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Rasheedat Modupe Mahamood

Laser Metal Deposition Process of Metals, Alloys, and Composite Materials

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This book is dedicated to Almighty God.

Foreword

Additive manufacturing process is an advanced manufacturing technology that offers lots of advantages to the manufacturing world, such as the ability to reduce the buy-to-fly ratio in the aerospace industry. With the additive manufacturing method, the complex part that could not be made using the traditional manufacturing process without being broken down into smaller units can now be made as a single unit object. The use of the additive manufacturing method helps to reduce the weight of the manufactured component by eliminating the extra materials needed for the assembly of the smaller units that the complex part is broken down into when the traditional manufacturing processes were used. It also helps to reduce product lead time, and new product can easily be brought into the market using the additive manufacturing technologies. Laser metal deposition process is an additive manufacturing technology that is useful for the production of new part and the repair of high-valued components. A number of industries are benefiting from these technologies such as the aerospace and the automobile industries. This book was written by the author to highlight the importance of this exciting additive manufacturing technology. I am also an expert in this field and have published a number of articles, book chapters and a number of conference papers, and I am in a good position to recommend this book to you. This book will benefit the industries by helping them to understand the capability of the laser metal deposition process. The upcoming researchers in the field of advanced manufacturing process and the professionals in this field will also find this book to be of great benefit.

The author of this book has published widely in this field of research which include journal articles, conference proceedings, book chapters and books. The author is in a better position to write this book as an expert in this field. The book began with introduction and the background of the laser metal deposition process. This book contains ten chapters. This introduction will provide the adequate background information for the readers and the new researchers in this field for proper understanding of the additive manufacturing processes. The information about laser is presented in Chap. 2. Laser plays an important role in today's world. The characteristics of laser that makes it important in the laser metal deposition process were well explained in Chap. 2. This will help the reader to understand how the properties of laser have helped in achieving what could not be achieved in the past in terms of manufacturing. The laser metal deposition process was described in Chap. 3. The solidification mechanism and the microstructural evolution were also fully explained in this chapter. Processing parameters have been found to play an important role, and they have serious influence on the properties of laser metal deposited materials. The different processing parameters that affect this additive manufacturing technology are presented in Chap. 4. The use of laser metal deposition process for metals and alloys is explained in Chap. 5 with the different materials that have been successfully deposited. The use of laser metal deposition for the processing of composite materials as well as functionally graded materials is explained in Chap. 6. A number of application areas exist for the laser metal deposition process. The author explained the different application areas for the laser metal deposition process are presented in Chap. 7. Laser metal deposition process is used in repair of high-valued part and as surface modification process to improve the surface properties of materials which are presented in Chap. 7. Case studies on the use of laser metal deposition of titanium alloy and titanium alloy composite are presented in Chap. 8 to enable the reader to further understand this important additive manufacturing process. The research progress in this field of laser metal deposition process is presented in Chap. 9. The book ends with the future research need and the summary of the book.

Haven read this book thoroughly and also being an expert in this field of research, I hereby strongly recommend this book to the readers because of the great benefits the book will offer and this book will help the new researchers to have the basic understanding required to succeed in this research field. I am in a good position to write this forward because I am also an expert in this research field and I want the readers to take full advantage of this subject by reading this book. This is the only book in the market right now that fully treat this subject which makes the book an important one.

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Preface

The laser metal deposition process is an important additive manufacturing process that has a great potential of revolutionizing the way products are made and remanufactured. This book starts with the introduction of the laser metal deposition process and a brief background of the process. A detailed introduction of the laser metal deposition process is presented in Chap. 1 of the book. Laser has a number of important characteristics that make its use in the laser metal deposition process an important one. The basics of laser principle are explained in Chap. 2. The characteristics of laser are also described in this chapter. The laser metal deposition process is fully described in Chap. 3. The important processing parameters in the laser metal deposition process are explained in Chap. 4. Laser metal deposition of metals and alloys and the laser metal deposition of composites and functionally graded materials are explained in Chaps. 5 and 6, respectively. The areas of application of the laser metal deposition process are presented in Chap. 7. Case studies on the processing of titanium alloy and titanium alloy composite using the laser metal deposition process are presented in Chap. 8. The research advancements in laser metal deposition process are presented in Chap. 9, while the future research direction and summary are presented in Chap. 10. This book is organized as follows:

Chapter 1—Introduction of laser metal deposition process and a brief background of the process are discussed in this chapter.

Chapter 2—Laser is an important invention the has helped to change the way many things are done this days. Laser is a unique source of light that is highly coherent and highly directional. These important laser characteristics of laser make it possible to control the energy to only the needed area. The basic principle of laser and characteristics of laser are explained in this chapter.

Chapter 3—The full description of the laser metal deposition process is presented in this chapter. The creation of the melt pool and the solidification process that results in the characteristics microstructures during the laser metal deposition process are fully described in this chapter.

Chapter 4—Processing parameters such as laser power, scanning speed, powder flow rate and gas flow rate are very important in the laser metal deposition process.

The influence of each of these processing parameters on the developed materials properties is explained in this chapter.

Chapter 5—A number of materials can be processed using the laser metal deposition process, and this is one of the reasons why this additive manufacturing process is an important one. The laser metal deposition process of metals and alloys is presented in this chapter.

Chapter 6—The flexibility offered by the laser metal deposition process is in its capability to process more than one material at the same time that makes it possible to be able to process composite and functionally graded materials. The use of laser metal deposition process for composite and functionally graded materials is presented in this chapter.

Chapter 7—Laser metal deposition process, like any other additive manufacturing process, can produce three-dimensional object directly from the three-dimensional computer-aided design data of the object by adding materials layer by layer. The laser metal deposition process is also useful in the repair of high-valued parts which cannot be achieved by any other process. The areas of applications of the laser metal deposition process are explained in this chapter.

Chapter 8—Case studies on the laser metal deposition process of titanium alloy and titanium alloy composite and the influence of the processing parameters on the evolving properties of the titanium and titanium alloy are presented in this chapter.

Chapter 9—Progress in terms of research in the laser metal deposition process is presented in this chapter.

Chapter 10 ends the book. The future research direction in the laser metal deposition process and the summary of the whole book are presented in this chapter.

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About the Book

The consumer demand is moving away from the standardized products to a more customized products, and to remain competitive in the industry, manufacturers require an alternative manufacturing process that is flexible and able to meet consumer demand at a low cost and also on schedule. Laser metal deposition (LMD) process is an alternative manufacturing process with lots of promises. This book, “Laser Metal Deposition Process of Metals, Alloys and Composites Materials”, presents the much needed knowledge about this field. Full description of the laser metal deposition process is presented in this book. The laser basics and the properties of laser that makes it important in material processing and in laser metal deposition process are also explained. Some of the research efforts in this field with case studies are also presented. The book contains ten chapters. Introduction and background of laser metal deposition process are presented in Chap. 1. The laser basics and laser–material interactions are explained in detail. The laser metal deposition process, solidification mechanism and microstructure formation are also explained in detail in this book. The processing parameters in the laser metal deposition process, the laser metal deposition of metals and alloys, the laser metal deposition of composites and functionally graded materials, and the areas of application of laser metal deposition process, are all explained in detail in this book. Research advancements in the laser metal deposition process are also presented in this book. The book ends with future research direction and summary. An extensive bibliography in this research field is contained in this book. This is the first book that gives a full treatment on the laser metal deposition process.

Contents

Chapter 1
Introduction to Laser Metal Deposition Process

Abstract Additive manufacturing process is an advanced manufacturing process that fabricates components through the addition of materials as against the labour and energy intensive manufacturing processes which are based on material removal, or on application of heat and pressure. Laser metal deposition process belongs to a class of additive manufacturing process that can be used to fabricate three dimensional (3D) computer aided design model of the part by adding materials in a layer wise manner. Apart from the fabrication of 3D objects, laser metal deposition process can also be used to repair broken down parts and for the fabrication of parts that are made of composite and functionally graded materials. This important additive manufacturing technology is comprehensively dealt with in this book. This chapter briefly introduced the additive manufacturing (AM) process, the various classes of the AM technologies, laser metal deposition process, and the advantages as well as the limitation of these technologies.

Keywords Additive manufacturing · Laser metal deposition · Functionally graded material · Advantages of LMD · Limitations of LMD

1.1 Additive Manufacturing Technology

Additive manufacturing (AM) process is an evolutionary manufacturing process with lots of advantages when compared to the conventional manufacturing methods [1]. Additive manufacturing process produces three dimensional (3D) component or part from the computer aided design (CAD) digital image of the part by the addition of materials layer after layer until the building process is completed [1, 2]. There are two broad classifications of AM process namely: laser based and non-laser based AM technologies [1]. There are over thirty different technologies that made up the additive manufacturing process, the ASTM International and international standard organization (ISO) committee on additive manufacturing standards (committee F42) has recently grouped AM technologies into seven classes [2]. These classes of AM that described the group of technologies that builds 3D objects in a similar

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manner. They are: Material Jetting, Vat Photo polymerization, Binder Jetting, Powder Bed Fusion, Sheet Lamination, Material Extrusion and Directed Energy Deposition. The schematic diagram of the seven classes of AM technologies is shown in Fig. 1.1.

The group of technologies under the material jetting class of AM process builds up the 3D object through the addition of materials in liquid form. The liquid material is deposited in jet form on the build platform in a similar way ink is being jet out in the ink jet printer. The jetted materials are then solidified through curing with ultraviolet light. The liquid Material is deposited from a nozzle that is moved horizontally across the build platform following the path dictated by the CAD profile data [3]. The difference in each of the group of these technologies is in the method of controlling the jetting of the materials. The commonly used materials are polymers and waxes. This group of AM technologies is used for building prototypes, tooling and consumer end use products.

The vat photo polymerization class is also a liquid based process which uses photopolymer materials such as resin that is hardened by visible light such as ultraviolet light.

These liquid materials are delivered onto the build platform by moving the build platform downward after a layer has been deposited and cured through the process called photo polymerization. The first commercialized AM technology, Stereolithography, belongs to this class of AM technologies that was invented by Hull in the eighties [4]. This group of AM technology produces part with high level of accuracy and good surface finish, the main disadvantage is that it takes longer

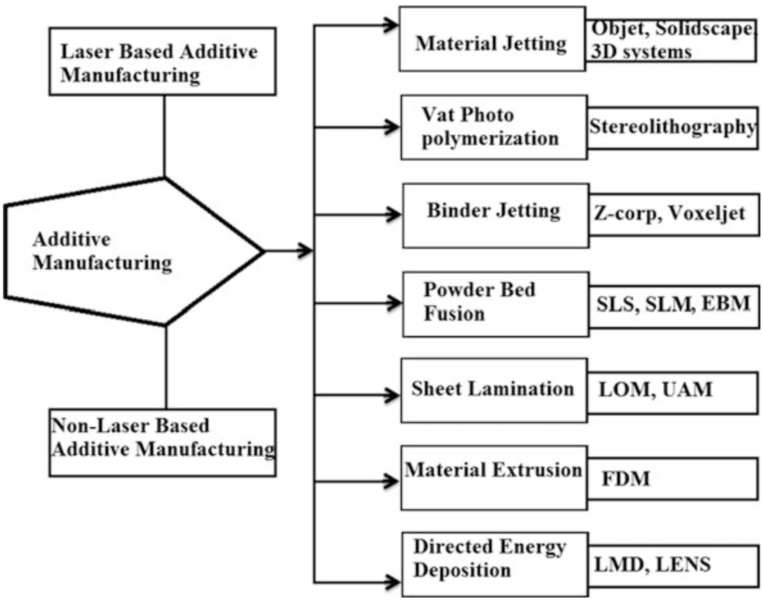

Fig. 1.1 Classification of additive manufacturing

time for the post processing operations such as: support structure removal and other strengthening processes [5–8].

The binder jetting class of AM technology is different from the material jetting and the vat photo polymerization classes of AM technology in that it uses two different materials together which are basically powdered material and a liquid material. The liquid material served as a binder for the powdered materials. The building process is similar to those two processes with the liquid material (that is the binder) put in the print head. The powdered material is spread in the build platform by one layer thickness and then the print head delivers the binder onto the powder bed based on the path defined by the 3D CAD digital data. The binder is immediately cured after the binder is deposited. The build platform is lowered a layer thickness distance and the powder is again spread over the platform and the cycle is repeated until the building process is completed. After the part is completed, the part is put in a furnace to further cure and strengthen the part. This class of AM technology can use polymers, metals, ceramic, and composite materials. 3D printing is an example of AM technology in this class of AM. This class is relatively faster than the other two classes and the speed can further be increased by the addition of several print heads [9–12].

The powder bed fusion class of AM is similar to the binder jetting class of AM technology with the only difference that the liquid binder is replaced with heat source (e.g. laser or electron beam). The 3D object is produced by spreading the powder material on the build platform and the heat source placed in the print head is used to fuse or bind the powder particles together or in some AM technology completely melt the powder. The build platform is lowered by one layer thickness, the powder is spread on the platform and the heat source repeated the scanning of the powder by following the direction that is dictated according to the generated CAD information. The object is built up by repeating this process until the part building is completed. A wide range of materials—metals, alloys, and composite materials can be used in this class of AM technology. This class of AM technology is used to produce prototypes, tooling and functional parts. Selective laser sintering and selective laser melting, are examples of this class of AM technology [13–17]. The main disadvantage of this class of AM technology is that surface finish is poor that makes the secondary finishing operation to often be required depending on the functionality demand of the component being made.

The sheet lamination class of AM technology is totally different from the other classes of AM technology. It is a solid state process that uses materials in sheet form. The sheet material is spread on the build platform, the print head delivered energy to bind the sheet materials together based on the CAD data information. The platform is lowered and the sheet material is spread on the platform while the print head scans over the spread sheet material. The process is repeated until the building of the part is completed. To ease the removal of the unbound sheet material after the building process, the unused sheets are shredded by cross hatching those areas during the building process. Examples of the technologies that belong to this class of AM include the ultrasonic additive manufacturing and laminated object manufacturing [18–23]. This class of AM can be used to produce prototypes; toolings as well as end used functional parts. Metallic and non-metallic materials can be used with this technology and the process is a low energy process. The main advantage of this class of AM technology is that it is a relatively cheap process with very low energy consumption. However, the surface finish produce is dependent on the material used and it require post processing depending on the desired properties.

Material extrusion class of AM technology produces 3D object by depositing material that is drawn by forcing the semi molten material through nozzle, layer after layer. The nozzle is located on the print head and it is moved in the horizontal direction following the path generated by the 3D CAD data. After each layer is deposited, the build platform is moved in vertical direction as required. The example of technology in this class of AM process is the fused deposition modelling process [24–28]. The technology uses less expensive materials such as polymers and plastics for the production of prototypes and functional products. The main advantage of this type of AM technology is that the process is inexpensive and it uses readily available inexpensive materials. The main disadvantage of this class of AM technology is that, the surface quality depends on the radius of the nozzle. The smaller the nozzle radius, the better the surface quality. This class of AM process is also slow when compared to other AM processes.

Directed energy deposition class of AM technology produce 3D component by completely melting the material to be deposited using the available energy in form of laser or electron beam. The material to be deposited in form of wire or powder is placed coaxially with the energy source and the beam creates a melt pool on the substrate where the material deposited is completely melted and form layers of solid material upon solidification. The creation of these layers is produced based on the direction spelt out by the 3D CAD information. The variant of technologies that belong to this AM class include: the laser metal deposition process, laser engineered net shaping, directed light fabrication and 3D laser cladding [29–34]. Different types of materials can be processed using this technology which include metals, alloys, and composite materials. The main advantages of this class of AM technologies include the ability to repair high valued component parts that were not repairable in the past due to the low heat affected zone produced in the process [35–43], and the possibility to produce functionally graded material because of the capability to handle multiple materials simultaneously [44–49]. The main disadvantage of this technology is that, the quality of surface finish is dependent on the type of material used and the processing parameters employed.

1.2 Brief Background of Laser Metal Deposition Process

Laser metal deposition (LMD) process also known as laser powder deposition process, direct metal deposition, laser cladding, laser engineered net shaping or digital light fabrication, belongs to the directed energy deposition class of AM process. Laser is used as the energy source in this process which is used in combination with the coaxial nozzle for material delivery to build 3D component or to achieve repair of worn out or failed parts. The use of LMD process in the repair of high valued parts which were in the past not repairable or difficult to repair was made possible with the less heat damage that is associated with the process through a well-controlled heat affected zone [40]. The early concept of this technology was presented in the patents [50, 51]. This concept has evolved over the years as described in the eighties by Brown et al. [52] in a patent. The capability of this technology for repair was described in a patent presented by Mehta et al. [53]. In the nineties, the technology was advanced by researchers at the Sandia National Laboratories and the process was named Laser Engineered Net Shaping (LENS) [53]. The technology was improved to utilize multiple material delivery nozzles that help in the efficient powder delivery system and the system has been improved over these years [54–58]. This advanced laser metal deposition technology called LENS is now the most widely used LMD technology in the academia and in the industries. Laser metal deposition process is also called laser powder deposition, laser material deposition, laser cladding, direct metal deposition, laser-aided direct metal deposition, laser-based multi-directional metal deposition, and laser metal deposition shaping [59–66].

1.3 Summary

Additive manufacturing process is an advanced manufacturing method with lots of advantages and promises, as the future manufacturing process has been introduced in this chapter. The various classes of additive manufacturing technologies have also been reviewed. A brief background of laser metal deposition process that belongs to the directed energy deposition class of additive manufacturing was presented. Laser metal deposition process is an important additive manufacturing process because of its capability in repair and production of composite and functionally graded materials apart from its use in the fabrication of new 3D parts. This laser metal deposition process is the focus of this book. The rest of this book is organized as follows. The laser basics and laser material interactions is presented in chapter two where the basic principles of laser, and the different types of lasers are explained. How the laser interacts with the materials in the laser metal deposition process is also explained. The laser metal deposition process is presented in detail in chapter three. The working principle of this AM technology, the advantages and limitations are also presented in that chapter. The solidification mechanism and the microstructural development in the laser metal deposition process are also presented in that chapter. The processing parameters that can be controlled in order to control the properties of the material being processed in the laser metal deposition process are analyzed in chapter four. Some of the research works in the laser metal deposition of metals and alloys are presented in chapter five. Research works on laser metal deposition of composites and functionally graded materials are also presented in chapter six. Areas of application of laser metal deposition process and laser metal deposition for repair are presented in chapter seven. Case studies on laser metal deposition of titanium alloy and titanium alloy composite are presented in chapter eight. The current research efforts in laser metal deposition process are presented in chapter nine. The book ends with the future research direction in laser metal deposition process and the summary of this book are presented in chapter ten.

