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ORIGINAL ARTICLE

Review on direct metal laser deposition manufacturing technology for the Ti-6Al-4V alloy

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Abstract

Direct laser metal deposition (DLMD) is a breaking edge laser-based additive manufacturing (LAM) technique with the possibility of changing the perception of design and manufacturing as a whole. It is well suitable for building and repairing applications in the aerospace industry which usually requires high level of accuracy and customization of parts; this technique enables the fabrication of materials known to pose difficulties during processing such as titanium alloys. Ti-6Al-4V, which is the most employed titanium-based alloy is one of the materials that are most explored for additive manufacturing process. However, this process is currently at its pioneer stage and very little is known about the fundamental metallurgy and physio-chemical basis that govern the process. Currently, the major problems faced in additive manufacturing include evolution of residual stresses leading to deformed parts and formation of defects such as pores and cracks which are detrimental to the quality of deposits. The presence of these unwanted defects on additively manufactured parts depends on the complex mechanisms taking place in the melt pool during melting, cooling, and solidification which are dependent on processing variables. In addition, during fabrication, some feedstock powder does not melt and thus does not make up part of the final product. The present text entails classification of LAM technologies, operational principles of DLMD, feedstock quality requirements, material laser interaction mechanism, and metallurgy of Ti-6AL-4V alloy.

Keywords DLMS · Process variables · Powder recycling · Ti-6Al-4V · LAM

1 Introduction

Material engineers continue to strive for development of new and existing fabrication techniques in an attempt to provide the world with resource-efficient, cheaper, and cleaner materials with enhanced service performance [1, 2]. It is a well-known fact that the alleviation of energy consumption and gas emissions is of paramount importance globally; which then necessitates the development of lighter materials using cost-effective and environmentally friendly techniques [3, 4]. Accordingly, numerous researches have been targeted in the exploration of techniques holding a promise to tackle these universal demands [5]. Additive manufacturing (AM) processes has come of age as a viable alternative to mainstream metal part fabrication techniques. This radical change is attributed to the additive manufacturing being popularized as a sustainable technology that is environmentally friendly, provides reasonable fabrication cost, and improves lead time [6]. In contrast to traditional fabrication techniques that incorporate subtractive methodologies wherein components are produced by the removal of unwanted materials from a larger block by machining, additive manufacturing entails a layer-by-layer fabrication of near net shape components [7, 8].

Additive manufacturing can be categorized according to their energy source, feedstock delivery system, and feedstock representation. Laser additive manufacturing (LAM) uses a laser beam as its energy sources and can be subdivided into laser-bed based fusion and direct laser metal deposition. There are several fields that can benefit from advantages offered by LAM; among these are the aerospace, automotive, and biomedical sectors. The potential development drivers comprise of weight reductions resulting in less fuel consumption and

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lower greenhouse emissions in aerospace applications as well as high precision implants in medical prosthetics [9, 10]. However, Wanhill laser additive fabrication methods are relatively new; hence, the knowledge of the multi-physics-related phenomena involved and the influence of operating parameters are a mystery [11]. This has a very negative feedback on practicing manufacturers longing to reap the benefits as they fear the risk of reducing their products quality [12]. Ti-6Al-4V is considered a workforce of titanium industry due to its desirability in various industrial applications. The attractiveness of this alloy in the various industries including the aerospace, biomedical, and chemical process is due to high strength-to-weight ratio, biocompatibility, and high resistance to corrosion. Despite the combination of such attractive properties, this alloy is still restricted in some applications because of its shortcomings. One of the major drawbacks of Ti-6Al-4V's wider application spectrum is related to high fabrication cost of which DLMD holds a potential to mitigate. Expensive extraction process of titanium is also a major contributor in making Ti-based alloys so expensive.

Many studies suggest that a certain amount of powder remain unfused during additive manufacturing processes [13]. In general practice, these powders are disposed which is very detrimental both economically and environmentally. In addition, this adverse feedback has a very bad influence in efforts made for industrial implementation of these processes [14]. Powder recycling refers to the process of recovering, reconditioning, and reusing the metallic powders that remain unfused during an additive manufacturing process. According to Seyda et al. [15], characteristics of the powder material change with repeated reuse times. As a result, the powder reuse times permitted before disposal carry a significant influence on powder characteristics and material use efficiency which both govern the component quality and overall fabrication cost, respectively. Sames et al. [16] recommended that it is important to take feedstock powder quality into consideration when aiming to produce a high-quality component.

In this research, the focus is on the effects of processing variables on material properties of Ti-6AL-4V alloy as well as the progress on powder recycling as means of improving material use efficiency for the direct laser deposition technology processes. This attempt is undertaken to widen the application scope of Ti-6Al-4V alloy which is commonly regarded as expensive due to high fabrication costs. In the present text, a brief overview of the laser engineered net shaping (LENS) process mechanisms, effect of processing parameters, and powder recycling with some other metallurgical concepts is briefly outlined.

2 Laser additive manufacturing

Laser additive manufacturing (LAM) refers to a wide range of advanced fabrication techniques that use a high-power laser to melt powder or in some cases a wire into a melt pool to progressively produce 3D near net shape components in a layer-wise fashion. These fabrication techniques originate from rapid prototyping, a technology developed in the 1980s for creating models to help the realization of what engineers have in mind [17]. LAM contrasts traditional techniques in that "near net shape" components are fabricated in a layer-by-layer fashion instead of machining out unwanted material from a bulk material to produce parts that have very low buy-to-fly ratio. Despite the many advantages offered by this technology, it does not seem much likely to take over from conventional manufacturing techniques in the near future. This is because very little knowledge regarding underlying physics has been established thus far [18, 19].

There are two classes of laser-based additive manufacturing techniques which are directed energy deposition and laser powder-bed fusion [20]. Table 1 shows the list and categorizes laser additive manufacturing technologies as per ASTM terminologies. These processes are similar in that the heat source (laser) follows the routes represented in the CAD file to construct the component layer by layer [21]. The radical change towards LAM technologies for industrial application carries a promise to fabricate custom-tailored, functionally graded, and/or geometrically complex objects typically unachievable by conventional techniques [22]. In addition, characteristics that make LAM techniques attractive over traditional methods are optimal raw material usage, fewer machine operations, reduced hard tooling, and reduced lead time [23].

2.1 Laser as an additive manufacturing tool

The term laser is an acronym that stands for light amplification by stimulated emission of radiation, and thus, a laser beam, like all other light waves, is a form of electromagnetic radiation [24]. Byren et al. [25] defined a laser as "a device that

Table 1 Different classes of laser additive manufacturing technologies

ASTM classification (acronym)	Commercial name (acronym)
Directed energy deposition (DED)	Laser engineered net shaping (LENS)
	Direct metal deposition (DMD)
	Laser consolidation
	Laser deposition
Laser powder-bed fusion (L-PBF)	Direct metal laser sintering (DMLS)
	LaserCUSING
	Selective laser melting (SLM)
	Direct metal production (DMP)
	Laser metal fusion (LMF)
	Selective laser melting (SLM)

produces optical radiation through the process of amplified stimulated emission in an excited medium." The applications of lasers have increased enormously through the years from its early days of invention when it was only explored through research [26]. In the manufacturing applications, lasers are now matured as a tool that has helped make production of a wide variety of new products possible. The type of laser and the wavelength desired for a specific application are determined by the laser medium which could be solid, liquid, or gas. The state or physical properties of the medium are used in naming and categorizing laser types [27].

