
Chapter 1 Introduction and Literature Review

This chapter is divided into three sections, the first section discusses about the additive manufacturing, Ti-6Al-4V material used in the present investigation, and different process parameters used during the additive manufacturing process. The second section introduces the literature review on different additive manufacturing processes and related to various aspects of build orientation and heat treatment effect on metallurgical and mechanical properties of laser-powder bed fusion processed Ti-6Al-4V alloy. This section also includes the literature review on methodologies utilized by various researchers to investigate the different additive manufacturing processes, their findings, and important factors that influence the product characteristics. The third section summarizes the research gaps based on literature reviews.

1.1 Introduction

Additive manufacturing (AM) is a process of making three-dimensional (3D) components through computer aided design (CAD) model by depositing the materials in a layered fashion, feeding the material in the form of either wire or powder, and using various melting sources available such as a laser beam or an electron beam [1, 2]. The flow chart of additive manufacturing process is shown in Figure 1.1. Design freedom for making complex components and no tooling cost has made additive manufacturing popular in recent years. Additive manufacturing processes have made an entry in aerospace [3], automobile [4], and biomedical sectors for making customized products [5].

According to ISO/ASTM standard, AM systems can be categorized into seven subcategories shown in Figure 1.2 [6]. For metallic materials such as Ti-, Al-, Fe-, and Ni-

based alloys, there are two types of AM systems - powder bed fusion (PBF) and powder feed or directed energy deposition (DED) [7]. The PBF class includes selective laser melting (SLM), direct metal laser sintering (L-PBF), electron beam melting (EBM), and selective heat sintering (SHS). For all these techniques, the term laser-based powder bed fusion (L-PBF) is recommended by ISO/ASTM standards [6]. In an L-PBF process, a required layer of the metal powder is applied to the build platform and the laser beam fuses the powder at selective points as per the computer-generated data. The build platform is then lowered, equal to the layer thickness, and another layer of powder is spread out. The material is then fused to form bonds with the layer beneath at predetermined points. This process continues until the component is fully built [8].

Ti-6Al-4V alloy is widely used for making aircraft parts, denture clasps [9] and several other components requiring high strength to weight ratio, chemical and biological inertness, and corrosion-resistance at elevated temperatures [10]. Additionally, the growing interest of using Ti-6Al-4V alloy in biomedical application is primarily due to a good combination of mechanical properties and corrosion resistance. However, it is challenging to fabricate using conventional machining techniques at room temperature due to significant tool wear and a low material removal rate. This alloy is kept in a difficult-to-cut material category because of poor thermal conductivity and low elastic modulus. This makes L-PBF process a viable option for the fabrication of complex Ti-6Al-4V components. To know the performance of L-PBF process, one must understand the microstructure evolved from the L-PBF process. During fabrication of the Ti-6Al-4V component by L-PBF process, due to the high rate of cooling, the α' martensitic phase completely dominates the microstructure. This α' martensitic phase can transform into $\alpha+\beta$ phases during the heat treatment process [11]. The additive manufacturing approach has drawn more attention in the field of manufacturing research because of its potential to

mitigate several significant shortcomings associated with conventional fabrication of Ti-6Al-4V components.

Various process parameters such as laser power, layer thickness, hatch distance, build orientation, and scanning velocity are used during the fabrication of components by the L-PBF process, which affect the tensile properties, microstructure, density, microhardness, surface finish, corrosion, wear, and biological behaviours of the final component. The average energy per unit volume of powder material during the scanning of a layer is known as energy density [12]. Out of various process parameters, the effect of build orientation also plays a crucial role on the microstructure, tensile properties, surface characteristics, corrosion, wear, and biological properties of L-PBF Ti-6Al-4V alloy.

Many studies have recently examined the performance of AM components by optimizing the process parameters of L-PBF process and also improving the microstructure through different heat treatment techniques [13]. By changing build orientation of the L-PBF processed components, their mechanical properties could be varied [14]. The as-built components fabricated by the L-PBF process exhibit high tensile strength, hardness, residual stress, porosity and martensitic α' -phase. All these factors lead to reduction in elongation [15] and that has been attributed to the difference in elongation of the different build orientations to manufacturing defects like weak bonding between two successive deposited layers, presence of partially melted or un-melted powder particles, etc. In the L-PBF process, it has been observed that thin α' martensitic laths form in the elongated prior β grains due to high temperature and fast cooling, resulting in high strength and low ductility [16]. After heat treatment, the α' martensite phase transforms into fine α platelets alongside of the β -phase. Due to presence of β phase, the total elongation increases, however, the strength decreases.

Therefore, a comprehensive study of the microstructure, tensile, corrosion, wear, and biological properties of L-PBF fabricated Ti-6Al-4V components is required before utilizing the L-PBF techniques. The components of the Ti-6Al-4V alloy have been fabricated by the L-PBF process with different build orientations (flat (0°), inclined (45°), and upright (90°)) and also subjected to heat treatment for relieving the associated stresses induced in the fabricated components. The aim of this study is to investigate the effect of build orientation and heat treatment on mechanical, corrosion, wear, and biological behaviour of the L-PBF Ti-6Al-4V components. The obtained results will aid in a better understanding of build orientation and heat treatment effect on mechanical, corrosion, wear, and biological behaviour of the L-PBF Ti-6Al-4V components used in aerospace and biomedical fields.

1.2 Literature review

This section discusses the literature review on overview, history, classification of additive manufacturing processes, different metallic materials fabricated by conventional as well as additive manufacturing, and their metallurgical, mechanical, surface, corrosion, wear, and biological properties.

1.2.1 Overview of additive manufacturing

Conventional manufacturing methods have limited use in manufacturing complex geometries of Ti-6Al-4V alloy. On the other hand, AM process is capable of manufacturing complex geometries used in the dentistry, aerospace, and automotive sectors [17]. Industries and researchers are attracted towards AM processes because these processes provide a unique opportunity to reduce lead time, eliminate dies, ease complex designs and optimization, and lighter components can be fabricated [15, 17]. The AM

process is a novel technique that can create 3D parts from the CAD model data through layer-by-layer deposition, it has been represented through the flow chart shown in Figure 1.1.

Components made by Additive Manufacturing (AM) have been extensively used in aerospace, defense, automotive, chemical, and nuclear industries [18]. However, by using subtractive manufacturing to produce complicated parts having inner cavities, cooling channels are very difficult to provide [19]. There are many disadvantages of subtractive manufacturing like high cost of prototyping, complex design, more setup time, wastage of materials, complex assembly required for complex designs, limited material combinations, etc. AM provides the platform where one can manufacture three dimensional components with many benefits over subtractive manufacturing like freedom of complexity, on-demand production, reduction in inventory, cost and time saving for prototyping, lighter and stronger better-performing parts enabled by design optimized software, reduction of wastage of materials, etc. [20-22].

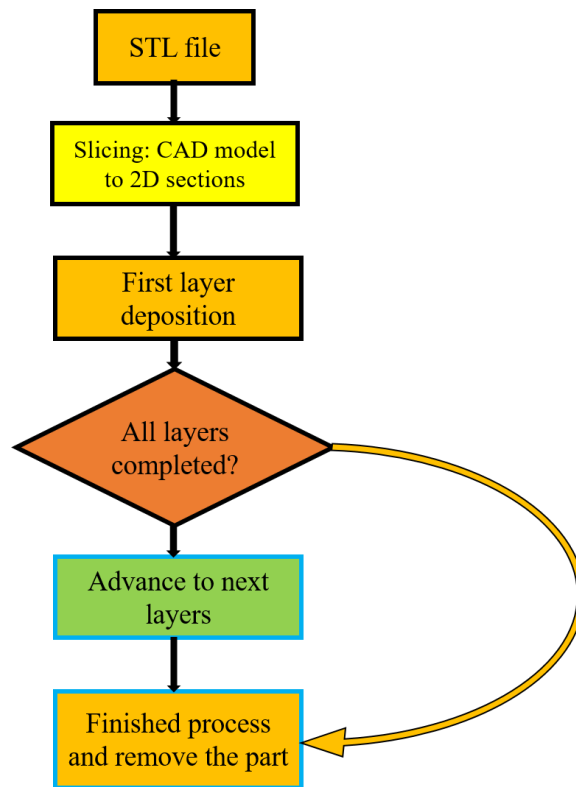


Figure 1.1 Flow chart of additive manufacturing process [23]

1.2.2 Classification of additive manufacturing processes for metals

The metal AM processes may be classified into four groups on the basis of the feedstock of material, energy supply, and build volume, among the other factors: (i) Sheet lamination or laminated object manufacturing (LOM); (ii) Powder bed systems; (iii) Powder feed systems or direct energy deposition (DED); and (iv) Wire feed systems [24]. Electron beam melting (EBM) and selective laser melting (SLM) are covered in powder bed systems, while powder feed systems include laser-engineered net shaping (LENS), direct metal deposition (DMD), and wire feed systems include wire arc additive manufacturing (WAAM) [25].

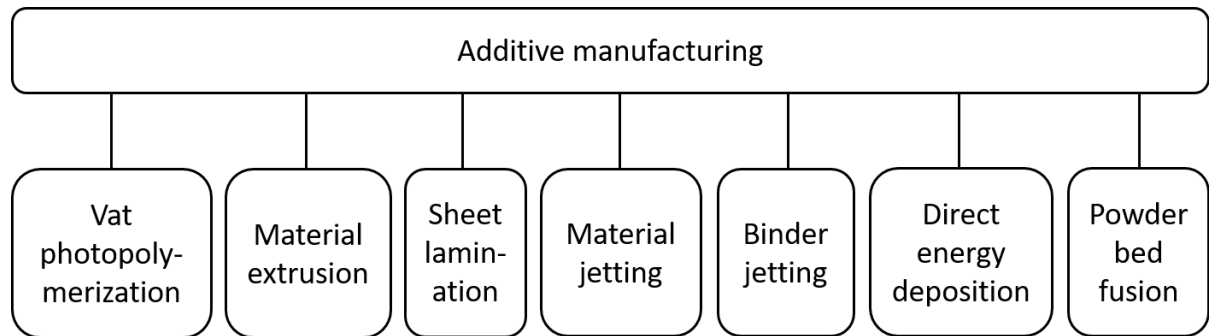


Figure 1.2 Classification of additive manufacturing

1.2.2.1 Sheet lamination or laminated object manufacturing (LOM)

The LOM method relies on cutting and laminating sheets in a layered fashion. Consecutive layers are precisely cut with either a laser beam, as shown in Figure 1.3, or a mechanical cutter and then bonded together (a technique known as form-then-bond) or vice versa (i.e., called the bond-then-form technique) [26]. Thermal bonding of metallic and ceramic materials is accomplished using the form-then-bond technique. This technique can also be used to create internal features by removing extra materials before bonding. The extra materials can be used as a support structure, and once completed, the support can be removed [27, 28]. Various materials such as paper sheets, ceramics, metallic tapes, and polymers could be used in this process, and post-processing techniques are also required depending on the different materials and required properties. This process has been used in a variety of industries, including foundry, paper, sensor, and processor manufacturing. Based on the LOM principle, ultrasonic AM is also on the rise, combining CNC milling with metal seam welding for the lamination process [29]. LOM has the distinct advantage of producing large structures while having low dimensional accuracy when compared to other AM processes. As a result, this process is not used for complex shapes or where precision is required [29, 30].