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Chapter 2
Laser Basics and Laser Material Interactions

Abstract LASER is an acronym termed Light Amplification by Simulated Emission of Radiation. The development of laser has evolved since its inception and its application has spanned every aspect of human Endeavour. Laser is a phenomenon that has revolutionized the human world. The unique properties of laser such as monochromaticity, directionality and coherency, are responsible for its being favoured in all its areas of application. The application areas span from the smallest laser found in the compact disc player to the large laser found in the industries. The brief history of laser and the basic principle of laser generation are presented in this chapter. Properties of laser, different types of laser, laser safety and their areas of applications are explained. The types of laser that are used in material processing are also presented. The laser material interaction and how important these lasers are in material processing and their use in additive manufacturing technologies, a revolutionary manufacturing process, are also presented.

Keywords Laser · Laser applications · Laser history · Laser material interaction · Laser safety

2.1 Introduction

Laser is an acronym that is used to describes the process of Laser. The full meaning of this acronym is Light Amplification by Simulated Emission of Radiation [1]. Laser is a technology that is based on light. It is generated from light source that has been amplified in a way similar to how a microphone is used to amplifies sound. The amplification of the light is achieved by a process referred to as simulated emission which is also known as the optical amplification [2].

The beam of light that is emitted from a light source is used to create an excitation in the atoms that is present in the lasing medium [3]. The lasing medium could be solid (e.g. Ruby), liquid (e.g. hydrogen fluoride) or gas (e.g. Co_2) [1]. The atoms of this materials in these lasing medium becomes excited which results in the

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emission of coherent type of light. The optical amplification is achieved by the resonance of these atoms through arrangement of mirrors in this chamber. The excited atoms bounce back and forth between these mirrors which results in a powerful amplified beam of light that is coherent, this is called a 'Laser' [1, 4]. This process can best be visualized by placing an object in between two parallel mirrors, the image of the object bounces back and forth thereby producing a countless number of images of the object. This is what is referred to as an optical amplification that has resulted in the generation of countless images of the object between the two mirrors. The same thing happens when a single light is placed between two mirrors.

The laser light is characterized by a single wavelength, a single colour light beam that is known as monochromaticity, same phase position known as coherency as well as low divergence, that is the beam that is spread out in parallel lines [1]. All these properties of the laser make the intensity of the laser beam that is produced to be concentrated thereby producing a high intensity laser beam. This unique properties of laser is responsible for its application in all the areas where it is used. The ability to direct the laser beam only to the point of interest makes laser to be mostly favoured. Laser has really revolutionized the world we live in, by making possible a number of things that were not achievable in the past.

In order to appreciate the technology of laser and its importance, the history of laser, properties of laser, principle of lasers, types of lasers and the areas of application of lasers are presented in this chapter. The development of laser through various evolutions are highlighted. The use of laser in the material processing is one of the major achievement of laser and it is also explained in this chapter. The laser material interaction in material processing are also explained in detail.

2.2 History and Development of Laser

The understanding provided by the work of Max planck in the late 1890s and early 1900s was a major breakthrough in science as his theory is what the revolutionary technology called laser is based [5–9]. It all started when Planck first proposed solution to the black body radiation problem in the year 1899 from the principle of elementary disorder. He derived what he called Wien-Planck's law from assumptions about entropy of an ideal oscillator. This law was found to be in no agreement with experimental results. Planck revised this law by including the energy quantization, and statistical mechanics, to derive a new law called the Planck black-body radiation law. The new law was found to be in good agreement with the experimental data [5]. The law was revised using the Boltzmann's statistical to interpret the second law of thermodynamics to further understand the principles behind his black body radiation law. He discovered that electromagnetic energy could be emitted only in quantized form. Planck discover the relationship that existed between radiation energy and the radiation. He found that energy could only be emitted or absorbed in a discrete chunks that he called 'quanta'. He provided the understanding that light is a form of electromagnetic radiation. His discovery of the elementary energy quanta was used to explain why the blackbody did not radiate all frequencies of light when heated up and compared to the way the same blackbody will absorb all the different wavelength of light and hardly reflect any. It was expected that blackbody should reflect radiation when heated the same way it will absorb when not heated. Planck became the originator of quantum theory with this discovery which provides a turning point in Physics and has since revolutionized the human understanding of the atomic and subatomic processes [10]. This understanding is responsible for what is now known as laser.

Albert Einstein continues this research in line with the work of Mac Planck and he first proposed the photoelectric effect in the year 1905 [11, 12]. He further supported the Plank's work through his work which proposed that the light delivers its energy in chunks form which is now referred to as photons. The work was referred to as the quantum theory of light and photons. Later in the year 1917, Einstein also proposed a process called the stimulated emission process. The research work explained the mechanism of stimulated emission. He hypothesized that it was possible to simulate electrons to emit light energy of a particular wavelength through the spontaneous absorption and emission of light [13]. He achieved this using the probability coefficients for the spontaneous emission, absorption, and emission of electromagnetic radiation. The work provide the theoretical background for the fundamental principle of laser. The theory of simulated emission explained how possible it was to amplify stimulated emission from an incident radiation by creating a population inversion between the upper and the lower energy levels in an atomic system. The amplified simulated emission produced would have the same frequency and phases [13]. The phenomena of the simulated emission and negative absorption, as well as how stimulated emission can be used to amplify short waves were also confirmed by a number of researchers [14, 15]. Optical pumping was also proposed in the year 1950 by Alfred Kastler and in the year 1952 it was experimentally validated [16].

Microwave amplification of simulated emission of radiation (Maser) was presented by Charles Towner in the early eighties [17] after the Joseph Weber described how simulated emission can be used to amplify microwave radiation [18]. The first microwave amplifier was produced, the difference between this device and the present laser is that the device was used to amplify the microwave radiation, an invisible radiation. The maser produced was not able to deliver a continuous radiation. It was suggested by other researchers in the field that if optical pumping can be produced, population inversion of the photons can be achieved [19]. The study was continued using a visible light and discover what was termed optical maser. The optical maser was a device that was used to produce a powerful beams of light using higher frequency energy to stimulate the beam of light. This discovery was then patented in the year 1958 by Arthur Schawlow and Charles

Towner [20]. The word laser was coined out by Gordon Gould in 1959 which has been used till date [21]. Although the laser was invented in the year 1958, but there was no possible application of this laser at that time, it was Gould that proposed the possible areas of applications for the laser [21]. The applications proposed include the spectrometry, radar, and nuclear fusion.

The first working laser was built and patented by Theodore Maiman in the year 1960 using ruby as a lasing medium which was stimulated using a high energy flashes of light [22]. The development of laser since the year 1960 has since been an explosive achievement in the history of science and engineering. The laser was able to produce different type of systems with a wide range of applications in a number of fields. The earlier work during this period were focused on the improvement of laser such as how the power can be improved by testing different types of lasing medium which has resulted in the different types of lasers that are being used today and a number of modifications and improvements has also been achieved through various research works [20, 23–42]. The different types of lasers are explained in the next section.

2.3 Types of Lasers

Since the time that the first working laser has been built, different types of lasers has be developed. The search for improving the first laser has resulted in a large number of lasers that is now being used in various field of human Endeavour. Lasers are grouped into five main categories which is based on the state of the lasing medium that the laser employed. These main categories are the solid state lasers, the liquid state lasers, the gaseous state lasers, the chemical laser and the semiconductor or diode laser. These lasers are presented in the following subsections.

2.3.1 Solid State Laser

Solid state laser are lasers in which the gain medium is solid at room temperature [1]. Solid state laser use crystalline solids or glass rod that is doped with ions. The solid state lasers are usually optically pumped using a flash tube or another laser with a shorter wavelength than the lasing medium wavelength. In the solid state laser, the electrons in the lasing medium are first excited to higher energy states through the absorption of photons that pumped on the electrons. The excited electron losses photons in order to be relaxed from their excited states. The quality of the photons released by the excited electrons will determine the quality and the quantity of laser light produced.

Neodymium-(Nd), is the most commonly used dopant that is used for solid state laser crystals such as yttrium orthovanadate (YVO_4), yttrium lithium fluoride (YLF) and yttrium aluminium garnet (YAG). Solid state laser are capable of producing high powers in the infrared light spectrum at a wavelength of 1064 nm. They are usually applicable in the cutting of metal and in the welding of metals and other materials. They are also used in spectroscopy and for pumping of dye lasers. The main limitation of solid-state lasers is the high temperature in the lasing medium which is produced from the excess pump power that heats up the lasing medium and reduces the quantum efficiency. Ruby Laser, the first built laser, is a solid state laser. The other types of solid state lasers include: the Ytterium Aluminium Garnet (YAG) based lasers such as Neodymium based YAG laser—Nd: YAG laser, Thulium based YAG laser—Tm: YAG laser, Ytterbium based YAG laser—Yb: YAG laser, Holinium YAG laser—Ho: YAG laser, Tunable Solid State Lasers, Alexandrite Laser, Ti: Sapphire Laser, Colour Center Lasers, Fiber Lasers, Ytterium doped glass laser (rod, plate/chip, and fiber), Chromium ZnSe (Cr: ZnSe) laser, Divalent samarium doped calcium fluoride ($Sm:CaF_2$) laser, Trivalent uranium doped calcium fluoride ($U:CaF_2$) solid-state laser, NdCrYAG laser, Er: YAG laser, Nd:YLF laser, Neodymium doped Yttrium orthovanadate ($Nd:YVO_4$) laser, Neodymium doped yttrium calcium oxoborate $Nd:YCa_4O(BO_3)_3$ or Nd: YCOB, Neodymium glass—Nd: Glass Lasers, and Titanium sapphire (Ti:sapphire) laser.

2.3.2 Gaseous State Laser

In gas lasers, the lasing medium is a gas. Helium-Neon laser was the first gas laser to be produced and since its invention, a number of gas lasers has also been developed [1]. Gas lasers generate stimulated emission from the low-energy transitions between vibration and rotation states of the gas molecular bonds. The main advantage of gas lasers is that they are relatively cheaper than other types of lasers. Gas lasers are also produced from vaporized metal ion to generate deep ultraviolet wavelengths, e.g. Helium-silver (HeAg) and neon-copper (NeCu). Other types of gas lasers apart from the first Helium–neon laser are the Argon laser, Krypton laser, Xenon ion laser, Nitrogen laser, Carbon dioxide laser, Carbon monoxide laser and Excimer laser.

2.3.3 Liquid State Laser

A liquid state laser is a type of optically pumped laser that its lasing medium is liquid at room temperature [26]. The optical pump that is used with this type of laser include the arc lamps, flash lamps, or other type of lasers. The liquid state laser allows a wide selection of the emission wavelength and polarization from the lasing medium. The spectrum spans from the near ultraviolet to the near infrared radiation which depends on the type of dye that is employed. The liquid used in this type of laser is basically a dye that is doped into the liquid crystal that produces a continuous spectrum of lasing that is also tunable. It is also possible to operate a liquid state laser in a pulse mode. When the dye that is placed in the flow cell is excited with the optical pump, the organic molecules excited at higher frequencies making this type of laser to have the characteristic broad band. The main advantages of liquid state lasers are the higher efficiency, and they can be tuned to various frequencies that makes them ideal for scientific, medical, and spectroscopic applications. The main drawbacks of this type of laser are the liquid instability as a result of high heat intensity and the change of refractive index of the active substance resulting from the heating that causes degenerated ray in the lasing medium.

2.3.4 *Chemical Lasers*

In chemical lasers, the lasing medium is powered by a chemical reactions that permit large amount of energy to be released quickly [1, 3]. Chemical lasers can produce as high as megawatt power levels. They are of most importance in the industries and in the military. Some of the examples of this laser include the oxygen iodine laser, all gas-phase iodine laser, deuterium fluoride laser, the hydrogen fluoride (HF) and deuterium fluoride (DF) lasers. There is also a deuterium fluoride–carbon dioxide laser.

2.3.5 *Semiconductor Lasers*

Semiconductor lasers are the type of lasers that the lasing medium is made up of semiconductor [25]. These type of lasers are usually excited by electrically pumping the lasing medium, that is, the interband transition under the conditions of a high carrier density in the conduction band. It involve different physical processes. Semiconductor lasers are also referred to as diode laser. The optical gain is achieved by the recombination of electrons and holes that were created by the applied current. Semiconductor lasers are cheaper to make and can be produced as small as require. The low to medium power laser used in laser pointers, laser printers and CD/DVD players are all made of semiconductor lasers. They can also be made as larger as required such as industrial semiconductor laser with high power output. The properties of laser are presented in the next section.

2.4 Properties of Lasers

Laser is a form of electromagnetic radiation with unique properties that cannot be found elsewhere. From the acronym, the operation of laser is fully captured in this acronym and it is responsible for the exciting properties of the laser [1]. Looking at the full meaning of laser- *light amplification by stimulated emission of radiation,* simply means that light or any electromagnetic radiation is magnified by a process of simulated emission of radiation. The process of achieving this magnification comes along with the characteristic of laser that makes it to be useful in a number of applications. This magnification of light is explained later in this chapter. The three basic properties that differentiate laser from any other forms of light or radiation and which are what makes this type of radiation (laser) an important one are explained in the following subsections.

2.4.1 Monochromaticity

An ordinary light sources emit light with a broad range of wavelengths which results in the many colours seen in this type of light. The White light contains all the seven colours of rainbow because it is made up of wavelengths in the range of 700 nm (red light spectrum) and 400 nm (violet light spectrum). Laser only emit a very narrow range of wavelength and is normally considered as being a single wavelength electromagnetic radiation [1, 4]. This important property of laser is responsible for the high intensity energy achievable in laser. This is because, all the energies are concentrated at this single wavelength. Other types of light apart from laser are referred to as polychromatic light while the laser is termed monochromatic light because of its single wave length and hence one colour property seen in the laser. The light that is coming out of a laser is typically from single atomic transition with one precise wavelength. This is what gives the laser the characteristic single spectral color that is, the purest monochromatic light ever created. Figure 2.1a shows the conventional light and a typical laser light is shown in Fig. 2.1b. Figure 2.2 shows a light from a candle, displaying the different colours including the white light.

The conditions that make the monochromaticity of laser possible are as follows:

- The laser light is originated from the stimulated emission process which is from a set of atomic energy levels, because laser transition can only occur in a well-defined energy levels.
- The generation of laser light involves the oscillation of the light in a resonant system which helps to sustain the laser oscillation at the cavity frequencies that results in narrowing of the laser light line width. This also helps to promote the production of the laser light single and pure wavelength leading to one colour light called monochromatic light.

Although, lasers light are termed monochromatic, but the degree of this monochromaticity was found to vary from one of laser to the other. The degree of chromaticity is dependent on the wavelength bandwidth or the frequency bandwidth of the laser. All lasers generate light in a narrow bandwidth around a single

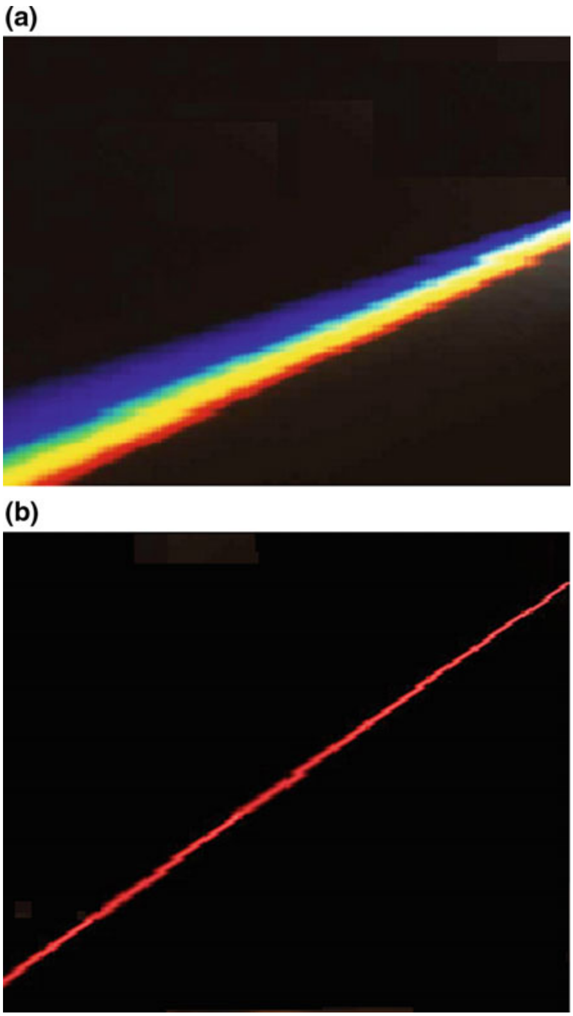

Fig. 2.1 **a** a light from traditional light source **b** a light from laser

wavelength but this band width still varies. The narrower the this bandwidth, the higher is the degree of monochromaticity of the laser. Monochromaticity is also referred to as the high frequency stability. This property is of most importance in some laser application because it has a great influence on the accuracy of such system. An example of such application is in the interferometric measurements. This property is highly needed in high-resolution spectroscopy for observing specific transitions in a medium. The wavelength is used to measure length and distance which must be known with extreme accuracy and precision and must not change with time. Also in scientific analysis applications for quality control. A very narrow line width of less than 0.05 percent of the central wavelength is important for applications such as sensors and in communications.

Fig. 2.2 A candle light showing different colours of light

2.4.2 Coherency

Coherency is another important property of laser that no other light possesses [1]. This is a same phase property of the electromagnetic radiation wave. All the electromagnetic waves in any laser are in the same phase. Laser waves have both temporal and spatial coherence. Spatial coherence is the ability to predict the amplitude of the wave at any given point in space and at any given time. If a wave has a given amplitude over a range of length, then such wave is said to be spatially coherent. The difference between the temporal coherence and the spatial coherence is that, for a temporal coherence, there is correlation between the waves at any given point along the path of a beam at any given time while for the spatial coherence there is correlation between different waves even in space. The process of generating laser beam is responsible for the production of beam that is coherent. The stimulated emission process is responsible for the emission of photons with a definite phase relationship with the photos that cause such emission resulting in coherent beam or same phase beam of light. Figure 2.3a shows a coherent light waves and Fig. 2.3b shows an incoherent light waves.

