Chapter 8
Additive Manufacturing:
Laser Metal Deposition and Effect of Preheating on Properties of Deposited Ti-4822-4 Alloy

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ABSTRACT

Three-dimensional printing has evolved into an advanced laser additive manufacturing (AM) process with capacity of directly producing parts through CAD model. AM technology parts are fabricated through layer by layer build-up additive process. AM technology cuts down material wastage, reduces buy-to-fly ratio, fabricates complex parts, and repairs damaged old functional components. Titanium aluminide alloys fall under the group of intermetallic compounds known for high temperature applications and display of superior physical and mechanical properties, which made them most sort after in the aeronautic, energy, and automobile industries. Laser metal deposition is an AM process used in the repair and fabrication of solid components but sometimes associated with thermal induced stresses which sometimes led to cracks in deposited parts. This chapter looks at some AM processes with more emphasis on laser metal deposition technique, effect of LMD processing parameters, and preheating of substrate on the physical, microstructural, and mechanical properties of components produced through AM process.

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INTRODUCTION

Additive manufacturing (AM) technique, a process of fabricating component parts from three-dimensional computer aided design (CAD) data has become a modern and advanced manufacturing technique that continues to witness tremendous improvements. Layer upon layer build-up are formed from the computational instructions of CAD to fabricate required parts (Aliakbari, 2012; Herderick, 2011). This method used by AM technology makes it possible to provide an alternative path as compared to conventional subtractive manufacturing path like machining. The AM technique is able to provide solutions to issues regarding global competitiveness facing the manufacturing industries. Some of the advantages of AM include improved product quality, customized product demand, low cost of production and reduce down time.

History of AM can be traced back to 1987 when 3D systems manufactured the first stereolithographic equipment. The main goal of AM is to improve the performance of fabricated parts through production cost, lead time and material usage (Kobryn et al., 2006). Some of the AM techniques use lasers as primary source of energy. These lasers provide fast heating and make it possible to manipulate operation processes. This is because, convection forces created by these lasers produce melt pool having the capacity to improve the diffusion rate and make it possible for powders introduced onto the melt pool to mix (Tlotleng et al., 2016). Common AM techniques available include: electron beam melting, direct laser sintering, easyclad and laser metal deposition. This chapter briefly explains some of these lasers AM techniques, their properties and applications. More emphasis was made on laser metal deposition technique of titanium aluminide, importance of preheating of substrate and effect of laser deposition parameters on the quality of fabricated parts.

LASER ADDITIVE MANUFACTURING TECHNOLOGY

Recently, light amplification by stimulated emission of radiation (LASER) gained more ground in different areas of applications. Laser is produced from light or sometimes referred to as electromagnetic radiation and then amplified (Singh et al., 2012). The ability of laser seen in it far reaching light travelling properties and showing very little divergence made laser highly useful for different applications. The applications of lasers as constantly witnessed in communication and office equipment (such as bar-code scanners, laser printers, laser scanners and video players), medicine for surgery, military (for locating and targeting) and in construction industries (for cutting, melting, boring, etc.). Laser is unique in its ability to concentrate its energy to create high energy intensities and remains almost the same over far distance due to its low divergent property. The high intensity of laser beam makes it possible to melt hard materials like metals within a short time. This useful ability of laser beam is what is employed in laser AM technology, and makes it possible to create melt pool on substrate on which metal powder is deposited.

Additive or layer manufacturing technology uses data from 3D model to build near-net-shape components through layer upon layer build-ups. This technique of manufacturing process is developing because of its ability to reduce energy usage, material wastage and component lead time. It also has the ability of fabricating complex and what seem impossible parts when traditional production methods are to be used (Herderick, 2011). Laser metal deposition process, an AM technology has the ability to produce near-net dense structures with improved mechanical properties (Dinda et al., 2009; Kobryn et al., 2006).The sophisticated ability of AM have made it possible to be used in numerous applications including medicine, biomedical, aerospace, automobile, defense, and energy generation (Abdulrahman et al., 2018).