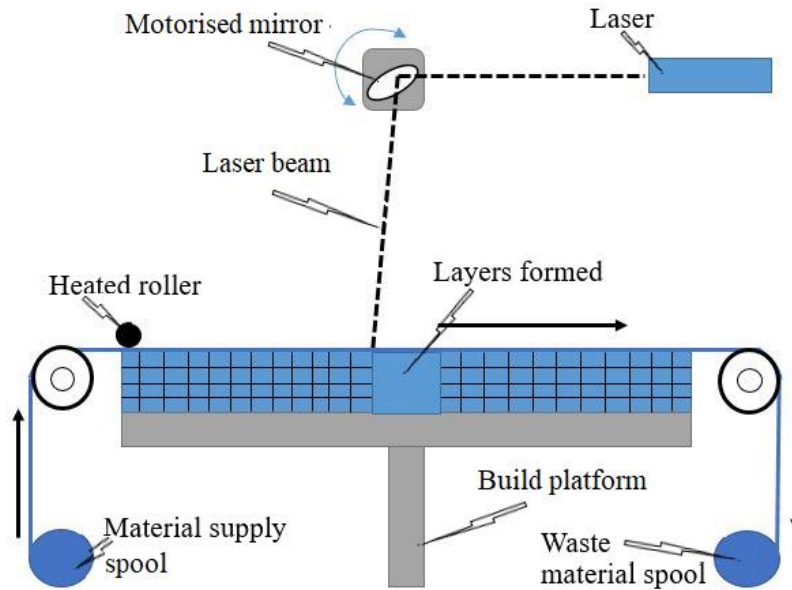


Figure 1.3 Schematic representation of laminated object manufacturing (LOM) process [31]

1.2.2.2 Powder bed fusion system

Powder bed fusion is employed in two common AM methods: selective laser melting (SLM) and electron beam melting (EBM). A metallic powder is dispersed into a thin layer and melted selectively by a precisely focused laser, fusing it to the previous layer. Part fabrication of customized metals and their alloys, such as maraging steel, Ti-6Al-4V, and Inconel alloy, is done in an inert gas-filled environment. Before proceeding with the actual process, the various laser process parameters such as power, spot size, wavelength, and laser type are optimized. Scanning process parameters include hatch spacing, scan strategy, and scan speed. Powder-related parameters include size, bed density, layer thickness, and powder morphology [32]. Unlike the laser beam in the SLM technique, the EBM method uses an electron beam to melt the metallic powder selectively. EBM, unlike SLM, fabricates parts inside a vacuum chamber with powder surrounding the part kept at a high temperature. Currently, EBM is also utilized to manufacture titanium alloy parts

[33]. The schematic representation of the selective laser melting method is shown in Figure 1.4.

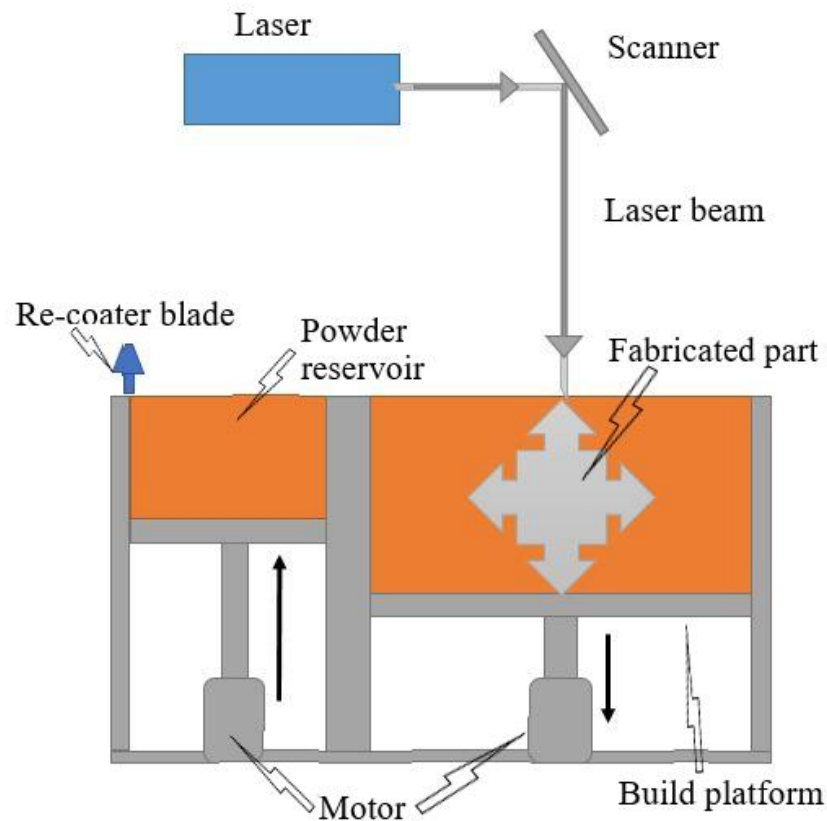


Figure 1.4 Schematic representation of powder bed system [34]

The EBM process is an AM method that involves melting metallic powders with an electron beam to obtain the geometry of a specific part. The use of an electron beam in the field of AM is relatively new. The schematic representation of the electron beam melting process can be seen in Figure 1.5.

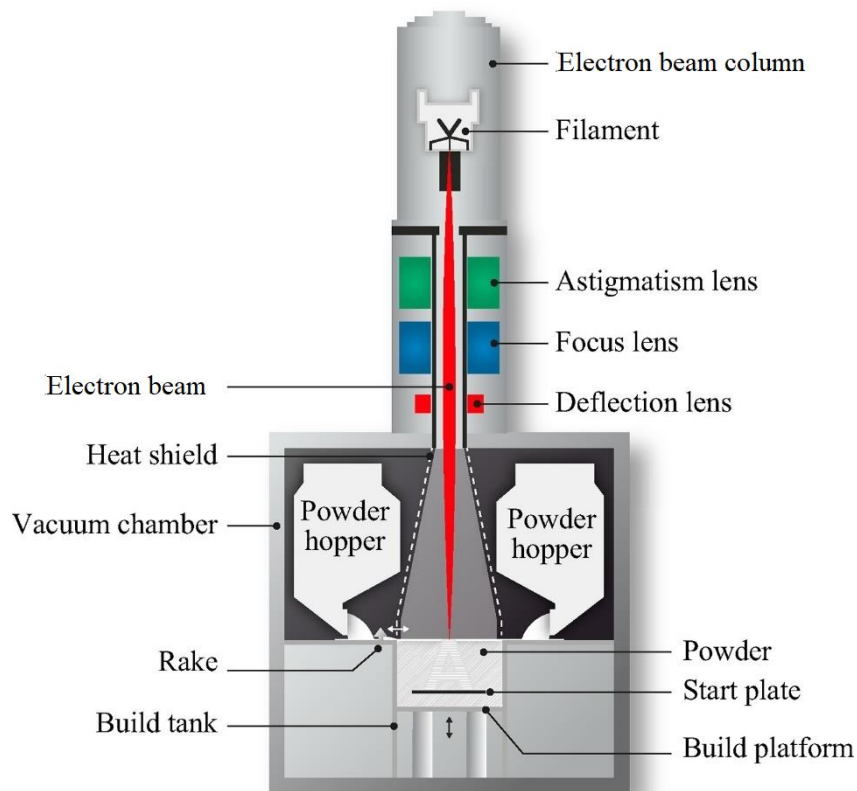


Figure 1.5 Schematic representation of Arcam electron beam melting process [35]

1.2.2.3 Powder feed systems or direct energy depositions (DED)

The DED process (also known as LENS) is used to fabricate high-performance alloys. This process is also called as direct metal deposition (DMD) and the electron beam melting (EBM) process [36-38]. As shown in Figure 1.6, a laser or electron beam is concentrated on a small area of the build plate and is utilized to melt feedstock powder material coming from the deposition head at the same time in a powder feed system. After the laser beam is moved, the molten material is placed and fused on the melting substrate, and the part solidifies [39]. There is no powder bed in this process, and similar to the fused deposition modelling process, the powder particles are melted with a lot of energy before deposition in a layered fashion. As a result, it is used for repairing, crack filling, and retrofitting manufactured components where SLM cannot be used. This method is

extremely useful for creating functionally graded materials (FGMs) by combining multiple materials, and it also allows multiple axis deposition [40, 41]. The main advantages of this method are its large work envelope and its high speed. However, when compared to SLM, this process has poor surface quality and dimensional accuracy and cannot produce high-complexity components [42]. This procedure is appropriate for large components, less complex components, and large-scale repair turbine engines [38]. The direct metal deposition method is displayed in Figure 1.6.

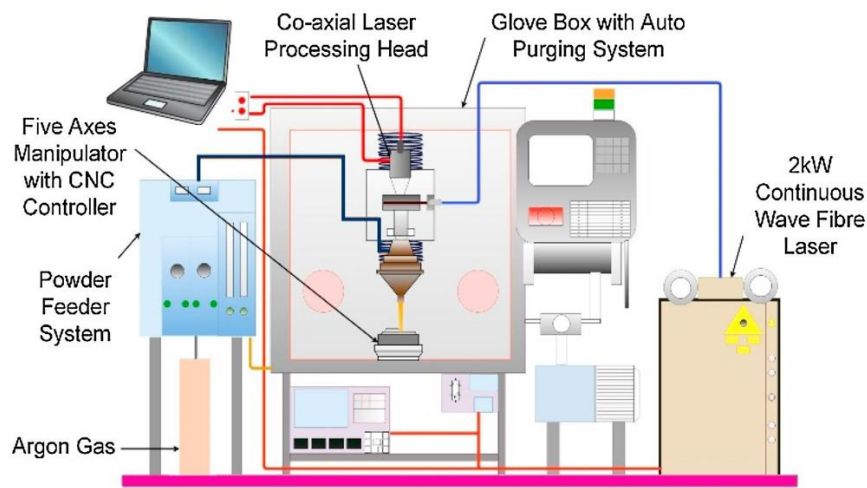


Figure 1.6 Schematic representation of direct energy deposition process [43]

1.2.2.4 Wire arc additive manufacturing (WAAM)

In many manufacturing industries, wire arc additive manufacturing (WAAM) has emerged as another technique for fabricating large metal components with high value. By considering the different types of heat sources, there are three primary WAAM techniques: Gas Tungsten Arc Welding (GTAW), Gas Metal Arc Welding (GMAW), and Plasma Arc Welding (PAW) [44]. WAAM (Figure 1.7) employs existing welding attachments, feedstock of welding wire, and electric arc as heat sources. Compared to

other AM technologies, this process has a higher material deposition rate. The energy and wire are fed simultaneously through consumable wire in the GMAW process [45]. The orientation of the welding wire feeding affects the accuracy and structure of the fabricated components. The GMAW offers some automation and productivity. The cold metal transfer technique based on the GMAW process has recently gained popularity due to its low heat input and efficient distribution of energy [46].