The atoms in the excited state are made to emit photons which are in phase with the incoming photons that stimulated such emission. When the emitted wave is joined with the incidence waves and the two waves are in phase, they produce a magnified wave that is even brighter that the incidence ones [25]. This process is explained later in detail in this chapter. The Photons are also produced from atoms of the traditional light but without any phase relationship with one another and hence are not coherent. In this ordinary light source, the photons are produced as a result of natural decaying of the atoms and are spontaneous, so the photons are emitted at irregular pattern and therefore out of phase with one another. The emitted photons are supposed to maintain this fixed phase relationship (coherency)

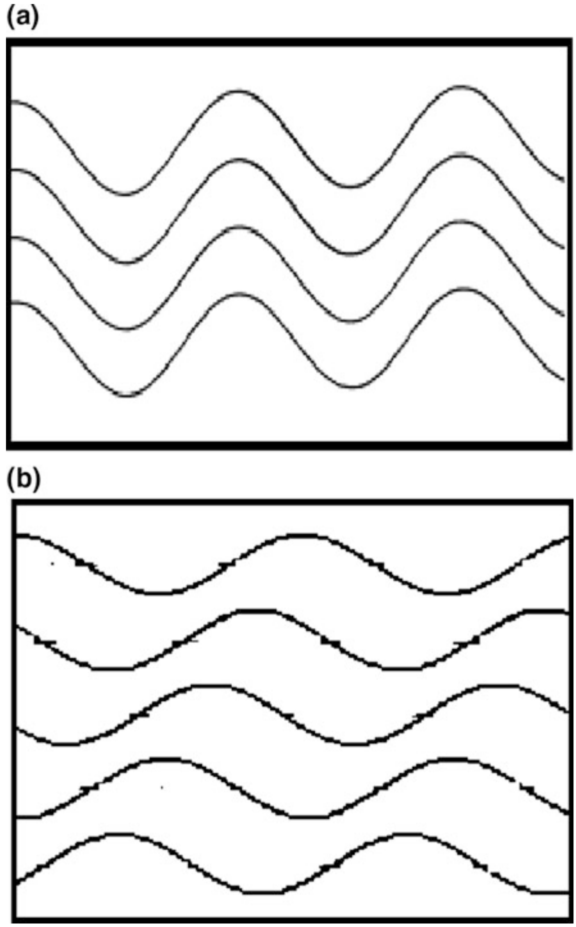

Fig. 2.3 **a** Coherent laser light waves **b** incoherent ordinary light waves

throughout the time they are required to hit their intended target and then return. This property is of utmost importance in applications such as alignment, bar code reader, radar, material processing and communication system. Another important application of this laser property is in the Doppler velocity measurements of a target using the frequency measurements shift of the moving targets. The measurement is taken from this frequency shift obtained from the target-reflected energy which is a function of the target's velocity. If the laser does not have this coherence property, there will be error in the measurement and the frequency shift will be partly from the incoherent light beam and the moving target. Therefore high coherency is required for such measurement.

2.4.3 Directionality

Directionality is the property of laser that described its divergence limited behaviour [1, 4]. To be able to understand this property, the behaviour of an ordinary light is first explained. The conventional light sources emit light in every direction because of the irregular spontaneous emission. This emitted photons are scattered all over and spread out very quickly. Lasers on the other hand emit light that are spread out only very little with distance. Figure 2.4 shows the conventional light beam and a typical laser beam with limited divergence behaviour. Laser beams do diverge as they move through space but the divergence is very limited.

This low divergence property of laser is also referred to as highly collimated beam. Meaning that, the laser light does not lose its intensity with distance unlike in the ordinary light where most of the light rays are scattered far apart as the distance is increased and most of the intensity are lost in the process (as seen in Fig. 2.4). Laser beam is a highly directional beam because the laser beam are produced from the resonant cavity that allows only the propagation of the waves along the optical axis. That is, the mirrors placed at opposite ends of a laser cavity causes the beam to oscillate and travel back and forth resulting in the stimulation of emissions of more photons that are at the same wavelength. This action results in the propagation of only photons that are traveling in a parallel line to the walls of the cavity leading to the production of highly collimated beam. Collimation is the degree to which the beam is parallel with distance. directionality of a laser beam can be described using divergence angle as shown in Fig. 2.5.

A perfectly collimated beam is shown in Fig. 2.6 which has a zero divergence angle, This is an ideal beam. This diffraction angle is small in laser as shown in

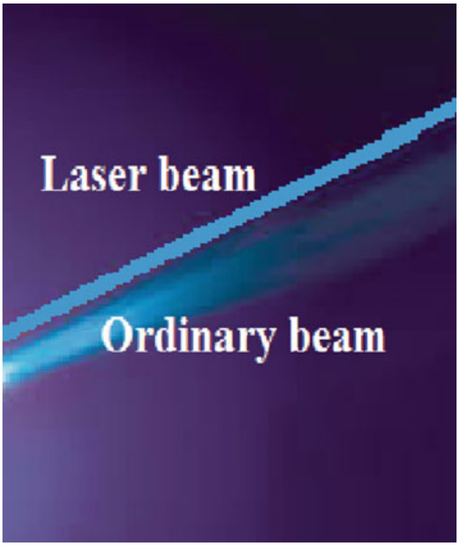

Fig. 2.4 Diagram showing the collimated laser beam and scattered light beam

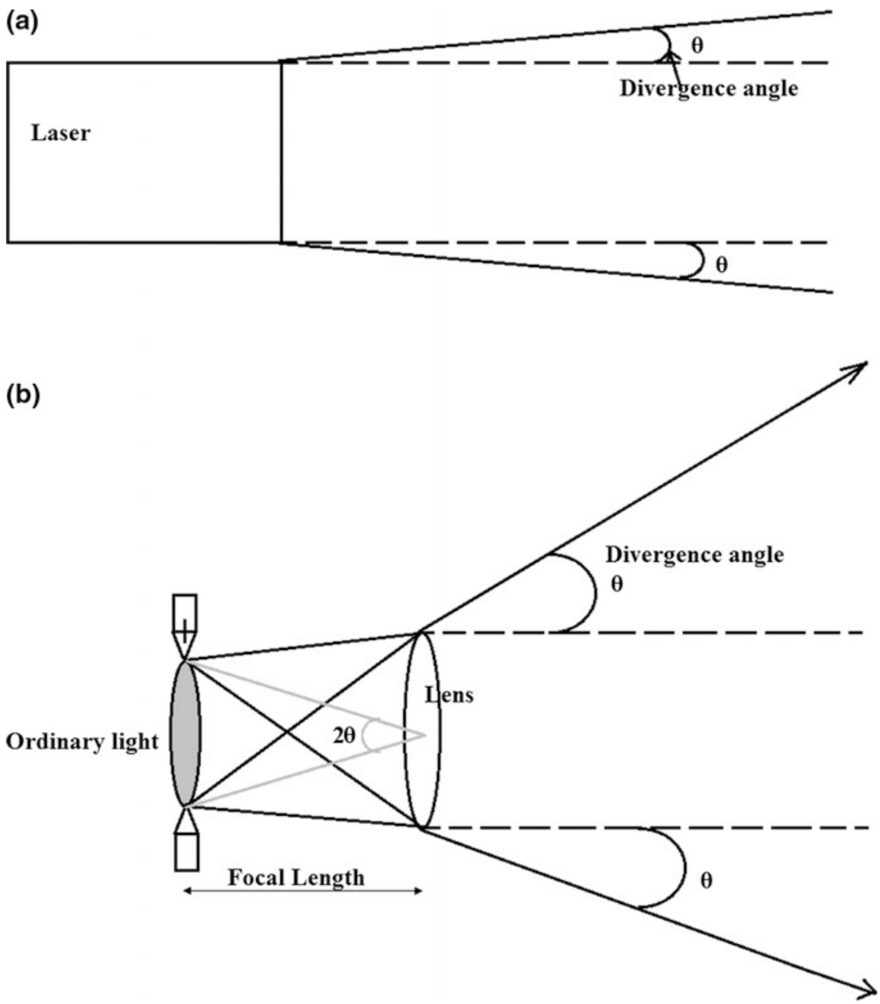

Fig. 2.5 **a** schematic diagram showing divergence angle of a (**a**) laser beam light and **b** an ordinary light

Fig. 2.5a while the value is large for an ordinary beam as shown in Fig. 2.5b. The diffraction property of a laser beam plays an important role in the determination of the laser spot size that is achievable over a given length. The directionality of laser is responsible for the high intensity of laser and helps to maintain this intensity over a large distance which is useful in applications such as material processing like drilling, welding and additive manufacturing. This property is also very important in space applications as well as in medicine.

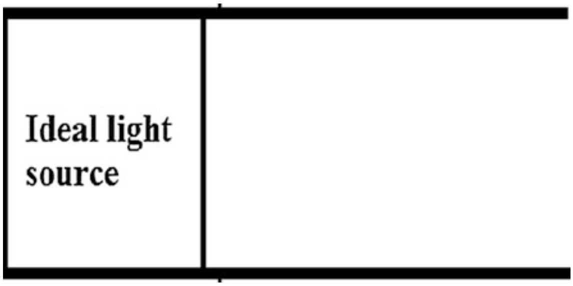

Fig. 2.6 An Ideal beam of light

2.5 Principles of Laser

The word ‘Laser’ is an acronym that is used to describe the generation of laser: Light Amplification by Stimulated Emission of Radiation. what this phrase means is that an electromagnetic radiation that is monochromatic, divergence limited and highly directional beam is produced from a light beam that is amplified by supplying a gain medium with energy that excites the atoms in the medium also stimulate this exited atoms to emit radiation [1, 3, 4]. Thereby magnifying the light and giving it the characteristic properties mentioned above. In other words a laser is a machine that makes billions of atoms to pump out trillions of photons at once so they are lined up to form a concentrated light beam.

A laser basically consists of three parts: a resonant optical cavity that is called the optical resonator, a laser gain medium (also called the active laser medium) and a pump source that is used to excite the particles in the gain medium. The process of generating laser is explained in this section.

In order to generate a laser beam, three basic components are required. A gain or amplifying medium is needed which could be gaseous, solid or liquid, Something to stimulate the atoms in the gain medium for example, a flash tube or even another laser. Lastly an optical resonance cavity. Each of these components are explained in detail in the following subsections.

2.5.1 Amplifying or Gain Medium

Gain medium is normally made of solid, liquid, or gas [3, 4]. These media are important because they are made up of atoms, molecules, ions or electrons. It is these atoms that are used to produce the exciting laser lights. the atoms will absorb energy, release this absorbed energy in form of light photons that are emitted at wavelength that corresponds to the energy differences between the orbital’s energy levels. Electrons in an elements are happy when they are in the lower energy state and they love to remain at this low energy level. This level is called the atom’s ground state. If energy is introduced to these atoms at this ground state, the energy is absorbed by these atoms and when the atom absorb enough energy it gets excited and move from the lower energy level to a higher energy level. This process is shown in Fig. 2.7. This process is called absorption process and the atom in this new energy state are said to be excited atoms. This excited state of the atom is an unstable state and the atoms are not comfortable in this state and always ready to return back to its ground state. The excited atoms are ready to give anything it takes to be able to return back to this ground state. This excited atom can be made to return back to the lower energy level in two different ways: either through the natural decay of the atom at the end of its life span of about 10^{-8} s or if the excited atom is impacted with another energy. To understand the absorption process better, the case of heating water in a container can be used as an example. When heat is applied to a container with water at room temperature, the water molecules very close to the bottom of the container gain heat and when enough heat is absorbed by the water molecules, the molecules become excited and move to the top of the water level in the container. These excited water molecules are seen as bubbles and these bubbles are also seen collapsing randomly. This is similar to the process happening in the gain medium of the laser generation process.

When the excited atom is made to return back to the lower energy level by natural decay, it gives up the energy absorbed by giving up photons in a random direction and it is referred to as a spontaneous emission process. The spontaneous emission is the process that takes place in an ordinary light such as electric bulb or candle light. In a candle light, for example, the chemical reaction between the oxygen in the air and the candle wax cause the excitation of the atoms releasing photons in every direction resulting in the glow that we see, that is produced by spontaneous emission process taking place inside this candle flame which does not have the laser properties.

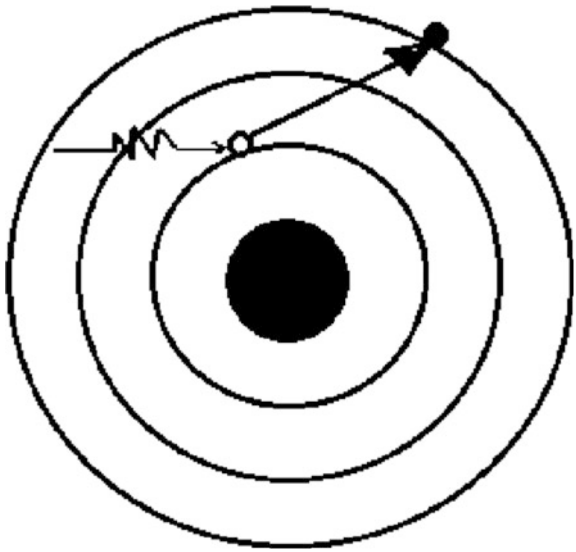

Fig. 2.7 Excitation of electrons

On the other hand, if the excited atom is made to return back to the lower energy level by being hit by another photon, the excited atom is stimulated to release photons that are of the same wavelength with the incident photon and also the two photons are in phase which results in a magnified photons as shown if Fig. 2.8a. This process is referred to as 'stimulated emission' which is what the lasing process needs [25, 26]. Although the spontaneous emission (see Fig. 2.8b) is not good for lasing because of the scattered nature of the photons that is produced, but they are needed to actually start the lasing process and it will be explained later in this chapter.

It can be seen in Fig. 2.8a that the photons that were released during this stimulated emission process, they all travel in the direction of the incoming energy.

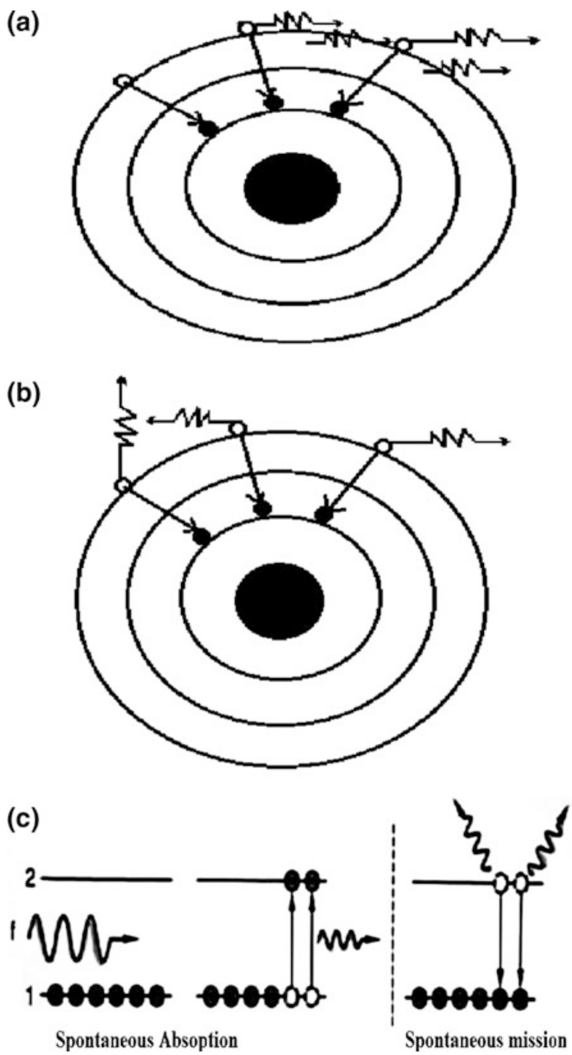

Fig. 2.8 **a** Schematic diagram of (**a**) stimulated emission **b** spontaneous emission **c** spontaneous absorption and emission

This is what helped to multiply the incoming radiation as it can be seen that one photon was used to stimulate the excited atom but two came out of the process. This is not yet regarded as a gain because remember that certain energy was also used to bring the excited atom to the higher energy level. The actual gain is produced through the use of optical resonance that is explained later. For this process to happen as required, there is need to have constant supply of atoms in the excited state and there should also be more atoms in the excited state than in the lower energy level. This is made possible through a pumping process that is introduced in the lasing system and it is explained in the next section.

2.5.2 Pumping System

To introduce energy into the gain medium of a laser system, the process known as pumping is used. This will create the conditions for the light amplification by supplying the necessary energy to excite and keep exciting the atoms during the lasing process [25]. There are different types of pumping system that are used in this process which include: optical pump e.g. tungsten-filament lamps, or other lasers; electrical pump e.g. electric lamp, or semi-conductors; and chemical pump where the exothermic reaction is used to excite the system. In order to have a lasing action, the number of atoms in the higher energy level must always be greater that the number of atoms in the lower energy level and this is made possible by the use of pump as shown in Fig. 2.9. The process of making the population of the atoms in the excited state more than at a lower energy level is referred to as ‘population inversion’.

Population inversion is a necessary condition for stimulated emission to take place which in turn results in the production of laser called ‘lasing’. When there are more excited atoms in the excited state than in the lower energy state, then the next thing is for the lasing to begin. Lasing actually begins through spontaneous emission of at least one of the excited atom. The photo that is released by this decayed atom hits another excited atom which then stimulates the release of another photon from this atom and the process continues. The two photons produced after putting one photon into the system to produce the simulated emission thus effectively doubles the number of photons.

These two photons are further used to stimulate other atoms to release their photons which eventually produce a cascade of photons through the chain reaction. Since these emitted photons from these atoms as a result of the stimulated emission and they have a definite phase relationship with one other, this will result in the production of a brighter beam of pure, and coherent laser light. This process is the amplification of light using stimulated emission of radiation. The two main conditions for the generation of laser are population inversion and stimulated emission, but the real magnification of the input energy into the system is achieved through the process known as optical resonance. This process is explained in the next section.

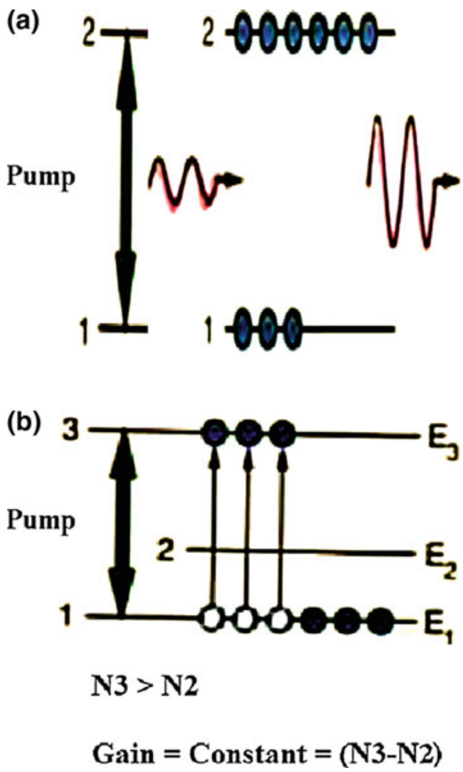

Fig. 2.9 **a** Population inversion. **b** How gain is calculated

2.5.3 Optical Resonance System

In order to achieve the needed magnification in the lasing medium, the gain medium is expanded to include a system that is known as an optical resonance system or a laser oscillator. The optical resonance system is contained of a pair of reflecting mirrors such as plain mirrors or curved mirrors or mixture of the two types of mirror. This mirrors are arranged in such a way that the objects in between these mirror are made to bounce back and forth. This process is similar to what we see when we stand between two mirrors that are parallel to each other, the multiple images we see inside these mirrors are produced from the bouncing back and forth of our image in the two mirrors. One of the two mirrors in the resonance system is made an output beam mirror in which an opening is made to enable part of the light wave in the cavity to be removed as an output bean which are then incident on other lens or mirrors for control purposes. The photons that are released through the stimulated emission are magnified by making these photons to bounce back and forth through the two mirrors in the resonance cavity [1,-4]. The schematic of a gain medium consisting of the resonance cavity as shown in Fig. 2.10. This bouncing back and forth helps to amplify the photons and thus help to compensate for the loss through the output coupler. The stimulated emission process is allowed to take place in this resonance cavity. The main idea of the magnification taking place inside the resonance cavity is that, by allowing the released photons to bounce back and forth, it is used to stimulate other atoms in the excited state at very high rate that prevent other spontaneous emission to take place apart from the one that was used to start the lasing process. A common photon triggers the emission events, which helps to provide an amplified light beam, these emitted photons are 'in step' and also in phase that generates coherent output. The output is exited through the opening on one of the mirrors that is called the output coupler. The implication process with the resonance cavity helps to maintain the phase and direction of the light, giving rise to the light beam output that is directional and coherent called laser. To maintain the efficiency of the gain medium the system needs to be cooled down because the processes taking place in the system results in higher temperature that must be controlled in order not to also damage the components in the system. This can be achieved for example in CO_2 laser, by the circulation of the laser gas that is passed through a heat exchanger to cool the laser medium down as shown in Fig. 2.10. Other laser can be cooled using appropriate cooling systems.