The available types of laser are glass lasers/semiconductor, solid state, liquid, and gas laser. Additionally, gas-based lasers are subdivided into neutral atom, ion, molecular, and excimer lasers. Lasers have also assisted in improving the manufacturing of existing products by introducing the possibility of new production techniques which improved productivity, quality of products, and fabrication costs. This has contributed a lot in growing the industrial laser market. Some of the main material processing applications of lasers include laser cutting, welding, drilling, marking, surface treatment, and the recent additive manufacturing [28].

2.2 Classification of laser additive manufacturing techniques

Additive manufacturing processes are classified according to the process' energy source and the method by which the material is transported to the melt pool. There are two major classes of additive manufacturing, namely, laser additive manufacturing and non-laser-based additive manufacturing [29]. The key elements for additive manufacturing are an energy source, beam delivery, and processing optics used to focus the beam and powder delivery, multi-axis computer numerical control (CNC) system coupled with a robotic system for controlling motion and the operating software. In the LAM technologies, the energy source is the laser, and therefore, classification proceeds only by feedstock material state (e.g., powder or wire) and material delivery system [4].

2.2.1 Direct laser deposition

Directed laser deposition (DLD) technique refers to a laser-based additive manufacturing technique which is a type of directed energy deposition process that is used to fabricate fully dense components. This process involves laser irradiation which is concurrent with directly injected powders or sometimes wire, tracing a route designed through slices of a 3D CAD file components which are built layer by layer [22, 30]. Some of the advantages of DED techniques such as LENS over other additive manufacturing systems are reduced production cost, refined microstructures, modifying/refurbishment of existing component during its lifecycle, and the ability to produce functionally graded material parts achievable through dual feeding system [31, 32]. In addition, the use of a coaxial or multi-jet nozzle enables fabrication freely defined geometries commonly unachievable by conventional techniques [13]. Fig. 1 depicts a schematic illustration of the direct metal laser manufacturing (DMLD) technology.

2.2.2 Laser powder bed fusion

Laser powder bed process involves laser scanning regions selected by computer-programmed patterns to melt preplaced laser bed which fuses with the substrate or preceding layer. The powder bed is lowered by a predefined layer thickness after each subsequent build layer. This process repeats following tracks layer by layer until a

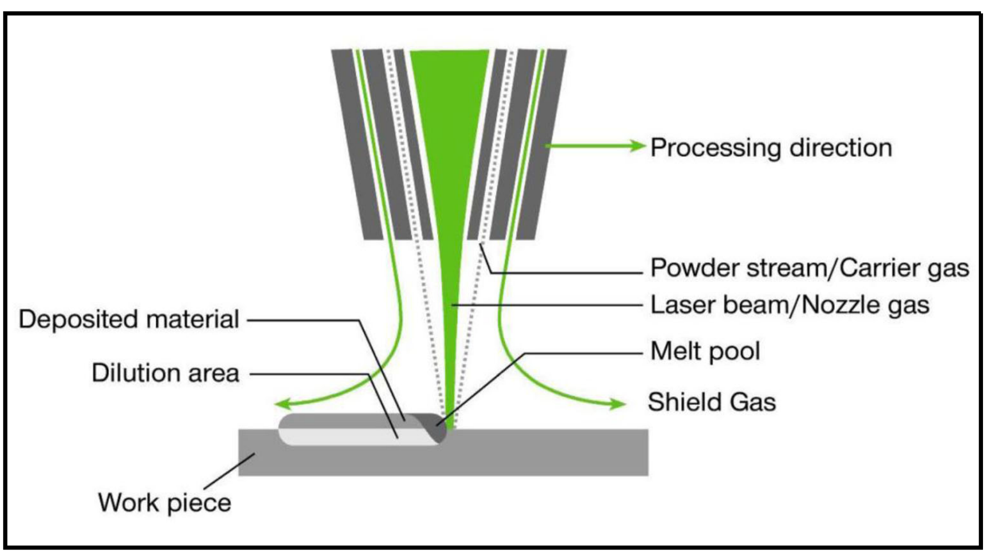

Fig. 1 Schematic illustration of the direct metal laser deposition (DMLD) additive manufacturing technique operational procedure [83]

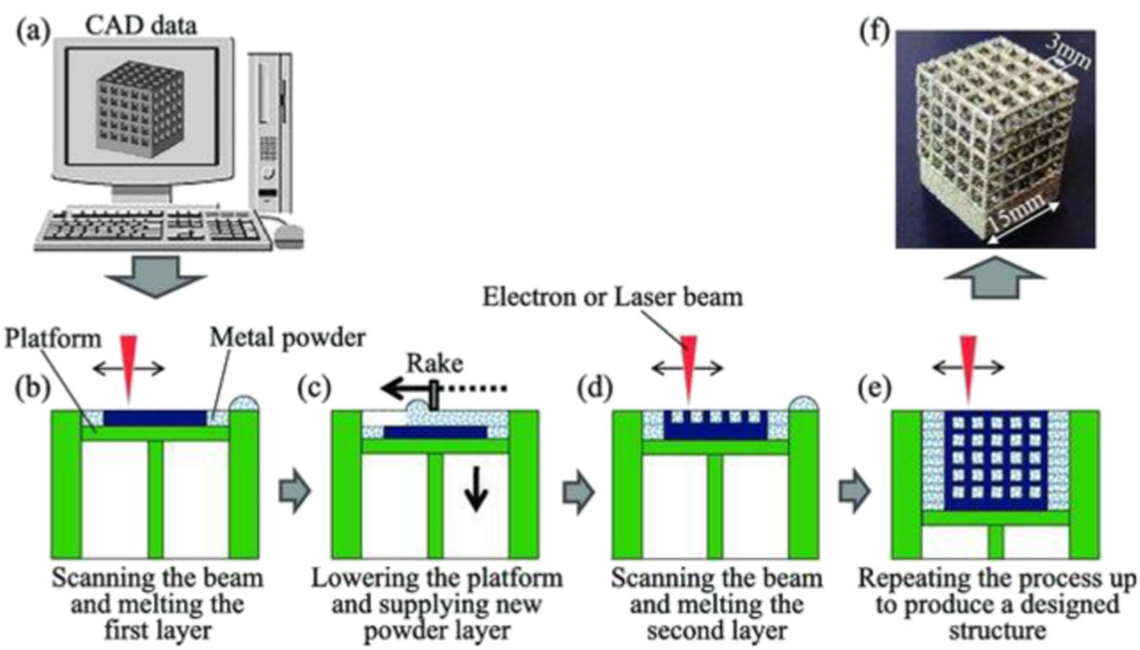

Fig. 2 Schematic illustration of the laser powder-bed fusion (LPBF) additive manufacturing technique operational procedure [33]

3D functional part is produced [18]. In Fig. 2, a schematic diagram of the laser powder-bed fusion operational procedure is shown.

Some of the advantages of laser powder bed fusion are part complexity and less surface roughness among others. Nonetheless, this fabrication technique has its downsides which include slow deposition rates and lack of adaptability in size which result in an inefficient energy use. In addition, this process requires a large amount of powder for preplacing a bed. This hinders the wide industrial application process as it reduces the material utilization efficiency. In general, largest components built by SLM which is a laser powder bed fusion process are half the ones fabricated by LENS [31].

