts of the object such as overhangs, thin-walled sections, and internal cavities.

• **Construct the Object Layer-by-layer Manner:** The fourth step is the actual construction of the part using a fixed AM process. The AM machine builds one layer at a time, typically from metal, ceramic, polymer, alloy, or composite powders. The 3D object is then created by the layer-by-layer consolidation of the deposited material layers. Each shaped layer represents a cross-section of the sliced CAD model.
Post Processing of the Part: The final step is the post-processing, which typically involves removing the prototype from the machine and eliminating the supports. Sometimes, prototypes may also require cleaning and surface treatment. Sanding, sealing, and painting the part are expected to improve its appearance and durability. For the metallic parts for the practical engineering applications, post-processing treatment such as furnace post-sintering, hot isostatic pressing (HIP), or secondary infiltration with a low-melting-point material is sometimes necessary to obtain the desired densification level and mechanical properties.

1.2.7 Classification of Additive Manufacturing (AM) Processes

![AM Technology Flowchart]

Figure 1.12: Detailed flowchart showing the classification of the additive manufacturing processes based on four major groups.
The AM processes can be classified into four different categories based on the technology used, the deposition mechanisms involved, the materials processed, and on the source of energy used during manufacturing (Figure 1.12). The various AM technologies use different processing techniques for the production of the parts/objects. For example, the fused deposition modeling technology (FDM) uses the extrusion process, whereas selective laser melting (SLM) uses melting. In addition, different types of energy sources are used in AM for a different type of technology. For example, a laser beam is used in both SLM, and Selective Laser Sintering (SLS), Digital Light Processing (DLP) uses ultraviolet radiation, ultrasonic waves are used in Ultrasonic Consolidation (UC), and an electron beam is utilized in Electron Beam Melting (EBM) process. In this study, selective laser melting (SLM) is used to melt single beads on the substrate.

1.3 Selective Laser Melting (SLM)

Selective laser melting (SLM) is one of the new additive manufacturing (AM) techniques that emerged in the late 1980s and 1990s and continuously developing through vigorous in-house and university-based research [27]. This process starts by slicing the 3D CAD file data, which is in .STL format, into layers and creating a 2D image of each layer. This sliced data file is then sent to preparation software package. This software assigns parameters, values, and physical supports and allows the file to be built by different types of AM machines [7].
Figure 1.13: Schematic diagram of Selective Laser Melting (SLM) [29].

Figure 1.14: Selective Laser Melting (SLM): Process flow diagram [30].
In SLM, the part is generated in the build cylinder, on top of a base plate or substrate. Next to the build cylinder, there is a feed container (also called powder depositor). Using the powder depositor, a thin layer of powder (known as layer thickness) metal evenly deposited on top of the metal substrate plate, by lowering the build cylinder and raising the feed container. After a layer deposition, a cross section of the component to be built is scanned with the laser such as Nd:YAG and ytterbium fiber laser, which produces hundreds of watts power. These cross-sections are calculated from a CAD model preparation software that discussed above. By scanning the surface of the powder layer, heat added to the material by absorbing the power. It melts the powder layer, and the molten pool solidifies quickly. The consolidated material starts to build the product. After a single layer is scanned, the building platform is lowered by an amount of layer thickness and a new layer is deposited upon the previous layer using powder depositor. The process will repeat layer after layer until the part is complete as shown in the Figure 1.14. The entire printing process takes place inside a chamber that contains a tightly controlled atmosphere of inert gas, either nitrogen or argon. In some cases, the bed of chamber is preheated. The temperature inside the chamber is uniformly distributed. The support structures also constructed in case of products, which involves a lot of complexity. The commonly used support structures are shown in Figure 1.15. Once the SLM process is complete, the substrate is removed from the build chamber, and the supports and parts are removed. The supports need to be carefully designed because they can be difficult to remove as they are the same dense metallic material as the part [26-28].
Various materials that can be processed include alloy steel, tool steel, bronze, stainless steel, titanium-aluminum, cobalt-chrome. All must exist in fine powder form and exhibit certain flow characteristics to be a process capable. A number of process parameters effects the SLM process and final products are discussed in the following sections.

1.3.1 Process Parameters in SLM

In additive manufacturing technology, many parameters influence the correctness of SLM process (Figures 1.16 and 1.17). By proper analysis of those parameters, one can understand the occurring mechanisms in an appropriate way to design the process. SLM is a complex process where a large number of parameters can influence the quality of the final part. In SLM, the main process parameters are laser power, laser beam diameter/spot size, scan speed, scanning pattern, hatch.
spacing, powder properties, layer thickness and the temperature inside the chamber [19, 31-33]. The various process parameters in different aspects are as follows:

Figure 1.16: Process parameters in SLM process [32].

Figure 1-17: Schematic diagram of SLM process parameters: laser power, scanning speed, hatch spacing, and layer thickness [31].
• **Laser Source:** Selection of the type of laser radiation source in the SLM process plays a key role because different materials have the varied parameters of the energy absorption. That parameter depends on the wavelength of the laser source [33]. The absorption of laser output at various wavelength for different materials is shown in the Figure 1.18.

![Image](image1.png)

Figure 1.18: The absorption of laser output at various wavelengths varies according to the materials involved [33].

• **Spot Diameter/Laser Beam Diameter/Spot Size:** A decrease in spot size will increase the energy density which increases energy absorption and leads to a reduction in the exposure area. The smaller spot size for a given power density allows for increased part definition during laser sintering, but will equally increase the build time during area coverage. An increase in spot size reduces the
energy density, i.e., energy absorption and increases the exposure area, which further leads to un-melted powder [34].

- **Hatch Spacing/Scan Spacing/Hatch distance**: The hatch distance is another important parameter associated with the SLM process. The Figure 1.17 illustrates how an object is made of linear laser tracks. Consider a layer of powder deposited on a substrate plate and the laser is activated to melt the powder selectively. The laser will melt the entire area of the powder in the form of several tracks. The width of the tracks depends on the laser power, the size of the laser beam, and the scanning speed. As shown in Figure 1.17, a single SLM layer consists of several hatches with hatch distance “h”. To have a better quality sample, conditions should be set in such a way that there will be an overlap between two hatches called the hatch overlap Δx. An overlap in the SLM parts is necessary to have continuity between the tracks leading to a solid sample. In most of the SLM processes, an overlap of at least 20% is maintained to have better quality samples [4].

- **Scanning Pattern**: The scanning pattern is another significant parameter in the SLM process. The scanning pattern is defined as the design or pattern in which the hatches are oriented within and between the layers. The scanning pattern can be varied in different ways, and the design depends on the creativity of the user and the specific requirements of the SLM part. Examples of basic hatch styles are shown in the Figure 1.18. These scanning patterns may be repeated every layer with or without the presence of scanning pattern rotations between the layers. The
rotation of the scanning pattern between the layers is carried out to have a better bonding between the layers [4].

![Diagram of different scanning patterns: (a) zigzag, (b) unidirectional, and (c) cross-hatching](image)

**Figure 1.19:** Examples of different scanning patterns: (a) zigzag, (b) unidirectional, and (c) cross-hatching [26].

- **Laser Power, Scan Speed and Energy Density:** Selection of laser power is related to the size of the focused laser spot and determines the choice of other parameters of the process. The quality and the properties of the SLM part need fine parameters tuning to optimize the energy density involved in the process. The laser energy density is a measurement of the averaged applied energy per volume of the material during the scanning of a layer and is a key factor that affects the final part’s quality in the SLM process to quantify energy input. In order to assess the combined effect of laser power (P) and scan speed (v) involved in the individual line scanning, an integrated parameter, i.e., “linear laser energy density” (LED) with a unit of joule/millimeter (J/mm), is defined to estimate the laser energy input to the powder layer being melted [7]:

24
LED = \frac{P}{v} \text{ J/mm}

where \( P \) = laser power (W), \( v \) = scan speed (mm/s).

Furthermore, the processing parameters laser power, scanning speed, hatching space, and layer thickness all have an influence on the densification, microstructural features, and mechanical properties of the final SLM processed three-dimensional parts. To evaluate the combined effect of these parameters and, thus, control the SLM process integrally, another single factor termed “volumetric laser energy density” (VED) with a unit of Joule/millimeter\(^3\) (J/mm\(^3\)) is defined as follows: [7]:

\[
VED = \frac{P}{v \cdot h \cdot t} \text{ J/mm}^3
\]

where \( P \) = laser power (W), \( v \) = scan speed (mm/s), \( h \) = hatch spacing (mm) and \( t \) = layer thickness (mm). The above equations emphasize that the energy density is strongly dependent on the incident laser power, laser scan speed, hatch distance, layer thickness, and laser beam diameter.