PROCESSES OR TECHNIQUES OF AM

There are different AM techniques currently being used. The name of each technique was given either by the company that developed the process or the method of process employed. Some of these processes are discussed below.

Laser Beam Melting (LBM) or Selective Laser Melting (SLM)

LBM, sometimes referred to as SLM, is the technique that has the ability to directly produce intricate parts from metal powder via computer aided design (CAD) model data. This is done by slicing the CAD model into tiny layers and transferring the data generated to LBM machine for production. The form or geometric data of each sliced layer are transferred onto the powder bed in an inert environment, where the surface area is scanned and a solid layer piece is then produced. This process (shown in Figure 1) continues until the whole solid part is produced from the sliced model layers. This process produced parts with excellent mechanical properties when compared to that produced by traditional process (Bremen et al., 2012). Research is still on going as to the appropriateness of the process for series production.

Electron beam melting (EBM): The energy needed for melting in this process comes from a high power electron beam. This process usually takes place in a vacuum at high temperature. The electron beam supplied the temperature needed for each layer of component to be achieved. Component produced through this method are mostly free of residual stresses and their microstructure are free of martensitic structures. Svensson et al., (2010) demonstrated the fabrication of gamma titanium aluminide component using the EBM process. 3 KW power was used to melt the metallic powder (-140/+325 powder size). The components produced have fine grain size with minimal internal defects. The EBM schematic set-up is shown in Figure 2.

Laser Metal Deposition (LMD)

The process employs the use of nozzle to directly deposits metal powder onto a desired molten surface created by laser beam, where solidification of the melted metal powder later takes place. The process has proven to be very effective when compared to the method of selective laser melting. One of the usefulness of laser metal deposition technique is it strength to concurrently use multiple material to produce composite and functionally graded materials

Figure 1. Laser beam melting process
Source: (Bremen et al., 2012)

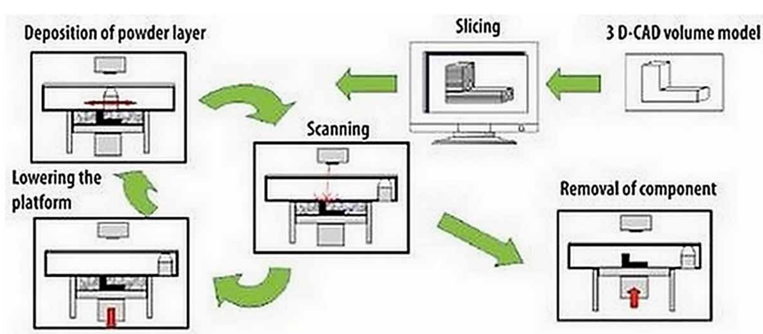
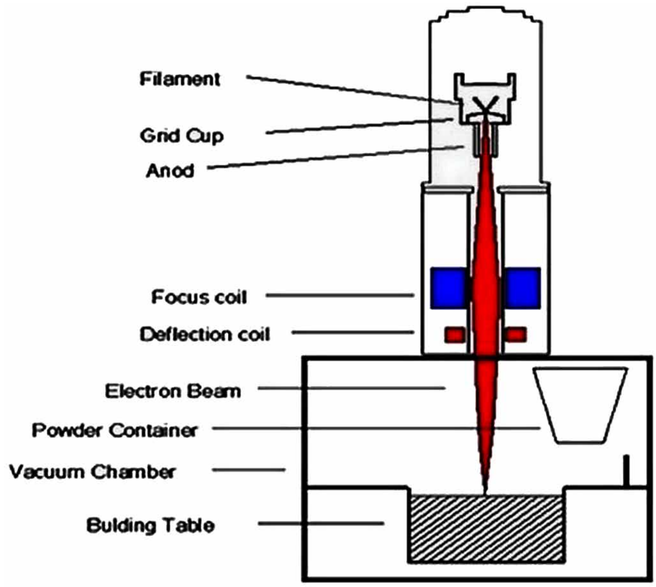