2.2.3 Additive/subtractive hybrid manufacturing

Hybrid manufacturing refers to a process which combines two or more manufacturing techniques with the aim of mutually benefiting both processes thus improving productivity, quality, etc. The process of pairing additive manufacturing and traditional subtractive techniques is one of the recent hybrid manufacturing technologies. Additive/subtractive hybrid manufacturing incorporates directly injected powder or selected regions of a powder bed by scanning an energy source which results in melting then solidification of materials forming a part while simultaneous machining is done to remove traces of unwanted materials for enhanced precision.

This alternating process is carried out repeatedly until the required geometry is achieved as illustrated in Fig. 3 [34]. Alternatively, this technology is employed for repair purposes whereby material powder is added layer by layer fitting to the defect geometry creating a metallurgical bond between new material and the damaged surface area of a part [4]. This reduces cost and extends service life of parts whether traditionally manufactured or 3D printed.

2.3 Industrial applications of laser additive manufacturing technologies

Laser additive manufacturing technique is increasingly becoming established in a wide range of industrial applications. It is best suited for rapid manufacturing, refurbishment, and surface coating mainly in the demanding industries such as aerospace, automotive, tool making, and biomedical applications [7, 32, 35]. In practice, the benefits presented by LAM include reduced production times, low fabrication costs, and freedom of design and customization. Aerospace components such as thin-walled structures such as combustion engines and turbine blades, are perfect examples of commercial product manufacturing of LAM technologies [8]. In medical applications, LAM enables production of better fitting transplants as well as it is easier to insert and secure [17]. The toolmaking industry is another beneficiary of LAM, as it helps produce highly complex tools needed for commercial manufacturing of products in various industries [36]. Despite these countless benefits additive manufacturing has to offer, the likelihood of the process to overtake the traditional methods in the near future (about a decade from now) is very much unlikely [16].

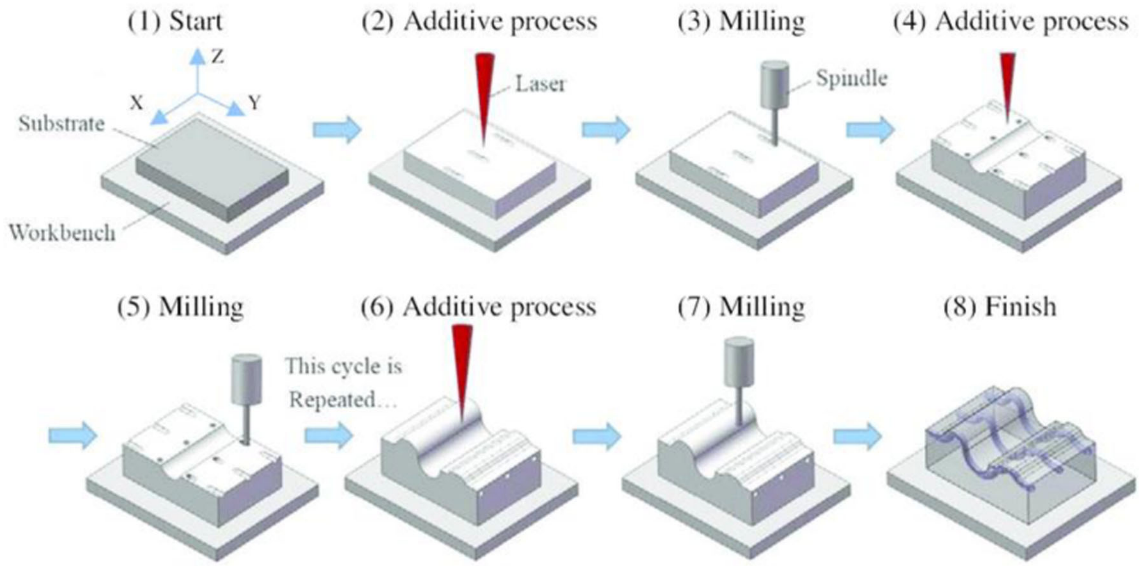

Fig. 3 Schematic illustration of the additive/subtractive hybrid manufacturing process (Du, Bai, and Zhang 2016)

3 Principles of laser-assisted additive manufacturing

Since its inception, laser additive manufacturing has attracted a significant amount of attention as a potential alternative manufacturing technique owing to its versatility. In comparison with other additive manufacturing technologies, LENS provides exciting advantages such as large material diversity and higher build-up rate and enables building on existing 3D parts referred to as refurbishment [27]. However, qualifying this manufacturing technique for industrial application requires reliable process repeatability, product reproducibility, and component quality. According to Thompson et al. [22], the mechanical behavior of the additive manufactured parts depends on thermal-history-dependent microstructure which can be controlled by an understanding of thermal gradients, localized solidification, and residual stresses occurring during deposition. Authors further stated that modeling the abovementioned events as function of relevant process parameters can enable in situ process diagnosis and feedback control providing application-optimized parts with tailored mechanical properties. In addition, improving material use efficiency of the expensive metal feedstock by powder recycling in order to avoid waste comparable to those in traditional techniques is essential for encouraging LAM vast industrial implementation [2, 37]. However, the challenge is the change in chemical composition, particle size, and morphology of the recycled powder which affect flowability and thus mechanical properties of the end product [38, 39]. Therefore, it is necessary to understand the influence of recycle on both the powders and the resultant component in order to establish a number of permitted reuse cycles.

3.1 Influence of process parameters in laser additive manufacturing

The implementation of widespread industrial application of additive manufacturing technologies requires that quality demands are to be fulfilled [15]. Various researchers stated that through controlling/monitoring process parameters such as laser power, scan speed, powder feed rate, beam diameter, and hatch spacing, quality deposits are achievable [40–42]. The desired mechanical properties of the components built by laser additive manufacturing technique such as LENS can be achieved through microstructure control which in turn is governed by the laser process parameters. Below are various processing variables and their influence in LENS fabrication process as well as the resultant components.

3.1.1 Laser power

The laser power is defined as the rate at which the energy is emitted from the laser [43]. Laser power is required in order to avail energy to be absorbed which is necessary for creating a melt pool and melting and fusion of materials. According to Popoola et al. [32], the energy injected to the melt pool increases with the laser beam intensity. The mechanical properties are governed by the microstructure of the material, which in turn is a function of laser power–dependent thermal history [44, 45]. Careful control of laser power and scanning speed is essential as the energy density of the system is dependent on them. The exaggerated laser power increases the heat input therefore causing distortions and larger heat affected zone as well as increased spatter ejection [16, 32]. Adequate laser power and energy density lead to increase in cooling