The overall effect of increasing power is to allow melting at faster speeds and greater depths of heat penetration. The faster the scan speed, the less time there is for heating and therefore, for a given laser power, less time for the heat to diffuse sideways, causing a narrowing of the melt region and heat affected zone.

- **Powder Size, Shape, and Particle Distribution**: The size, shape and distribution of powder grains play a critical role in SLM process. Particle size distribution is a mathematical function that defines the relative amount of particles (by mass)
according to their size ranges. This property represents a significant powder property - the flowability of the material. The ratio of the larger to smaller particles in the powder can dictate the flowability [35]. In SLM technology, the thickness of layers should be small, and the maximum grain size cannot be greater than the layer thickness. Other factors like humidity and particles shape, can also affect the flowability. The selected powder also must be spherical as the shape determines the possibility of powder processing. In SLM, the powder is deposited by gravity through a system of valves. If the powder is irregular, it will strike in the valves and creation of smooth layer may not be possible [33, 36] (Figure 1.20).

![Figure 1.20: Layer deposition [33]: (a) Spherical powder, and (b) Irregular powder.](image)

The presence of a high volume fraction of small particles helps in reducing the energy required to melt the material and can improve the surface roughness of the SLM parts and layer thickness can be reduced [37]. Mazumder et al. [38] have reported that, with an increase in the layer thickness, the laser beam has to diverge
by a larger distance to form a melt pool. In this case, the thickness of the pool at the bottom will be greater than at the top, which results in an asymmetry in the pool width. This asymmetry can be reduced by reducing the layer thickness, which means by reducing the particle size that helps in reducing the surface roughness of the parts along their sides. In this way, the particle size, as well as the particle size distribution, plays a significant role in the SLM process not only determining the process parameters but also in deciding the final quality of the parts.

- **Powder Density:** The density of the powder is another significant property in SLM process. The density can be classified into two types: the individual particle density and the packing density. The individual particle density is an intrinsic property of the metal or alloy system, whereas the packing density is dependent on the particle morphology and the size and distribution of the particles. The thermal conductivity of a powder bed depends on the number of contact points between the particles. The higher the packing density, the more numerous will be the contact points and the higher will be the heat transfer across the powder layer.

- **Layer Thickness:** A thin layer of powder is an essential requirement for layer manufacturing because the bond required to fuse consecutive layers is often difficult to achieve by the pre-placed powder layer because the underlying solidified layer needs to be remelted to make a strong fusion bond. However, the substrate is not directly irradiated, the degree of remelting will depend on the transmitted energies through the powder layer. Hence, there is general agreement that a smaller layer thickness will increase the bond between layers, resulting in higher density components [40].
• **Temperature:** The temperature inside the building chamber significantly affects the SLM process, and this should be properly set for better results. This temperature selection will depend on the material using in that process. Generally, the higher temperature is better for processing, and it should be uniformly distributed. The properties of metal powder like flowability, creating and melting of powder layers are better with preheated powder.

• **Atmosphere:** The next important thing is the atmosphere in which the process takes place. The high temperature accompanying the SLM process and the presence of oxygen in the chamber lead to oxidation. Incorrectly selected protective atmosphere may cause decarburization and reduction of the hardness of the entire sinter, which has negative effects on mechanical properties such as fatigue strength, ductility, and abrasion resistance. Proper selection of the chemical composition of the atmosphere gives the possibility to combine elements, which are particularly vulnerable to oxidation, such as aluminum, chromium, manganese, titanium, and silicon due to their high affinity for oxygen [41].

During the process, Oxygen, which is located in the chamber, is also responsible for the presence of pores in the final material. When the temperature is lowered in the process of solidification that increases the formation of oxygen and carbon monoxide, which are trapped in the solidifying metal, create gas bubbles. A suitable SLM gas of high purity is to be filled in the chamber to reduce the oxygen content [43]. Nitrogen, argon, and helium are the most commonly used protective gas in SLM processes.
Table 1.1: Ionization potential of different gases [42].

<table>
<thead>
<tr>
<th>Gas</th>
<th>Ionization potential [eV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helium</td>
<td>24.46</td>
</tr>
<tr>
<td>Argon</td>
<td>15.68</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>14.54</td>
</tr>
<tr>
<td>CO₂</td>
<td>14.41</td>
</tr>
<tr>
<td>Water vapor</td>
<td>12.56</td>
</tr>
<tr>
<td>Oxygen</td>
<td>12.50</td>
</tr>
</tbody>
</table>
CHAPTER 2

LITERATURE REVIEW AND MOTIVATION

2.1 Overview

An aim of this literature review is to discuss the previous research on selective laser melting (SLM), in the aspect of different materials such as titanium, steel, copper, gold, silver, tungsten, nickel alloys and aluminum alloys. In addition, the studies related to SLM process parameters are also presented.

2.2 Literature Review

Attar et al. [44] studied the manufacturing of commercially pure titanium (CP-Ti) parts using SLM and powder with a grain size range up to 100 μm. The optimum set of SLM manufacturing parameters was applied and produced nearly full dense (99.5%) parts without any post-treatments. They also conducted experiments for the compressive, tensile strengths and microhardness of SLM-processed CP-Ti parts, compared the results with the properties of those manufactured by conventional/traditional manufacturing technologies and found that the optimum manufacturing parameters improve the hardness and strength of CP-Ti by maintaining the ductility of titanium. Tolosa et al. [45] performed similar studies, using 316
stainless steel powder. They manufactured tensile test specimen with different manufacturing strategies and compared their properties with wrought products. They used a layer thickness of 30 μm and 100 μm, scan speed up to 1,000 mm/s and a laser spot size of 80-300 μm. They found the strength properties after SLM are higher to corresponding properties of this alloy in the rolled condition. Resilience tests (Charpy) results are slightly lower to those specified to wrought products. Hardness tests (Vicker’s) results are homogeneous and similar to those found in wrought products of this alloy. Related to titanium and its alloys, Zhang et al. [46] published a review paper on the recent progress in SLM of Ti alloys and Ti composites for biomedical applications, especially in developing a new titanium powder for SLM. They presented parameters involved in SLM technology as well as unfavorable concerns like balling effect and other defects. They have also discussed the relationship between SLM processing parameters, and resulting final properties and microstructure of the different type of Ti materials.

Childs et al. [47] compared theoretical results with experiments for different tool steels and stainless steels. A CO₂ laser source with 10 to 200 W power, scan speeds up to 50 mm/s and an argon shielding gas was used. The tests were concluded that the quality of the molten pool is affected by scanning speed and laser power. A higher scanning velocity speed and a lower laser power cause the non-continuous molten pool. Too large scanning space will make the molten pools are not close enough to each other. Kruth et al. [48] also determined scanning strategy along with scan speed, layer thickness, scan spacing, laser power, powder size and its distribution statistical methods. They conducted experiments for hardness (Brinell),
density (principle of Archimedes), and surface roughness. They used different levels for each parameter and determined the optimum levels. The similar study, i.e., the influence of parameters is done by Yadroitsev et al. [49], investigated the effect of parameters for building a single line, using SLM machine PM 100 and stainless steel powder and stability and instability zones of melt pool. They found that instability zones were appeared at low scanning speed in the form of distortions and irregularities, and, on the contrary, excessively high speed gives rise to the balling effect. They also found the range of the optimal scan speed is larger for higher laser power, and it narrows for material with high thermal conductivity.

Figure 2.1: Sketch map of four kinds of laser scanning strategies [50]: (a) layers and turning, (b) blocks and turning, (c) internal to external circular and (d) jumping and turning.

Wei et al. [50] investigated all steps from single track, single layer to solid cubes made of 316 stainless steel. For single layer experiments, four scan strategies were used: 1) vertical lines, 2) single line blocks that were patterned orthogonally versus each other, 3) lateral increasing squares and 4) “jumping and turning”. They showed that the quality of the molten pool was affected by scanning speed and laser power. A higher scanning velocity and a lower laser power cause the in-continuous molten pool. Too large scanning space will make that the molten pools are not close
enough to each other. Conversely, the metal accumulation occurs. For scanning strategies 1 and 3, they observed balling and deformation or metal accumulation. Scan method 2 showed similar problems at the boundaries of each square. However, the best results were obtained with scanning method 4. Similarly, Thijs et al. [26] determined the influence of scanning speed, hatching spacing and scanning strategy on the properties of bulk material produced by SLM using a plasma atomized Ti-6Al-4V powder of 5-50 µm particle size. The spot diameter used is 52 µm. The optimized laser power, scanning velocity, and hatching spacing are 42 W, 200 m/s and 75 µm respectively. Rectangular samples with 5 mm width, 10 mm length and 5 mm were produced. Three types of scanning strategy used are zig-zag, unidirectional and cross-hatching. They found that the hatch spacing and scanning velocity significantly affect the hardness and melt pool width such a way that hardness increased by decreasing hatch spacing and melt pool width increased by reducing scanning velocity and melt pool is less stable at very low scanning velocities.