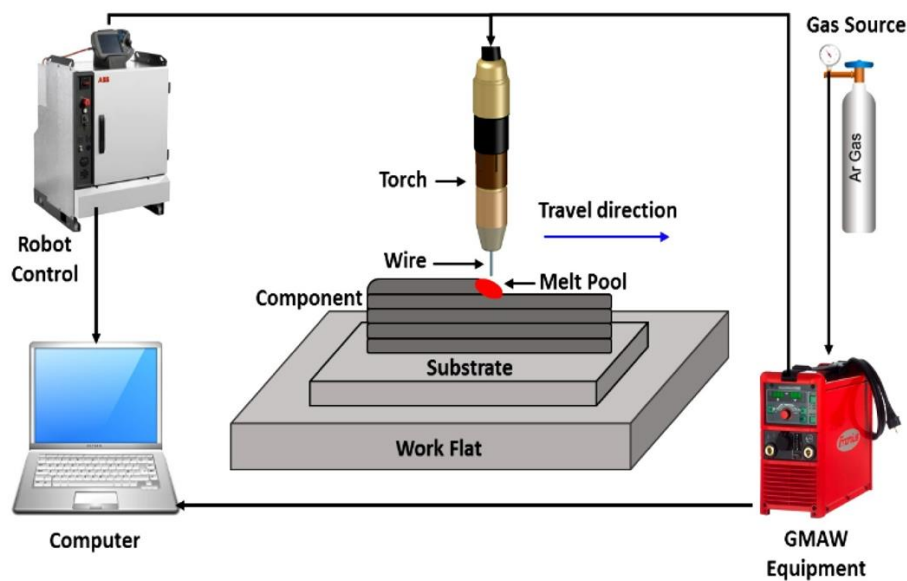


Figure 1.7 Schematic representation of wire arc additive manufacturing process [47]

1.2.3 Metallic materials for additive manufacturing

Any fabrication method, including AM, requires feedstock to be supplied in a form that is in line with the process (e.g., liquid, wire, sheet, and powder). In order to function well in the application, the material must have appropriate service qualities. The AM components are frequently post-processed in some way for the most demanding service applications to optimise the microstructure, reduce porosity, and minimise roughness in order to fulfil the

geometrical tolerances [48]. Table 1.1 categorizes the different types of materials used in the AM processes.

Table 1.1 Commercial materials for different AM processes

S No	Materials used	AM Process	References
1	Copper, tungsten carbide cobalt	Binder jetting	[49, 50]
2	Al alloys, Ti alloys, Co-Cr alloys, IN718, IN625, Maraging steel, Stainless steel	Selective laser melting (SLM)	[51, 52]
3	Al alloys, Ti alloys, Co-Cr alloys, IN718, IN625, Maraging steel, Stainless steel, Magnesium alloys, precious metals, Ni-Ti alloys, functionally graded materials	Direct energy deposition (DED)	[53]
4	Al alloys, Ti alloys, Inconel alloys, Fe-Al intermetallic	Wire arc additive manufacturing (WAAM)	[54]

The PBF and DED processes are used for metal and its alloys. The laser and electron beam-based AM techniques such as SLM/DMLS, DED, and EBM have been thoroughly explored to the point where they are now commercially available for a variety of standard metals, and alloys including steels, nickel-based superalloys, titanium, aluminium, magnesium, cobalt-chromium alloys, etc. The usage of a support structure is to control the part distortion during the build, managing cooling rates and scan strategies [55]. For the AM process, aluminium alloys are in high demand. The high heat conductivity, formation of oxides, and considerable solidification shrinkage are among the physical features of aluminium alloys that make them less suitable for the fabrication of repeatable and dependable parts. However, processing solutions have been devised to overcome these problems. For both powder and wire feedstock, PBF and DED processes may be utilized [56]. For fabricating Ti-6Al-4V alloy, the DED, SLM, and EBM processes are mostly used. Because of superior mechanical properties, steels (stainless steel, tool steel,

maraging steel) have been used in many applications like chemical, automobile, nuclear sectors, and processed by DMD, SLM, and EBM. The AM process has proven to be a feasible choice for the production of Co-Cr alloy removable partial denture (RPD) frameworks [57].

Because of unique functional qualities such as low rigidity, resistant against corrosion, excellent shape memory, superelasticity, low rigidity, biocompatibility, and damping properties nickel-titanium (NiTi) is a popular alloy. The AM approaches have gained popularity in recent years to produce sophisticated NiTi structures directly based on lattices and hollow constructions with applications in biomedical and aerospace sectors [58, 59].

1.2.4 Ti-6Al-4V alloy fabricated by conventional and additive manufacturing processes

While conducting the study of the existing literature, the earlier works undertaken by researchers are broadly classified into the following categories. The first section discussed literature reviews based on the effect of build orientation and heat treatment on microstructure and mechanical properties of additively manufactured Ti-6Al-4V alloy. In second section, literature reviews of surface characteristics of L-PBF Ti-6Al-4V alloy in dry, wet, and cryogenic environments have been discussed. Literature reviews based on corrosion behaviour of L-PBF Ti-6Al-4V alloy has been discussed in third section and literature reviews based on the wear and biological behaviour of L-PBF Ti-6Al-4V alloy have been discussed in the last section.

1.2.4.1 Effect of build orientation and heat treatment on microstructure and mechanical properties of additively manufactured Ti-6Al-4V alloy

Various process parameters are used during the fabrication of components by additive manufacturing process, which affect the tensile properties, microstructure, density, microhardness, and surface finish of the final component. The average energy per unit volume of powder material during the scanning of a layer is known as energy density [12]. Out of various process parameters, the effect of build orientation also plays a crucial role on the metallurgical and tensile properties of AM Ti-6Al-4V alloy. Hence, dedicated studies are needed to study the effect of build orientation.

Due to process parameters (laser power, beam width, layer height, build rate) involved in additive manufacturing of the Ti6Al4V alloy, defects like un-melted powder, pores, anisotropy in microstructure, residual stresses, and surface roughness are produced [60, 61]. Defects like un-melted powder and pores are created due to lack of fusion caused by insufficient power source, high built rate and trapped gas, which usually occur between layers and may be diminished by increasing laser power [62]. Spherical or round pores are developed by trapped gas inside the atomized powder, while irregular pores are produced by un-melted areas as shown in Figure 1.8 [61].

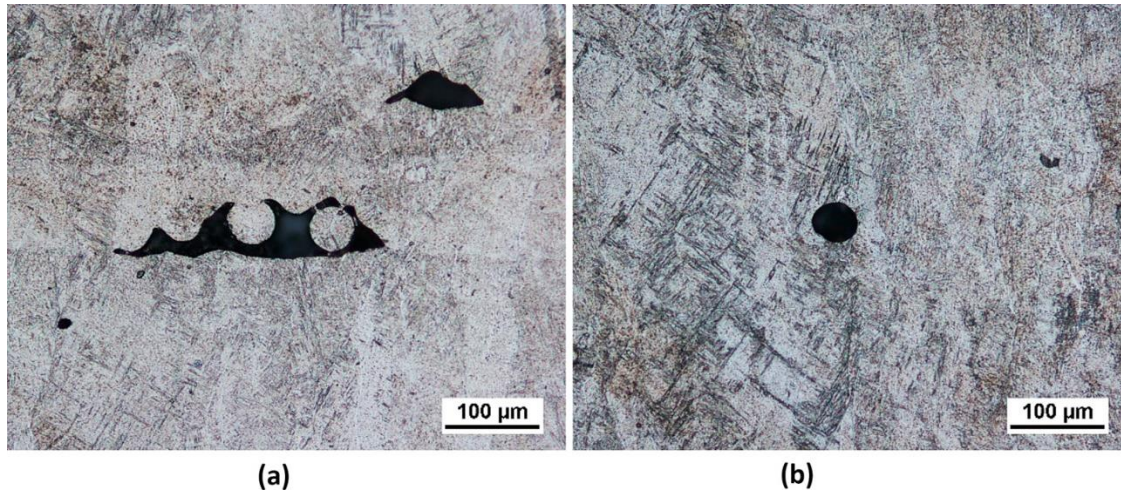


Figure 1.8 Porosity present in electron beam melting of Ti6Al4V: (a) pore due to lack-of-fusion and (b) gas pore [61]

Thijs et al. [12] discussed the microstructural evolution after selective laser melting process. They observed martensite phase in as-built samples due to high cooling rate during the AM process and the direction of elongated grains depended on the local heat transfer condition which was determined by scanning strategy. The elongated grains formed due to partial remelting of the previous layers. Simonelli et al. [13] fabricated Ti-6Al-4V alloy parts by SLM process and studied mechanical properties and fracture modes of SLM Ti-6Al-4V samples. They also observed α' martensite phase formed in the as-built components, after heat treatment at 730°C the residual stresses were relieved. The stress relieved samples had larger elongation at fracture but their yield strength and ultimate tensile strength were lower than that of the as-built samples. Yan et al. [63] fabricated Ti-6Al-4V ELI (extra-low interstitial) samples by SLM process and heat treated at 800°C for 1.5 h in an argon atmosphere to eliminate the residual stress, and cooled in furnace. They observed that the as-built samples exhibited high tensile strength but poor ductility compared to heat treated samples.

In recent years, many researchers studied the performance of AM components by optimizing the process parameters of L-PBF process and also improving the microstructure through different heat treatment techniques [13]. By changing build orientation of the L-PBF processed components, mechanical properties could be varied [14].

Ren et al. [15] fabricated Ti-6Al-4V samples with different orientations relative to build platform by SLM process and found difference in mechanical properties with different build orientations due to presence of residual stress, pore distribution and texture. The tensile strength of SLM Ti-6Al-4V alloy was minimum in 90° sample. The elongation of SLM Ti-6Al-4V was maximum in the 0° sample.

Hartunian and Eshraghi [11] investigated the effect of build orientation on tensile properties and microstructure of Ti-6Al-4V components, fabricated by the L-PBF technique. They observed that elongation at fracture of the 90° (upright) oriented sample was lower as compared to that of the 0° (flat) and 45° (inclined) oriented specimens. The 90° oriented samples failed shortly after loading and the fracture was brittle. They attributed the difference in elongation of the different build orientations to manufacturing defects like weak bonding between two successive deposited layers, presence of partially melted or un-melted powder particles. In the L-PBF process, thin α' martensitic laths form in the elongated prior- β grains due to high temperature and fast cooling, resulting in high strength and low ductility [16].

Simonelli et al. [14] discussed the effect of build orientation on tensile properties and modes of fracture and found that ductility and strength of the edge-orientated tensile specimens were higher, and due to the absence of α -colonies, the mode of fracture was

intergranular α along the boundaries of prior- β grain; heat treatment modified the phase composition of components.

Vilaro et al. [64] discussed the effect of heat treatment on mechanical properties and microstructure of L-PBF processed Ti-6Al-4V alloy and attributed the difference in mechanical properties and their fracture behaviour to manufacturing defects. Wauthle et al. [65] also investigated the effect of build orientation and heat treatment on mechanical properties and microstructure of the Ti-6Al-4V alloy prepared by L-PBF process and found that α' martensite phase transformed into fine α platelets alongside the β -phase. Due to the presence of β phase, the total elongation increases, however, the strength decreases. Some researchers have also used various characterization techniques like optical microscopy, scanning electron microscopy (SEM), diffraction technique, and electron backscattered diffraction (EBSD) to check the anisotropy of fabricated components, microstructure, and fracture modes under tensile loading.

The residual stress is an important defect that is generated due to the large temperature difference during the AM process. Residual stresses can result in deformation and distortions, and in some extreme cases, can cause cracking of parts or even build plates. Ultimately it causes accuracy problems in built part. The residual stress is affected by the following parameters [15, 66]:

- i. Heat conduction
- ii. Specimen height
- iii. Porosity
- iv. Support structure

The main reason for the generation of residual stress in the as-built samples is non-uniform phase equilibrium and plastic deformation during melting and solidification.