Figure 2. Schematic EBM process set-up
Source: (Svensson et al., 2010)

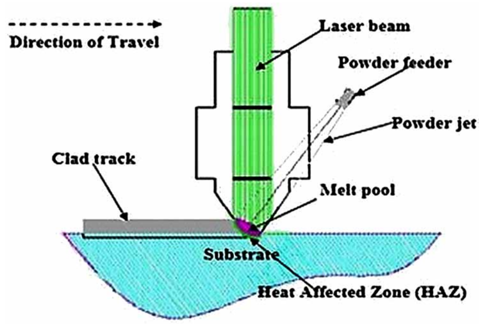


(Balla et al., 2016; Mahamood & Akinlabi, 2017). The technique produces high quality parts. Some of the other qualities of the process include it ability of repair damaged parts, addition of new features on existing parts and deposition control ability. The limitation of the technique lies in the size of parts that can be produced as this mainly depends on the size of the LMD machine. Schematic view of laser deposition process is shown in Figure 3. Difficult to machine materials such as titanium and its alloy can easily be fabricated using AM technologies.

TITANIUM AND ITS ALLOYS

Titanium is an impure oxide that was first found by William Gregor in 1791. Mathew Albert Hunter in 1910 was able to produce titanium metal after processing titanium tetrachloride and sodium. And by 1932, Wilhelm Kroll produced large amount of titanium from titanium tetrachloride and calcium and by 1948, Dupont Company became the first company to commercially produce titanium (Peters et al., 2003b). Titanium is one of the most abundant and one of the lightest metals known to man (Balla et al., 2016). Titanium has

Figure 3. Schematic view of laser metal deposition process
Source: (Akinlabi & Akinlabi, 2016)



low density, good strength, high resistant to corrosion and good resistance to fracture. At high temperature, alloys of titanium are highly reactive with atmospheric gases such as nitrogen, oxygen and hydrogen (Nurul Amin & Shah Alam, 2012).

Titanium aluminide is an intermetallic compound classified under high temperature structural materials with superior properties which make it highly applicable in automotive, aircraft engines and gas turbines (Lapin, 2009). The unique properties of such intermetallic compound have been known to include: high strength to low weight ratio and good corrosion resistance which is the main reason why they are mostly needed in the aerospace, chemical and medical industries.

Titanium alloying process by adding other elements (such as Mo, Vn, Sn, Nb, Cr, etc.) are done as a way to further improve the properties of the titanium alloy. This action is seen when element such as tin are added to produce Ti-5Al-2.5Sn specifically for high temperature applications. Also molybdenum, a β-stabilizer have been added to titanium alloy to produce Ti-7Al-4Mo (α+β) alloy suitable for high strength applications. Other alloys that have been developed include Ti-13V-11Cr-3Al (β titanium alloy), Ti-6Al-4V (α+β) alloy. Ti-6Al-4V alloy possesses superior properties and despite being so expensive, still remains the most preferable titanium alloy. The high cost of titanium alloy is one of the factors responsible for creating a manufacturing process that will reduce and made rapid prototyping (additive manufacturing) technique a viable alternative rout (Yvonni-Effrosyni, 2014). Silicon has also been introduced (as a creep resistant enhancer) to titanium alloy to form Ti-4Al-4Mo-2Sn-0.5Si (Lutjering & Williams, 2003). Other alloys that have been developed over the time include Ti-6Al-7Nb, Ti-5Al-2.5Fe and Ti-48Al-2Cr-2Nb. It is possible to achieve very high strength of titanium alloys at higher temperatures but the high oxidation behavior at maximum temperature application process makes it difficult to achieve, which is why intense research are still on in the development of other titanium alloys (Peters et al., 2003a).

RESEARCH WORKS ON LASER METAL DEPOSITION (LMD) PROCESS

As earlier discussed, the laser metal deposition (LMD) process is one of the techniques of additive manufacturing that is used to clad, repair, add new feature or produce an entirely new part. The technique uses laser to create melt pool on to which metal powder is deposited. Several researches are being carried out in the deposition process using this technique because of its numerous advantages.