In 2007, Zhu et al. [35] investigated the influence of the powder density (apparent density) on the final product for selective laser sintering (SLS). Different copper powders were used, and powder packing models were considered. They noted that there exists an influence of surface roughness and shape of the powder on the packing density. The final density of the object increases with the increase of apparent density. The apparent density can be enhanced by mixing different size powders. If two different powder sizes were used, the limiting density can be computed using:

\[ \rho = \rho_L + \frac{\rho_S}{1 - \rho_L} \]
where \( \rho \) is limiting density, \( \rho_L \) is the density of large powder diameter, and \( \rho_S \) is the density of small powder diameter.

Mumtaz et al. [29] investigated the behavior of a commercial nickel super alloy. They measured the contact angle and bead geometry, respectively, and analyzed the bonding behavior using metallographic micro sections. Different parameters were changed, e.g. pulse width, percentage overlap, hatch strategy and scan strategy, etc. They depicted the results in a process map, displaying pulse width against specific energy. It was shown that higher levels of porosity were produced at lower pulse energies, and the formation of these pores predominantly exists around layer boundaries. Related to nickel, Yadroitsev et al. [51] used nickel-based powder (Inconel 625) for their studies. They investigated the optimal hatch distance in relation to porosity and applied a scan method with dual heating of the powder bed. The optimum hatch distance (120 \( \mu \)m) is established for powder Inconel 625 at the given parameters of the SLM process. The analysis of mechanical properties of the samples fabricated employing various strategies did not show essential differences in the yield strength and ultimate tensile strength values for “vertical” and “horizontal” samples at whatever angle to the scanning direction – 0°, 45° or 90° – they were built. The Young’s modulus value for the “horizontal” samples is by 1.5 times higher than that for the “vertical” ones and is close to that of wrought Inconel 625 (about 200 Mpa). Yadroitsev et al. [52] also performed investigation related to hatch distance but using stainless steel 904L powder. They worked on the influence of the hatch distance and thickness of powder layer on the morphology of the first layer using SLM machine PM 100. It was shown that changing of hatch distance
caused a modification in geometric characteristics of tracks and, consequently, in the surface morphology. They reported that if the hatch distance was too large, undesired surface effects were the consequence.

Chlebus et al. [53] presented the results of processing titanium-rhenium (Ti-Re) alloys by combining mixtures of both metal powders with the use of SLM Realizer II machine. Ti-based alloys containing 0.5, 1 and 1.5% Re were obtained. By considering minimum porosity of manufactured parts and maximum effectiveness of dissolving Re particles in molten Ti as the criterion, optimum process parameters were determined. About 90–95% of Re powder (by volume) was dissolved in molten Ti and almost fully dense (99.9% density) specimens were produced. This required five times of decrease in scanning speed in relation to the optimum speed determined for CP-Ti processing, without changing other processing parameters such as layer thickness, laser power, hatch spacing and characteristics of powder particles. They also investigated the effects of rhenium content on the mechanical properties and microstructure of SLM processed parts in as-built condition. Related to the study of mixtures, Zhang et al. [54] studied the influence factors of magnesium and aluminum mixture with less than 10% aluminum using an MCP 250 II SLM machine with an Nd:YAG laser and built cubes with 5 mm edge length. Further parameters were layer thickness 50 μm, and hatch spacing 80 μm. They measured the microhardness and inspected the parts using optical and scanning electron microscopes. Furthermore, they showed the results in a process map displaying the relationship between laser power and scanning speed. They used seven levels for power and eight levels for scanning speed, respectively. Finally, they reported that for high energy inputs of 60
to 110 W at all scanning speeds and 30 W at low scanning speeds, they could not form solid lines due to evaporation of Mg. For lower inputs (scan speeds of 0.08 m/s and above at 10 to 30 W) bonding mechanisms did not occur sufficiently. Best results were obtained within the “forming zone” of low powers and low scan speeds although stratification, and balling were reported.

Gong et al. [55] melted single beads of Ti-6Al-4V on the substrate of same material, using SLM with multiple scan speed and laser power combinations and constant layer thickness. They characterized the surface morphology and dimensions of single beads. They also measured geometrical features of the melt pools after polishing and etching of the cross section of each single bead. From melt pool characterization results, hatch spacing distance can be estimated based on the single bead/melt pool width.

Osakada et al. [56] compared FEM model to the parts made by SLM with a laser power of 50 W, the scan speed of 4-8 mm/s and a hatch distance of 0.75 mm using aluminum, chromium, iron, stainless steels, copper, titanium, and nickel-based alloys. Balling and linear solidification were detected. They conducted finite element simulations and showed stress distribution within the single solid layer formed on the powder bed during forming. Furthermore, they suggested some methods to avoid defects like balling in the produced products. Additionally, they proposed different post treatment methods such as annealing and hot isostatic pressing to improve the mechanical properties of the finished model.
Gu and Shen [57] focused on balling effects of copper-based metal alloys. They determined three different principles that cause balling. Fundamental mixing was 30% CuSn 10% CuP, and the rest was pure copper. They used a CO\(_2\) laser source with a maximum power output of 2 kW. Powder thickness was 200 μm before melting. The spot size was 300 μm, power 300-500 W and scan speed 30-70 mm/s. The hatch distance was 150 μm, and no shielding gas was used. The two typical balling types with big-sized and small-sized scales were detected in their study. They observed that the first line scan on the substrate yields to balling due to the high thermal gradients imposed on the melt and using a higher scan speed gives rise to ‘shrinkage induced balling,' due to a significant capillary instability effect. The ‘self-balling’ prevails at the combination of a high laser power and a low scan speed, because of an excessive liquid formation and a too long lifetime. Zhou et al. [58] did a similar investigation on balling using tungsten powder. They studied the effect of exposure time and multiple layers on balling. They concluded that the predominant solidification yields to balling of large melt droplets and causes surface roughness. Using stainless steel and nickel, Li et al. [59] studied the effect of laser power, layer thickness and scanning speed on the balling effect. They found that higher scanning speed, lower laser power, and higher layer thickness are unfavorable and leads to balling.
2.3 Thesis Objectives

In view of the experimental studies on various process parameters in above literature, melt pool characteristics and the effect of laser power and scan speed on melt pool geometry and hardness of melt pool are studied by conducting single bead experiments with commercially pure titanium (CP-Ti) and Ti-6Al-4V alloy using an in-house built SLM machine. The specific technical objectives of this study are summarized as below:

- Analyze the surface morphology of single beads/melt pools produced by SLM using multiple combinations of laser power and scan speed.

- Analyze the unfavorable effects such as inconsistent melt pool formation, balling, and porosity in the melt pools.

- Measure the melt pool geometry (width, depth, and height) and investigate the effect of laser power and scan speed, laser energy density on melt pool geometry.

- Study the effect of laser power and scan speed, and laser energy density on mechanical properties such as hardness.

- Suggest the optimal parameters in the perspective of better mechanical properties such as hardness.
CHAPTER 3

METHODOLOGY

3.1 Overview

The present chapter deals with materials and methods used in sample preparation by SLM process. The production of single beads/welds in two different cases, i.e., powder and no powder are discussed in this chapter.

3.2 Materials

The SLM single bead experiments are conducted for melt pool characterization and to analyze the effect of laser power, scan speed, and laser energy density on melt pool geometry and hardness of melted zone, using CP-Ti (commercially pure titanium) and Ti-6Al-4V alloy in both bulk (for substrate) and powder (for producing beads) forms. The powder particles of both CP-Ti and Ti-6Al-4V are mostly spherical in shape with the average particle size of 40 µm.

3.2.1 Commercially pure titanium (CP-Ti)

CP-Ti is widely used because it combines excellent formability and moderate strength with superior corrosion resistance. This combination of properties makes CP-
Ti a candidate for a large variety of chemical and marine as well as aerospace and medical applications. CP-Ti has a low yield strength and fracture toughness, because of this CP-Ti has found its usage which does not require high strength. Some of the other areas where CP-Ti has its usages are heat exchangers and reaction chambers of chemical plants [60-62].