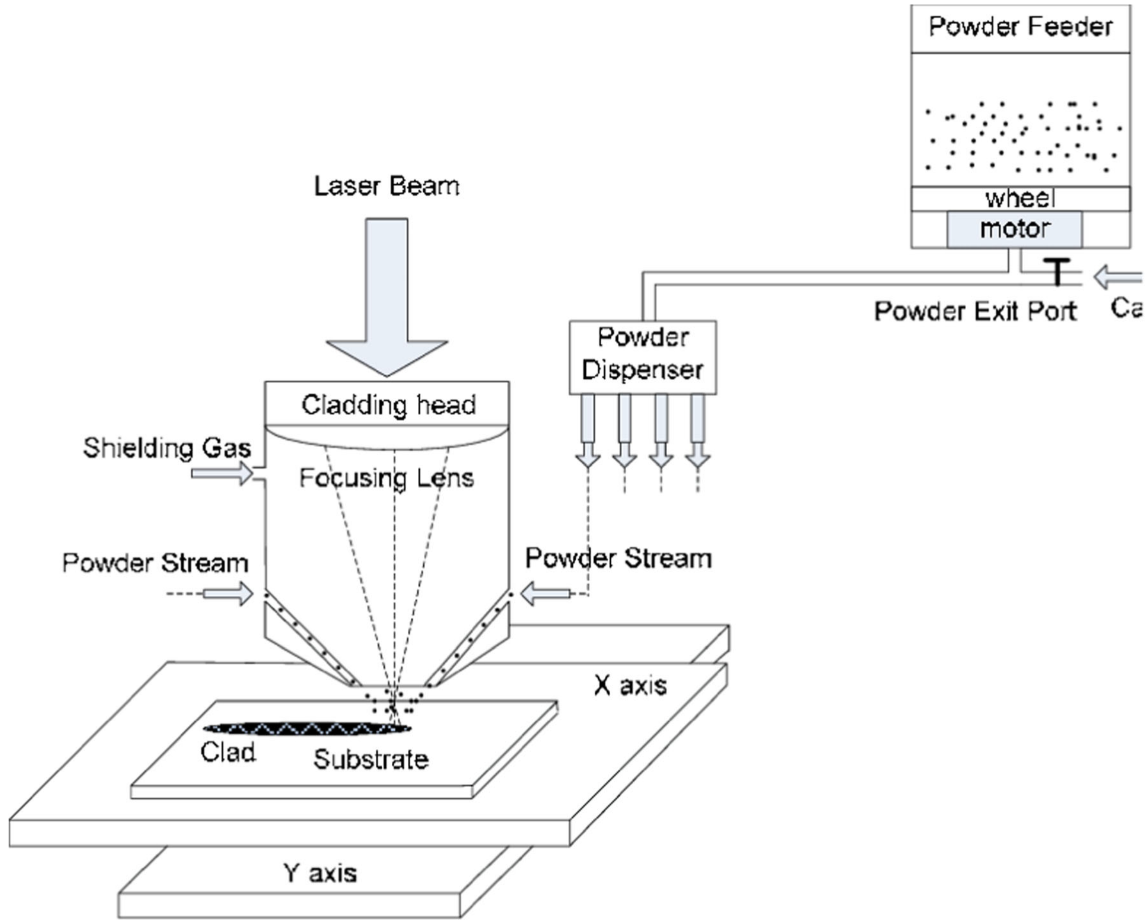

Fig. 4 Schematic illustration of the DMLD powder delivery system [65]

rate; thus, refined microstructures are achieved. Nevertheless, absorption of insufficient amount of energy by the substrate or preceding layer may result in lack of fusion or no melting at all [42].

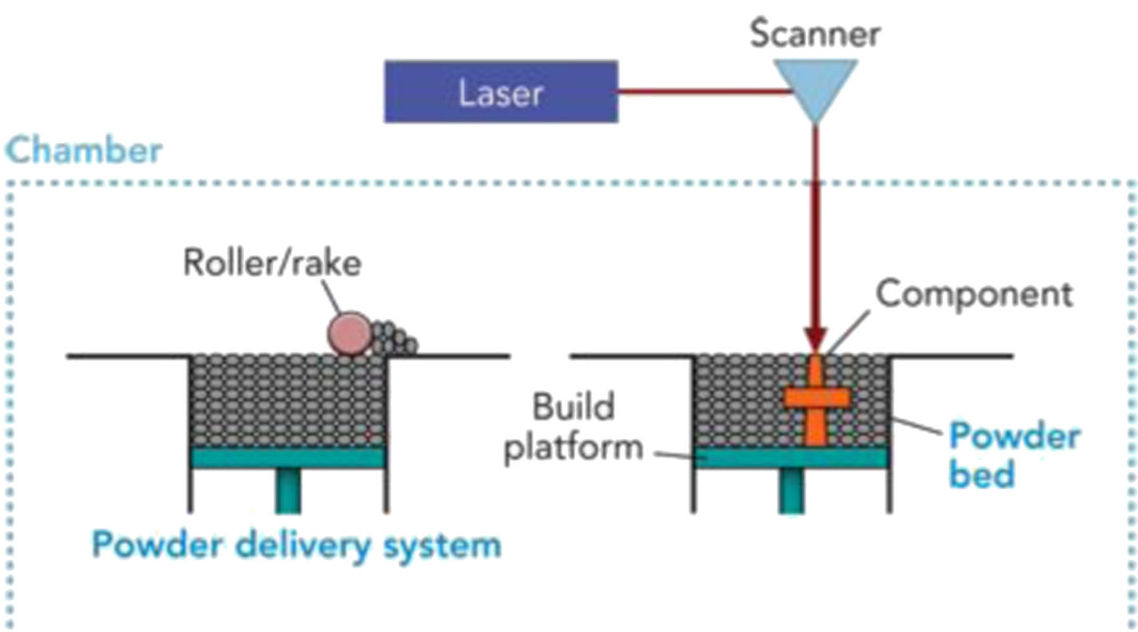

Fig. 5 Schematic illustration of the LPBF powder delivery system [84]