Akinlabi and Akinlabi, (2016) did a research using LMD process to deposit aluminum powder on titanium substrate. The depositions were done at a constant laser power of 1 kW, gas flow rate of 1.5 l/min and scanning speed varied from 0.5 m/min to 3 m/min. The research revealed that at a lower scanning speed, alpha phase grains microstructures were observed. While at higher scanning speed, beta phase grains were noted. It was however noted that the laser-material interaction lead to changes in the geometrical properties (like height, width and heat affected zone) of deposited samples. The research summarized that increase in scanning speed lead to decrease in the geometrical properties and also lead to increase in the microhardness and corrosion rates of deposited samples.

In another research carried out by Yvonni-Effrosyni, (2014), the direct laser metal deposition technique was used to study the effect of deposition parameters on the mechanical properties and microstructure of deposited samples. Ti6Al4V was deposited at 500 W laser power and other samples re-melted at 600 W at scanning speed of 200 and 400 mm/min. The re-melted samples revealed homogenous distribution of dendrites and the samples deposited at 200mm/min has better surface roughness and hardness.

Effect of deposition parameters in the deposition of pure titanium powder using laser net-engineered shaping (LENS) process was studies by Hu et al., (2016). Laser power, scanning speed and powder feed rates were varied for the deposition sixteen layers of for each sample where first layers where taken as substrate on which other layers were deposited. The outcome of the work revealed that the height of deposits increases with respect to increase in laser power, decrease in scanning speed and increase in powder flow rate. The hardness of the deposited samples increases with respect to increase in laser power and decrease in scanning speed. Also it was noted that increase in powder feed rate from 0.5 to 1 rpm resulted to a sharp drop in hardness.

In the work of Yan et al., (2017), functionally graded material (FGM) was produced using LMD process. Ti-48Al-2Cr-2Nb powder was deposited on pure titanium substrate. The deposition process was carried out by varying the incident energy input which is mostly responsible for crack formations in deposited samples if not properly controlled (Balla et al., 2016). The deposition process uses high energy input at the beginning and later reduced to avoid overheating. Scanning speed was kept at 600 mm/min while the laser power was varied. Primary phases of α, α_2 and γ were discovered within the alloy gradient. Basket-weave microstructures were noted at the region where the energy input was higher and lamella structure was seen at the final region where the energy input has been reduced. Fine grain structures were noted at the top due to increase in cooling rate from the top to the bottom of deposits which account for the higher ultimate tensile strength achieved. Hardness slightly increased as the percentage weight of Ti4822 increased in the region and led to material brittleness.

DEPOSITION PARAMETERS IN LMD PROCESS

Deposition parameters or sometime referred to as processing parameters in deposition processes play paramount role in the quality and properties of fabricated parts. Proper understanding of the interaction of between the parameters will ensure the right selection of deposition parameters needed in the deposition processes (Bayode et al., 2018). As such, careful selection and control of deposition parameters is paramount in ensuring that high quality parts are produced. Most commonly employed processing parameters in deposition processes include the spot size of laser, laser power, and laser scanning speed and powder flow rate. These parameters are briefly discussed below.

Spot Size of Laser

The laser spot size plays a critical role in the laser deposition process. This spot size is determined by the laser beam diameter which can be used to influence the laser beam concentration on any particular spot. The relationship between the spot size and beam intensity is inversely proportional. As such, the smaller the spot size, the higher the beam intensity.

Laser Power

Laser power is another vital process parameter that plays an incredible role in deposition process. This is because it is not only responsible for the creation of melt pool but also play important role in the quality and properties of deposited parts as it was clearly demonstrated in literatures (Sharman et al., 2018; Yan et al., 2017; Yvonni-Effrosyni, 2014). Some of the work that have been carried out clearly demonstrated that laser power apart from having the ability to reduce cracks in fabricated parts also play tremendous role in microstructural and mechanical properties of parts. This is because laser power plays a role in laser-material interaction and rate of cooling in the solidification process.