2.6 Laser Safety

The key important properties of laser that makes them to be an important tool is used in different areas of human endeavour are the same reason why they are extremely dangerous which necessitate that care should be taken when working

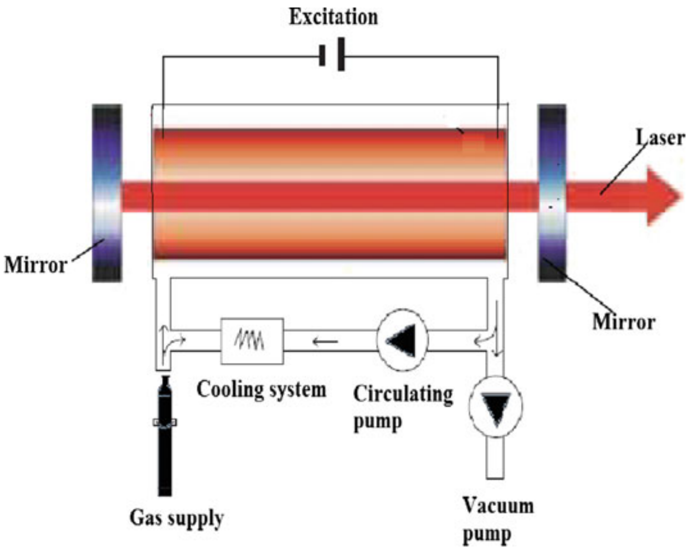

Fig. 2.10 Schematic diagram of a laser gain medium with the resonance cavity

with laser or when in an environment where laser is used [4, 25, 26]. The very first laser produced (Ruby laser) was recognized to be potentially dangerous and that it could burn through a razor blade. The lowest power laser can be hazardous to human eyes. The collimated, directional and coherent beam when hits the eye either directly from laser of from the reflected beam after hitting a reflective surface can be focused by the eye to a very small spot on the retina which would cause a localized burning in this site and result in a permanent damage in a matter of milliseconds. Lasers are classified based on the degree of the potential danger they can produced and are given a safety class number. The safety class label carried by any laser gives an idea of the type of safety rules that must be observed and the type of safety gadget that is required to be worn around such laser. There are basically four classes of laser based on safety.

Class one lasers are the safest class because this type of lasers are in an enclosure. An example of such lasers include the laser CD players and DVD players. Class 1 M laser have moderate risk. The Class two lasers are regarded as being safe during normal use although they are not enclosed like class one lasers. Such class of laser usually have power of up to 1 mW and they cannot cause serious damage to the eyes. A quick blink through the reflex action of the eyes can prevent any damage to the eyes. Example of class two lasers include the laser pointers used in presentations. The class 3R lasers are formerly known as class 3a lasers, they have power of up to 5 mW. This class of laser can cause minimal damage to the eyes within the time of the blink reflex. If this class of laser is stared into, for couple of seconds, will cause damage to the eyes. Class 2 M lasers have a higher risk than class 2 lasers. Another class of laser is the class 3B lasers which are very dangerous to the eyes. Immediate exposure to the eyes can cause permanent damage to the eyes. Class 4 lasers can cause damage to the skin, and eyes. Class 4 lasers can also cause fire. Most industrial and scientific lasers belongs to this class. It is important to wear safety gadget when around any class 3 and class 4 lasers. Lasers that are used in material processing belongs to these classes of lasers. Safety eye goggles with correct safety number that are designed to absorb light of a particular wavelength and that are labeled as such should be worn. Also, Smoke evacuator and good ventilation should be provided where the use of laser resulted in the production of plumes that are hazardous when inhaled, hence nose coverings should also be worn when people are around such lasers. Nose covering such as sub-micrometer surgical filter masks provide some protection against inhalation when they are worn properly.

2.7 Areas of Application of Laser

Application of lasers range from domestic use of laser as small as microscopic diode lasers to industrial and research use of as large as a football field sized neodymium glass lasers that is used for inertial confinement fusion, in nuclear weapons research and other high energy density physics experiments [25]. Lasers are found almost everywhere we are. barcode reader, laser disc player and laser printers are among the early applications of lasers. Some of the application areas of lasers are summarized in Fig. 2.11 and explained as follows:

- Lasers in entertainments: Optical discs e.g. CDs, DVDs and so on, Laser lighting displays; Laser light shows.
- Lasers in product development/commercial: laser printers, barcode scanners, thermometers, laser pointers, and holograms.
- Lasers in defense: lasers are used in weaponry. The use laser-beam to hit a target that causes severe shockwaves that damage the target. Lasers are also used in

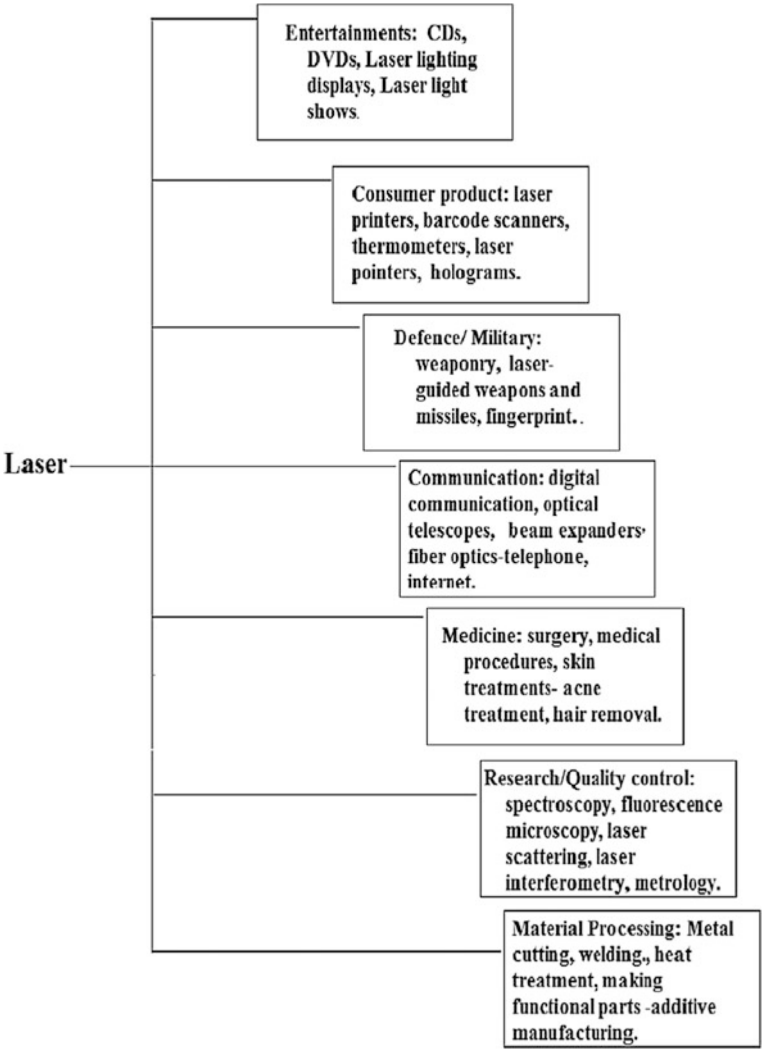

Fig. 2.11 Some of the applications of lasers

laser-guided weapons and missiles. for marking targets, guiding ammunitions, electro-optical countermeasures (EOCM), alternative to radar, and blinding troops. Lasers are also used in latent fingerprint detection for forensic identification.

- Laser in communication It is used for range-finding and precision tools, digital communication, for optical telescopes as beam expanders in space exploration. fiber optics for mobile phones and internet are also part of this applications of lasers in telecommunication.
- Lasers in medicine: surgeries and medical procedures such as: laser healing, surgical treatment, cancer treatment, kidney stone treatment, and in dentistry. Lasers are used for cauterizing blood vessels for correcting problems such as laser-eye surgery, fixing of detached retinas, and in the treatment of cataract. lasers are also used for medical procedures in skin treatments such as: acne treatment, cellulite and hair removal.
- Lasers in Research and Quality control: Lasers are used in the research applications such as spectroscopy, fluorescence microscopy, laser scattering, laser interferometry, and metrology.

Lasers in Material Processing: Metal cutting and welding.

The properties of lasers that allow them to be accurately directed and pointed to where needed allow their use in cutting of metals and the welding of dissimilar metals. lasers are also used for heat treatment, making functional parts (additive manufacturing), laser ablation, laser annealing, and in non-contact measurement of parts. The importance of lasers in material processing is revolutionary and it has helped in the fabrication of part that could not be produced through any other process. How this laser interacts with materials in material process are explained in the next section.

2.8 Laser Material Interaction

The unique properties of laser such as directionality and high power enables a number of material processing to be performed with lasers. The high directionality of laser and small high resolution spot size allows the processing to be achieved without causing any significant alteration to the surrounding bulk material properties. The laser is used to perform operations that it heat up the material to a certain temperature of even cause the material to melt completely depending on the type of material processing being undertaken. In either ways, the material under processing and the laser interact in certain ways depending on a number of factors such as the laser beam parameters such as the laser wavelength, the beam spot size, power etc. and the material properties such as reflectivity, and the thermal conductivity property of the material [43]. The wavelength of laser has a greater influence on the assumption of laser energy in materials depending on the type of material. The behaviour of some lasers in various materials according to the laser's wavelength is shown in Fig. 2.12. The behaviour of laser with materials during laser material processes are analyzed in this section. The laser interact with the material being processed in two basic ways that is, coupling or absorption of the laser rays by the material and heating or melting of the material.

When the laser beam hits the surface of the material being processed, some of this beam are reflected while some are absorbed depending on the property of this material. The beam that are absorbed into the material are said to have coupled or engaged with the material. When the atoms or electrons in this material have absorbed enough energy based on the laser properties and the processing parameters that are employed, the atoms becomes excited. A large number of atoms leave the lower energy state for a higher energy state which causes series of collations between these excited atoms. These atoms release energies during these collisions and return to the lower energy state [1, 3].

The released energies during these collisions are dissipated as heat to the surrounding lattice that causes a rise in the material temperature [44]. The temperature distribution in the material depends on a number of factors such as the material properties- the reflectivity and the thermal conductivity; and if the material is close to a phase change, for example if the material is near the melting point -from solid to liquid [43]. The conversion of the released energy by the colliding atoms into heat occur through energy transfer to the lattice which is described by the energy relaxation time based on the material properties and the laser energy intensity.

Depending on the application that is required from the laser in material processing, the laser may be used to melt, vaporize or to just heat the material as used in additive manufacturing, drilling/cutting or heat treatment respectively. In cutting operation, the laser may be required to remove material in form of liquid, vapour, or

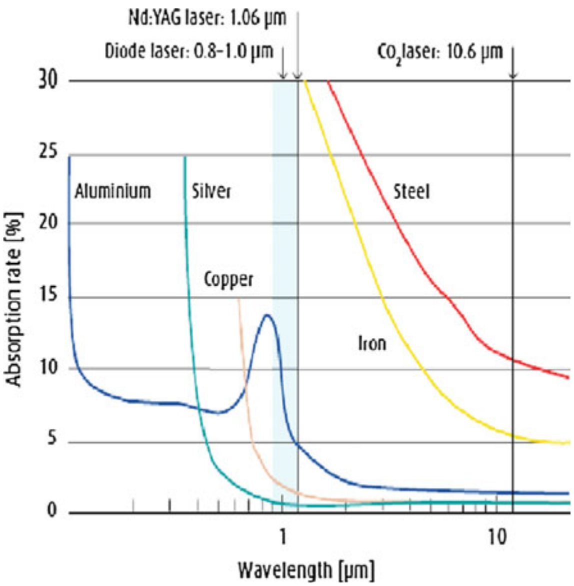

Fig. 2.12 Absorption rate of laser radiations in cold metal [46]

plasma. Plasma is formed at a certain laser intensity as a cloud of vapour from the material [45]. It is important to control the laser intensity or the laser material interaction time during material processing so as not to produce plasma in some material processing application such as laser alloying and additive manufacturing. When melting do occur during laser material interaction the latent heat also come into play. It is not all the energy required to melt the material that needs to be produced by the laser. That is, the amount of heat necessary to melt the material also depends on the volume of material to be melted.

2.9 Summary

The basic principle of laser and brief historical background of laser were presented in this chapter. The unique properties of laser such as monochromaticity, directionality and coherency, that makes it to be useful in different areas of application are also analyzed. The different types of laser that are used are presented and the safety aspect of laser safety are also highlighted. various areas of applications were explained and the use of lasers in material processing are also highlighted. The laser material interaction, its importance in material processing such as welding, cutting and additive manufacturing are also presented.

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Chapter 3
Laser Metal Deposition Process, Solidification Mechanism and Microstructure Formation

Abstract Laser metal deposition process is an advanced manufacturing process that can be used to fabricate three dimensional (3D) parts from the 3D computer aided design (CAD) model of such parts by adding materials in layers. The CAD digital data of the part is used to generate a motion controlled computer program that is used to control the movement of a laser which then trace all profile of the CAD by injecting the material into the laser focal region of the laser, melted and solidify to form a fully dense track through a moving molten pool that is created by the laser. Tracks and layers are stacked in order to produce the entire component of fused metal that represents the desired 3D CAD object. An important characteristics of this manufacturing process apart from creating a 3D object is its ability to repair high valued parts. Aerospace industry in particular has benefited greatly from this important technology. In this chapter, the detailed process description with the various steps involved in the manufacturing process are explained. The solidification process in the laser metal deposition process with the mechanism of microstructural evolution during this process that give materials processed using this technology, unique properties are also explained in detail.

Keywords Additive manufacturing · Laser metal deposition · Repair · Solidification process · Microstructural development

3.1 Introduction

Additive manufacturing (AM) technology is an advanced manufacturing technology that produces three dimensional (3D) part from the 3D computer aided design (CAD) image of the part by adding materials in layer wise fashion [1]. This technology has promised to revolutionized the manufacturing world [2]. Additive manufacturing will change the way products are designed and manufactured. With the conventional manufacturing technology, products are designed based on the functionality desired from the product and the ease with which the product can be manufactured. This usually resulted into breaking down of complex parts and then design each part based

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on different manufacturing processes that are suitable. The parts are then assembled together using different joining techniques which contribute additional material and weight to the manufactured complex part. This is a very cumbersome design and manufacturing process that is laborious and time consuming. Additive manufacturing process does not require any of these time and energy consuming processes, product just need to be designed based on the functionality demand from the product without any need to consider how it will be manufactured. Any product that can be drawn with any 3D CAD software can definitely be manufactured. The part is produced through the addition of material layer by layer directly from the 3D CAD data of the part the same way a house is built by laying blocks in layers. This is totally different from the conventional manufacturing processes that involves material removal in order to shape a part in a subtractive manufacturing process; or application of high energy and pressure in a formative manufacturing process. There are seven classes of additive manufacturing technologies which were already explained in Chap. 1. Laser metal deposition process, which is one of the classes of additive manufacturing technologies is described in this chapter.

Laser metal deposition (LMD) process is a member of directed energy deposition class of additive manufacturing technology, that can be used to repair high valued part apart from its use in the fabrication of new 3D parts [3]. This AM technology is so flexible that it can use wire and powder as its material feedstock [4–7]. Functionally graded materials are now desired in many applications and their production using the conventional manufacturing process involves lots of process that are energy intensive and time consuming, but can be created with the needed varying properties to match the localized service requirements within the 3D components using the LMD process and can also be produced in a single manufacturing run. That is, the laser metal deposition process has the flexibility to use more than one material simultaneously, that makes it suitable for the fabrication of part with functionally graded materials [8–11]. The development of LMD technology was as a result of research activities at Los Alamos and Sandia National Laboratory, Albuquerque, both in New Mexico, that developed the directed light fabrication and the ground breaking laser engineered net shaping (LENS) that is capable of fabricating components from any metal system into a near net shape with properties approaching those found in the traditional wrought products or even exceeding their properties in some cases. This important additive manufacturing technology is of promising applications in a number of industries such as the aerospace. automobile, and the medical industries because of the flexibilities it offers and the ability to greatly reduce by-to-fly ratio especially in the aerospace industry [12]. The capability of the LMD for fabricating difficult to machine materials and for production in mass customization, is another attractive feature for industries like medical and automobile industries [13–15].

The full description of laser metal deposition process is presented in this chapter. The advantages and limitation of the LMD process are explained. The solidification process that results in the microstructural development during the laser metal deposition process is also analyzed. Some of the properties resulting from the developed microstructures are also explained.

3.2 Laser Metal Deposition Process Description

The laser metal deposition process is achieved through the supply of continuous material feedstock being fed into the laser focal area on the substrate where the material (powder or wire) is melted, forming a melt-pool which become solidified as the laser beam is moved away from this melt-pool across the substrate. The Laser metal deposition process takes the advantage of the coherent and the directionality properties of a laser to create a melt-pool on the surface of the substrate as the beam hits the surface. The wire or the powdered material feedstock is delivered onto this melt-pool and melted. A solid track of the deposited material is produced upon solidification of this melt-pool and are seen along the laser path. In the case of the production of composite materials or functionally graded materials, different material feedstock are placed in different powder feeding hoppers or wire feeders and the materials are delivered simultaneously or sequentially to produce the composite with the choice of material composition relative to location within the part through the coaxial nozzles located beside the laser outlet. The schematic diagram of laser metal deposition process is shown in Fig. 3.1.