Table 3.1: Chemical composition of CP-Ti [62].

<table>
<thead>
<tr>
<th>Element</th>
<th>% wt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
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</tr>
<tr>
<td>Oxygen</td>
<td>0.18 - 0.25</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>0.02</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>0.01</td>
</tr>
<tr>
<td>Iron</td>
<td>0.05-0.20</td>
</tr>
<tr>
<td>Titanium</td>
<td>Balance</td>
</tr>
</tbody>
</table>

3.2.2 Ti-6Al-4V

Ti-6Al-4V is an alloy consists of alpha-beta phase. Ti-6Al-4V considered in any application where a combination of excellent corrosion resistance, light weight, and high strength at low to moderate temperatures are required. This alloy is widely used and accounts for 80% of usage of titanium in the aircraft industry. Some of the many applications where this alloy have been used include medical devices, aircraft structural components, high-performance automotive parts, aircraft turbine engine components, aerospace fasteners, marine applications, and sports equipment. Ti-6Al-4V can be produced in various formulations. Depending on the field of application
the amounts of oxygen and nitrogen in the alloy can be controlled. The amount of oxygen in the alloy is between 0.14 to 0.17 %, and the maximum concentration of nitrogen is 0.05%. The higher concentrations of nitrogen and oxygen result in greater strength of the alloy; conversely, lower concentrations of nitrogen and oxygen increase the ductility, fracture toughness, stress corrosion resistance and resistance to crack growth [62-64].

Table 3.2: Chemical composition of Ti-6Al-4V [62].

<table>
<thead>
<tr>
<th>Element</th>
<th>% wt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>0.02</td>
</tr>
<tr>
<td>Oxygen</td>
<td>0.14 - 0.17</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>0.02</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>0.013</td>
</tr>
<tr>
<td>Iron</td>
<td>0.05 - 0.25</td>
</tr>
<tr>
<td>Aluminum</td>
<td>5.50 - 6.75</td>
</tr>
<tr>
<td>Vanadium</td>
<td>3.5 – 4.5</td>
</tr>
<tr>
<td>Copper</td>
<td>&lt; 0.10</td>
</tr>
<tr>
<td>Tin</td>
<td>&lt; 0.10</td>
</tr>
<tr>
<td>Yttrium</td>
<td>&lt; 0.005</td>
</tr>
<tr>
<td>Titanium</td>
<td>Balance</td>
</tr>
</tbody>
</table>
3.3 Preparation of Samples

Figure 3.1: The in-house built SLM machine by Mound Laser & Photonics Center Inc. (MLPC).
An in-house built SLM machine by Mound Laser & Photonics Center Inc. (MLPC) is utilized for single bead experiments. This SLM installation is equipped with Ytterbium fiber laser, which produces a laser beam with a wavelength of 1064 nm and a maximum of 500 W power. A focused laser beam is guided and located through an optical system to the desired positions of the powder bed to melt the metallic powder. Bed is not preheated, and the room temperature is maintained inside the chamber. The argon gas atmosphere is created throughout the chamber. Single scans are performed for multiple combinations of laser power and scan speed. The laser beam diameter and layer thickness are maintained as constant and not considered as variables in this study.

The experiments are done for two cases: powder case and no powder case. For powder case, two samples are prepared, one sample using CP-Ti and other sample using Ti-6Al-4V alloy. To prepare these samples, a 50 µm thin layer of metal powder (CP-Ti powder for CP-Ti sample and Ti-6Al-4V powder for Ti-6Al-4V sample) is deposited on the substrate (made of CP-Ti for CP-Ti sample and Ti-6Al-4V for Ti-6Al-4V sample). The single beads/welds are produced on the substrate by melting the layer of powder deposited on the substrate. For no powder case, two samples are prepared, one sample using CP-Ti and other sample using Ti-6Al-4V alloy. In this case, the single beads/welds are directly scanned on the substrate, without using any powder. For this, out of focus technique is employed to get wider melt pools. By taking the laser out of focus but increasing the power can affect more material, so the interaction creates a greater melt pool. The four different samples prepared are:

1. CP-Ti sample (powder case) with 25 beads
2. Ti-6Al-4V sample (powder case) with 16 beads
3. CP-Ti sample (no powder case) with 9 beads
4. Ti-6Al-4V sample (no powder case) with 9 beads

Table 3.3: Parameters used for the preparation CP-Ti sample (powder case).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser power ‘P’ (W)</td>
<td>100, 120, 140, 160, 180</td>
</tr>
<tr>
<td>Scan speed ‘v’ (mm/s)</td>
<td>150, 200, 300, 500, 600</td>
</tr>
<tr>
<td>Laser beam diameter ‘d’ (µm)</td>
<td>100</td>
</tr>
<tr>
<td>Layer thickness ‘t’ (µm)</td>
<td>50</td>
</tr>
</tbody>
</table>

Table 3.4: Parameters used for the preparation Ti-6Al-4V sample (powder case).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser power (W)</td>
<td>91, 194, 297, 400</td>
</tr>
<tr>
<td>Scan speed (mm/s)</td>
<td>200, 500, 800, 1100</td>
</tr>
<tr>
<td>Laser beam diameter ‘d’ (µm)</td>
<td>100</td>
</tr>
<tr>
<td>Layer thickness ‘t’ (µm)</td>
<td>70</td>
</tr>
</tbody>
</table>

Table 3.5: Parameters used for the preparation CP-Ti sample (no powder case).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser power ‘P’ (W)</td>
<td>276, 318, 360</td>
</tr>
<tr>
<td>Scan speed (mm/s)</td>
<td>20, 60, 100</td>
</tr>
<tr>
<td>Laser beam diameter ‘d’ (µm)</td>
<td>115</td>
</tr>
</tbody>
</table>
Table 3.6: Parameters used for the preparation Ti-6Al-4V sample (no powder case).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser power (W)</td>
<td>276, 318, 360</td>
</tr>
<tr>
<td>Scan speed (mm/s)</td>
<td>20, 60, 100</td>
</tr>
<tr>
<td>Laser beam diameter ‘d’ (µm)</td>
<td>115</td>
</tr>
</tbody>
</table>

Figure 3.2: CP-Ti sample (powder case) with 25 beads.
Figure 3.3: Ti-6Al-4V sample (powder case) with 16 beads.
Figure 3.4: CP-Ti sample (no powder case) with 9 beads.

Figure 3.5: Ti-6Al-4V sample (no powder case) with 9 beads.
CHAPTER 4

RESULTS AND DISCUSSION

4.1 Overview

In this chapter, the surface morphology of single beads of CP-Ti and Ti-6Al-4V is discussed. Moreover, the hardness and geometry of melted zone such as melt pool width, depth, and height of beads are presented. Furthermore, the effect of variation in laser power, scan speed, and laser energy density on the melt pool geometry and hardness are discussed.

4.2 Surface Morphology of Single Beads

4.2.1 Powder Case

For the powder case, a thin layer of metal powder is spread on all over the substrate plate. It is hard to guarantee that the thickness of metal powder is uniform throughout the substrate, and it may vary slightly, due to the surface roughness of substrate, and some minor errors in leveling the base plate of the chamber. The single beads are generated by melting powder that deposited on the substrate plate, which formed a uniform melt pool and solidified together. The surface roughness of melt
pools is worse (Figures 4.1 and 4.2). The variation in the width of each single bead is not significant, except at the start and end points of melted region. The melt pool is wider and rounded at these areas as shown in the Figures 4.1 and 4.2 due to scan speed fluctuation while shifting from one bead to other.

Figure 4.1: Start and end points of CP-Ti single beads (140 W and 500 mm/s).

Figure 4.2: Start and end points of Ti-6Al-4V single beads (400 W and 200 mm/s).