Laser Scanning Speed

Laser scanning speed is another deposition parameter that have been proven to also have a great influence in the deposition process and in determining the quality and property of deposited parts. Laser scanning speed is a parameter used in describing the speed at which the laser moves along a desired path. Just like laser power, laser scanning speed has a relationship with the laser material interaction and rate of cooling in the solidification process. Sobiyi et al., (2017) looked at the influence of laser scanning speed on titanium and titanium carbide metal powders on titanium alloy substrate. The outcome revealed that the heat affected zone (HAZ) increases with increase in scanning speed and that the height of deposits also varied with the change in laser scanning speed. It was also found that the microhardness of samples increases with increase in laser scanning speed. However, the conclusion reached that HAZ increased with increase in scanning speed might not be the case, because increase in scanning speed means the reduction in energy density and will results to reduction in laser material interaction time. Therefore, it is logical to think that there will be reduction in HAZ as the scanning speed increases.

It is however good to note that the laser spot size, laser power and scanning speed do have a relationship that connect them together. This is because the three parameters central around energy input involve in the deposition process. The interaction between these parameters gives what is referred to energy density. This energy density is the total incident energy input per unit area (Mazumder et al., 1999) and calculated with the equation below:

$$Energy\ \ density\left(E\right) = \frac{P}{VD}$$

where the energy density *(E)* is in J/mm^2, laser power *(P)* in watt (W), scanning speed *(V)* in mm/s and spot size dimeter *(D)* in mm. The energy density therefore becomes a very crucial factor and its influence in deposition process has well been established in literatures (Hu et al., 2016; Tang et al., 2007; Zyl et al., 2016). The influence of energy density was also noted by Liu & Dupont, (2004), that the increase in laser beam incident energy will result in crack frequency decrease in deposited parts. This is because the cooling rate is inversely proportional to laser heat input (Kou, 1987). The cooling rate of any material in deposition process is largely dependent on laser heat input.

Powder Flow Rate

Powder flow rate referred to the amount of powder flowing out to the deposition zone per unit time. It normally carries the unit g/min and sometimes revolution per minute (rpm). The flow ability of any metal powder mainly revolves around its morphology and particle size. Spherical shaped metal powder is believed to be most preferable for laser metal deposition process because of its ability to react with laser beam better (Schade et al., 2014). Some literatures have discussed on the influence of powder flow rate in deposition processes. Powder flow rate have been proven to have an effect on material efficiency and dimensional accuracy of laser deposited parts (Kumar et al., 2014; Schade et al., 2014). Powder flow rate have also been investigated to affect the resistance of deposited parts (Saboori et al., 2017; Shukla et al., 2012). Other property such as surface roughness can also be affected due to powder flow rate as noted by Shah et al., (2010).

ESSENCE OF PREHEATING IN LMD PROCESS

Different researchers continue to stress the importance of preheating especially in the LMD process of titanium aluminide parts. This is because LMD process involves rapid heating and cooling which sometimes resulted to residual stresses in fabricated parts and made them highly susceptible to cracks. To prevent or reduce cracks in LMD processes, careful control of process parameters and preheating are mostly recommended. As such, several works that have been carried out on laser deposition additive manufacturing of titanium aluminide all agreed that it is quite impossible to fabricate parts that are crack-free, unless additional heating system is provided which may be in the form of an induction coil or a heating bed to control the cooling rate (Sharman et al., 2018). In the study carried out by Liu & Dupont, (2004), it was discovered that thermal cracking can only be reduced by increasing incident laser energy through the use of higher laser power and lowering the laser scanning speed. This action only reduces the thermal cracking and to completely eliminate cracking, it was recommended that additional heating system should be provided to preheat the substrate to 450^0C before commencing the deposition.