When metal powder is melted by the action of a laser, the nearby region of the melting zone generates sudden thermal distortion. When the laser beam is displaced from the region of molten zone, the molten zone solidifies and contracts. Due to the difference in temperature between the melting region and the nearby region, compressive stress is induced in the solidified region, therefore, residual stress is induced in the as-built AM components [55, 67]. According to many research papers, the induced residual stress can be eliminated by heat treatment at approx. 800°C for 2 hours [15, 64].

The microstructure of Ti-6Al-4V components manufactured using an AM process is typically composed of an acicular α' martensitic microstructure with low ductility. The microstructure produced by the AM process is neither equivalent to wrought nor cast part microstructures. Thus, heat treatment can help to increase ductility by reducing the strength of components. The heat treatment at 650°C for 1 h resulted in no microstructural changes, but heat treatment at the same temperature for 2 h resulted in fine β phase precipitation along the boundaries of the needle type α' phase [68, 69]. Heat-treated samples at 800°C for 2 hours underwent complete martensitic decomposition while retaining their refined microstructure, increasing ductility with a minor decrease in tensile strength, and microhardness [64, 65]. The influence of HT on the tensile properties and hardness of the AM Ti-6Al-4V components has been tabulated in Table 1.2.

Table 1.2 Effect of heat treatment on tensile properties and hardness of AM Ti-6Al-4V components

Sample	Hardness (HV)	Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation (%)	References
DMLS as-built	-	1070	1155	4.1	[70]
DMLS after HT	-	948	1008	8.4	[70]
DED as-built	-	1105 ± 19	1163 ± 22	4 ± 1	[71, 72]
DED after HT	-	907	956	10.8	[73]
SLM as-built	430 ± 10	1002.15	1023.9	11.5 ± 1.5	[11, 15, 74]
SLM after HT	340 ± 15	743 ± 19	964 ± 56	24.3 ± 0.7	[74, 75]
SLM ASTM F2924	-	825	895	6 - 10	[10]
EBM as-built	-	982.9 ± 5.7	1029.7 ± 7	12.2 ± 0.8	[76]
EBM after HT	-	778 - 943	885 - 1015	3 - 9	[77]
Wrought	370 ± 30	849 ± 1	934 ± 1	16 ± 1	[78]

It can be seen from Table 1.2 that mechanical properties of the AM components before the heat treatment, which showed high strength but low elongation at fracture. Due to this, these components could not be allowed to be used in high-loaded conditions. After HT, elongation at fracture of the components increased significantly, while strength decreased. Phase composition changed from α' to α and β phases and the ductility increased. Components after HT could be used in high loaded parts because of their high ductility with a decent level of strength.

Most of the earlier studies are centred on fabrication and characterization of L-PBF Ti-6Al-4V components with build direction parallel and perpendicular to thickness and only a few studies limited to lattice structures have been carried out on inclined orientations. Moreover, the combined effect of build orientation and heat treatment of the L-PBF components on their microstructure and mechanical properties has been less explored. Thus, it is essential to carry out systematic investigation on the microstructure and mechanical properties of the specimens of Ti-6Al-4V alloy with different build orientations in as-built and heat-treated conditions for proper inception of L-PBF as a potential process of manufacturing.

1.2.4.2 Surface characteristics of L-PBF Ti-6Al-4V alloy in dry, wet, and cryogenic environments

A major problem for end-users is the high surface roughness (Ra 5 to 10 μm and above) of additively manufactured Ti-6Al-4V alloy because of layered fabrication, which produces a stair casing effect on the surface of the specimens. Figure 1.9 (a) shows 3D CAD model generated by any commercialized software. Figure 1.9 (b) shows the slicing of 3D model into two-dimensional (2D) layers. Figure 1.9 (c) shows the actual physical output formed by AM process. Due to stacking of 2D layers, the generated model had

poor surface finish because of the “Stair Casing Effect”, as shown in Figure 1.9 (d). Many factors play an important role in deciding surface roughness of the AM fabricated samples, as follows:

- i. Layer thickness
- ii. Material
- iii. Powder particle size and their distribution on build platform
- iv. Wettability and viscosity
- v. Part orientation

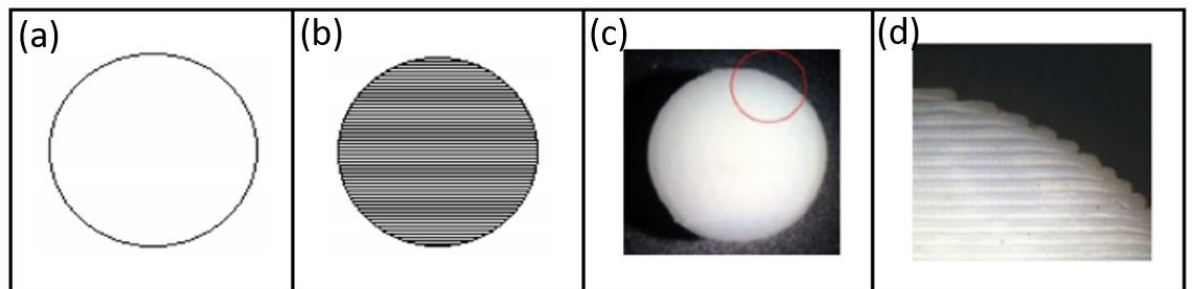


Figure 1.9 Layer-based additive manufacturing processes and related stair-stepping effect: (a) CAD model, (b) slicing, (c) actual output by AM, and (d) stair casing effect [79]

The components fabricated by AM processes have poor surface quality due to the use of large-sized powder particles (30-120 μm). However, ideally it will be beneficial to use small size powder particles $\leq 20 \mu\text{m}$ in order to have good surface characteristics after fabricating the components by AM processes [80]. But small sized powder particles influence the flowability of the powder and fail to spread the powder uniformly on the substrate, hence it is not desirable [81]. In addition to this, the production of small-sized powder particles will raise the fabrication cost of the components. The quality of the surface in the case of the EBM method is also critical [82]. This reflects that the

requirement for the quality of the surface plays a crucial role in considering the different post-processing techniques.

Several researchers have discussed and worked on various input process parameters related to the DMLS process such as layer height, scan orientation angle, and part orientation to minimize the stair casing effect [79, 83], and also some researchers focused on different post-processing techniques to get the desired surface finish [84, 85]. Post-processing techniques such as abrasive blasting, polishing, and abrasive grinding are used to achieve the desired surface roughness or finish of AM built models. Some of them are discussed below:

1.2.4.2.1 Polishing

Mechanical polishing is a type of mechanical surface processing that works by removing material from the top surface of the samples. It involves the use of fine abrasive particles to achieve a certain desired surface texture by removing the micron-sized chips from the surface [86]. Abrasive particles are stacked on polishing pads that are rubbed over the workpiece gradually. With the help of different grit sizes of polishing pads, mechanical polishing is used in stages to decrease the surface roughness gradually. After polishing with pads, a cloth pad is used for final polishing with mirror finish [87, 88]. A comparative optical microscopic image and color map can be seen in Figure 1.10. It can be seen from Figure 1.11 that the surface finish is improved from 15.22 μm to 9.12 μm after mechanical polishing [89]. Again, a comparative 3D surface profiles of as-built and mechanically polished Ti-6Al-4V samples can be seen in Figure 1.11 (c) and (d).

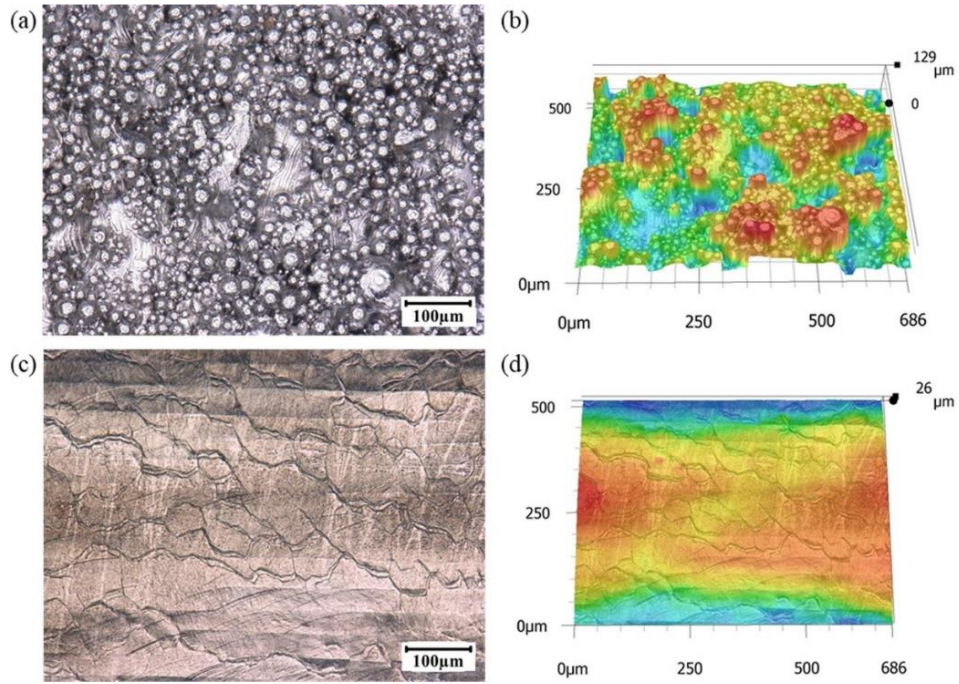


Figure 1.10 (a, b) Optical image and color map before polishing, and (c, d) optical image and color map after polishing [88]

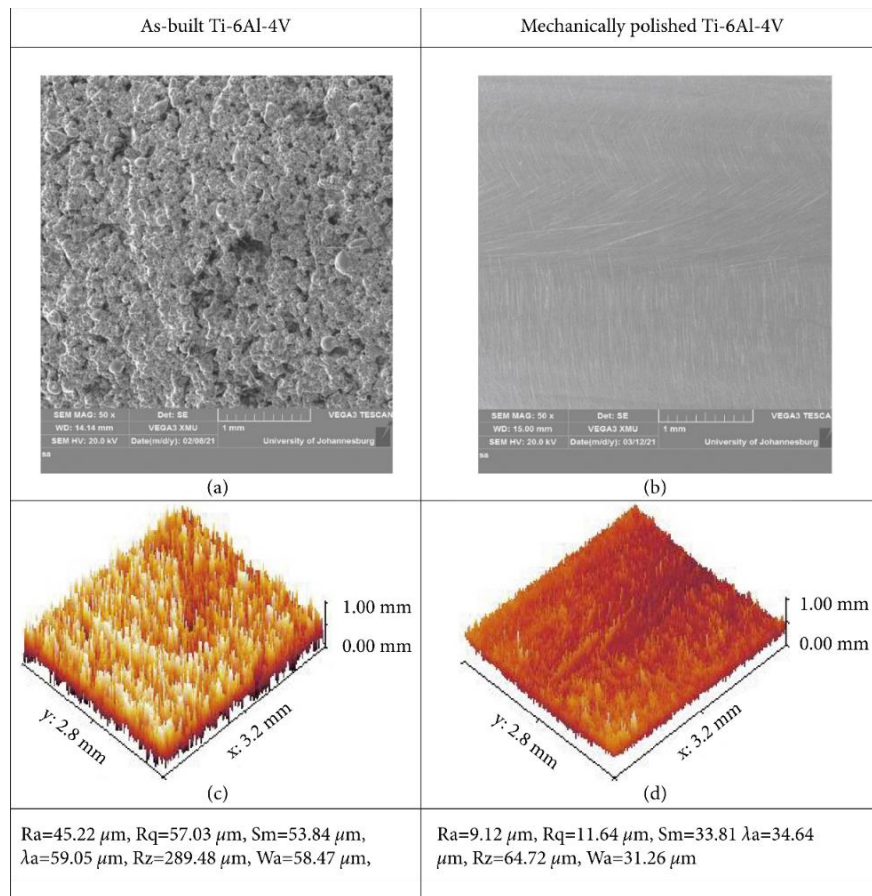


Figure 1.11 SEM micrographs of (a) as-built, (b) mechanically polished, (c) as-built 3D surface profile, and (d) polished 3D surface profile of AM Ti-6Al-4V samples [89]

1.2.4.2.2 Electropolishing

As a part of the post-processing method, electropolishing is used to provide a superior surface finish profile of the as-built Ti-6Al-4V alloy. As compared to other post-processing techniques, electropolishing has the advantage of polishing complex designed shapes quickly. Furthermore, despite the chemical and electrical combination in the process, the mass loss on the samples can be controlled [89]. Titanium alloys are recognized for their high oxygen affinity, which results in formation of a durable oxide coating that is resistant to disintegration. Despite utilizing an electrolyte solution with low water content, uncontrolled oxide film is formed during electropolishing of the Ti-6Al-4V alloy.