All single beads of CP-Ti are consistent and continuous as shown in the Figure 4.3, and no significant balling phenomena observed. In the perspective of balling effect and consistency in the melt pool, the selected laser powers and scan speeds are in optimum range. Several Ti-64 beads created at non-optimal process conditions appeared to be inconsistent, especially at low power and high scan speed (at low energy density) as shown in Figure 4.4. This type of inconsistent melt pools are typical at these conditions because at low power and high speed the heat generation
is very poor and there is less time for heating, so a little amount of powder (sometimes none) melts that results in inconsistent and non-continuous melt pools. After preparing Ti-6Al-4V (powder case) samples, it was identified that the substrate surface was slightly slanted, where the beads of 800 mm/s and 1100 mm/s were created. This uneven surface leads to increase in layer thickness at that particular area and further yields to balling and inconsistent melt pools as shown in the Figures 4.6 and 4.7. Because of this, 1100 mm/s scan speed beads were repeated. This unfavorable phenomenon can be explained as follows. Firstly, for higher layer thickness, the laser energy absorbed per unit volume of powder is insufficient; hence, the temperature of the molten pool is low, resulting in a weak flowability and balling phenomenon. Secondly, although a larger layer thickness could enable a big molten pool, the molten pool is far away from the substrate, leading to a relatively small contact area between the melt pool and the substrate, as schematically illustrated in Figure 4.5. In this condition, the small wetting area could not support a big molten pool; thereby the molten track tends to break up into balls [59].

![Figure 4.3: Consistent melt pool of CP-Ti sample: (a) 140 W and 500 mm/s, and (b) 100 W and 300 mm/s.](image)
Figure 4.4: Inconsistency and balling in the melt pool of Ti-6Al-4V sample: (a) 91 W and 1100 mm/s, and (b) 91 W and 800 mm/s.

Figure 4.5: Schematic diagram showing the effect of layer thickness on the wetting condition.
Figure 4.6: Inconsistency and balling in the melt pool of Ti-6Al-4V sample: (a) 400 W and 800 mm/s, and (b) 297 W and 800 mm/s.

Figure 4.7: Balling in the melt pools of Ti-6Al-4V sample (1100 mm/s).
Balling is also observed on the sides and top of Ti-6Al-4V melt pool at high laser power and low scan speed even the layer thickness is uniform (Figure 4.8). Under this condition, a significantly enhanced energy absorbed by the powder that lead to a larger amount of liquid formation. The excessive liquid formation accompanied by a long liquid lifetime will result in a considerably lower melt viscosity, a higher degree of superheat and Marangoni effect, thereby forming a large amount of small individual balls with diminishing surface energy [57]. There is another theory to explain the balling shown in Figure 4.6, 4.7 and 4.8. For titanium, the solidification time increases significantly with the increase of the melt temperature. At a particular temperature (around 2100K) the solidification time exceeds the spreading time, which ensures the possibility of completely spreading of the melt droplets, yields to balling [58].
### 4.2.2 No Powder Case or Substrate Remelting

For no powder case, laser scans are performed on a bare substrate plate; single beads are formed by remelting and solidification of the substrate material. The surface roughness of melt pools is much better than powder case (Figures 4.9 and 4.10). The width of all single beads is almost consistent, except at the start and end points of melted region. Due to speed fluctuations in laser, while shifting the layers, the melt pool is narrow and rounded at the start and no melt pool formation at the end. The start and end point of both CP-Ti and Ti-6Al-4V single beads are shown in Figures 4.9 and 4.10.

All single beads of CP-Ti and Ti-6Al-4V are consistent without any interruption, except at low power and high scan speed as shown in Figure 4.11. The reason for this is similar to that of powder case explained above. The balling phenomena is not occurred in no powder case as the substrate is directly melted without using powder.

![Narrow melt pool and No melt pool formation](image)

**Figure 4.9: Start and end points of CP-Ti single beads (318 W and 20 mm/s).**
Figure 4.10: Start and end points of Ti-6Al-4V single beads (380 W and 20 mm/s).

Figure 4.11: Inconsistency at 276 W and 100 mm/s: (a) CP-Ti, and (b) Ti-6Al-4V.

4.3 Melt Pool Geometry

After melting single beads on the substrates, the melt pool geometry such as melt pool width, depth, and height for each single bead are measured using an optical microscope. Figure 4.12 shows the schematic diagram of the melt pool profile and geometry.
4.3.1 Melt Pool Width

The width of each single bead is measured using an optical microscope at multiple locations (far away from the starting and ending points) as shown in the Figure 4.13 and 4.14. The idea of taking multiple measurements of the melt pool is to obtain average width dimensions, which gives an exact trend with laser power and scan speed. The power and scan speed affect the melt pool individually. By combining these two parameters into a single parameter, i.e., linear energy density, which is a measure of the averaged applied energy per unit scan length of the material during the scanning of a layer. It can be expressed as [7]:

$$\text{LED} = \frac{P}{v} \text{ J/mm}$$

where $P$ = laser power (J/s), $v$ = scanning speed (mm/s).
Figure 4.13: Measuring melt pool width: (a) CP-Ti, powder case, 100 W and 500 mm/s., and (b) Ti-6Al-4V, powder case, 400 W and 500 mm/s.

Figure 4.14: Measuring melt pool width: (a) Ti-6Al-4V, no powder case, 318 W and 100 mm/s., and (b) CP-Ti, no powder case, 276 W and 100 mm/s.

The melt pool width measurements and variation in melt pool width due to variation in laser powder $P$ and scan speed $v$ are represented as follows.
Table 4.1: Average melt pool width measurements of CP-Ti sample (powder case).

<table>
<thead>
<tr>
<th>Laser power $P$ (W)</th>
<th>Scan speed $v$ (mm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>150</td>
</tr>
<tr>
<td>100</td>
<td>286.5</td>
</tr>
<tr>
<td>120</td>
<td>301.2</td>
</tr>
<tr>
<td>140</td>
<td>335</td>
</tr>
<tr>
<td>160</td>
<td>337.5</td>
</tr>
<tr>
<td>180</td>
<td>356.7</td>
</tr>
</tbody>
</table>

Figure 4.15: Laser power $P$ vs. melt pool width plots for CP-Ti sample (powder case).
Figure 4.16: Scan speed $v$ vs. melt pool width plots for CP-Ti sample (powder case).

Figure 4.17: Energy density $E$ vs. Melt pool width fit for CP-Ti sample (powder case).
Table 4.2: Average melt pool width measurements of Ti-6Al-4V sample (powder case).

<table>
<thead>
<tr>
<th>Laser power $P$ (W)</th>
<th>Scan speed $v$ (mm/s)</th>
<th>200</th>
<th>500</th>
<th>800</th>
<th>1100</th>
</tr>
</thead>
<tbody>
<tr>
<td>91</td>
<td>186.8</td>
<td>109.8</td>
<td>89.2</td>
<td>84</td>
<td></td>
</tr>
<tr>
<td>194</td>
<td>268.5</td>
<td>198.2</td>
<td>156</td>
<td>108.6</td>
<td></td>
</tr>
<tr>
<td>297</td>
<td>356</td>
<td>227.8</td>
<td>185.7</td>
<td>149.8</td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>412</td>
<td>306.6</td>
<td>206.2</td>
<td>156.2</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4.18: Laser power $P$ vs. melt pool width plots for Ti-6Al-4V sample (powder case).
Figure 4.19: Scan speed $v$ vs. melt pool width plots for Ti-6Al-4V sample (powder case).

Figure 4.20: Energy density $E$ vs. Melt pool width fit for Ti-6Al-4V sample (powder case).
Figure 4.21: The fitted curves for melt pool width measurements at each energy density $E$ (for powder case).

Table 4.3: Average melt pool width measurements of CP-Ti sample (no powder case).

<table>
<thead>
<tr>
<th>Scan speed $v$ (mm/s)</th>
<th>20</th>
<th>60</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser power $P$ (W)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>276</td>
<td>829.5</td>
<td>461.1</td>
<td>294.2</td>
</tr>
<tr>
<td>318</td>
<td>953.9</td>
<td>629.9</td>
<td>430.5</td>
</tr>
<tr>
<td>360</td>
<td>1018.5</td>
<td>715.9</td>
<td>554.2</td>
</tr>
</tbody>
</table>
Figure 4.22: Laser power $P$ vs. melt pool width plots for CP-Ti sample (no powder case).

Figure 4.23: Scan speed $v$ vs. melt pool width plots for CP-Ti sample (no powder case).
Figure 4.24: Energy density $E$ vs. Melt pool width fit for CP-Ti sample (no powder case).

Table 4.4: Average melt pool width measurements of Ti-6Al-4V sample (no powder case).

<table>
<thead>
<tr>
<th>Laser power $P$ (W)</th>
<th>Scan speed $v$ (mm/s)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20</td>
<td>60</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>276</td>
<td>894.7</td>
<td>564.3</td>
<td>382.4</td>
<td></td>
</tr>
<tr>
<td>318</td>
<td>983.6</td>
<td>637.3</td>
<td>477</td>
<td></td>
</tr>
<tr>
<td>360</td>
<td>1054.2</td>
<td>717</td>
<td>560</td>
<td></td>
</tr>
</tbody>
</table>
Figure 4.25: Laser power $P$ vs. melt pool width plots for Ti-6Al-4V sample (no powder case).