EXPERIMENTAL CASE STUDY OF LMD OF TITANIUM ALUMINIDE (TI-4822-4)

There are currently few studies on the fabrication of titanium aluminide (Ti-48Al-2Cr-2Nb or simply known as Ti-4822-4 according to manufacturer's label). These limited studies currently show limitations in its usage as more still need to be known in terms of its properties and suitability in different applications. Most of the studies are geared to finding optimum processing parameters, studying the emerging properties and fabricating crack-free parts. This is because titanium aluminides are crack sensitive materials (Brueckner et al., 2015).

Studies done by Weishiet et al., (2000) on TiAl revealed that lowering the power density and laser scanning speed only reduced the cracking and did not totally eliminate it and that cracking could only be prevented through preheating of substrate to about 400^0C. The work of Srivastava et al., (2000) revealed that the continuous increase in the built height of TiAl strips keeps led to increase in length and frequency of cracks which is often linked to residual stress produced by high thermal gradient. As such, different attempt made researchers to conclude that it is impossible to produce TiAl parts that are crack-free except when an additional heating system is provided in the laser deposition process (Sharman et al., 2018).

In the experimental case study that is about to be discussed, TiAl powder has been deposited on preheated pure titanium substrate (CP-Ti) via laser deposition process called laser engineered net shaping (LENS) technique. Studies on quality of deposits, microstructure and microhardness have been carried out.

MATERIALS AND METHODS

In this study, spherical shaped TiAl powder of particle size range of 45 to 150 μm gotten from Praxair surface technologies USA was deposited on CP-Ti (of size 10 x 10 x 6 mm) substrate. LENS 850R laser machine at Council for Scientific and Industrial Research (CSIR), Pretoria, South Africa have been used for the deposition process. The elemental composition of the metal powder used for the deposition is shown in Table 1. The substrate was first sand blasted and cleaned with acetone to remove the oil deposit and other impurities that may be on it after which the substrate was preheated to 450^0C before the deposition was started using a spot size of 1.4 mm. Deposits of five layers were produced according to parameters highlighted in Table 2 while the powder flow rate was kept constant at 2.8 g/min.

After the depositions, a digital Vernier caliper was used to measure the heights of each deposit, to determine the relationship between deposition parameters and height of deposits. The deposits were later section perpendicularly and prepared using standard metallographic procedure for titanium alloy (Taylor, 2015). A Tescan scanning electron microscope was used to analyze the microstructure of deposited samples. The microhardness of deposits was determined using a Vickers microhardness tester. Microhardness

Table 1. Metal powder elemental composition

Aluminum	Chromium	Niobium	Other elements, Total	Titanium
34	2.6	4.8	<0.10	Balance

Table 2. Deposition parameters

Sample designation	Laser power (KW)	Scanning speed (mm/s)	Energy input (J/mm^2)
A	0.40	3.17	90
B	0.45	3.17	101
C	0.40	2.65	108
D	0.45	2.65	122

measurements were taken by applying a load of 500 g over a dwelling time of 15 s to specimens from top to bottom at 0.5 mm interval.

RESULTS AND DISCUSSION

After the deposition process, the physical examination of the deposits with naked eye, revealed the presence of micro-cracks on deposited sample A (as shown in Figure 4a) and C. After the samples were examined under the scanning electron microscope (SEM), the result revealed that increase in energy input (increase in laser power from sample A to B and reduction in scanning speed from sample C to D) led to tremendous decrease in micro-cracks. Table 3 gives the deposits height and microhardness of deposited samples.

From Table 3, it is clear that increase in laser power or reduction in scanning speed in the deposition process influenced the outcome of heights and microhardness of deposited samples. Increase in laser power form 0.4 W to 0.45 W and reduction in scanning speed from 3.17 mm/s to 2.65 mm/s resulted in a corresponding increase in deposits height. Also, reduction in microhardness was witnessed when the laser power was increased from 0.4 W to 0.45 W at scanning speed of 3.17 mm/s. The relationship between deposition parameter and height and microhardness of deposits can be linked to the laser material interaction and rate of cooling experienced in the deposited samples.