A laboratory power supply is used for electropolishing of the Ti-6Al-4V alloy. The anode is built of the fabricated Ti-6Al-4V specimen, and the cathode is made of a stainless-steel plate. The purpose of electropolishing is to improve surface finish of the as-built additively manufactured samples [89, 90]. Generally, the electrolytic polishing condition is determined after a significant number of trials. Using a roughness measuring tool, the surface roughness is assessed before and after electropolishing [91, 92]. The lowest surface roughness is measured as $9.52 \mu\text{m}$ [89]. The final SEM micrographs and 3D surface profile of electropolished AM Ti-6Al-4V alloy in electrolytes 1, 2, and 3 can be seen in Figure 1.12.

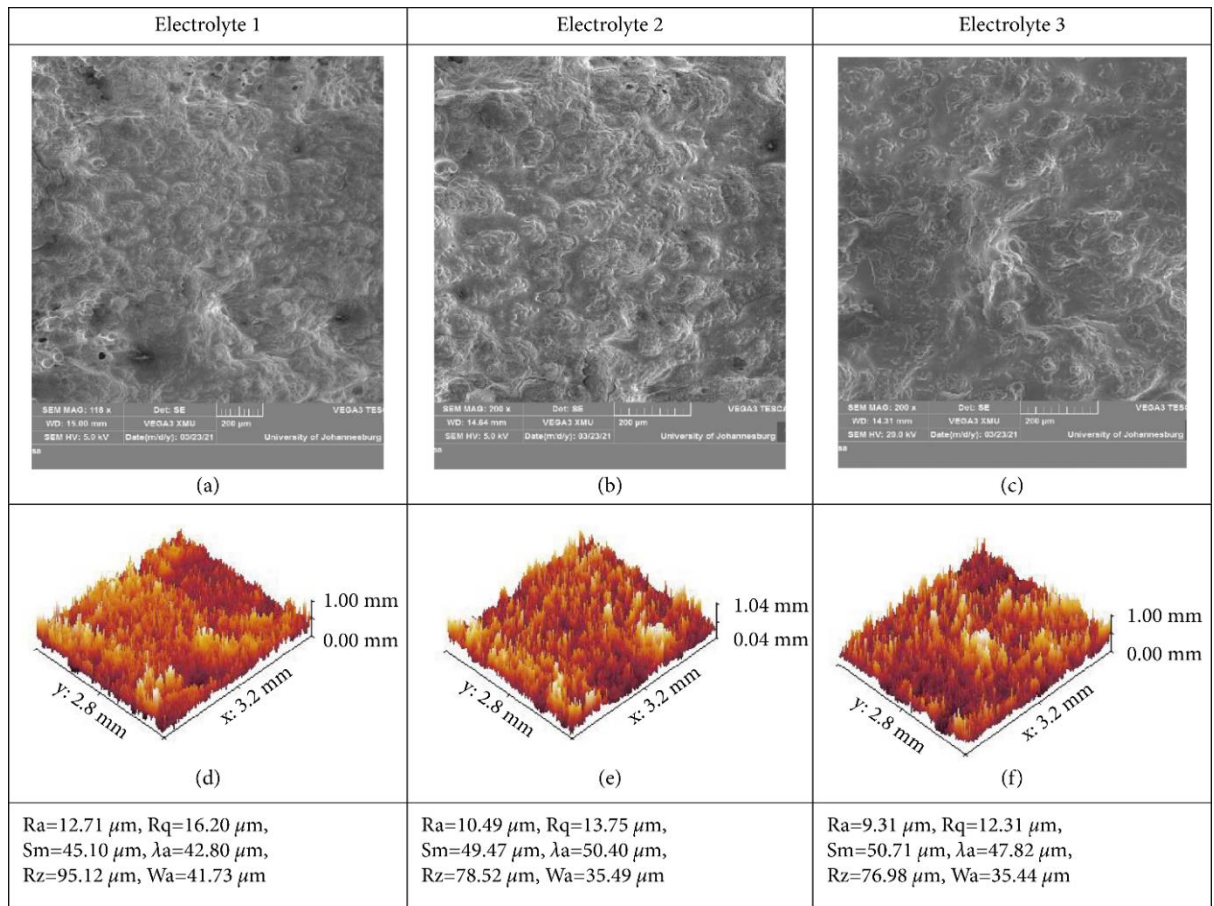


Figure 1.12 SEM micrographs of electropolished AM Ti-6Al-4V samples in (a) electrolyte 1, (b) electrolyte 2, (c) electrolyte 3, and (d), (e), and (f) 3D surface profiles of same samples in electrolyte 1, 2 and 3 respectively [89]

1.2.4.2.3 Abrasive flow machining

Abrasive flow machining polishes surfaces and edges by driving a flowable abrasive medium through or across the samples. Abrasion occurs where the flow of media is blocked and other regions are unaffected [85, 93]. It may process many passages on a sample at the same time, reaching locations that are normally inaccessible. This process is advantageous for finishing of difficult to access components [94, 95]. A single fixture may handle dozens of pieces at a time, resulting in output speeds of hundreds of parts per hour [96]. With the help of this process, surface roughness can be reduced from 53 μm to 2 μm [97, 98]. This process is applied to remove the surface defects produced due to

balling defects and the sticking of powder. The comparative analysis of the as-built and final polished surface texture can be seen in Figure 1.13.



Figure 1.13 Comparison of the as-built and the finished surface after AFM process [94]

1.2.4.2.4 Abrasive blasting/bead blasting

Abrasive blasting is a type of mechanical abrasive machining process that involves use of fine abrasive particles that are accelerated in a gas stream toward the surface to be treated to remove the material and change the texture of the surface of the as-built AM components [99, 100]. The particles slowly remove surface material when they hit the upper surface of the samples. The desired surface texture is achieved by repeating the process until the desired surface texture is reached, as shown in Figure 1.14. When abrasive particles collide on the surface of workpiece they may scatter or collide and produce indentations in ductile and craters in brittle materials. For this process, the impact velocity of abrasives is the important parameter. If this velocity is lower than the critical value, then abrasive particles will rotate only and material removal cannot be done because of insufficient energy [101].

In Figure 1.14 (a) and (b), SEM micrographs of the as-built and hot isostatic pressed AM samples have been shown, where unmelted and partially melted powder particles are clearly visible. In Figure 1.14 (c), SEM micrograph of sand blasted samples has been

shown, where sand blasting process is used to increase surface finish of top surface of the AM samples. If the impact velocity is high enough, then the abrasives rotate, scatter, and create a crater on the surface of the samples [101]. Other than impact velocity, the feeding medium, geometry, and type of abrasive are also important factors to improve the surface texture and tribological behaviour of the samples. The final micrographs of sand blasted, polished Ti-6Al-4V components can be seen in Figure 1.14 (c) and (d), respectively.

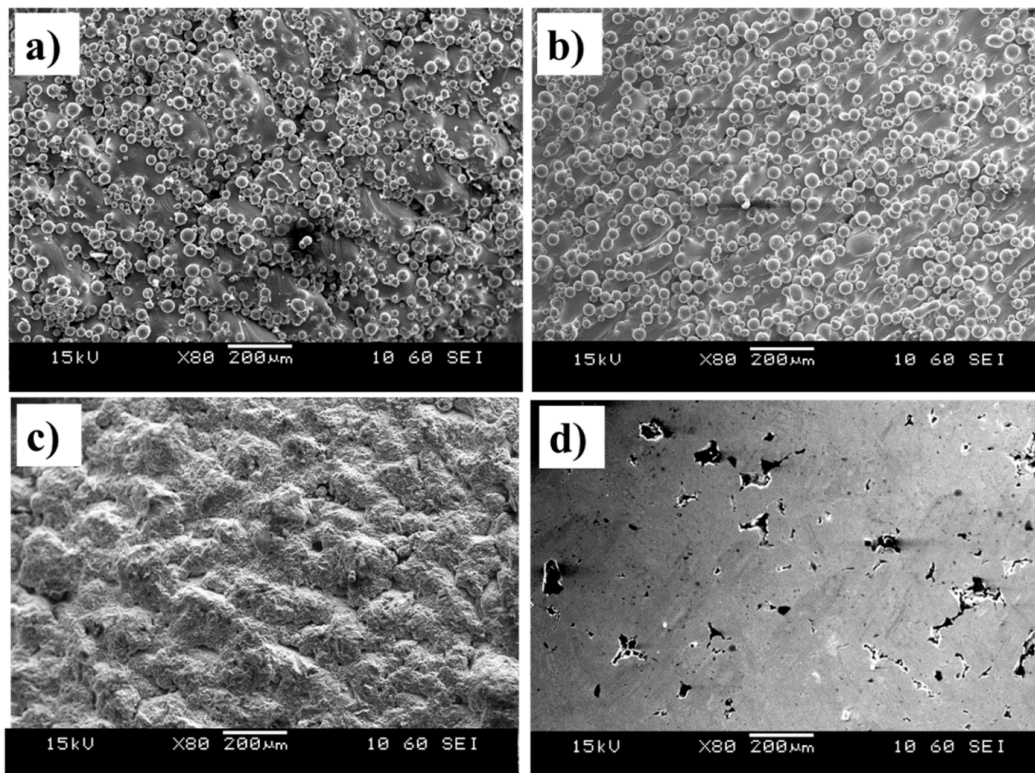


Figure 1.14 SEM micrographs of top surfaces of (a) as-built with samples after post processing ; (b) HIP, (c) sand blasted, and (d) polished AM Ti-6Al-4V components [100]

1.2.4.2.5 Abrasive finishing/grinding

Grinding is an abrasive finishing technique that can provide smooth surfaces and very accurate dimensions on machined components [102]. In abrasive grinding process, the surface finish and surface quality can be improved by using different grinding

environments. During abrasive grinding, samples are finished by removing the materials by the shearing and ploughing action of randomly distributed abrasive grits and can get close dimensional tolerances are achieved by the abrasive grinding process, changing the different input parameters like depth of cut, table speed, and using different grinding environments like dry, wet, and cryogenic.