Figure 4.26: Scan speed $v$ vs. melt pool width plots for Ti-6Al-4V sample (no powder case).
Figure 4.27: Energy density $E$ vs. Melt pool width fit for Ti-6Al-4V sample (no powder case).

Figure 4.28: The fitted curves for melt pool width measurements at each energy density $E$ (for no powder case).
From above results, the high power and slow scan lead to wider melt pools whereas low power combined with fast scan results in narrow melt pools. Coming to the trend of melt pool width, it increases with laser power and decreases with scan speed while all other parameters are constant. By combining laser power and scan speed, the rise in laser energy density leads to rising in melt pool width. The almost same trend is observed in all samples. The variation in melt pool width with energy density is represented with a curve fit, which gives the melt pool width value at a particular laser power and scan speed. For example, consider the curve fit (Figure 4.17) for melt pool width measurements of CP-Ti sample (powder case):

\[ y = 104.91 \ln(x) + 325.46 \]

It can be write in terms of melt pool width and energy density \( E \) as:

\[ \text{Melt pool width} = 104.91 \ln(E) + 325.46 \]

In terms of laser power \( P \) and scan speed \( v \):

\[ \text{Melt pool width} = 104.91 \ln(P/v) + 325.46 \]

Consider laser power \( P = 150 \) W and scan speed \( v = 400 \) mm/s. By computing melt pool width using the above equation gives the value of 222.5 \( \mu \)m. In this way, the melt pool width can be estimated at a particular laser power and scan speed. In the following sections, some geometrical features are computed using fitted equation as shown above.
4.3.2 Melt Pool Profiles

The surface topology and melt pool width of single beads are discussed in the previous sections. For further investigation, all single beads are sectioned in the middle (far away from the start and end points), perpendicular to the scanning direction, using electronic discharge machine (EDM). The sectioned samples are mounted in 2” mounts as shown in the Figure 4.29, and the cross sections are finely polished. The polished surfaces are etched so that the geometrical and dimensional features are clearly visible under the microscope.

Figure 4.29: Sectioned, mounted, and polished sample (CP-Ti, powder case, 160 W and 500 mm/s).

For Ti-6Al-4V samples, it can be observed that the melt pool profile is clearly distinguished from the substrate plate material because the microstructure of the melt pool is transformed to alpha phase (martensite) due to the fast cooling rate. Heat affected zone is observed in the peripheral area of the melt pool, which has rich alpha and poor beta phase [160] (Figure 4.30). High laser power combined with slow scan
speed (high laser energy density) result in large or deeper melt pools with keyhole geometry, and the combination of low laser power and fast scan speed (low laser energy density) lead to small melt pools. For example, as shown in Figure 4.31, the melt pool of 400 W laser power & 200 mm/s scan speed (2 J/mm energy density) is larger than the melt pool of 194 W laser power & 1100 mm/s (0.176 J/mm energy density) in Ti-6Al-4V sample (powder case).

Figure 4.30: Microstructure of melt pool (Ti-6Al-4V, powder case, 297 W and 500 mm/s).
Figure 4.31: Melt pool profiles of Ti-6Al-4V sample (powder case): (a) 400 W and 200 mm/s, and (b) 194 W and 1100 mm/s.

Figure 4.32: Melt pool profiles of CP-Ti sample (powder case): (a) 120 W and 100 mm/s, and (b) 140 W and 100 mm/s.

For CP-Ti samples, the melt pool profiles are not clearly visible even after fine polishing and etching. However, the heat affected zone is partially visible (Figure 4.32) as the grains are rearranged during melting. The reason for this is CP-Ti only contains alpha phase and after cooling the melt pool and substrate contains same
phase, i.e., alpha, which can not allow to differentiate between the substrate (heat affected zone) and melt pool. So the melt pool depth measurements for this sample are not considered in this study.

It is identified that pores are commonly observed inside melt pools of high laser energy density as shown in the Figure 4.33. Fast cooling process during solidification increases the formation of oxygen and carbon monoxide due to poor gas shielding, which is trapped in the solidifying metal, creating gas bubbles [74].

![Pore Image]

(a) (b)

Figure 4.33: Porosity observed in melt pools of Ti-6Al-4V sample (powder case): (a) 400 W and 200 mm/s, and (b) 297 W and 500 mm/s.

4.3.3 Melt Pool Depth

After polishing and etching the mounted samples, the depth of each single bead is measured using an optical microscope as shown in Figures 4.31 through 4.35. For the melt pool depth data, only one measurement is considered throughout the melt pool. It is observed that melt pools are showing abnormal profiles for Ti-6Al-4V sample (powder case) of scan speed 800 mm/s (at 400 W, 198 W, and 91 W) and 1100
mm/s (at 91 W). These abnormal profiles may be caused by either occasional laser power fluctuations during the melting process since laser power instability is more likely at process extremes, and these fluctuations could produce lower amounts of energy and result in smaller melt pools (Figure 4.34). Another possibility is that the sectioning may happen at inconsistent melt pool. Some of the melt pool depth measurements for 800 mm/s beads of Ti-6Al-4V sample (powder case) are not considered in the following plots and estimated using the fitted equation.

Figure 4.34: Abnormal melt pool profiles of Ti-6Al-4V sample (powder case): (a) 400 W and 800 mm/s, (b) 194 W and 800 mm/s, (c) 91 W and 800 mm/s, and (d) 91 W and 1100 mm/s.
Figure 4.35: Measuring melt pool depth: (a) Ti-6Al-4V sample, powder case, 297 W and 800 mm/s, and (b) Ti-6Al-4V sample, no powder case, 318 W and 60 mm/s.

The melt pool depth measurements and variation in melt pool depth due to variation in laser powder $P$ and scan speed $v$ are represented as follows.

Table 4.5: Melt pool depth measurements of Ti-6Al-4V sample (powder case).

<table>
<thead>
<tr>
<th>Laser power $P$ (W)</th>
<th>Scan speed $v$ (mm/s)</th>
<th>200</th>
<th>500</th>
<th>800</th>
<th>1100</th>
</tr>
</thead>
<tbody>
<tr>
<td>91</td>
<td></td>
<td>17.7</td>
<td>12.7</td>
<td>7.6</td>
<td>5</td>
</tr>
<tr>
<td>194</td>
<td></td>
<td>38.1</td>
<td>30.4</td>
<td>55.8</td>
<td>55.8</td>
</tr>
<tr>
<td>297</td>
<td></td>
<td>165.1</td>
<td>45.7</td>
<td>160</td>
<td>101.6</td>
</tr>
<tr>
<td>400</td>
<td></td>
<td>401.3</td>
<td>157.4</td>
<td>112.8</td>
<td>134.6</td>
</tr>
</tbody>
</table>
Figure 4.36: Laser power $P$ vs. melt pool depth plots for Ti-6Al-4V sample (powder case).

Figure 4.37: Scan speed $v$ vs. melt pool depth plots for Ti-6Al-4V sample (powder case).
Figure 4.38: Energy density $E$ vs. Melt pool depth fit for Ti-6Al-4V sample (powder case).

Table 4.6: Melt pool depth measurements of Ti-6Al-4V sample (no powder case).

<table>
<thead>
<tr>
<th>Scan speed $v$ (mm/s)</th>
<th>20</th>
<th>60</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Laser power $P$ (W)</strong></td>
<td>276</td>
<td>101.8</td>
<td>44.2</td>
</tr>
<tr>
<td></td>
<td>318</td>
<td>135.2</td>
<td>61.4</td>
</tr>
<tr>
<td></td>
<td>360</td>
<td>158</td>
<td>72.9</td>
</tr>
</tbody>
</table>
Figure 4.39: Laser power $P$ vs. melt pool depth plots for Ti-6Al-4V sample (no powder case).

Figure 4.40: Scan speed $v$ vs. melt pool depth plots for Ti-6Al-4V sample (no powder case).
From above results, the melt pool depth is increases with laser power almost in all samples and decreases with scan speed, except for 297 W and 194 W laser power Ti-6Al-4V (powder case) sample. The melt pool depth for these powers are first decreasing and then increasing, which is an unexpected trend. This might have happened due to abnormal melt pool formation and/or sectioning the sample at inconsistent melt pool. By combining laser power and scan speed, the increase in laser energy density leads to rising in melt pool depth. The almost same trend is observed in all samples. The variation in melt pool depth with energy density is represented with a curve fit, which gives the melt pool depth value at a particular laser power and scan speed. Due to abnormal melt pool profiles, some of the melt pool depth values for 800 mm/s scan speed of Ti-6Al-4V sample (powder case) are
computed using the curve fit obtained from other values and those values are represented in red (Table 4.5).