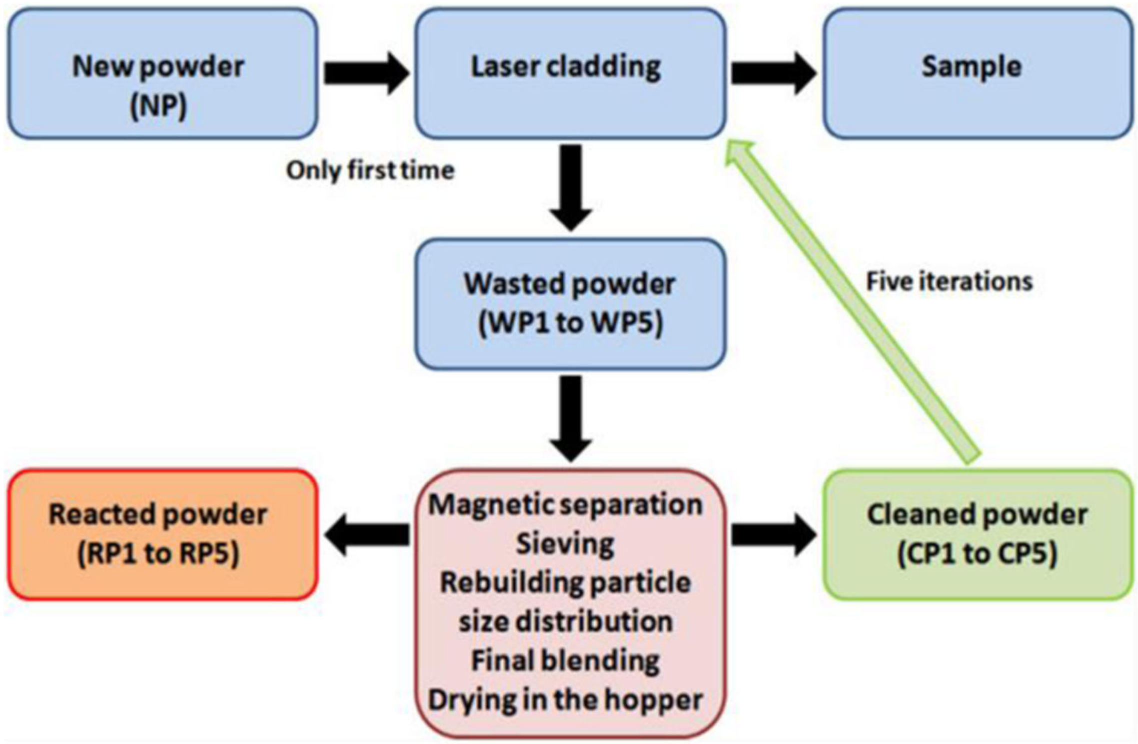

Fig. 6 Schematic diagram illustrating the powder recycling procedure for laser metal deposition [13]

3.1.2 Laser scan speed

The scan speed refers to the laser beam's rate of change in distance along the substrate/previous layer while processing. The scan speed has an influence on the laser/material interaction time, with slower scan speeds resulting in longer interaction time leading to high temperature gradient and slow cooling [46, 47, 28]. Short interaction times may cause some material to be left unfused because of the inability of substrate or layer surfaces and powders to absorb energies enough to reach melting necessary for fusion thus increasing porosity [42]. The low amounts of powder available for melting is an issue related to high laser scan speeds as nozzles are attached to the same head with the laser beam. Melt pool shape is also highly sensitive to scan speeds, typically elongating and becoming shallower at faster scan speeds [22].

3.1.3 Powder feed rate

The powder feed rate is defined as the amount of powder material in leaving the nozzle per unit time commonly measured in grams per minute (g/min). The powder feed rate determines the amount of powder available in melt pool and thus governs the layer thickness of the build. The use of a high powder feed rate results in large amounts of materials in the laser/material interaction zone which reduces the laser energy

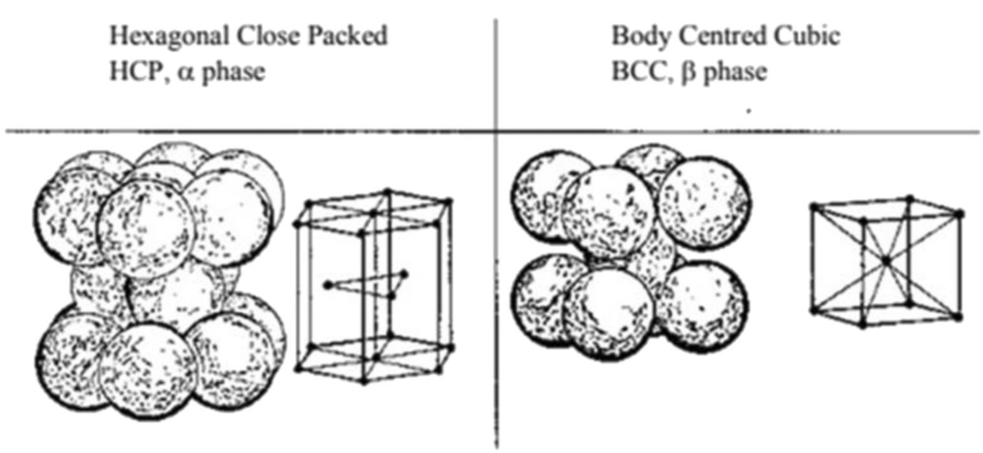

Fig. 7 Description of the allotropic transformation of pure titanium [74]

density on materials. Within a certain range, the molten pool created by the heat from laser irradiation can catch more powder material as the powder feed rate increases. However, at exaggerated feed rates, some powders remain unmelted/unfused during processing, and this is associated with the formation of the lack-of-fusion pores consequently increasing porosity. On the other hand, deposition at low powder feed rate increases the material utilization efficiency [19]. In addition, the trace height is considerably dependent on the rate at which powder is fed [30].

3.1.4 Hatch spacing

According to Krishna et al. [41], hatch spacing is the distance between two successive metal roads or laser scan tracks. The hatch spacing is related to the overlap distance between two parallel layers. Pupo et al. [48] stated that the overlap distance has a considerable influence on the heat accumulation in additive manufacturing. The heat accumulation during processing affects the rate of cooling and solidification which thus governs the microstructure and the mechanical properties that result. In addition, the porosity of a built component increases with an increase in hatch spacing [1].

3.1.5 Gas flow rate

The gas fed into the laser metal deposition system has two functions, to deliver powder material to the weld pool and to prevent contamination by a surrounding environment [49]. Gas flow rate refers to the rate at which the gas that transports the powders from the dispenser through the tubes until nozzles into the weld pool flows. This gas is not only for transportation but also for protection of the powder from contamination. Optimizing this parameter is necessary to avoid high flow rate which may blow the powders away from the melt pool and avoid low flow rate to provide a sufficiently inert surrounding.

3.1.6 Laser beam spot size

The laser beam spot size also referred to as the laser beam diameter is defined as the width of the laser beam measured at a given focal distance. The powder material use efficiency is largely dependent on the laser beam spot size; this follows that the smaller the spot size–dependent melt pool results in fewer powder melting and fusing to form the final part.

3.2 Mechanism of heat transfer in laser additive manufacturing

Heat transfer is defined as science that describes the amount of heat energy transferred from a region of high temperature to a region of low temperature which is caused by a temperature difference across the system boundary. This energy transfer is a very important phenomenon in many laser processes including additive manufacturing, welding, and surface treatment [27]. The understanding of this phenomenon is based on the knowledge of thermal equilibrium, mechanisms or modes of transfer, and the laws governing them. The rates of heat transfer play an important role in controlling/estimating the cooling and solidification rates in laser material processing systems [50, 51]. The abovementioned is paramount as thermal history generated during processing is essential for determining the microstructure, material properties, residual stresses, and distortion resulting on the end product [21, 52]. The three unique modes of heat transfers, namely, conduction, radiation, and convention, are briefly explained below.

3.2.1 Conduction

Conduction is the flow of heat within or between solid, liquid, or gas mediums as a result of a thermal gradient. This phenomenon occurs on principle of either identical or different conducting mediums in contact. The rate of heat conduction is governed by Fourier's law which states that the rate of heat transfer per unit area is proportional to the normal temperature gradient. That is:

$$q_{\text{cond}} = -KA\frac{\delta \boldsymbol{T}}{\delta \boldsymbol{x}} \tag{1}$$

where K (W/m/K) is the thermal conductivity of the material, and the negative sign denotes the direction heat flow which is in the direction from the hotter to colder temperature. q is the rate of heat transfer and $\frac{\delta T}{\delta x}$ is the temperature gradient in kelvin per meter. The heat transfer by conduction can also be represented by a 3D Cartesian plane with energy flow in the x, y, and z direction. In general, the heat flux is a vector quantity expressed by an equation below:

$$q_{\text{cond}} = -K\nabla T \tag{2}$$

where q is local heat flux (W/m^2), K is thermal conductivity of material,(W/m/K), and ∇T is temperature gradient (K/m)

3.2.2 Radiation

Radiation is the emission or transmission of energy in a form of waves or particles flowing from one body to the other while they are not in direct contact or separated from each other by an aerated or vacuum space. This is an electromagnetic phenomenon which is propagated as a result of a temperature difference. Radiant heat is the term used to describe this type of energy transfer mechanism. Although all bodies continuously emit radiant heat at the speed of light, it is common to neglect it for bodies at low temperatures but becomes increasingly important at increased temperature. The heat transfer between two surfaces by emission and later absorption by electromagnetic radiation is described by an equation below:

$$q_{\mathrm{rad}} = \sigma \times \varepsilon \times A\delta T^4 \quad (3)$$

where σ is Stefan-Boltzmann's constant, 5.66×10^{-8} ($\mathrm{W/m^2\ K}$); ε is emissivity, which varies from 0 to 1 (dimensionless); A is area of the radiator body; and δT is temperature difference.