Rotella et al. [103] discussed the quality of machined surface of the AM titanium materials and compared them with the conventionally manufactured components. They performed turning operation and checked the influence of the manufacturing method on surface topography of the final components. The surface finish trend demonstrated that the surface roughness of the conventionally manufactured components is superior to that obtained on the AM parts. Various researchers have demonstrated that machining process depends on the initial manufacturing methods (conventional and AM) even when the chemical composition of the powder materials does not change [103-105].

In the dry grinding process, there is a chance of heat accumulation in the machining area, which reduces the performance of abrasive action [106]. Due to this, problems have been encountered like over burning of the sample surface, lack of surface integrity, and also an increment in the grinding force. To overcome these problems, coolants are used to liberate the heat resulting in the machining region during the grinding process [107], and also for micro-chips from the grinding area during the finishing process.

Further, the friction between the abrasive tool and workpiece can also be reduced through the provision of enough lubrication [108, 109]. On the other hand, due to high rpm of the grinding wheel, a strong air zone forms near the wheel. As a result, traditional coolant is not effective in reaching the grinding zone, and it becomes difficult to control the generated heat at increased feed, which leads to thermal damage [110]. Furthermore,

cutting fluids boil and evaporate quickly at high temperatures, endangering the operator's health and the environment.

As a result, cryogenic cooling was considered, which is important for the finishing of rough AM samples. Balaji et al. [111] used cryogenic cooling as a replacement of traditional cutting fluids, which usually dissipates the heat produced during grinding and improves the cutting conditions in low temperature environment. Also, the cryogenic cooling medium improves the grinding wheel life and machinability by modifying the conditions of cutting tool and workpiece material properties [106]. Umbrello et al. [112] and Kaynak et al. [113] established that the surface roughness, grinding force, cutting temperature, and cutting responses have been considerably improved with cryogenic cooling as compared to dry grinding. Cryogenic grinding considerably contributes to the increased functional performance of grinded samples due to its excellent and preferable surface quality features.

In Table 1.3, the values of average surface roughness (R_a) and peak to valley height (R_z) are reported for evaluating the surface quality of the samples. The average surface roughness (R_a) parameter is the most important parameter according to the applications [114, 115]. Figure 1.15 shows the variation of average surface roughness obtained from different manufacturing and finishing processes. The values of surface roughness vary between different AM processes. The AM bar is far away from most of the processes and the challenge is to bring the bar to left, to match the average surface roughness obtained from other processes. In addition, it also depends on the metal powder particle size used in different AM processes. Finally, the surface quality of the components depends on the type of required applications. Small powder particle size is beneficial for mirror finished

samples so that the as-built surfaces become less rough before their applications and achieve the required surface without post-processing [116].

Table 1.3 Summary of surface roughness before surface finishing and after surface finishing roughness parameters in the literature

Sample	Before surface finishing		After surface finishing		References
	R_a (μm)	R_z (μm)	R_a (μm)	R_z (μm)	
Manual polishing	19.3 ± 2.4	133.9 ± 11.6	1.4 ± 0.5	7.0 ± 2.6	[90, 117]
Abrasive grinding	19.3 ± 2.4	133.9 ± 11.6	0.7 - 0.9	-	[116, 118]
Abrasive blasting/bead blasting	6.2	29.5	5.1	27.0	[116, 119]

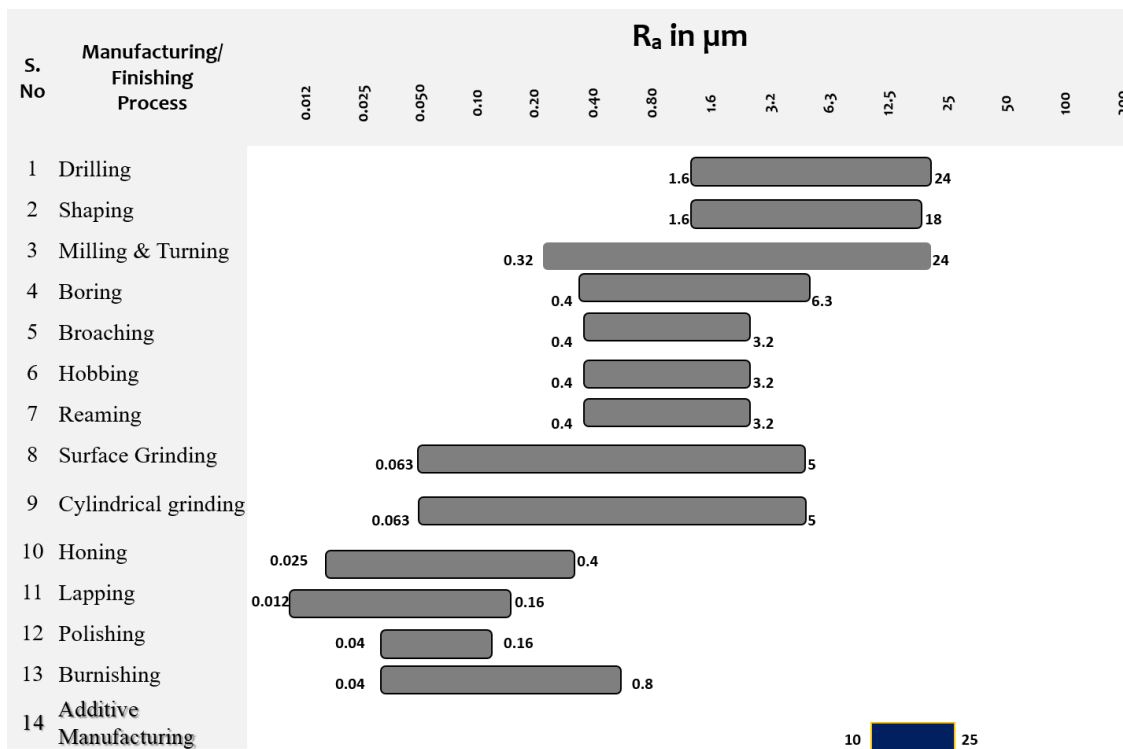


Figure 1.15 Surface roughness variation of different manufacturing and finishing processes

Although the use of dry, wet, and cryo environments in grinding operations has been demonstrated for different steels, there are few publications on cryo grinding of AM Ti-

6Al-4V alloy. The goal of this study is to elucidate the surface finish of additively manufactured Ti-6Al-4V alloy under different grinding environmental conditions. Grinding studies have been carried out on AM Ti-6Al-4V specimens at varying the depth of cut (DOC) and table speed under dry, wet, and cryogenic conditions. The best grinding conditions have also been optimized from the regression model. To determine the impact of the grinding environment, the additively manufactured Ti-6Al-4V alloy has also been finished with optimal settings to validate the regression model. Several characteristics like grinding forces, surface roughness, microhardness, and surface morphology have been evaluated.

1.2.4.3 Corrosion properties of L-PBF Ti-6Al-4V alloy

Nowadays, Additive Manufacturing (AM) is often utilized to manufacture metallic customized implants and medical devices [120]. Conventional manufacturing methods have limited use in manufacturing complex geometries. On the other hand, AM process is capable of manufacturing complex geometries used in the dentistry sector [121].

The number of patients requiring artificial alternatives or implants to replace failed tissue, such as hip joints, dental implants, prostheses, and surgical instrumental applications, has increased in recent years [120]. Many efforts have been made to identify appropriate biomaterials for the fabrication of long-lasting medical implants [122, 123]. The appropriate biomaterials should be biocompatible and cause no adverse reactions when using in the targeted applications [124]. Biomaterials should have superior mechanical properties and high corrosion resistance [125].

Many metallic materials such as 316L stainless steel, Co-Cr alloy, and titanium alloys are utilized as a biomaterial with desirable properties for replacing the failed tissue. Ti-6Al-4V alloy is becoming one of the most promising engineering materials used in the

biomedical field due to its exceptional biocompatibility, desired compressive strength, and good resistance to corrosion because of oxide films formed on the surface [126]. The growing interest of using Ti-6Al-4V alloy in biomedical application is primarily due to a good combination of mechanical properties and corrosion resistance [127].

Initially, commercially pure titanium (CP-Ti) was the favourable biomaterial for the fabrication of implants. The characteristics of CP-Ti may be improved by introducing some alloying elements like aluminium and vanadium. Ti-6Al-4V is among the most significant alloys, because of its superior strength-to-weight ratio, the existence of a non-reactive oxide film, and good mechanical properties [128]. A layer of passive film, composed of oxides of titanium, aluminium and vanadium, increases corrosion resistance of the Ti-6Al-4V alloy. The main disadvantage of Ti-6Al-4V alloy is that it degrades when it comes into contact with body fluids and may create some health issues [129]. In order to lessen these health risks, innocuous alloying elements like tantalum (Ta) and molybdenum (Mo) are added. These additions also stabilise the β -phase that is present in the microstructure [130]. However, the presence of these elements increases the component density, which may limit their usage for implant development [131].

Various chemical species like calcium chloride, phosphate ions and sodium chloride, are present in body fluids and interact with L-PBF fabricated implants. According the literature, these chemical species cause degradation of titanium alloy during interaction with body fluids [132].

Geetha et al. [133] indicated that 41 % biomedical implants fabricated from Ti-6Al-4V and 316L steel is failed due to corrosion and a combination of erosion-corrosion. Many attempts have been made regarding fabrication processes to improve the corrosion resistance of Ti-6Al-4V alloy. It has been noticed that the alloy produced with different

fabrication techniques may have slightly different corrosion resistance and, as a result, perform differently, even though with the same composition [134, 135]. Initially, wrought manufacturing techniques like casting, powder metallurgy, and machining were employed to fabricate biomedical implants of Ti-6Al-4V alloy [128]. But these techniques are very costly for fabrication of patient-specific implants. Therefore, additive manufacturing came into biomedical fields to fabricate the patient-specific implants. This study was focussed on corrosion behaviour of the Ti-6Al-4V alloy fabricated via additive manufacturing technique, under Ringer's solution.

One of the most utilized AM methods is laser-powder bed fusion (L-PBF) technology to fabricate Ti-6Al-4V alloy, with the advantages of customized fabrication, low cost, resource saving, and delivery at appropriate time [136]. The quality of additively manufactured Ti-6Al-4V implants depends on the size and shape of powder particles, process parameters, build orientation, and the selected additive manufacturing technique [123].

Furthermore, researchers have also investigated the effect of process parameters such as laser powder, hatch pattern, layer thickness, and build orientation on corrosion resistance of Ti-6Al-4V and manganese steel alloys [136-138]. The additive manufacturing methods utilized to fabricate biomedical implants include laser powder bed fusion, direct energy deposition, powder feed system, and electron beam-based powder bed fusion system. In laser powder bed fusion (L-PBF) process, the sample is fabricated in layer-by-layer fashion, as a result, high temperature gradient occurs during the process. The solidification rate in L-PBF process is different from the wrought methods, and that causes variation in corrosion resistance and mechanical properties.

The wrought fabricated Ti-6Al-4V alloy possesses better corrosion resistance compared to the laser-powder bed fusion processed Ti-6Al-4V alloy and the electron beam melted Ti-6Al-4V alloy is the most susceptible of all the samples tested [139, 140]. The grade 5 titanium alloy consists of α and β phases and the SLM processed Ti-6Al-4V alloy consists of acicular α' martensite with less amount of β phase. Corrosion resistance of β phase titanium alloy is high compared to α and β phase titanium alloy [141, 142]. This is the reason that SLM Ti-6Al-4V sample exhibits poor corrosion resistance than the wrought fabricated sample, as shown in Figure 1.16 [143]. So, the order of corrosion resistance in titanium alloys is $\beta > \alpha > \alpha'$. Sui et al. [144] discussed the effect of build orientation on corrosion resistance of selective laser melted Ti-6Al-4V alloy in 3.5 wt. % NaCl solution. They found that the 90° build oriented sample, exposed in the cross-section face, possesses better corrosion resistance than 0° and 45° oriented samples, while the 0° build oriented sample exposed in the longitudinal section possesses better corrosion resistance than 90° and 45° oriented samples. A similar conclusion was made also by Gong et al. [145] and Qian et al. [146].