### 4.3.4 Bead Height

The height of each single bead is measured using an optical microscope as shown in the Figures 4.42. The bead height data is not accurate as only one measurement is considered throughout the melt pool. As discussed in the previous section, the melt pool profiles are abnormal for 800 mm/s scan speed of Ti-6Al-4V (powder case) sample and the data related to this is not considered in the following plots and estimated using the fitted equation.

![Figure 4.42: Measuring bead height: (a) CP-Ti sample, powder case, 180 W and 300 mm/s, and (b) Ti-6Al-4V sample, powder case, 91 W and 500 mm/s.](attachment:image.png)
The bead height and variation in bead height due to variation in laser powder $P$ and scan speed $v$ are represented as follows.

Table 4.7: Bead height measurements of CP-Ti sample (powder case).

<table>
<thead>
<tr>
<th>Laser power $P$ (W)</th>
<th>Scan speed $v$ (mm/s)</th>
<th>150</th>
<th>200</th>
<th>300</th>
<th>500</th>
<th>600</th>
</tr>
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<tbody>
<tr>
<td>100</td>
<td>22.4</td>
<td>13.4</td>
<td>11.9</td>
<td>7.5</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>120</td>
<td>27.9</td>
<td>23.9</td>
<td>21.4</td>
<td>13.9</td>
<td>10.4</td>
<td></td>
</tr>
<tr>
<td>140</td>
<td>27.4</td>
<td>23.4</td>
<td>22.2</td>
<td>15.9</td>
<td>11.9</td>
<td></td>
</tr>
<tr>
<td>160</td>
<td>36.8</td>
<td>29.4</td>
<td>22.9</td>
<td>20.9</td>
<td>15.4</td>
<td></td>
</tr>
<tr>
<td>180</td>
<td>37.3</td>
<td>34.3</td>
<td>27.9</td>
<td>21.4</td>
<td>15</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4.43: Laser power $P$ vs. Bead height plots for CP-Ti sample (powder case).
Figure 4.44: Scan speed $v$ vs. Bead height plots for CP-Ti sample (powder case).

Figure 4.45: Energy density $E$ vs. Bead height fit for CP-Ti sample (powder case).
Table 4.8: Bead height measurements of Ti-6Al-4V sample (powder case).

<table>
<thead>
<tr>
<th>Laser power $P$ (W)</th>
<th>Scan speed $v$ (mm/s)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>200</td>
<td>500</td>
<td>800</td>
<td>1100</td>
</tr>
<tr>
<td>91</td>
<td>71.6</td>
<td>62.2</td>
<td>45.9</td>
<td>43.9</td>
</tr>
<tr>
<td>194</td>
<td>92.5</td>
<td>74.6</td>
<td>62.5</td>
<td>49.4</td>
</tr>
<tr>
<td>297</td>
<td>100.3</td>
<td>75.6</td>
<td>71.9</td>
<td>59.1</td>
</tr>
<tr>
<td>400</td>
<td>109.5</td>
<td>104.5</td>
<td>78.5</td>
<td>69.2</td>
</tr>
</tbody>
</table>

Figure 4.46: Laser power $P$ vs. Bead height plots for Ti-6Al-4V sample (powder case).
Figure 4.47: Scan speed \( v \) vs. Bead height plots for Ti-6Al-4V sample (powder case).

\[ y = 22.005 \ln(x) + 93.769 \]
\[ R^2 = 0.9097 \]

Figure 4.48: Energy density \( E \) vs. Melt pool depth fit for Ti-6Al-4V sample (no powder case).
From above results, an increasing trend in bead height with laser power and decreasing trend with scan speed is observed. By combining laser power and scan speed, the increase in laser energy density leads to rising in bead height. The variation in bead height with energy density is represented with a curve fit, which gives the bead height value at a particular laser power and scan speed. Due to abnormal melt pool profiles, the bead height values for 800 mm/s scan speed of Ti-6Al-4V sample (powder case) are computed using the curve fit obtained from other values and those values are represented in red (Table 4.8).

4.3.5 Hardness of Melt Pool

Hardness is a commonly investigated mechanical property for almost all AM-processed components. In most cases, the hardness of laser-processed materials are superior to conventional or casting materials. In this study, the hardness of melt pool is measured using micro Vickers hardness tester as shown in Figures 4.50-4.52, operating at indent force of 500 grams and indentation time of 13 seconds. As discussed in previous sections, the sectioned samples are mounted and polished to analyze the melt pool geometry. The indentations are applied on the polished surface of melt pool, for powder case samples. Only one measurement is taken for each melt pool as the area of sectioned melt pool is small, which does not allow for multiple indentations. As the better surface roughness of melt pools in case of remelted samples, the hardness is measured at multiple points along the melt pool to get mean hardness. The ratio of melt pool hardness to substrate hardness is compared for different laser energy density and suggested for optimal parameter set.
As discussed in previous sections, the sectioned samples are mounted and polished to analyze the melt pool geometry. The indentations are applied on the polished surface of melt pool, for powder case samples. Only one measurement is taken for each melt pool as the area of sectioned melt pool is small, which does not allow for multiple indentations. As the better surface roughness of melt pools in case of remelted samples, the hardness is measured at multiple points along the melt pool to get mean hardness. The ratio of melt pool hardness to substrate hardness is termed as “hardness ratio” and compared for different laser energy density and suggested for optimal parameter set.
Figure 4.50: Measuring hardness of Ti-6Al-4V sample, powder case, 91 W & 500 mm/s.

Figure 4.51: Measuring hardness of Ti-6Al-4V sample, no powder case, 276 W & 60 mm/s.
The hardness and variation in hardness due to variation in laser powder $P$ and scan speed $v$ are represented as follows.

Table 4.9: Hardness ratio measurements of CP-Ti sample (powder case).

<table>
<thead>
<tr>
<th>Laser power $P$ (W)</th>
<th>Scan speed $v$ (mm/s)</th>
<th>150</th>
<th>200</th>
<th>300</th>
<th>500</th>
<th>600</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>100</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.979</td>
<td>0.993</td>
<td>0.903</td>
<td>0.958</td>
<td>0.972</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.903</td>
<td>0.958</td>
<td>0.910</td>
<td>0.958</td>
<td>1.006</td>
</tr>
<tr>
<td></td>
<td></td>
<td>140</td>
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<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td>1.006</td>
<td>1</td>
<td>0.875</td>
<td>0.862</td>
<td>0.862</td>
</tr>
<tr>
<td></td>
<td></td>
<td>160</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>0.896</td>
<td>0.931</td>
<td>0.903</td>
<td>0.979</td>
<td>0.937</td>
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<td></td>
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<td></td>
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<tr>
<td></td>
<td></td>
<td>0.882</td>
<td>1</td>
<td>0.924</td>
<td>0.882</td>
<td>0.813</td>
</tr>
</tbody>
</table>

Figure 4.52: Laser power $P$ vs. Hardness ratio plots for CP-Ti sample (powder case).
Figure 4.53: Scan speed $v$ vs. Hardness ratio plots for CP-Ti sample (powder case).

Figure 4.54: Hardness ratios at each energy density $E$ of CP-Ti sample (powder case).
Table 4.10: Hardness ratio measurements of Ti-6Al-4V sample (powder case).

<table>
<thead>
<tr>
<th>Laser power $P$ (W)</th>
<th>Scan speed $v$ (mm/s)</th>
<th>200</th>
<th>500</th>
<th>800</th>
<th>1100</th>
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</thead>
<tbody>
<tr>
<td>91</td>
<td></td>
<td>0.925</td>
<td>0.763</td>
<td>0.800</td>
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<tr>
<td>194</td>
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<td>1</td>
<td>0.917</td>
<td>0.908</td>
<td>0.821</td>
</tr>
<tr>
<td>297</td>
<td></td>
<td>1.049</td>
<td>0.846</td>
<td>0.917</td>
<td>0.842</td>
</tr>
<tr>
<td>400</td>
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<td>1.053</td>
<td>0.950</td>
<td>0.958</td>
<td>0.858</td>
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</tbody>
</table>

Figure 4.55: Laser power $P$ vs. Hardness ratio plots for Ti-6Al-4V sample (powder case).
Figure 4.56: Scan speed $v$ vs. Hardness ratio plots for Ti-6Al-4V sample (powder case).