3.2.3 Convection

Convection heat transfer is related to the conduction of heat taking place either between the solid surface and adjacent flowing fluid particles or between two flowing fluid particles which mix whereas are initially at different temperatures. This phenomenon is categorized into two classes which are natural convection and forced convection both depending on the velocities of fluid and the nature of the forces which cause fluids to flow. The heat transfer is called forced convection if material transport and mixing of fluids are induced by an external force. On the other hand, free convection happens when material transport and mixing occur as a result of difference in density caused by temperature gradient in the medium. The heat transfer by convection is expressed in the equation below:

$$q_{\mathrm{conv}} = hA\delta T \quad (4)$$

where h is convection heat transfer coefficient, A is surface area, and δT is temperature difference.

3.3 Melt pool dynamics and fluid flow mechanism

In order to achieve deposition in laser additive manufacturing, the formation of the melt pool whereby powder materials are injected is necessary. The melt pool is formed by beam irradiance experienced on the surface of the build plate or the previously built layers. The melt pool dimensions are determined by the degree of the material absorptivity and the incident laser intensity; therefore, controlling process parameters enables the estimation of the amount of heat generated as well as the molten material in the melt pool [53]. The main laser process variables that affect melt pool dimensions whish are the ones related to the energy density such as laser power, scan speed, beam diameter, and powder [54].

The laser produces a beam that follows Gaussian (normal) distribution; i.e., the beam energy is greatest at the center of the beam and gradually decreases towards the ends of the circumference; the fact that heat generation is largest at the center, one would expect the melt pool depth largest at this region and becomes shallow at its edges which is typical in laser material processing. This temperature gradient experienced by the melt pool has an influence on the surface tension of the molten liquid metal. The surface tension is the fluid material property which depends on fluid temperature and composition; increase in either one decreases surface tension [55]. Since melt pools are hottest at their cores, this results in surface tension gradients thus inducing the Marangoni convection also known as thermocapillary convection; in turn, this affects the subsequent rapidly solidified melt pool shape [56–58].

3.4 Solidification and operational microstructure evolution

The laser additive manufacturing process involves the incorporation of materials directly injected into a localized yet mobile laser birthed melt pool. The solidification of these consolidated materials is determined by the thermal distribution and gradient around the melt pool which govern the rate of cooling to freezing temperatures. In general, solidification occurs in two stages which are (i) nucleation, occurring when a nucleus (small stable solid particle) evolves from the liquid phase, and (ii) growth, which involves the attachment of atomic liquid particles onto the nucleus as they transform to solid phase. In general, nucleation initiates at the melt pool because these are the coolest regions; then, growth would occur inwards to the center [24].

In general practice, pure metallic materials are seldom deployed for application; therefore, solidification may take place while temperature decreases whereby the interface between solid and liquid phases is either planar, cellular, or dendritic. The dendritic structure is known to appear either as columnar or equiaxed grains. In laser metal deposition methodologies, the grain structure is governed by the composition of the constituents in the alloy whereby solidification initiates at elements with higher melting point and gradually proceeds till the last drop of liquid (containing mainly of atoms with lowest melting point) freezes [24].

3.5 Operational mechanical properties

The mechanism of the phenomenon described in this section is dependent on the process parameters of which additive manufacturing's versatility enables their control as a result giving these technologies an edge to tailored microstructures; thus, desirable mechanical properties are achievable [59]. An effect of typically rapid cooling rates is an added advantage as this results in finer grains thereby resulting in enhanced mechanical characteristics [20]. An ideal microstructure for additive manufactured components is defect free and consists of phases that enhance mechanical properties of the built part. However, the formation of undesirable artifacts such as pores, cracks, or incomplete melting is possible depending on the chosen process parameters and the consequential interactions in the melt pool.

Additionally, the distinctive rapid solidification characteristic of laser material processes also means that the melt pool solidifies while the dynamic phenomena described above are still in action. This may lead to entrapment of gasses, recoil pressure expansion, and spattering depending on selected process parameters and the corresponding melt pool properties [29, 60]. The melt pool with high temperature gradients and thus high surface tension gradient experience increased Marangoni flows which may lead to rough surface texture of the build surface while recoil pressure induces the formation of pores thereby reducing the mechanical performance in as-fabricated components [56–58].

Many experimental and computational research works have been carried out with the sole aim of improving the mechanical properties of additive manufactured components through understanding the mechanisms and interactions occurring during processing. The most widely studied additive manufacturing processes are laser metal deposition and selective laser melting with properties of interest being mainly the strength/structural properties, surface texture, and geometrical accuracy [26, 40, 61–64].

4 Feedstock for powder-based laser additive manufacturing systems

4.1 Feedstock powder characteristics

The powder characteristics (particle size distribution and particle shape) and material properties (absorptivity, melting point, thermal conductivity) are as important as the laser process parameters (laser power, scan speed, powder federate, and gas flowrate) in additive manufacturing processes [49]. This is because the evolution of defects is a result of the feedstock quality which is determined by both powder characteristics and its material properties.

The abovementioned defects are related to porosity and their origin is attributed to powder feedstock quality. According to Anderson et al. [38], the spherical geometry is the most compatible shape for powder particles used in additive manufacturing technologies as they improve flowability, layer spreading, and loose powder packing. The authors further stated that direct energy deposition processes are less affected by geometry of the powder particles so long as the feed rate remains constant.

4.2 Feedstock powder delivery

The powder-based additive manufacturing processes encompass either the continuous direct powder injection or periodic subsequent layering of a powder bed after each build cycle. In these sections, these feedstock transport mechanisms are briefly conferred in terms of their operational principle, machinery components that carry out each specified task, and their advantages over counterparts.

4.2.1 Direct powder injection systems

Direct metal laser deposition by powder feedstock is one of the most studied and commercialized additive manufacturing technologies among others [16]. The powder delivery system consists of a direct current (DC) motor and a transport system which includes a pipe, powder dispenser, and a deposition head (composed of coaxial nozzle, focusing optics, and a cooling system). In this system, powder can be transferred to the melt pool either coaxially around the laser beam or laterally from the sides of the laser beam [27]. The DC motor speed governs the powder feed rate (transported by pressurized argon gas) to the dispenser where it is split into four streams. These streams are carried through tubes to the coaxial nozzle, where they converge to form a cone-shaped powder stream that has the same central axis as the laser beam before finally reaching the melt pool created by the laser beam [65].