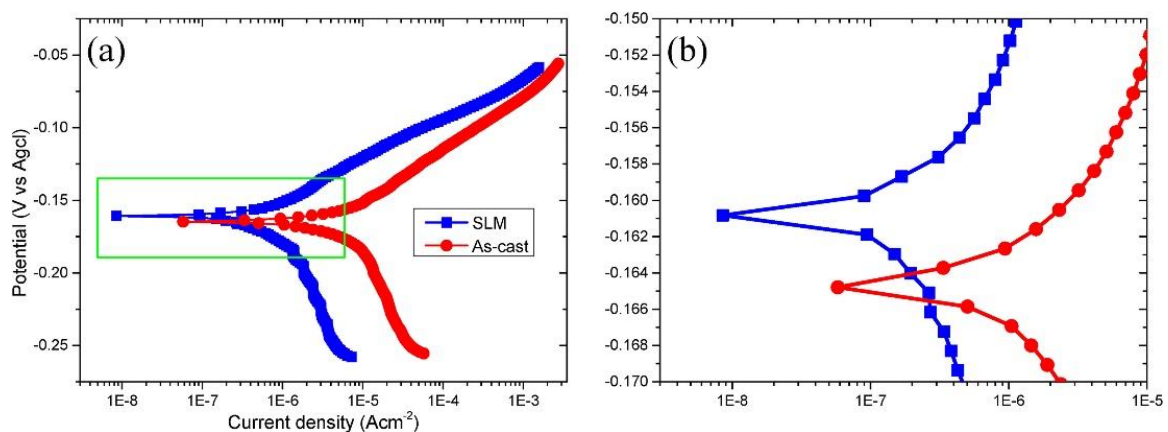


Figure 1.16 Tafel plots of (a) casted and SLM printed Ti-6Al-4V samples, (b) magnified view of (a) [143]

In addition, many researchers studied the effect of heat treatment on corrosion behaviour of Ti-6Al-4V alloy in Ringer's solution and found that heat treatment improves corrosion resistance of the Ti-6Al-4V alloy [147, 148]. In as-built SLM fabricated Ti-6Al-4V samples, the fine acicular α' martensitic microstructure was observed with fabrication defects like pores and residual stresses [15]. After heat treatment at 900°C for 1 h, the fine martensitic microstructure transformed into α and β phases, which increases the corrosion resistance [128, 134]. In addition, this phase transformation also increased the chance of the development of protective passive layers on the surface of the heat-treated components, which are not conductive. Developed oxide layers protect the surface of the Ti-6Al-4V from extreme conditions.

There is hardly any literature on the combined effect of build orientation and heat treatment on corrosion behaviour of the L-PBF Ti-6Al-4V alloy in presence of various chemical species. The microstructural and chemical analysis, following corrosion test has not been discussed thoroughly. Also, no detailed chemical analysis has been carried out to assess the improvement in corrosion resistance following HT and build orientation.

1.2.4.4 Wear and biological behaviour of L-PBF Ti-6Al-4V alloy

1.2.4.4.1 Wear behaviour of L-PBF Ti-6Al-4V alloy

In recent years, laser-powder bed fusion (L-PBF) process is a widely used technology for fabricating components of Ti-6Al-4V alloy, popularly known for excellent strength-to-weight ratio, corrosion resistance, and biocompatibility [149]. This alloy is extensively used in orthopedic implants due to its biocompatibility and excellent mechanical properties [150]. During chewing, micromovements may occur between prosthetic joints causing a relative motion between contacting surfaces, leading to wear [151].

However, the associated hardness of the as-built AM samples has an adverse impact on their wear properties and limits their applications, which exhibit sliding motion when in contact against any mating components. The variation in hardness of the Ti-6Al-4V alloy originates from the fabrication of components in different build orientations, where sample is fabricated at angles of 0° , 45° , and 90° with respect to build platform. The wear volume increased with increased normal load, as shown in Figure 1.17 (a). The wear was dominated by abrasive wear and slight adhesive wear under a low load, and delamination, oxidative wear, and adhesive wear coexisted under high loads. The wear volume first increased and then decreased with increased sliding velocity, as shown in Figure 1.17 (b). The wear mechanisms were abrasive wear at a low sliding velocity and oxidative wear at a high sliding velocity [152, 153].

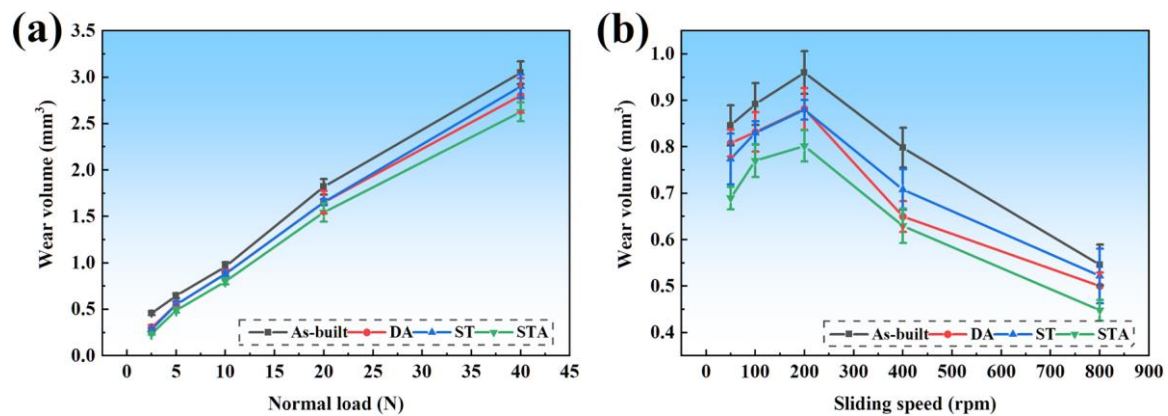


Figure 1.17 Wear volumes versus (a) normal loads and (b) sliding velocities for all the tested Ti-6Al-4V alloy samples [152]

Bartolomeu et al. [154] studied the influence of the processing routes, conventional casting, hot pressing and selective laser melting, on tribological behaviour of the Ti-6Al-4V biomedical alloy. They performed experiments on reciprocating ball-on-plate tribometer and found that the highest hardness and wear resistance were obtained for the Ti-6Al-4V alloy processed by selective laser melting, due to a markedly different cooling

rate that leads to significantly different microstructure compared to that processed by hot pressing and casting, as shown in Figure 1.18. Sliding grooves are observed on all the samples due to abrasive wear, as shown in Figure 1.19. The largest wear track was obtained in the cast Ti-6Al-4V samples (Figure 1.19 (a₁–a₃)) and lowest wear track width was found on Ti-6Al-4V samples fabricated by the SLM process (Figure 1.19 (c₁–c₃)).

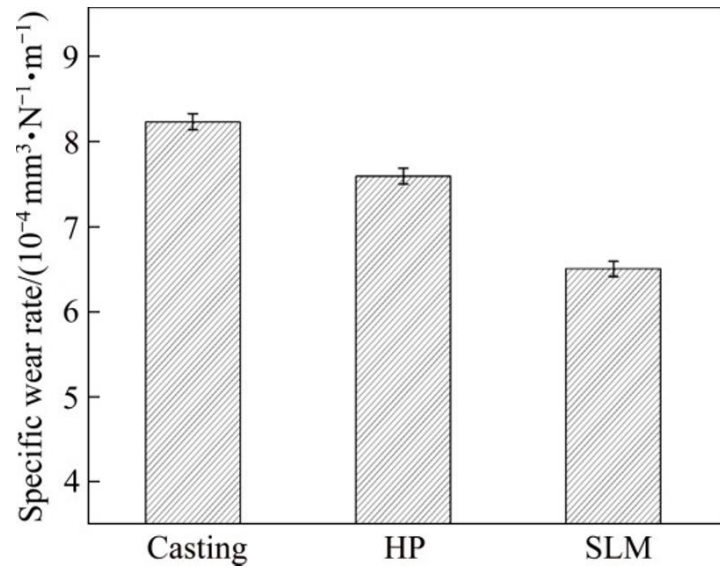


Figure 1.18 Specific wear rate of Ti-6Al-4V plates fabricated by casting, HP and SLM against Al₂O₃ ball [154]

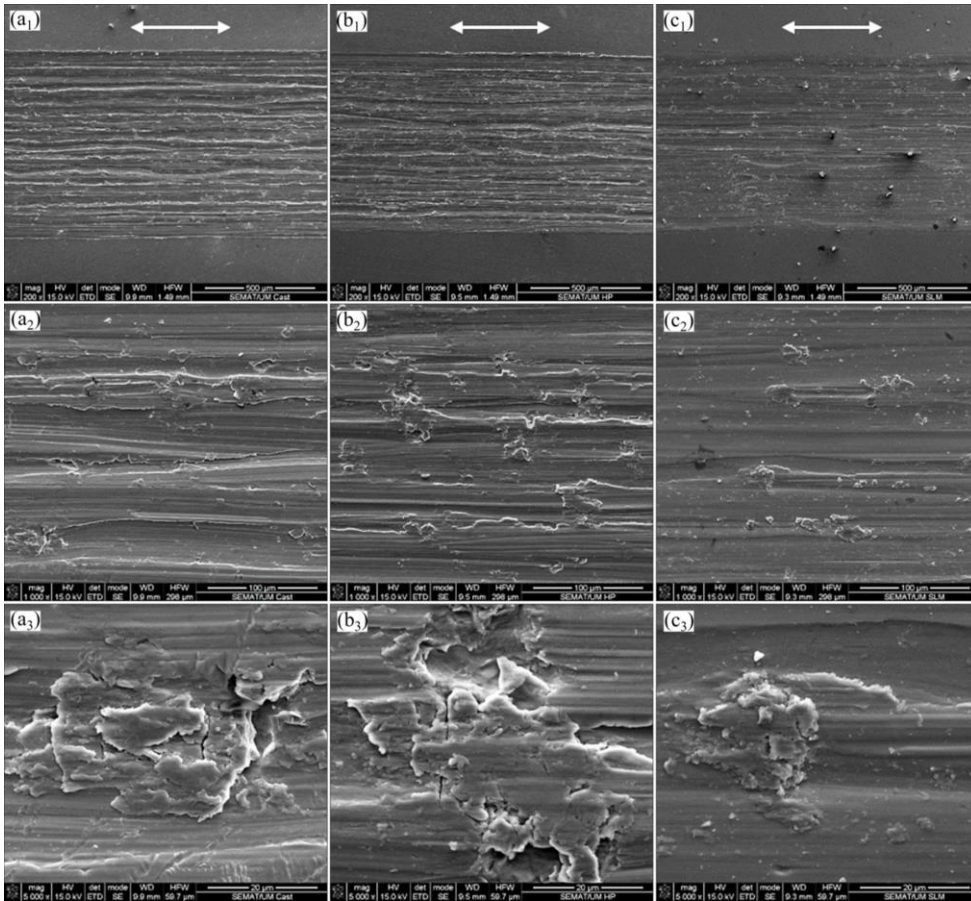


Figure 1.19 SEM micrographs of wear tracks formed after reciprocating sliding tests of Ti-6Al-4V alloy against Al_2O_3 balls in the presence of PBS solution: (a₁–a₃) Casting; (b₁–b₃) HP; (c₁–c₃) SLM [154]

Hua Li [155] conducted dry linear reciprocating experiments on selective laser melted (SLM), electron beam melted (EBM), and conventionally processed (CP) Ti-6Al-4V alloy to evaluate their wear resistance. The insignificant difference in wear rate among the three types of samples has shown that wear rate is not inversely proportional to hardness, that varies due to the difference in the three manufacturing routes of the alloy used in this study: high hardness (428 HV) in SLM samples, medium hardness (359 HV) in EBM samples and low hardness (324 HV) in CP samples. Ti-6Al-4V alloy with higher hardness may collapse under a high normal load or high sliding velocity, which will be highly detrimental for industrial applications. It is qualitatively suggested that the inverse relationship between strength and ductility of the alloy explains that why hardness has no

effect on wear rate. A large deformation zone resulted due to low hardness and thus low strength of the alloy, but higher ductility of the alloy permits a greater degree of deformation without increasing the risk of fracture and wear loss [149].