The diagram described the production of a composite material of titanium alloy and titanium carbide according to Mahamood et al. [16]. There are five basic steps that are involved in the laser metal deposition process. The flow chat of the five steps is shown in Fig. 3.2 and the steps are explained as follows:

- Step one: The development of the CAD model of the part to be made is the first step. This is done using any of the CAD software available such as AutoCAD and Solid Edge, and this occur outside the LMD machine. This 3D CAD file is then loaded into the LMD machine. It is the 3D CAD file that is used after the necessary conversion and other processes to create a motion paths for the deposition process.
- Step two: The CAD file is then converted to a standard triangulation language (STL) file or an Additive-Manufacturing File (AMF) [1]. The STL file format was the old file format that was used by additive manufacturing machines but with a number of limitations such as: its inability to describe curved triangles and defining functionally graded materials. The new file format, AMF, is based on an open standard Extension Mark-up Language (XML) that is capable of describing in detail, the colours, the curve triangles, the texture, the lattice structure, the texture, the functionally graded materials [1] that are absent in the old STL file format. The 3D CAD is converted to the AMF to represent the 3-D surface assembly of planar and curved triangles with the co-ordinates of the vertices of these triangles.
- Step three: After the conversion process is completed, the AMF is then sliced into two dimensional (2D) profile sections which is used to define the geometry of the 3D CAD data. The slicing is performed based on the chosen build orientation. The building orientation is the direction with which the building process will take which is normally determined by the orientation that give better stability to the part being made. this will help to reduce the need for

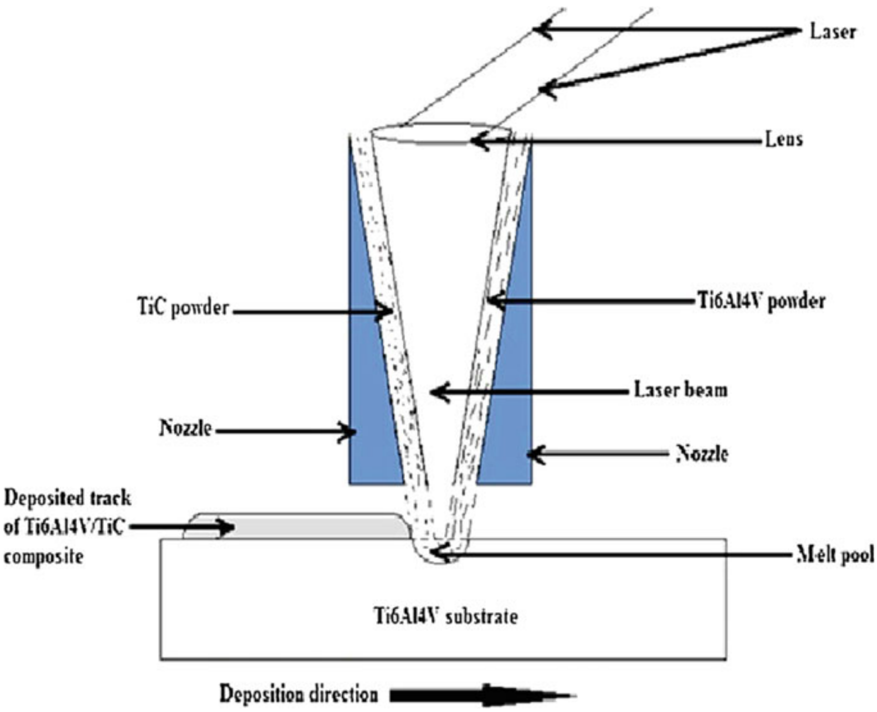

Fig. 3.1 Schematics diagram of the LMD process [16]

support structure. For example, the build orientation can be chosen from the bottom to the top, or from one side to another side. The operator may choose the building orientation, or the software will automatically choose the building orientation based on the stability of the part. Why it is necessary to chose the right building orientation is to reduce the need for secondary finishing operations. If the chosen build orientation chosen is such that it needs a lot of support structure will constitute to increase time of production and also this support structures needs to be removed during the finishing operations.

If needed, the support structures are also generated at this stage and also sliced simultaneously [17]. After the slicing process is completed, the next step is the actual building of the part.

- Step four: The building process is achieved by creating the melt pool on the substrate; and the materials feedstock located coaxially to the laser axis are delivered onto the melt pool to create a solid mass that is a representation of the 2D profile sections as traced by the laser. The laser continues to follow the path dictated by the 2D profile track by track, and layer by layer until the building process is completed and the 3D part is created.

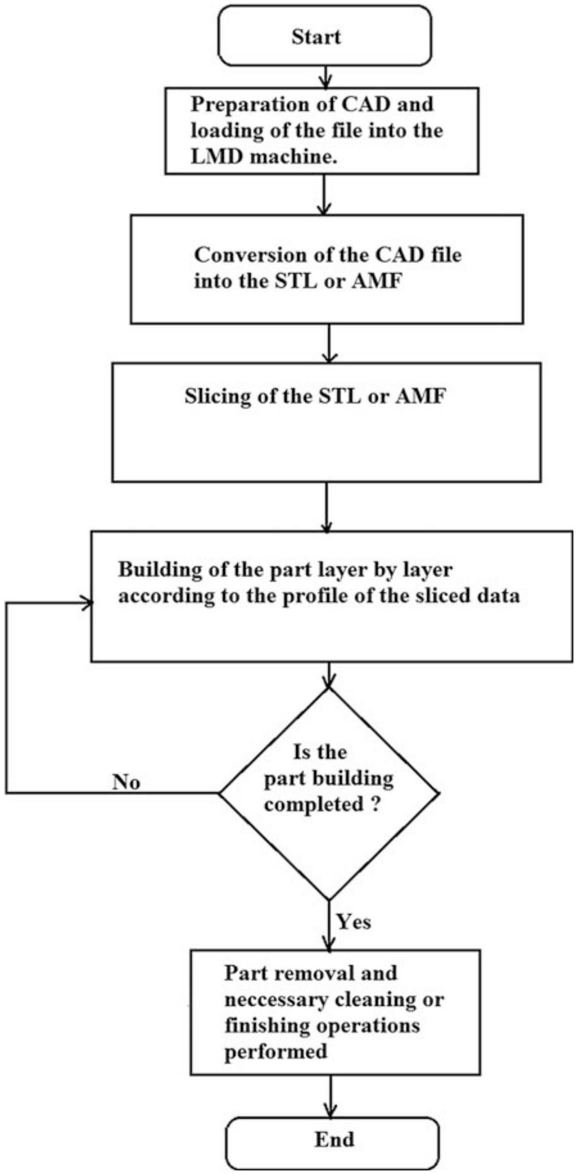

Fig. 3.2 Flow chart of steps in LMD process

- Step five: After the building process is completed, the 3D part is removed from and cleaned up. The support structures are removed if any, and finishing operations and heat treatment are performed if needed and depending on the service performance that is required from the part. The advantages and limitations of the laser metal deposition process are presented in the next section.

3.3 The Advantages and Limitations of Laser Metal Deposition

Some of the advantages offered by laser metal deposition process highlighted bellow:

- Laser metal deposition process can be used for the production of new parts and the process can also be used to create a new part on existing parts with strong metallurgical integrity for part modification, repair or remanufacturing processes [18]. This is one of the advantages that the LMD process has over other additive manufacturing technologies and any conventional manufacturing process. In conventional manufacturing processes, the parts are usually joined together using bolts, nuts rivets etc. These point where the parts are joined always produce high stress concentration due to mismatch in properties and discontinuity. This site is where failure usually begins especially in moving parts. This type of problem is completely eliminated in the laser metal deposition process because the new part is built directly onto an existing part without the need for any joining processes such as welding or the use of bolts and nuts, creating a metallurgical bonded parts with the associated weight and material saving. This process will reduce the high energy intensive recycling process and also help to reduce the weight of moving products in the aerospace and automobile industries with direct translation into reducing the carbon foot print of these industries. Hence this manufacturing process is indeed a green manufacturing technology.
- The laser metal deposition process provides design flexibility for machine designers because any part that can be modelled digitally can definitely be fabricated. Existing designs can also be modified without having to start from the scratch, and an obsolete equipment can be made to become new again thereby saving a lot of energy, time, materials, and above all the entire cost of production.
- The flexibility of the laser metal deposition process makes it possible to fabricate parts that is made up of functionally graded materials, and it can be use to repair worn-out parts that were prohibitive to be repaired in the past.

In spite of all these advantages, there are still a number of challenges that is faced by this important additive manufacturing process, that has limits the use of this process for production of critical parts, most especially in the aerospace industries. The Laser metal deposition process is a relatively new AM technology, and some of the underlying physics of this process is yet to be fully understood. The characteristics of the produced parts must be predictable and also controllable. More research is needed to fully establish this properties of the parts produced using this technology in order to be able to predict these properties and also to be able to control these properties. Also the surface finish is poor and needs to be improved in order to eliminate the need for secondary finishing operations.

3.4 Solidification and Microstructural Evolution During the LMD Process

The melt pool created on the surface of the substrate in which the feedstock is deposited during the laser metal deposition process interaction started to solidify immediately the laser is moved away from the melt-pool region. The solidification process and the solidification rate depend on a number of factors. These factors include: the processing parameters employed in the LMD process (detail explanation on processing parameters are provided in Chap. 4), and initial temperature of the substrate before the laser was applied. For example, if a high laser power, is used with low scanning speed, this will cause the laser material interaction time to be prolonged and the melt pool that is created will be large resulting in a lower solidification rate [19–21]. The solidification mechanism will determine the microstructural development that is produced during the LMD process. When the melt-pool is large and the solidification rate is low, the result is melting of the substrate or the preceding layers whose dept will depend on how long the melt-pool takes to solidify [22]. The low rate of solidification causes the melt pool to stay longer on the surface of the substrate or the preceding layer causing melting or re-melting of these surfaces. Another factor that affects the solidification rate is the initial temperature of the substrate or the preceding layer. For a cold substrate, the solidification rate is quite rapid because the substrate acts like a heat sink and the solidification is also directional towards the surface of the melt-pool. The heat in the melt pool is conducted away towards the cold substrate, thereby causing the solidification to be very rapid. For a high scanning speed, the melt-pool that is created is smaller compared to the one produced at low scanning speed because, the laser material interaction time is low; and melt pool solidifies very quickly [23].

The solidification process starts from the solid-liquid interface region, usually, the interface between the melt pool and the substrate, or the interface between the melt pool and the preceding layer [22]. This interface is the nucleation site for the crystal to be developed and grow. The crystal that is nucleated on the substrate or on the preceding layer forms the seed crystal that grows bigger and bigger as the solidification process progresses. This crystal growth follows a crystallographic orientation with respect to the substrate crystal or the preceding layer crystal that is referred to as ‘epitaxial grains’ [22] as shown in Fig. 3.3.

As the solidification process continues, the epitaxial grains continue to grow in a perpendicular direction to the substrate and in the opposite direction to the direction of the heat flow which is towards the substrate [24]. Since the heat flow is towards the substrate, it follows that the direction of the grain growth is in the opposite direction of the heat flow and towards the surface of the deposition. This grain growth shows a characteristic structure that is observed in laser metal deposition process and it is referred to as columnar grain [14, 24]. The columnar grain structures is shown in Figs. 3.4 and 3.5.

The microstructure of the heat affected zone is characterized by globular grain structures as shown in Fig. 3.3. The globular grains are produced as a result of the

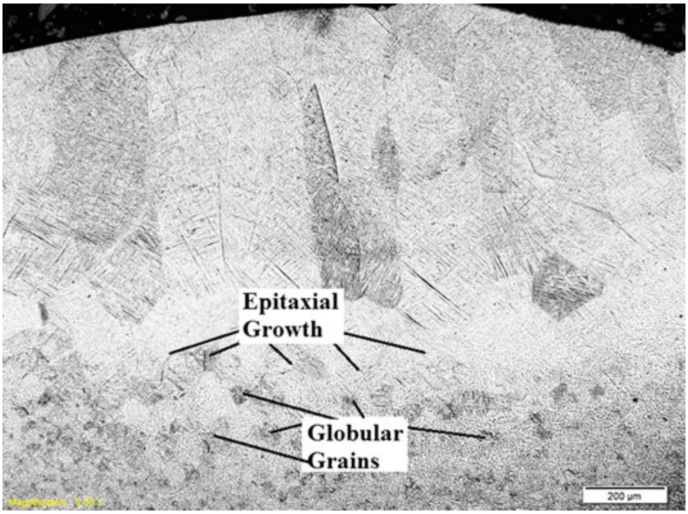

Fig. 3.3 Epitaxial and columnar grain structure in Ti6Al4V

heat that was transferred from the melt pool to the substrate. The grains that are very close to the melt pool region gain enough heat and the grains began to Marge and become bigger and bigger, resulting in the characteristic globular grain structure as seen in Figs. 3.3 and 3.5b. As can be seen in the Figures, the size of the globular grain reduces as the position is far away from the melt pool region.

And the closer the grain is to the melt pool region, the bigger the size of the globular grain. The solidification rate is related to the scanning velocity, and it is

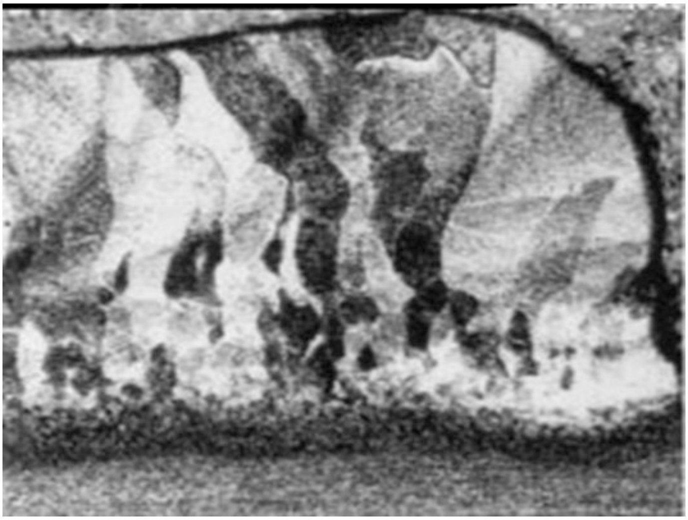

Fig. 3.4 Microstructure of Ti6Al4V showing columnar grain structure [24]

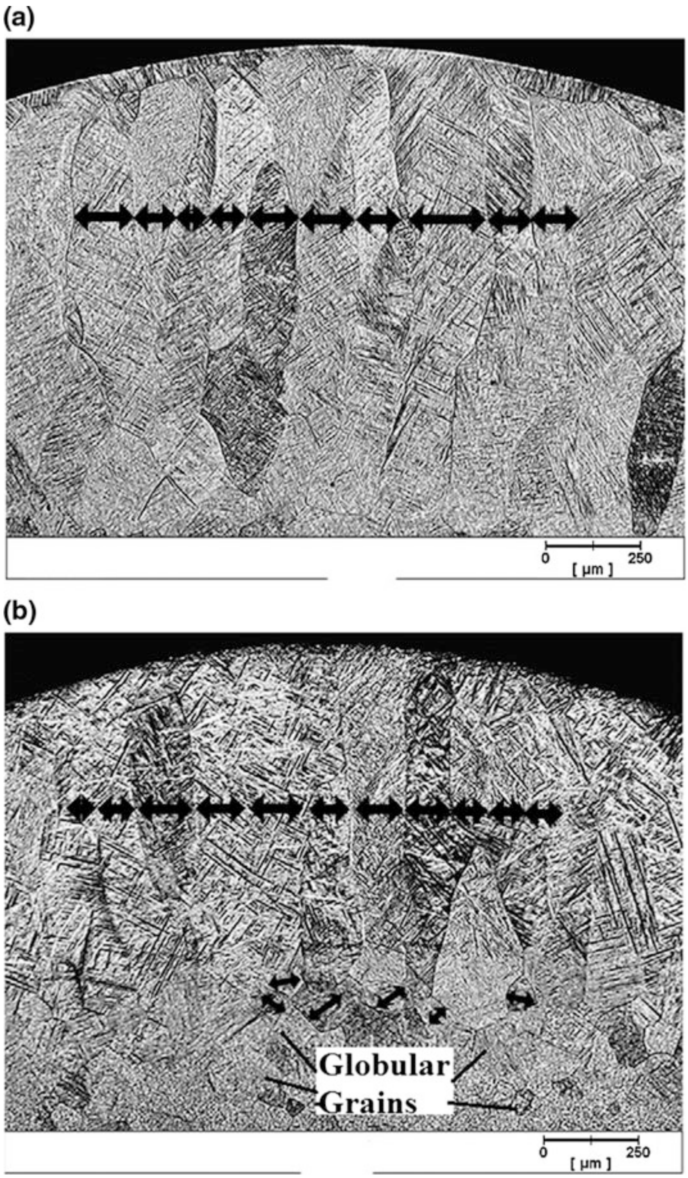

Fig. 3.5 Microstructure of Ti6Al4V showing columnar grains with the arrows indicating the width of columnar grains [14]

described by Eq. (3.1) according to Steen [25]. The solidification rate is directly proportional to the scanning velocity, and the constant of proportionality is the sine of the angle between the tangent of the growth vector and the scanning direction.

$$R = v \sin \theta \quad (3.1)$$

Where R is the solidification rate, v is the scanning velocity, and θ is the angle between the tangent of the growth vector and the scanning direction.

From Eq. (3.1), it can be seen that, the higher the scanning velocity, the higher the solidification rate. The rate of solidification has a direct influence on the microstructure that is developed. For example, at higher scanning speed, which results in higher solidification rate, produces columnar and globular grains that have smaller width and smaller in sizes respectively as shown in Fig. 3.5 [14]. Also, when the solidification rate is rapid, it promotes the formation of martensitic microstructures in the metal and alloys which are very hard [23] and tend to produce more of dendritic microstructure in metal-ceramic composite materials as shown in Fig. 3.6 [26]. A more equilibrium microstructure are produced at low solidification rate such as Widmastätten alpha microstructure. The martensitic microstructure is shown in Fig. 3.7a while the Widmastätten alpha microstructure is shown in Fig. 3.7b. The coarser or the finer is the developed microstructure also depend on the cooling rate [25]. The higher the cooling rate, the finer the microstructure produced while at lower cooling rate the developed microstructure becomes coarser. On the other hand, at a very high solidification rate, the microstructure tends to become equiaxed [25]. The solidification behaviour of the molten material, that is fused to the preceding layer is also going to affect the evolved microstructure depending on the position in the component being processed that has been subjected to a complex thermal history. This can be explained for example, the location in the middle of the deposited sample that has first undergone a rapid solidification and then re-heated by the additional layer of molten materials and then cooled down again.

The microstructure produced will keep changing as layers are added and this can result in the development of complex, heterogeneous and anisotropic microstructures that is entirely different from what is achievable in the traditional wrought parts. This shows that the processing parameters play an important role in achieving the desired solidification rate and also to obtain the desired microstructure and hence, the desired properties.