4.2.2 Powder-bed based systems

Powder bed fusion is a widely known process category in laser additive manufacturing technologies [66]. This process consists of a laser scanning system, powder bed delivery system, roller, and fabricated piston. Fabrication by powder bed fusion involves spreading and subsequently compressing the powder followed by fusion of this powder through a laser beam guided by a scanner system over a selected region of the laser bed. This process repeats itself while piston moves down a distance equivalent to the built height until the whole part is successively built [67].

4.3 Mechanism of beam/material interaction

Direct metal laser deposition involves laser irradiation coupled with simultaneous feeding of metallic powders to a localized molten region on the build plate or a preceding layer depending on the building stage. In this instant, the laser beam travels through and interacts with the cloud of powder particles before reaching the workpiece. These powder particles may absorb, reflect, and transmit some of the laser irradiance and therefore experience a change in temperature. As the beam intersects the powder cloud, its energy and intensity decrease through absorption and reflection [27].

Once the beam reaches the build platform, a rapid increase in surface temperature is experienced at the eradiated area then dissipated throughout the material by convection and changing the kinetic energy of the nearby atoms; thus, thermal stresses induce deformation. However, this sudden increase in temperature does not only affect the build plate as some of the feedstock that scatter outside the melt pool also experiences temperature increase and therefore becomes prone to change quality through coalescence forming agglomerates and oxidation which changes their composition. Therefore, it becomes a necessity to develop techniques dedicated to better preserve or restore the quality of the feedstock as it is well agreed upon that alterations may weaken the mechanical performance of deposits [68].

4.4 Powder recycling

In recent years, an increasing focus has been placed on environmentally sustainable practices particularly in manufacturing with the aim to reduce material waste and fabrication costs [3, 5]. In additive manufacturing processes, the requirement to achieve deposition is that the metallic powders be directly injected into the melt pool to fabricate a near net shape component only consuming the material necessary required for fabricating the final part. This is the major contributor making this fabrication process a sustainable one. This is true when considering only the material consumed to produce the final component. However, there is a large amount of powder that ends up being misdirected to non-melted regions outside the melt pool which therefore remains undeposited [39, 69]. Renderos et al. [13] mentioned that a large amount of powder up to 60% of the feed may be lost to waste depending on the process configuration and spot size.

One possible way to avoid this waste is through recycling since most of the unfused scattered powders remain undamaged. However, some of the powders may be heat affected; hence, partial oxidation, partial melting/fusion, and/or chemical contamination are plausible. Powder materials used for additive manufacturing processes are commonly very expensive, and therefore, reusing the non-trapped powder is economically advantageous [69]. However, the highly localized melting and resolidification that occur during the additive manufacturing of metallic powders are sensitive to defect incorporation (primarily porosity) from non-uniform powder flowability. Therefore, powder agglomeration through coalescence which generally affects the flowability dependent powder feed rate increases porosity [38].

5 Metallurgy of titanium and its alloys

Titanium is the fourth most abundant structural metal on the earth crust after aluminum, iron, and magnesium in descending order. The titanium-based alloys have gained increasingly predominant attention over the recent decades. This abrupt attention is owed to the aerospace industry's critical need for new materials with superior strength to weight ratios. These materials possess high specific strength, excellent corrosion resistance, and high temperature capability at a very light weight thus making them stand out in a wide range of applications [35, 70, 71].

The properties of titanium alloys are determined by the crystalline structure with which it exists in the particular temperature range as well as the grain size, grain shape, and microstructure. Normally, elemental titanium undergoes allotropic transformation by a nucleation and shear-type process as it cools from beta phase field through the transus temperature to alpha phase field. This transformation results in a change in crystal structure from a body centered to closed-packed hexagonal crystal structure [72]. In general, there are three alloy categories by which titanium is classified. These three classes depend on the composition and the predominant application temperature range [73].

5.1 Crystal structure of titanium alloys

Pure titanium experiences allotropic transformation at a temperature of 882.5 °C from a close-packed hexagonal crystal structure (HCP) to a body-centered cubic (BCC) as temperature is increased and vice versa with decrease in temperature [74]. The alpha phase (HCP) is stable below the allotropic temperature (882.5 °C), and the beta phase (BCC) is stable above this temperature. The crystallographic structure with which titanium exists determines the functional properties and thus its applicability in industrial [75]. Shown in Fig. 8 is the schematic description of the allotropic transformation of pure titanium.

In general practice, alloying elements are added to force the reorganization of titanium atoms into either one of the abovementioned phases depending on desire/requirement. The additions of alloying elements result in alterations in transformation temperatures and/or produce a dual-phase field where the alpha and beta phase co-exist. Alloying elements having extensive solubility in beta phase typically depress the alpha/beta transformation temperature and are called beta stabilizers, and vice versa can be said about the alpha stabilizers [76].

Aluminum is the principal element used for stabilizing the alpha phase in titanium alloy. Furthermore, alternative to aluminum other alpha stabilizers such as gallium, germanium, carbon, oxygen, and nitrogen which favor the alpha crystal structure can be used as well as (Davis 2001). Alternatively, stabilizing the beta phase requires additions of beta stabilizers which include vanadium, molybdenum, chromium, and copper. Neutral additives are sometimes used as alloying agents. However, these have close to zero influence on phase evolution in titanium alloys [77].

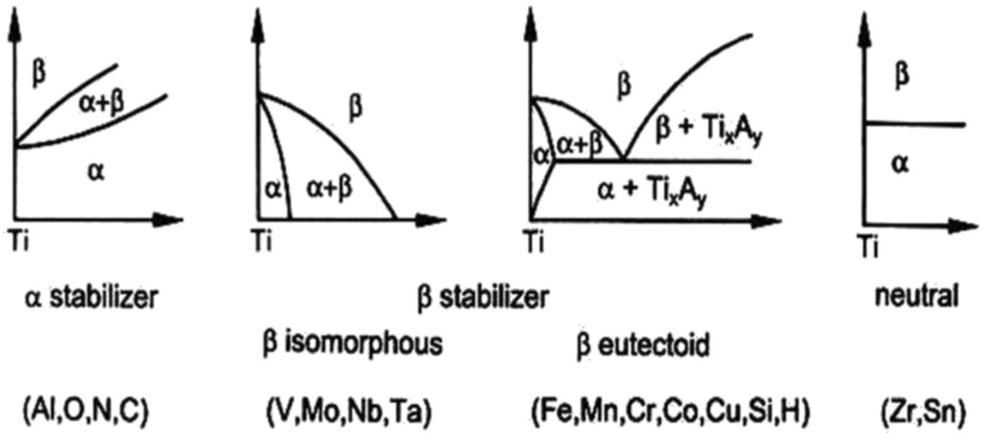

Fig. 8 Schematic illustration of the influence of alloying elements on equilibrium phase diagrams of titanium alloys [72]

5.2 Classification of titanium alloys and their properties

There are three main equilibrium constitution dependent types into which titanium alloys are classified; these are alpha, alpha-beta, and beta alloys [72]. Each of these distinguishable alloy types serves a specific role [73]. According to Froes [77], these materials are distinguishable by their crystal structures present at or close to room temperature. In addition, the material properties depend on these crystallographic structures. Figure 9 depicts the general description of different phase diagrams of titanium-based alloys.