The effect of build orientation on wear behaviour of the additively manufactured Ti-6Al-4V alloy has also been reviewed. Palanisamy et al. [156] investigated the effect of build orientation on wear volume loss of a laser additive manufactured Ti-6Al-4V alloy. Rotary wear tests were carried out under varying loads of 5 N, 15 N and 25 N at 25 m/s. They proposed that the as-built vertical sample exhibited more wear volume loss than the as-built horizontal sample due to the less formation of protective oxide layer.

In addition, As-built AM parts require additional post processing steps to achieve the desired surface characteristics. The heat treatment process has positive impact on tribological performance of the L-PBF processed Ti-6Al-4V components. Palanisamy et al. [156] also investigated the effect of heat treatment on the wear volume loss of a laser additive manufactured Ti-6Al-4V alloy specimen. They proposed that the heat-treated sample exhibited less wear volume loss than the as-built samples due to compact oxide debris on the surface. They also proposed that the heat treatment showed more influence than build direction on wear of laser additive manufactured Ti-6Al-4V alloy.

Su et al. [152] implemented the different heat treatment techniques like direct aging and solution-aging treatments on a laser powder bed fusion-processed Ti-6Al-4V alloy to enhance its tribological performance, as shown in Figure 1.20 (a). Dry sliding wear tests (Figure 1.20 (b)) were performed over a wide range of normal loads from 2.5–40 N and sliding velocities from 50–800 rpm. Wear volume of the Ti-6Al-4V alloy increased with an increase in the applied load, while the coefficient of friction (COF) decreased

simultaneously. The decrease in the COF can be attributed to the integrated effects of frictional heat and movable oxide particles.

However, these studies are mainly focused on the samples fabricated parallel to the build plate and their effect on wear behaviour of those samples. For the L-PBF processed Ti-6Al-4V samples, the combined effect of build orientation and heat treatment on the tribological performance has not been investigated yet.

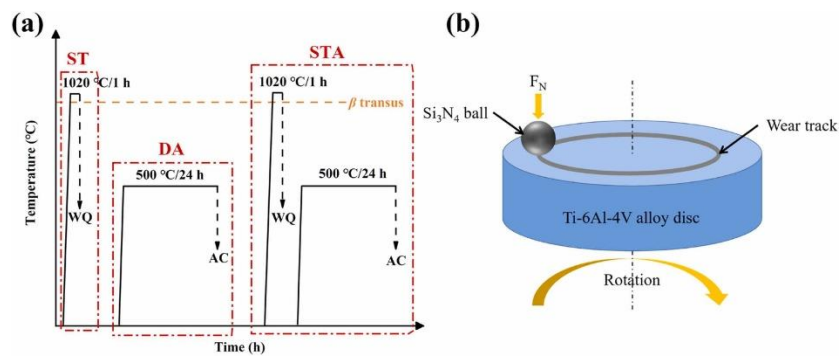


Figure 1.20 Experimental details: (a) illustration of the heat treatment processes and (b) schematic diagram of the ball-on-disc measurement [152]

1.2.4.4.2 Biological behaviour of L-PBF Ti-6Al-4V alloy

Titanium and its alloys are most popular material in biomedical applications because of high corrosion resistance, high strength to weight ratio, and low density [157]. Ti-6Al-4V is used mainly in Cardiovascular, Orthopedic, and Craniofacial division of biomedical applications [158]. Customized components are needed in biomedical fields and for this additive manufacturing is playing important role in fabricating customized components.

Romero-Resendiz et al. [159] studied the feasibility of an electron beam melted Ti-6Al-4V alloy as biomaterial for implants and compared with conventional Ti-6Al-4V alloy. Cells were cultured for 5 h and 27 h for the cell adhesion and proliferation assays

respectively. They observed that higher area average roughness boosted the adhesion, proliferation, and biofilm formation of osteosarcoma (MG-63).

Singh et al. [160] fabricated the Ti-6Al-4V samples by hybrid manufacturing technique combining EBM with friction stir processing to enhance the implant surface properties. The EBM with friction stir processed surface observed an increase in the cell viability as compared to the unprocessed EBM surface because of reduction in roughness from 44.77 μm to 15.82 μm . Surface with appropriate roughness can provide more attachment sites for cells, promoting better adhesion and spreading. However, excessively rough surfaces may hinder cell adhesion and proliferation.

Bernhardt et al. [161] fabricated Ti-6Al-4V ELI samples and then post-processed to adjust the surface roughness using the various surface improvement techniques such as sand blasting, electro polishing, or vibratory finishing. They observed that the cells are attached with good adhesion and proliferation on all the finished samples. Chudinova et al. [162] fabricated Ti-6Al-4V scaffolds by EBM process and observed that the additively manufactured Ti-6Al-4V scaffolds are promising material for bone repair.

1.2.4.5 Modelling and simulation of additively manufactured Ti-6Al-4V alloy

Additive manufacturing (AM) of Ti-6Al-4V has become popular due to its ability to produce complex geometries and achieve high strength-to-weight ratios. However, the unique thermal history experienced during AM processes leads to complex microstructures and residual stresses, significantly impacting the material's properties. Modelling and simulation are powerful tools for understanding and predicting the behaviour of additively manufactured Ti-6Al-4V alloy. The different aspects of modelling and simulation are described in brief below.

Thermal Modelling

A key aspect of AM simulation is accurately predicting the temperature distribution within the build. Finite element analysis (FEA) is a commonly used technique that considers factors like laser power, scan speed, and layer thickness to model the heat source and its interaction with the surrounding material. This information is crucial for understanding:

- **Melt pool dynamics:** Modelling the melt pool behavior helps determine factors like molten metal flow, solidification rates, and potential defects like porosity.
- **Residual stress formation:** The rapid heating and cooling cycles during AM create significant thermal gradients. Thermal modelling allows prediction of these gradients and their contribution to residual stresses, which can affect mechanical performance.

Mirkoohi et al. [163] proposed a physical based analytical model to predict the temperature profile during metal AM processes. The authors considered the effect of temperature history in each layer, latent heat and temperature sensitivity of material properties. The suggested model can be used to forecast temperatures in laser-based metal AM systems. The authors also conducted a numerical analysis to simulate the temperature profile in metal AM processes.

Microstructure Modelling

The complex thermal history experienced during AM significantly influences the microstructure of Ti-6Al-4V. Modelling this evolution helps predict final properties like grain size, phase fractions, and texture. Common approaches include:

- **Phase-field models:** These models simulate the evolution of microstructure based on thermodynamic principles and diffusion phenomena. They can predict the formation of different phases (e.g., α' , α , β) and their distribution within the material [164].
- **Cellular automata models:** These models represent the microstructure as a grid of cells, with each cell representing a specific phase or grain. The model evolves based on predefined rules governing grain growth and phase transformations [165, 166].

Chen [167] discussed the phase-field model for different material processes, including solidification, solid-state structural phase transformations, grain growth and coarsening, domain evolution in thin films, pattern formation on surfaces, dislocation microstructures, and crack propagation.

Material Property Modelling

By coupling thermal and microstructure models with material property databases or constitutive equations, researchers can predict the mechanical properties of the additively manufactured Ti-6Al-4V component. This allows for virtual testing and optimization of build parameters for desired properties.

Despite the advancements in modelling the AM of Ti-6Al-4V, several challenges remain:

- **Model Validation:** Experimental validation of model predictions is crucial for ensuring their accuracy. However, obtaining high-fidelity experimental data on microstructure and mechanical properties at the microscale can be challenging.
- **Multiscale Modelling:** Integrating models operating at different scales (atomic, grain, macroscopic) is desired to capture the complex interplay between processing, microstructure, and properties.

- **Process-Specific Modelling:** Different AM techniques (e.g., Selective Laser Melting (SLM), Electron Beam Melting (EBM)) have distinct process characteristics. Tailoring models to account for these specificities can improve accuracy.

By addressing the current challenges and exploring new avenues, researchers can further use these models for optimizing AM processes and designing high-performance components.

1.3 Research gaps identified from the literature review

From the literature review, it has been concluded that followings are research gaps in the area of L-PBF Ti-6Al-4V alloy.

1. Most of the earlier studies are centred on fabrication and characterization of L-PBF Ti-6Al-4V components with build direction parallel and perpendicular to thickness and only limited studies on lattice structures have been carried out on inclined orientations.
2. The combined effect of build orientation and heat treatment of the L-PBF components on their microstructure and mechanical properties has been less explored.
3. No discussion has been carried out on the effect of build orientation and heat treatment on residual stress of L-PBF Ti-6Al-4V samples.
4. Although the use of dry, wet, and cryogenic environments in grinding operations has been demonstrated in grinding operations of materials like different types of steels, there are few literatures on cryogenic grinding of L-PBF Ti-6Al-4V alloy.
5. No experimental investigations have been carried out on the effect of build orientation and heat treatment on corrosion behaviour of L-PBF Ti-6Al-4V alloy.
6. No experimental investigations have been carried out on the effect of build orientation and heat treatment on wear and biological behaviour of L-PBF Ti-6Al-4V alloy.

1.4 Objectives

Based on the research gaps, following objectives have been planned for the current study.

1. Fabrication of Ti-6Al-4V samples by Laser-Powder Bed Fusion process in different build orientations of 0°, 45°, and 90°, followed by heat treatment at 800°C for 1.5 h in an argon atmosphere and cooled in furnace.
2. A comprehensive study on the effect of build orientation and heat treatment on the microstructure, residual stress, mechanical properties, and fracture mechanism of the L-PBF produced Ti-6Al-4V alloy.
3. To examine the effects of grinding environments (dry, wet, and cryo) on surface roughness and microhardness of the L-PBF Ti-6Al-4V alloy, followed by characterization of grinded surfaces.
4. To evaluate corrosion behaviour of the L-PBF Ti-6Al-4V alloy with potentiodynamic polarization (PD) and electrochemical impedance spectroscopy (EIS) tests.
5. To evaluate wear and biological behaviour of the L-PBF Ti-6Al-4V alloy fabricated in different build orientations.

With the above introduction and literature review on mechanical, corrosion, and biological behaviour of additively manufactured Ti-6Al-4V alloy, materials and methods have been discussed in chapter 2.