3.5 Properties Resulting from LMD Process

The microstructures produced during the solidification process greatly influence the mechanical properties of laser metal deposited parts. The processing parameters also have a role to play in the resulting microstructure and hence the mechanical properties. When a fully dense part is desired in order to satisfy the required optimum mechanical properties, the right combination of process parameters (as explained in Chap. 4) need to be employed. A number of research work has appeared in the literature, demonstrating properties that are comparable to the part

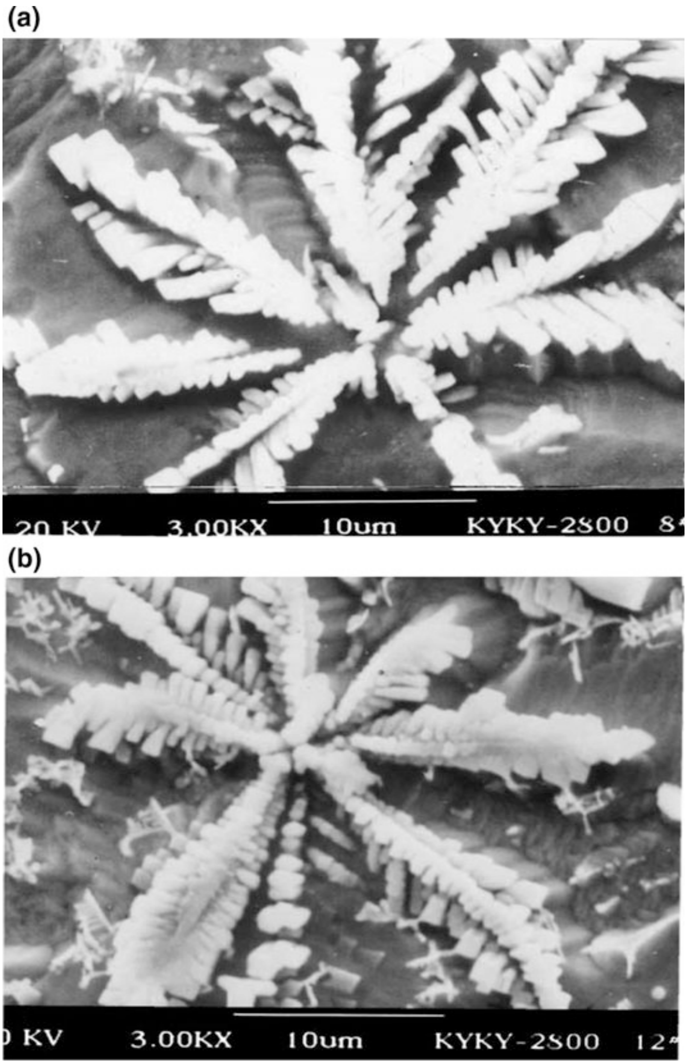

Fig. 3.6 SEM micrograph showing dendritic TiC microstructure at **a** low scanning speed **b** higher scanning speed [26]

manufactured through the conventional manufacturing processes and even in some cases the properties of laser metal deposited part even surpass those of the conventionally produced parts. Some of these research works are presented in this section as follows.

Cao et al. [27] used Laser metal deposition process to produce a part with TiC nano particles reinforced Inconel 625 composite. The mechanisms of microstructure

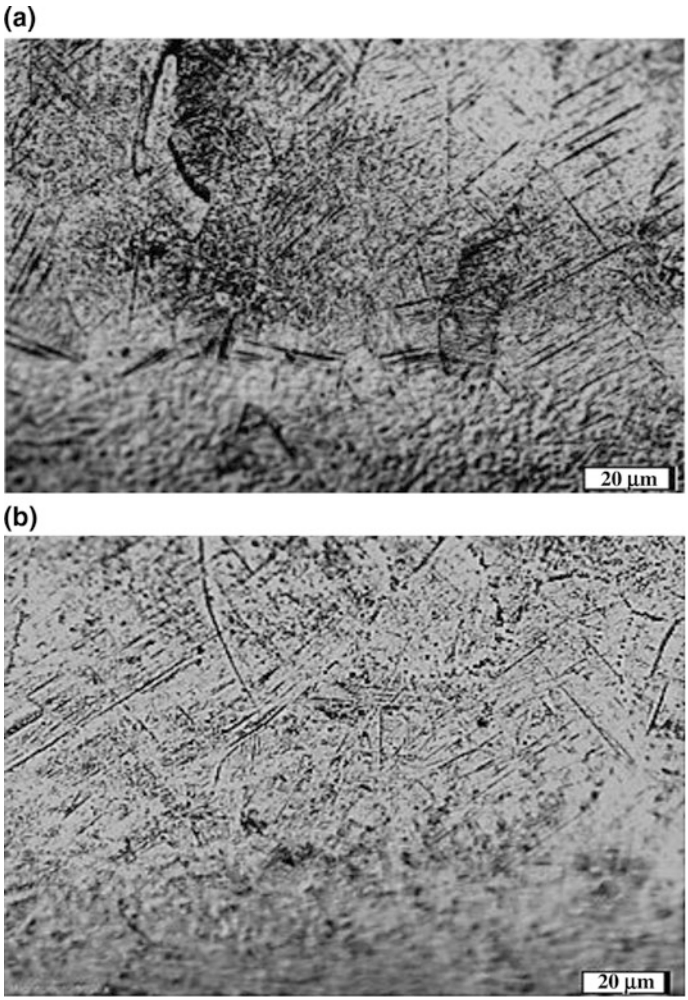

Fig. 3.7 The micrograph showing **a** martesitic microstructure at rapid solidification rate and **b** Widmastätten alpha at low solidification rate [23]

evolution and mechanical property in the different zones of the various molten pool that were produced were investigated. The microstructural study revealed that the microstructures in the upper part of the molten pool consist mainly cellular structures, while those at the bottom and edge region were dominated by columnar dendrites as shown in Fig. 3.8. The increasing ratio of the temperature gradient to the solidification velocity was found to be responsible for the resulted gradual change from the columnar dendrite growth to the cellular grain growth in the microstructure. The factor that could be contributing to the development of the continuous columnar dendrite epitaxial growth was the re-melting effect that is happening in the overlapping region in both the tracks and layers.

The orientation of the columnar dendrites in the bottom of the molten pool was seen to be parallel to the build height direction and which at the edge was gradually at an angle until it became parallel to the horizontal direction. This was due to the presence of a large heat sink effect of the cooler region thereby creating a strong heat flux. Different sizes of the cellular grains and dendrite spacing were also observed and were believed to be as a result of the varied cooling rates in different regions in the molten pool and the heat affect the overlapping zones. The faster cooling rate was found to have improved the number of nucleation site which of course increased the rate of nucleation which does not support sufficient grain growth and hence produced refined grains structures.

However, the coarse cellular grains nearby the re-melting zone were obtained due to the heat affecting. The microhardness was found to vary at different region similar to the microstructural observations. The reason for the varying microhardness was attributed to the sizes of grains, the TiC reinforcing particles and the solid solution strengthening that occur during the solidification and cooling processes. The ultrafine TiC reinforcing particles produced in large number which are evenly distributed in the cellular grain region were attributed to have contributed to the dispersion strengthening achieved and the increase in the elemental concentrations of the Mo and Nb in the cellular grain zone as compared to in the columnar dendrite zone could have resulted in the solid solution strengthening. Also the considerably refined grain of matrix and the resultant high density of grain boundaries resulted in the fine grain strengthening obtained. The ratio of the temperature gradient to the solidification rate (G/R) was determined through numerical simulation using a finite volume method. The simulation result showed that by increasing the ratio G/R, resulted in a gradual change in the solidification regime from the columnar dendrite growth to the cellular grain growth. This is in good agreement with the experimental results.

Pia et al. [28] studied the mechanical behaviour of laser metal deposited titanium alloy- Ti-6Al-4V, using wire as the feedstock. The mechanical properties were studied in two different orientations in the deposited samples namely: along the deposition direction and perpendicular to the deposition direction. The results showed that the yield strength, the ultimate tensile strength and the elongation were found to be dependent on the orientation of the specimens with respect to the deposition direction. The specimens in the perpendicular orientation showed higher elongations than the specimens in the parallel orientation. The specimens in the parallel orientation is higher in the ultimate tensile strength and yield strength than those in the perpendicular orientation. This showed the anisotropic behaviour of the deposit in respect to the deposit direction. The mechanical properties were also related to the evolved microstructures as shown in Fig. 3.9. The microstructure of was found to consist of columnar prior beta grains that grow towards the direction

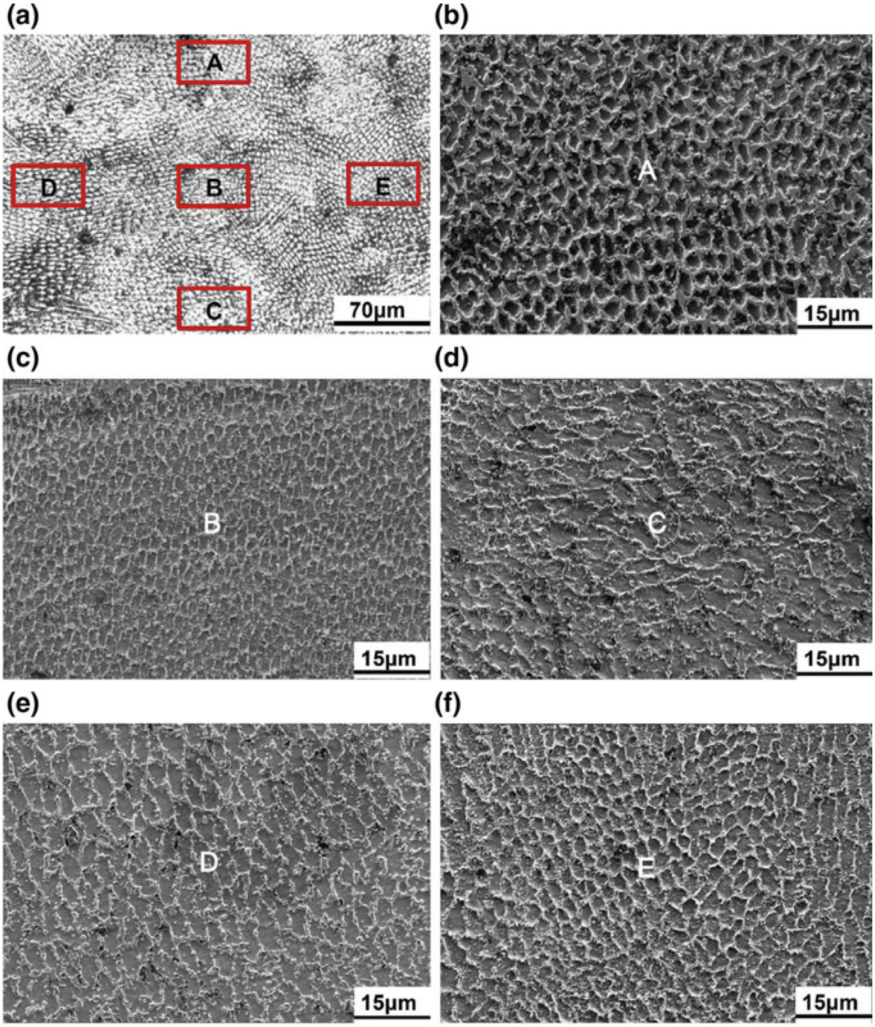

Fig. 3.8 **a** The optical microscopy image showing the cellular microstructures in the molten pool of the LMD-processed TiC/Inconel 625 composite. SEM images showing the cellular structure characteristics in the different zones of the molten pool: **b** in the location *A*; **c** in the location *B*; **d** in the location *C*; **e** in the location *D* and **f** in the location *E*. [27]

of the heat source. The rapid solidification in the process was said to resulted in the smaller microstructural features of the prior beta grain size and the alpha colony.

The was responsible for the improvement in the yield strength and the ultimate tensile strength, but it lowers the elongation. The degree of anisotropy was found not be influenced by the thickness of the grain boundary alpha. The ultimate tensile

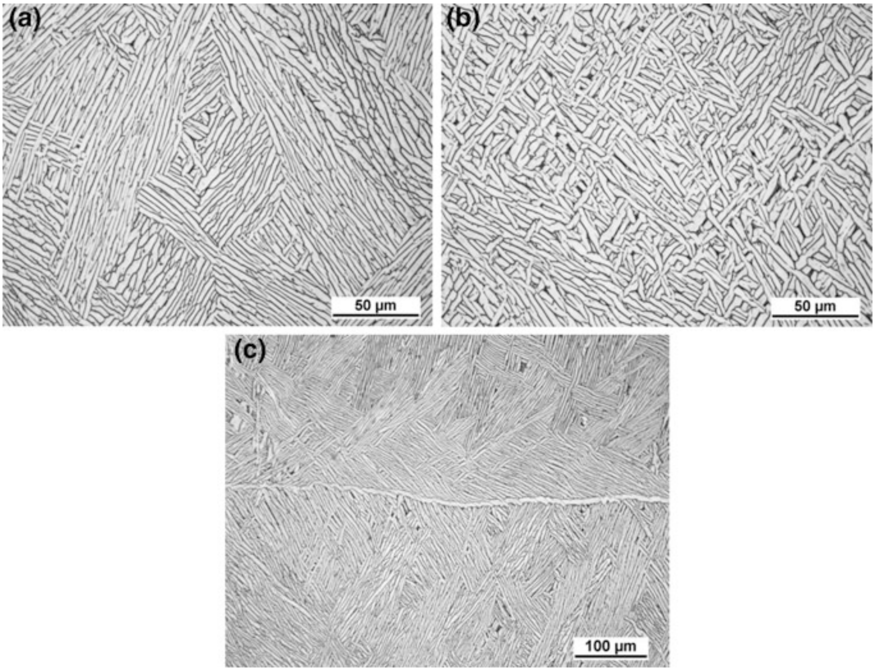

Fig. 3.9 Typical appearance of **a** alpha colony microstructure, **b** basket weave microstructure, and **c** grain boundary alpha along the prior beta grain boundary [28]

strength of the laser metal deposited titanium alloy produced was found to be higher than those of the forged Ti-6Al-4V at room temperature.

A similar study was conducted by Zhang et al. [29], the microstructural evolution and tensile properties of TC11/Ti2AlNb dual alloy thin walls produced by laser metal deposition process were investigated. The properties of the deposited samples, perpendicular to the interface after different heat treatments were studied. The results showed that there were two distinct composition transition zones between these two alloys due to the dilution effect during the deposition process. The as-deposited samples were found to have better mechanical properties than the heat treated samples both at room temperature and at 650 °C elevated temperature. The heat treatment was found to have altered the microstructure as shown in Fig. 3.10 that could be responsible for the poor performance. For all the samples, both the as-deposited and the heat treated samples, the fracture positions were not located within the interface zone, which indicates that there was good mechanical performance of the interface zone. To further demonstration this result, a TC11/Ti2AlNb dual alloy blisk as shown in Fig. 3.11 was deposited using the laser metal deposition process. It was concluded that the laser metal deposition process is capable of integrating the fabrication of multi-materials component with complex shape as shown in Fig. 3.11.

Yadollahi et al. [30] studied the microstructural and mechanical properties of 316 l stainless steel produced using the laser metal deposition process. These properties were investigated and compare with those produced with the conventional manufacturing process. Cylindrical samples were produced and the effect of the thermal history and heat treatment on the microstructural and the mechanical properties were studied. The influence of time interval during the deposition process on the resulting properties were also investigated. The results showed that the laser metal deposited samples have a higher yield strength and a higher ultimate tensile strength when compare to those of their cast and wrought counterparts. The thermal

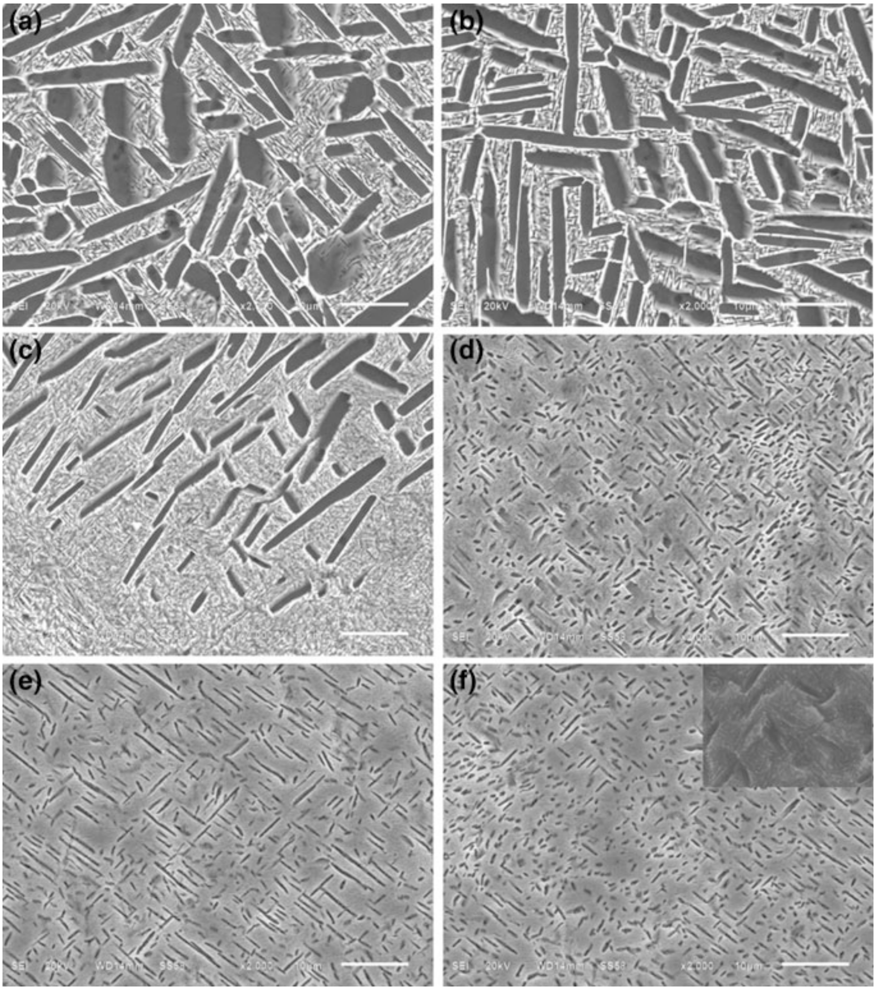

Fig. 3.10 SEM morphology of the TC11/Ti2AlNb dual alloy after HT2 treatment **a** inside of TC11 alloy; **b** TC11 alloy side close to TZ1; **c** TZ1; **d** TZ2; **e** Ti2AlNb alloy side close to TZ2; **f** inside of Ti2AlNb alloy [29]

Fig. 3.11 Direct laser deposited TC11/Ti2AlNb dual alloy blisk [29]

history, the microstructural evolution, and the mechanical properties of laser metal deposited 316 L stainless steel samples were shown to be dependent on the time interval between deposits. The longer deposition time intervals was found to result in higher cooling rates, that produced finer microstructures, higher to uniform strength and lower elongation to failure.

While the samples produced with shorter deposition time intervals were found to have coarser microstructure, lower strength and higher elongation to failure. The coarser microstructure was attributable to lower cooling rates as a result of an increased bulk temperature in the samples. The fracture surface of the samples are shown in Fig. 3.12.

REN et al. [31] investigated the microstructural and mechanical (Room temperature tensile properties) properties of a rectangular plate of Ti–6.5Al–3.5Mo–1.5Zr–0.3Si titanium alloy produced with the laser melting deposition process.

The results revealed that the macro-morphology is dominated by large columnar grains crossing the multiple deposited layers. Wide bands and narrow bands, are observed in the microstructure. The wide band is seen to consist of α lath and Widmanstätten α colony. while the narrow band consists of α lath and transformed β grains (see Fig. 3.13). The formation mechanism of the two bands was thoroughly investigated. The narrow band was found to be formed in the narrow solid region that is very close to the melting pool region.