5.2.1 Alpha alloys

The alpha alloys predominantly consist of the alpha single-phase titanium, which is stable in room temperature up to the allotropic transformation. In some cases, these alloys contain small traces of beta-stabilizing elements which are intentionally added to improve the processing characteristics and permit greater microstructural management. In addition, these alloys may contain neutral elements which are soluble in both alpha and beta solid phase; this addition helps strengthen the alpha phase. The alpha alloys are characterized by a reasonable strength, formability, toughness, creep resistance, excellent corrosion resistance, good high temperature properties, high stability, and weldability. Their formability decreases with any improvements in strength. In addition, these alloys have limited slip movement during deformation, thus, hot working treatment processing is problematic and improvement in mechanical properties through heat treatment is barely obtainable (Marsumi and [74, 78]). Examples of these alloys include commercially pure titanium, Ti-2.5Cu and Ti-5Al-2.5Sn [79].

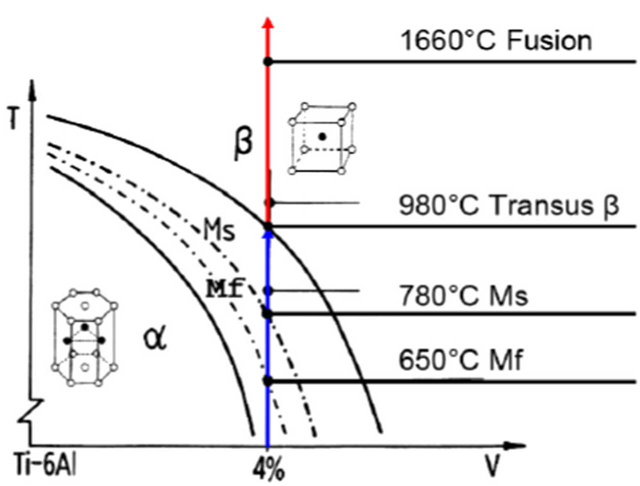

Fig. 9 Schematic pseudo-binary phase diagram of Ti-6Al-4V

5.2.2 Alpha + beta alloys

The alpha + beta alloys consist of a dual phase at ambient temperatures. The presence of beta phase at the temperatures where its normally unstable is enabled by the addition of 4–6% beta stabilizer. These alloys contain both the alpha and the beta stabilizers; this is because the beta stabilizers cannot strengthen the alpha phase. In the cases of small contents of beta stabilizer, the alpha + beta alloy is referred to as the near alpha alloy [76]. The mechanical properties of this alloy type depend on the relative amounts and distribution of the alpha phase and beta phase present [79]. In general, the equiaxed and bi-modal microstructures are preferred for these alloys as they give them good balance of strength, ductility, fatigue, and creep resistance [80]. However, they possess relatively poor creep resistance compared with the alpha alloys. Ti-6Al-4V, the prime alloy of this class, also predominates the overall uses of titanium in general.

Figure 10 shows a schematic pseudo-binary phase diagram illustrating the temperature-dependent phase transformations between alpha and beta phases for Ti-6Al-4V alloy. These alloys possess good response to heat treatments because of the two-phase field which allows the relative amounts of alpha and beta phases to be alpha made. Other examples of alpha +

beta alloys include Ti-6Al-6 V-2Sn, Ti-6.5Al-3.2Mo-1.8Zr-0.25Si.

5.2.3 Beta alloys

Beta alloys are the type whereby a small volume of material is quenched from above the allotropic temperature using ice water to produce a beta phase without martensitic decomposition [76]. These alloys generally contain large amounts of transition metals which act as beta stabilizing agents. These alloys consist of a metastable beta phase, which decomposes in case of cold working or a slight change in temperature resulting in decomposition to alpha phase. Although these alloys are relatively high in density, their strength is high enough to give them strength-to-weight ratios surpassing those of alpha + beta alloys. Furthermore, these alloys offer high toughness and fatigue strength and excellent combustion resistance and are easy to heat treat. The improvement of the weight-to-strength ratio to its heights is achieved through solution treatment which transforms some beta phase to alpha and causes the formation of finely dispersed alpha in the retained beta phase. The properties of each beta alloy vary from the other depending on the stabilizing agent [73, 74]. The disadvantages of the beta alloys are high density, low modulus, poor low- and high-temperature properties, microstructural instabilities, segregation, and interstitial pick up.

5.3 Microstructures and mechanical properties of Ti-6Al-6V

The mechanical properties of alpha titanium alloys strongly depend on the microstructural evolutions birthed by the composition, processing history, and thermal treatment. Since composition of Ti-6Al-4V is known, the rate at which the alloy cools from above the transformation temperature is the determinant of the microstructure that will be achieved. Therefore, it is of paramount importance to identify and classify the possible microstructural forms as well as the conditions that favor their evolution thereof.

5.3.1 Lamellar microstructure

The lamellar microstructure, alternatively known as basket weave, forms as a result of slow cooling from above the beta single-phase field through the beta transus temperature. The gradual decrease in temperature results in the formation of a crystallographic relationship between the evolved alpha phase and the remainder of the beta phase. In addition, intermediate cooling rates result in a formation of Widmanstätten structures. The basket weave microstructure is characterized by coarse grains with large amounts of alpha phase and significantly smaller amounts of beta phase found at the boundaries. The characteristics of a lamellar microstructure include a moderate fatigue resistance, good creep resistance, crack growth resistance, and a relatively poor tensile ductility [81].

5.3.2 Equiaxed microstructure

The equiaxed microstructure contains about the same amount of alpha and beta phase. This form of microstructure is common with significant mechanical working in the alpha + beta phase region. Alternatively, recrystallization annealing process can be used to achieve an equiaxed microstructure [82].

5.3.3 Bi-modal microstructure

The combination of lamellar and equiaxed microstructures is classified as the bi-modal microstructure. This microstructure consists of isolated primary α-grains in a transformed β matrix. Bi-modal microstructure is obtained by an anneal high in the $\alpha+\beta$ region followed by an air cool [83].

5.3.4 Martensite microstructure

The rapid cooling from temperatures above the martensite start temperature and the beta transus results in the formation of martensite microstructures [84].

6 Summary and conclusion

Laser additive manufacturing processes hold a promise to improving the mechanical performance as well as the fabrication cost of titanium alloy (particularly Ti-6Al-4V) which is commonly employed in aerospace applications among others. Employment of lightweight materials for the aerospace industry helps in mitigating the fuel consumption which will have a direct impact in reducing the greenhouse gas emission thus reducing the effects the industry has on global. In addition, fabrication of lightweight components at economical costs will help reduce the travel costs via cheap energy efficient aircrafts. Despite the potential these technologies hold for the aerospace industry especially when their advantages are coupled with desirous materials, some hindrances still persist, which necessitates the continual process development and improvement in order for the technology to maintain the prominent position or even upgrade it. On the other hand, the aerospace industry has always been quality-driven but is constantly becoming more cost driven over recent years which makes it a major requirement to develop techniques by which waste in both fabrication cost and material be minimized. One method to achieve this is by developments in the present energy-efficient additive manufacturing processes that will enable optimal material use efficiency such as reliable powder recycling procedures which will contribute largely in economical value.

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