Figure 4.57: Hardness ratios at each energy density $E$ of Ti-6Al-4V sample (powder case).
Table 4.11: Hardness ratio measurements of CP-Ti sample (no powder case).

<table>
<thead>
<tr>
<th>Laser power $P$ (W)</th>
<th>Scan speed $v$ (mm/s)</th>
<th>20</th>
<th>60</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>276</td>
<td>0.984</td>
<td>1.006</td>
<td>0.970</td>
<td></td>
</tr>
<tr>
<td>318</td>
<td>0.939</td>
<td>1.006</td>
<td>0.977</td>
<td></td>
</tr>
<tr>
<td>360</td>
<td>0.846</td>
<td>1.006</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4.58: Laser power $P$ vs. Hardness ratio plots for CP-Ti sample (no powder case).
Figure 4.59: Scan speed $v$ vs. Hardness ratio plots for CP-Ti sample (no powder case).

Figure 4.60: Hardness ratios at each energy density $E$ of CP-Ti sample (no powder case).
Table 4.12: Hardness ratio measurements of Ti-6Al-4V (no powder case).

<table>
<thead>
<tr>
<th>Laser power $P$ (W)</th>
<th>Scan speed $v$ (mm/s)</th>
<th>20</th>
<th>60</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>276</td>
<td>1.019</td>
<td>0.965</td>
<td>0.96</td>
<td></td>
</tr>
<tr>
<td>318</td>
<td>1.013</td>
<td>0.977</td>
<td>0.949</td>
<td></td>
</tr>
<tr>
<td>360</td>
<td>0.962</td>
<td>1.004</td>
<td>0.947</td>
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</tr>
</tbody>
</table>

Figure 4.61: Laser power $P$ vs. Hardness ratio plots for Ti-6Al-4V sample (no powder case).
Figure 4.62: Scan speed $v$ vs. Hardness ratio plots for Ti-6Al-4V sample (no powder case).

Figure 4.63: Hardness ratios at each energy density $E$ of Ti-6Al-4V sample (no powder case).
Figure 4.64: The fitted curves for Hardness ratio measurements at each energy density $E$ (for no powder case). 

From above results, it’s hard to find the individual effect of laser power and scan speed on the hardness of melt pools. The better way is to combine laser power and scan speed, which gives laser energy density. As the ranges of laser energy density for CP-Ti sample (powder case) and Ti-6Al-4V sample (powder case) are small (0.2-1.2 J/mm for CP-Ti and 0.08-2 J/mm for Ti-6Al-4V), there is no significant variation in hardness with laser energy density. For no powder case samples of both CP-Ti and Ti-6Al-4V, the first increase (approximately up to 9 J/mm for CP-Ti and 11 J/mm for Ti-6Al-4V) and then decrease in the hardness of melt pool is observed with laser energy density. When laser energy density is low, not enough power is being put in for good melting. When laser energy density is high, the melt pool is
probably getting too hot, leading to a too high cooling rate and the possible inclusion of gas bubbles. Each of these cases leads to lower hardness, and an intermediate value of laser energy density gives the best material properties.
5.1 Summary

In this study, an introduction to additive manufacturing (AM) and selective laser melting (SLM) is discussed in details including the advantages and applications of AM, steps involved in AM, and process parameters in SLM. The previous studies related to SLM of different materials and SLM process parameters are presented. In the present work, an SLM machine built in-house by Mound Laser & Photonics Center Inc. (MLPC), which uses Ytterbium laser source is used to produce single beads of commercially pure titanium (CP-Ti), and Ti-6Al-4V alloy on a substrate under room temperature and argon gas shielding atmosphere without preheating the bed. The substrate used is the same material as the powder. Total four samples are prepared, two samples by melting the powder layer that deposited on the substrate, and two samples by remelting the bare substrate. Various combinations of laser power and scan speed are used for single bead fabrication while the laser beam diameter (100 µm for powder case and 115 µm for no powder case) and layer thickness (50 µm for CP-Ti and 70 µm for Ti-6Al-4V) are kept constant.
The melt pools are clearly observed under an optical microscope, and the surface morphology is analyzed. The causes for unfavorable effects such as inconsistent melt pool formation, balling are discussed in detail. The average width measurements of each single bead are taken and variation in melt pool width with laser power, scan speed, laser energy density is presented. The samples are cross-sectioned in the middle, mounted, polished and etched to observe melt pool profiles. The depth of each melt pool and height of each bead are measured and discussed. Finally, hardness tests are conducted on the melted zones of each single bead using micro Vickers hardness tester. The optimal parameter set is suggested in the perspective of mechanical properties such as hardness.

5.2 Conclusions

From the optical microscopic view, the surface roughness of CP-Ti and Ti-6Al-4V melt pools for powder case is worse when compared to no powder case (remelted). In both cases, the variation in the width of each single bead is not significant along the melted region, except at the start and end points. Due to scan speed fluctuations, while shifting from one bead to other, the melt pool of powder case are wider and rounded at start and end points, whereas the melt pool of no powder case is narrow and rounded at the beginning and no melt pool formation at the ending.

The remelted CP-Ti and Ti-6Al-4V beads are almost consistent at all selected laser powers and scan speeds. It is concluded that the selected laser powers and scan speeds used to produce CP-Ti single beads (using powder) are in optimal range as the
melt pools are consistent, and no significant balling effect is observed. On the contrary, a significant inconsistency observed in the beads of Ti-6Al-4V (using powder), particularly at the fast scan speed and low power, which generates very low heat (energy density) within a short time of contact with powder layer. So limited amount of powder melts and results in inconsistent melt pools. It is also observed that the surface roughness of substrate plays a key role in melt pool quality in such a way that the uneven surface yields in a greater amount of balling effect and inconsistency by altering the powder layer thickness. At higher energy, the long lifetime of the excessive liquid pool that has low viscosity leads to form a large amount of small individual balls.

After fine polishing and etching, the melt pool profile of Ti-6Al-4V and heat affected zone are clearly visible due to alpha phase (martensite) transformation in the microstructure of melted zone because of fast cooling, and rich alpha and poor beta phase transformation in the microstructure of heat affected zone. On the contrary, the melt pool profiles of CP-Ti are not clearly visible due to the same phase (alpha) of melt pool before and after melting. High laser energy density (high laser power combined with slow scan speed) results in larger or deeper melt pools with pores due to bubble formation, whereas low laser energy density (the combination of low laser power and fast scan speed) lead to small melt pools and abnormal melt pool profiles. The uneven surface of the substrate also leads to abnormal melt pool profiles.

Although, some melt pool profiles are abnormal, it can easily be concluded that the melt pool width, depth and bead height increase with laser power, decrease with scan speed, and increase with laser energy density. The individual effect of laser
power and scan speed on hardness is hard to explain as there is no particular trend. However, the laser energy density shows a significant effect on hardness. There is no much variation observed in hardness for CP-Ti (powder case) and Ti-6Al-4V (poeder case) as the selected parameters are in limited range of laser energy density. In the case of both CP-Ti and Ti-6Al-4V remelted beads, the first rise and then fall in hardness is observed. The optimal parameter set is the one which gives consistent melt pools without balling and pores and better hardness when compared to the substrate. The fitted curves are plotted to estimate melt pool geometry and hardness within the particular range of parameter set. Some geometrical features of abnormal melt profiles are ignored while computing fitted equations for the plots.

5.3 Recommendations for Future Work

In this study, the effect of two parameters such as laser power and scan speed on melt pool formation, geometry and hardness are investigated. Besides the laser power and scan speed, the other influential parameters in SLM include powder layer thickness, laser beam diameter, laser source, hatch spacing, scanning pattern and shielding gas (atmosphere), which will significantly affect the quality, geometry and hardness of melt pool. All such parameters are not considered in this study. Therefore, the following works are recommended for future study:

- Examine the effects of layer thickness on the quality, geometry, and hardness of melt pool.
• Investigate the effects of laser beam diameter on the quality, geometry, and hardness of melt pool.

• It is possible to change the laser source to ND:YAG or CO$_2$ and find the melt pool quality, geometry, and hardness of melt pool.

• Study the effect of shielding gas on quality of melt pool and hardness.

• Produce two beads on the substrate instead of the single bead by varying the hatch spacing and study the effect of hatch spacing on the quality and width of melt pool.

• Extend the study by varying the directions of two scans and investigate the melt pool quality and hardness.
REFERENCES