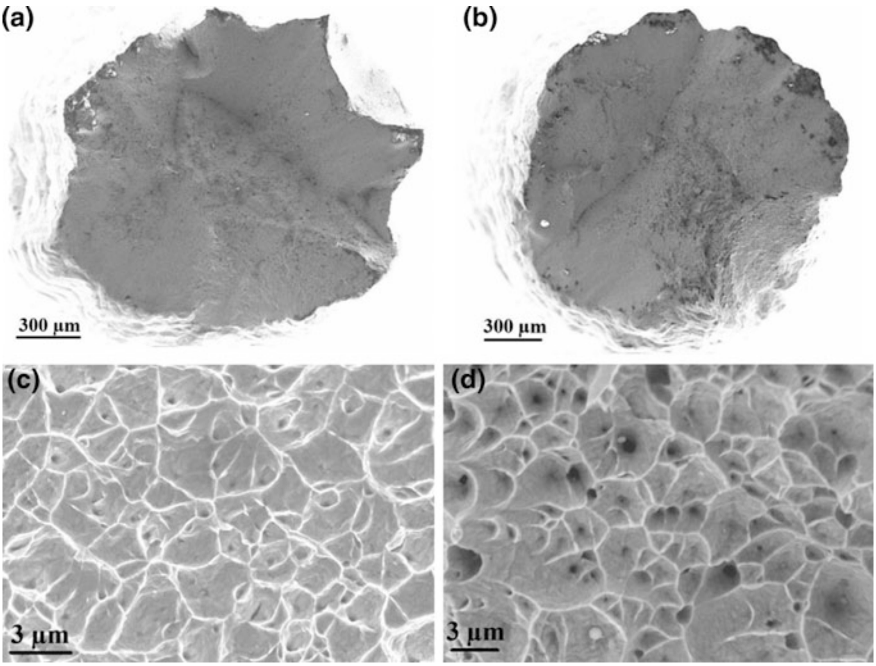

Fig. 3.12 Tensile fracture surfaces of single-built specimens in **a** as-built and **b** heat treated conditions (RA: reduction in area). Higher magnification of dimples on fracture surfaces of **c** as-built and **d** heat treated specimens [30]

While the wide band was found to be formed in the region that is closer to the β-transition region. These could be attributed to the effect of heat produced by the subsequent deposited layers on the previous layers. The room temperature tensile strength of laser deposited Ti–6.5Al–3.5Mo–1.5Zr–0.3Si was found to be comparable to that of wrought bars. While the ductility was relatively poor due to the large number of grain boundaries and their orientation perpendicular to the loading direction.

Zhong et al. [32] studied the properties of Inconel 718 (IN718) produced by laser metal deposition process with the aim of improving the properties of this material. The poor mechanical properties observed in the laser metal deposited samples were significantly improved by a combination of Hot Isostatic Pressing (HIP) and proper heat treatments. The poor mechanical properties in the as-deposited samples were attributed to presence porosity in the as-deposited IN718 and the columnar grains of the as-deposited material that have regular orientation could results in the material anisotropy (see Fig. 3.14). The results showed that the columnar grains produced during the laser metal deposition process can be transformed to equiaxed grains through homogenization heat treatment, thereby eliminating the material anisotropy. The precipitated Laves (intermetallic) phase that was found mainly at the inner dendrite areas, could also be dissolved through the solution heat treatment and

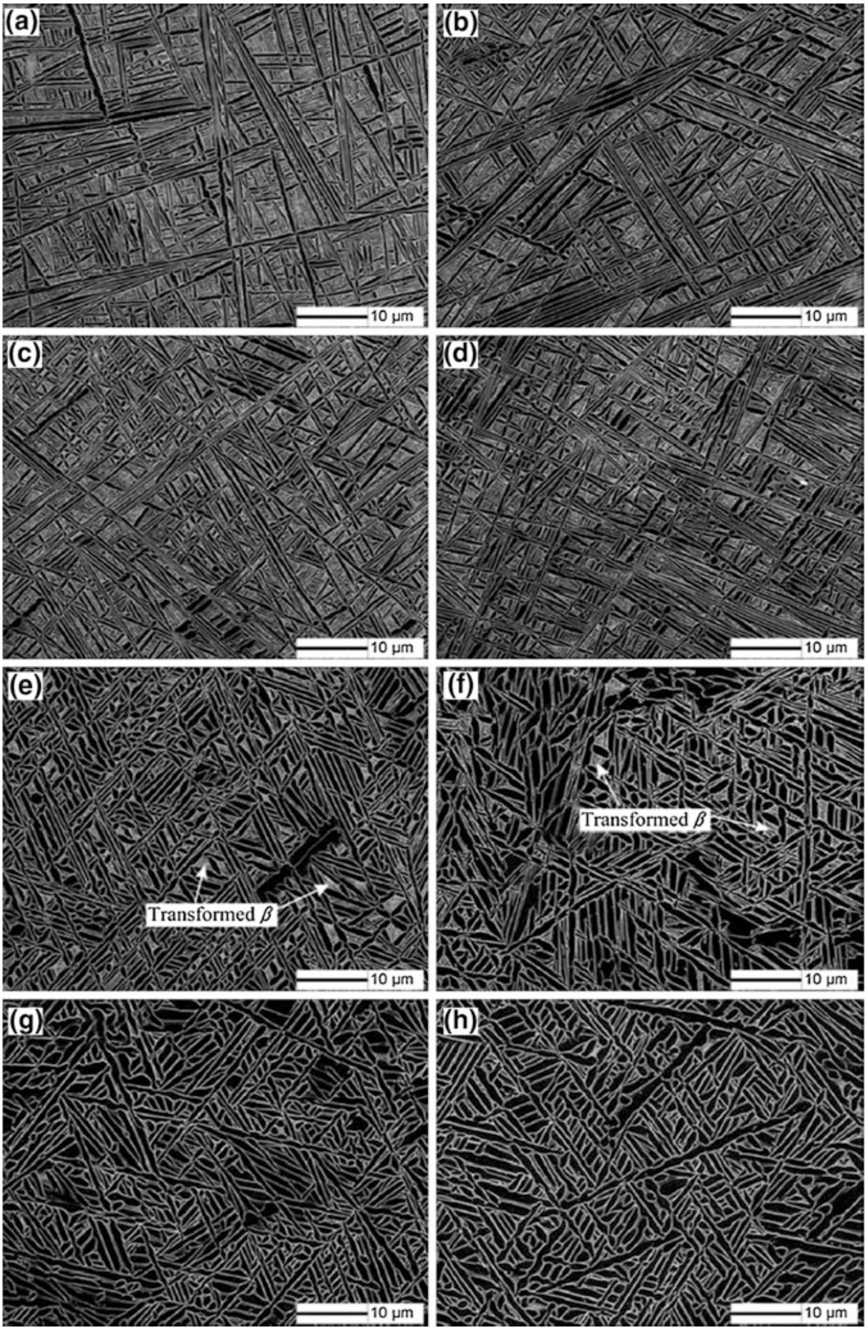

Fig. 3.13 Micrograph showing the microstructures of last eight deposited layers [31]

then be transformed to the needle-like δ phase. The strengthening phases can also be precipitated by double aging heat treatment, therefore producing an overall improvement in the mechanical properties of the material. The mechanical properties of the heat-treated material were found to be superior to AMS specifications for IN718 fabricated by conventional manufacturing processes. It was concluded that the HIP can be used to significantly reduce the porosity in the as-deposited material that causes the poor mechanical performance of the material. It was concluded that with HIP and appropriate heat treatments, it was possible, to produce IN718 using the laser metal deposition process with the mechanical properties, the hardness and the tensile properties, of the heat-treated material could be even be higher than AMS specifications for IN718 fabricated by the conventional manufacturing processes such as casting and forging. There are also a number of research works in the literature that studied the influence of processing parameters on the evolving properties in the laser metal deposition process which can be consulted for further reading [16, 33–38].

3.6 Summary

In this chapter, the laser metal deposition process was described. The solidification mechanism and the microstructural development in laser metal deposition process were explored. The evolving properties from the microstructural development were also analyzed. the capability of the laser metal deposition process in repair, remanufacturing and in the production of functionally graded materials were also highlighted. The use of laser metal deposition process for the fabrication of parts

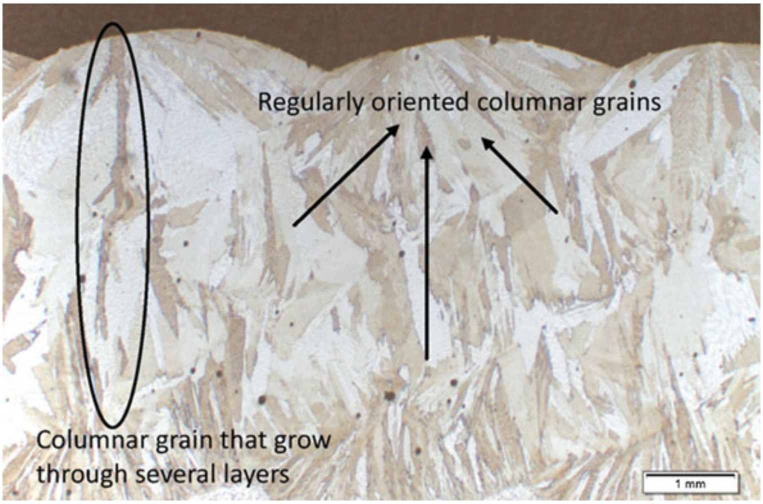

Fig. 3.14 Optical micrograph showing the grain orientations of the as-deposited material [32]

with properties marching those of the part produced through the traditional manufacturing processes were analyzed through various research works in the field. It was seen in this chapter that, laser metal deposition process is an important additive manufacturing process with lots of advantages and also a promising manufacturing process for the future.

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Chapter 4
Processing Parameters in Laser Metal Deposition Process

Abstract Laser metal deposition process is an important additive manufacturing process that is used to not only fabricate new three dimensional parts but can also be used to repair high valued parts. Laser metal deposition process has also position itself for product remanufacturing because of its capability to add a new part to an old part and with high metallurgical integrity. Processing parameters play an important role in the evolving physical, metallurgical and mechanical properties of the parts produced. The key processing parameters that influence the material properties in laser metal deposition process include: laser power, scanning velocity, powder flow rate, and gas flow rate. Laser metal deposition process is a highly non-linear process. A slight change in the processing parameters can result in a big change in the material properties. There is also a very strong interaction among these processing parameters. These processing parameters are analyzed in this chapter. There influences on the properties of the produced parts are explained. Some of the relevant literatures in this field are also presented.

Keywords Gas flow rate · Laser power · Powder flow rate · Process parameters · Scanning speed

4.1 Introduction

The invention of laser metal deposition process was the beginning of good things for the manufacturing industry. The major breakthrough of this important additive manufacturing technology is in its capability to effectively repair parts that were considered to be un repairable in the past and were discarded [1]. One of the unique properties of laser metal deposition process is the low heat affected zone produced in this process that makes it possible to bring an old part into as new working condition. Laser metal deposition process can also be used to fabricate three dimensional parts, no matter the complexity, directly from the 3D computer aided design (CAD) model of the part through material addition in layers [2]. Another important and attractive quality of the laser metal deposition process is the ability to

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control material properties such as hardness, yield strength, tensile strength and surface finish [3–5]. The microstructural evolution has a direct relationship with these evolving properties. The primary determining factor in the evolving microstructure is the solidification or cooling rate [6]. Processing parameters have a number of relationships with the solidification and cooling rate in the laser metal deposition process [7].

The solidification mechanism and microstructural development was the subject of discussion in Chap. 3. In this chapter, the various processing parameters used in the laser metal deposition process and their influence on the physical, metallurgical, tribological and mechanical properties are explained. The processing parameters that are considered in this chapter are the laser power, scanning speed, powder flow rate, gas flow rate, overlap percentage, and the laser beam diameter.

4.2 Processing Parameter in Laser Metal Deposition Process

There are a number of processing parameters in laser metal deposition process which include laser power, scanning speed, powder flow rate, gas flow rate, beam spot size and overlap percentage. These processing parameters have varying effect on the properties developed during the laser metal deposition process. Some of them have greater influence on the properties of the deposited sample while some have less significant influence on the properties of the deposited samples. These processing parameters are analyzed in the following sub-sections.

4.2.1 Laser Power

Laser power is the amount of heat energy delivered by the laser and used in the processing of material. Research has shown that laser power has a great influence on the processed material properties. Laser power affects the physical properties such as surface finish [8, 9]. Laser power also has great influence on the microstructural properties. Laser power is an important process parameter that needs to be controlled during the laser metal deposition process. The laser power selected depends on the material being processed and other processing conditions. The laser power must not be too high and should not be too low. Too high a laser power could result in high dilution between the substrate and the deposited materials, too high a laser power can also result in the vaporization of the deposited material or formation of plasma. None of these conditions are needed in the laser metal deposition process, although material vaporization or plasma formation may have application in other laser material processing. On the other hand, if the laser power is too low, this could cause improper melting of the deposited material which could result in different types of porosity such as lack of fusion porosity. If the laser power is extremely low, this could even result in no melting at all. This is why it is extremely important to establish the optimum laser power with respect to other processing parameters for the intended material processing. Also, laser power has influence of the properties of the deposited material and laser power value that gives the desired material properties should be established. In this section some of the research work that have demonstrated the influence of laser power on the resulting properties (surface roughness, material efficiency, microhardness, and wear resistance) of laser metal deposited material are presented.

4.2.2 Effect of Laser Power on the Surface Finish

Mahamood and Akinlabi [8] investigated the influence of laser power on the surface finish produced when titanium alloy was deposited on titanium alloy substrate using the laser metal deposition process. The laser power was varied between 0.8 and 3.2 kW while the remaining processing parameters were kept constant. It was shown in this study that the laser power has a very strong influence on the quality of the surface finish produced. The surface roughness was found to reduce as the laser power was increased as shown in Fig. 4.1a and the waviness was also found to be reduced as the laser power was increased as shown Fig. 4.1b. This could be attributed to proper melting of the deposited powder at higher laser power as well as lower solidification rate as a result of larger melt pool created at such higher powers.

The surface profile of sample at a very low laser power is shown in Fig. 4.2a while that of the sample at a very high laser power in shown in Fig. 4.2b.

The high waviness can be seen at low laser power which could be due to the presence of unmelted powder particles in the deposit.

Gharbi et al. [9] carried out investigations on the influence of a pulsed laser power regime on the surface finish produced during laser metal deposition process of titanium alloy (Ti6Al4V). The study revealed that by using high mean laser powers can greatly improve the surface finish obtained. The study also observed that by operating the laser in a quasi-continuous pulsed mode produced better surface finish than fully-continuous wave mode when performing laser reheating. This was seen from the results that for similar average powers, the use laser in a pulsed mode with large duty cycles produced smoothening effects on the samples. The influence of laser power on the surface finish is shown in Fig. 4.3. The surface roughness is seen to reduce as the laser power was increased from sample at low laser power shown in Fig. 4.3a to the very low surface roughness observed at high laser power as shown in Fig. 4.3d. The reason for the finer surface produced at higher laser power was attributed to the formation of larger and more stable melt pools produced at such higher laser power. The melt pool were found to have less pronounced lateral curvatures at higher laser power because of the reduced thermal gradients and the reduction in the Marangoni flow effect in the external sides of the fusion zone. Marangoni effect is also known as the Gibbs Marangoni effect and it is the mass transfer that occurs along the interface because of surface tension gradient.

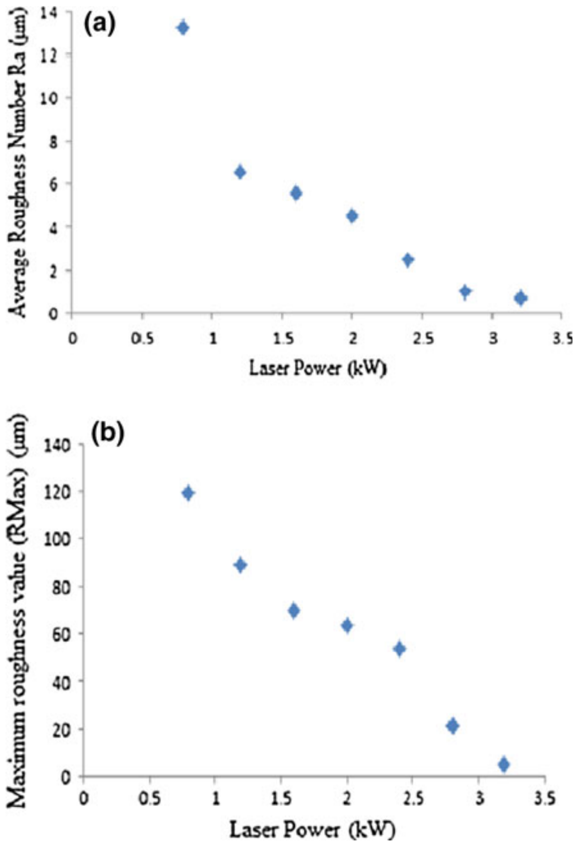

Fig. 4.1 The plot of **a** Average roughness value (Ra) against laser power **b** Maximum roughness value (Rmax) against laser power [8]

The phenomenon is also called thermo-capillary convention where temperature gradient exists.

In a similar study conducted by Rombouts et al. [10] where a substantial improvement in surface quality of a laser metal deposited part was achieved by varying the laser power during remelting after powder deposition. Figure 4.4a showed the surface profile obtained at a laser power of 550 W and Fig. 4.4b showed the surface profile obtained after laser remelting with 1000 W laser power. The deposit produced at the low laser power was characterized by a regular waviness in a direction perpendicular to the deposition direction while the waviness was significantly reduced with the use of higher laser power as can be seen in Fig. 4.4b. To really confirm the influence of the higher laser power on the improvement of the surface finished obtained, a laser power of 500 W was used to remelt the deposited layer and it was observed that there was no improvement in the surface finish because the laser power was too low to be able to remelt the surface sufficiently deeper as compared to what was seen at the higher laser power.