Table 3. Height and microhardness of deposits

Sample designation	Deposit height (mm)	Deposit microhardness (Hv)
A	1.6	565
B	2.1	536
C	2.3	550
D	2.7	560

Figure 4. Shows the (a) Cross sectional image of sample A (b) Phase transition in sample B (c) microstructure of sample A and (d) microstructure of sample B

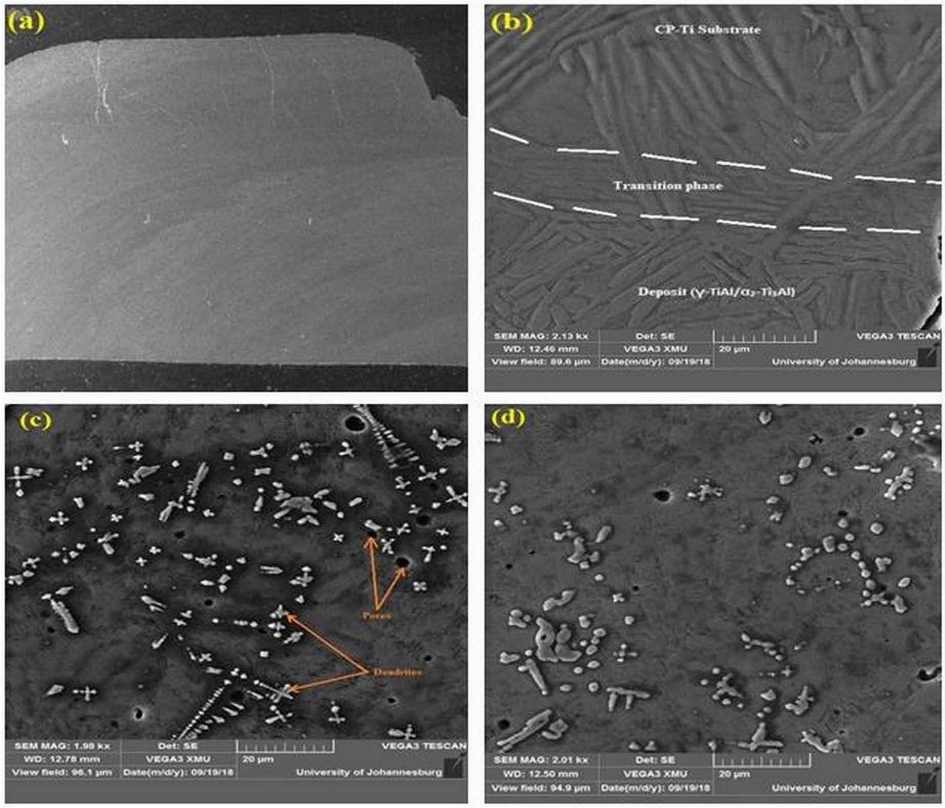


Figure 4b shows a transition phase of sample B characterized by needle-like (columnar) grains and witnessed across all the deposited samples. The transition layer observed between the substrate and the deposit show a good bonding between the materials. The SEM result show that the samples (as shown in Figure 4c and 4d) are characterized with dendrites and pores which reduce as the laser power increases and scanning speed reduces. Considerably, a homogenous microstructure comprising of lamellar γ-TiAl and α_2-Ti_3Al regions were obtainable in the deposits.

CONCLUSION

Laser metal deposition (LMD) is an additive manufacturing technique that has proven to be very effective in the production and repair of parts. However, the parts formed through the technique are prone to cracks to due to residual stresses. Cracking in deposited samples can be reduced or eliminated by careful selection of processing parameters and provision of additional heating system. This chapter has clearly looked at some of the AM processes with more attention on laser metal deposition (LMD), effect of LMD deposition parameters and preheating on the physical, microstructural and microhardness of components produced through the process. The outcome of a case study revealed that increase in input energy and preheating of substrate can hugely reduce cracking. The outcome also revealed that process parameters also have a great influence in the microstructural and mechanical properties of deposited parts.

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