A related study was carried out by Ghadi et al. [11]. In this study, the influence of laser power on melt pool size and the resulting surface finish during the laser

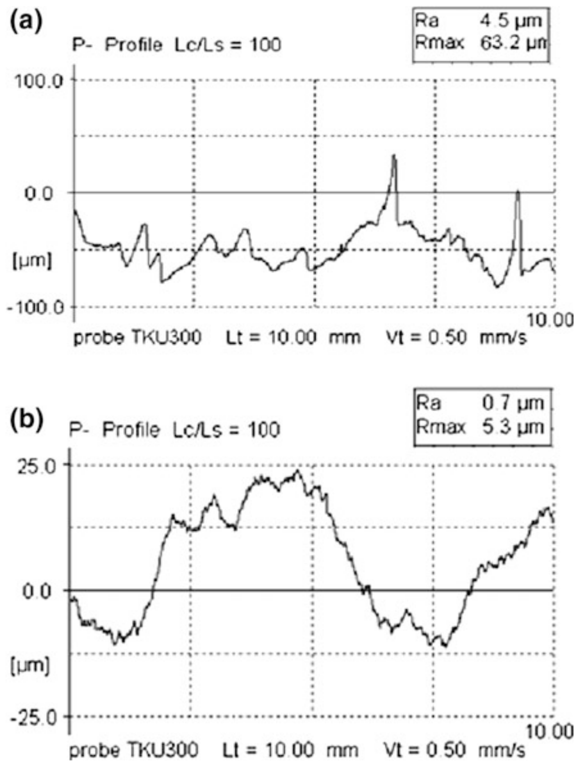

Fig. 4.2 Surface roughness profile at **a** low laser power **b** high laser power [8]

metal deposition process of titanium alloy. The laser power was varied between 320 and 700 W operated in continuous mode. The study of the melt pool was conducted using two synchronized fast cameras with C-Mos sensors (Photron), operated at a frequency rates of up to 5000 Hz. The aim of the study was to understand the physical mechanisms that could be responsible for poor surface finish in laser metal deposition process. The study revealed that the sticking of the unmelted or partially melted powder particles on the surfaces of the deposit was responsible for the poor surface finish and also the formation of menisci with more or less pronounced curvature radii. It was observed that, increase in the melt-pool volumes helps to re-melting this unmelted powder particles which was observed at a higher laser power. The large melt-pools produced at high laser power was found to improve the surface finish, A numerical model was developed in the study for prediction the surface finish and the model was validated experimentally with good agreement. A high laser power was found to reduce both the waviness and surface roughness parameters as shown in Fig. 4.5.

The cross section of the deposited sample showed that the lateral menisci are smoothed by the use of a higher laser power that produced the melt pool with lower curvature angle as a result of negative Marangoni flow effect that pushed the central part of the melt-pool upwards.

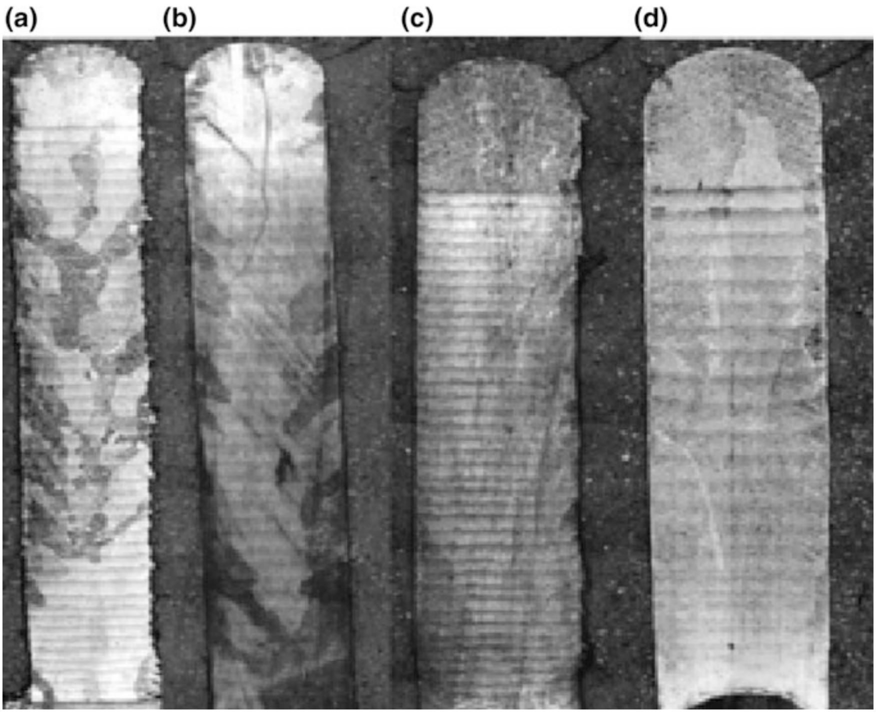

Fig. 4.3 Improvement of surface finish using with increasing power from **a** to **d** [9]

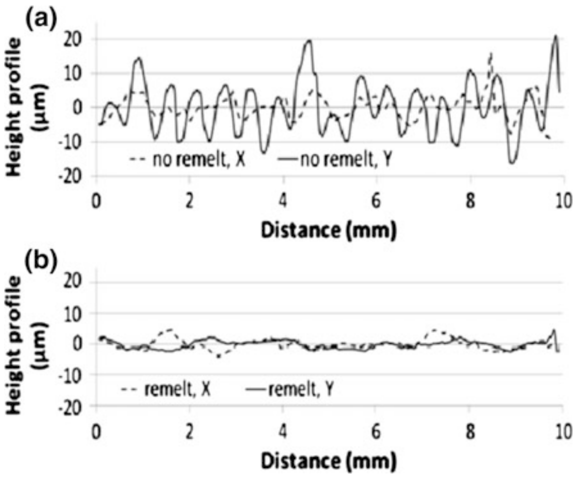

Fig. 4.4 Surface profile LMD part **a** at 550 W laser power **b** with Laser re-melting at 1000 W laser power [10]

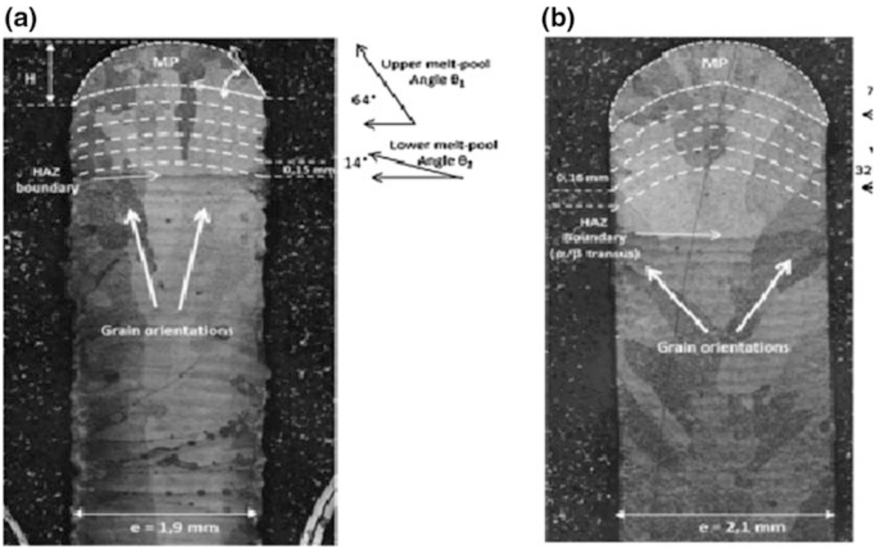

Fig. 4.5 Cross sections of Ti6A4V walls at a laser power of **a** 320 W **b** 500 W [11]

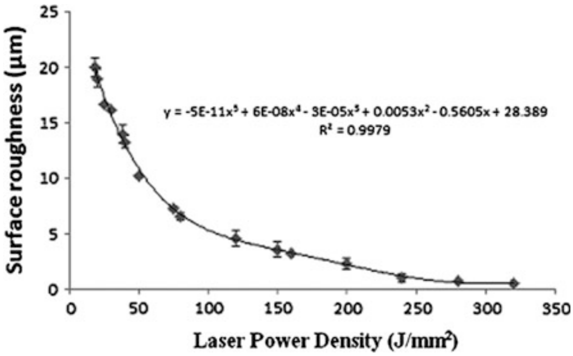

Fig. 4.6 Plot of power density versus surface roughness [4]

Mahamood et al. [4] reported the influence of laser power density on the developed surface finish during laser metal deposition of titanium alloy. The power density was varied between 18 and 320 J/mm^2 which was achieved by either increase the laser power or decreasing the scanning speed. The results show that the higher the laser power density the smoother was the surface finish that was obtained as shown in Fig. 4.6. The result was attributed to the proper melting of the deposited powder as the laser power density was increased which produces larger melt pool that solidified much slower than at low laser power density. It was concluded that it was possible to achieve better surface finish in laser metal deposition process by using high laser power density which will help to reduce the need for the secondary finishing operation especially in parts with certain intricacies where it may be difficult to perform secondary finishing operations.

4.2.3 Effect of Laser Power on the Microstructure

Laser power show a very strong influence in the evolving microstructure of laser metal deposited part and it has direct relationship with the melt pool produced as well as the solidification and the cooling rate. High laser power tend to favour the generation of large melt pool and the larger the melt pool, the longer the solidification time which in turn favour more of equilibrium microstructure to the formed and less of non equilibrium microstructure to be produced. Microstructural development in laser metal deposition process is an important research area because; it affects the evolving properties of the part being produced. Controlling laser power during the laser metal deposition process is an important task because it has been reported that it has great influence on the microstructure and hence the developed properties. Some of these research works are analyzed in this section.

Ravi et al. [12] investigated the influence of laser power on the microstructure of Ti6Al4V samples fabricated using the laser metal deposition process. The laser power was varied between 480 and 1800 W and the influence of operating mode, continuous wave mode and pulse wave mode on the microstructure was also studied. The sample produced at a laser power of 480 W and in continuous wave mode was labeled CW1 and the one produced at a laser power of 1800 W in continuous mode was labeled CW2. The samples produced at pulsed wave operating modes are designated as CWP, with the one at a laser power range between 300 and 400 W labeled CWP1 and the one produced at a high laser power of between 1200 and 1600 W was labeled CWP2. The results of the microstructural analysis showed that both laser mode and laser power have significant influence on developed grain structures. The samples produced at continuous wave mode result in the development of well-formed large columnar grains structures while the samples produced at pulsed wave mode tend to develop much finer equiaxed grains structures as shown in Fig. 4.7. The samples produced at higher laser powers both in continuous and pulse wave modes (CW2 and CWP 2) were found to produce more of larger grains and coarser microstructures. As shown in Fig. 4.7, the laser power was found to show more significant influence in the microstructure than does the laser operation mode. At low laser powers (CW1 and CWP1) the microstructures are predominantly mixtures of very fine needle like martensitic alpha phase structures while a mixture of alpha and beta phase lamellar structures with coarser basketweave microstructures were seen at higher laser powers (CW2 and CWP2).

It can be concluded that the laser operating mode does not have a significant influence on the evolving microstructure but the laser power strongly influence the developed laser power and hence the resulting material properties. Through proper control of laser power, the microstructures can be controlled and hence the properties can be controlled.

The effect of laser power on microstructure of titanium copper alloy produced using laser metal deposition process was investigated by Erinosho et al. [13]. The laser power was varied between 600 and 1800 W and the resulting microstructures were studied. The microstructures were found to consist mainly dendrites of

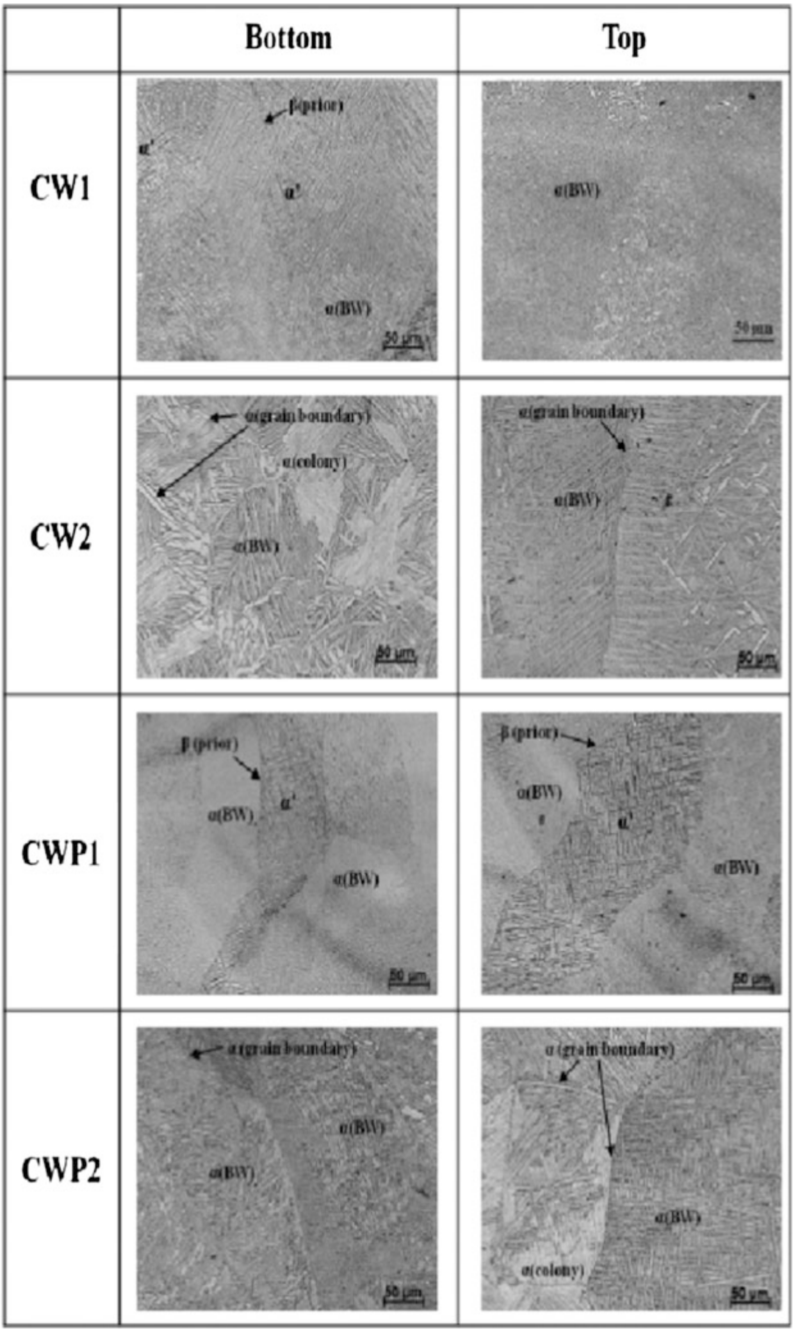

Fig. 4.7 Micrograph showing microstructures of Ti6Al4Vsamples at various laser power and laser mode (BW is basketweave) [12]

primary, secondary and tertiary arms, acicular microstructure and alpha/beta eutectic structures. The microstructure of the sample produced a laser power of 1200 is shown in Fig. 4.8a and the microstructure at higher magnification is shown in Fig. 4.8b. The Sample produced at a laser power of 600 W is shown in Fig. 4.8c and the sample produced at laser power of 900 W is shown in Fig. 4.8d. The sample in Fig. 4.8a is characterized by dentritic grains. The thickness of the dentritic arms were found to decrease as the laser power was reduced. The reason for this type of microstructural formation can be attributed to the rapid solidification happening at lower laser power due to smaller melt pool produced that tends to favour more dentritic arms that are thinner. At higher laser power on the other hand, the large melt pool created takes longer to solidifies and permit a thicker dentritic arm growth. This microstructures of cause have a great influence in the resulting properties and effective control of these microstructural formation will go a long

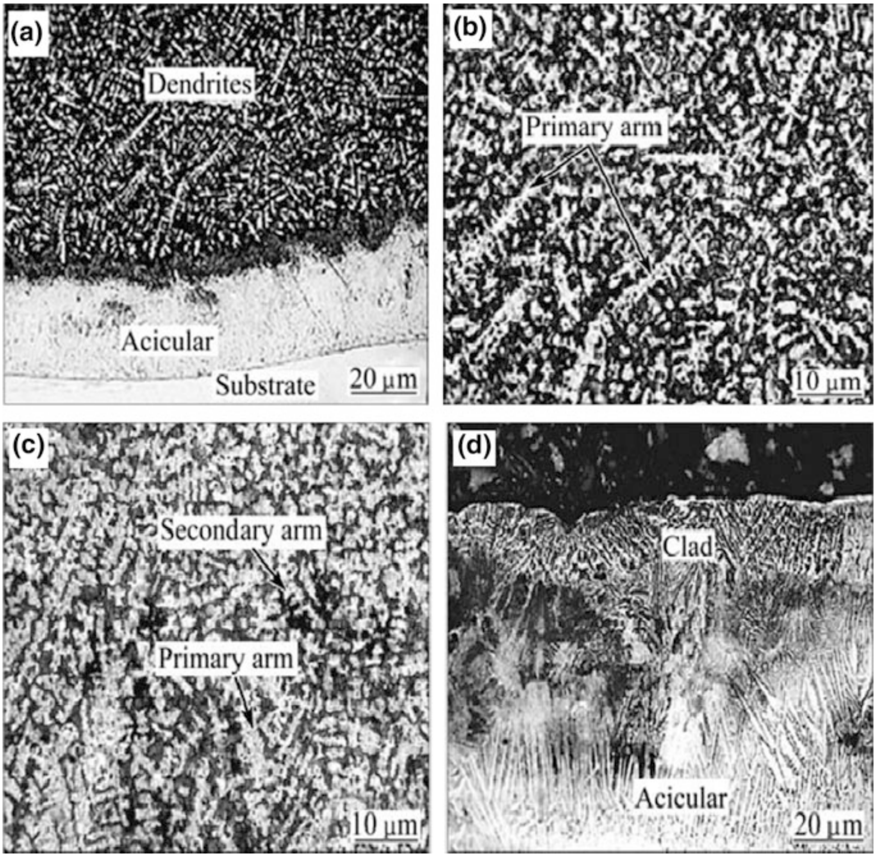

Fig. 4.8 Micrographs of Samples produced at a laser power of **a** 1200 W **b** 1200 W at higher magnification **c** 600 W **d** 900 W [13]

way in controlling the evolved properties through the effective control of laser power.

Yu et al. [5] investigated the effect of laser power on the developed microstructure in laser metal deposition of Ti6Al4V. The laser power was varied between 380 and 570 W. The result of the microstructural analysis showed prior columnar beta grains structures that consists acicular alpha and martensitic alpha as shown in Fig. 4.9. The microstructure consists of prior columnar beta grains structure whose direction is towards the building direction. The prior beta grains structure were found to grow epitaxially which becomes larger as the laser power was increased. This can as well be attributed to the fact that at higher laser power, the larger melt pool generated stays longer on the substrate that allows the grain growth in the heat affected zone of the substrate to become larger.

The grains of the deposited materials grow epitaxially on this heat affected zone larger grains and hence a larger prior beta grains seen at higher laser power. At lower laser power on the other hand, the melt pool is smaller and solidification is more rapid, there was no enough time to cause substantial grain growth which then translate to a smaller epitaxial prior beta grain growth observed at low laser power.

The developed microstructure will definitely influence the resulting microstructure and the proper control of the laser power during the laser metal deposition process is key to achieving the desired properties from the part produced. A related study was conducted by Mahamood et al. [4]. The influence of laser power density on the microstructure of the produced titanium alloy using the laser metal deposition process. The laser power density was varied between 18 J/mm^2 and a high laser power density of 240 J/mm^2. The results revealed that as the laser power density was increased, the microstructure was found to change from finer martensitic alpha grain to coarser Widmastätten alpha grain structure as shown in Fig. 4.10. At a very low laser power density (18 J/mm^2), that available laser energy was insufficient to completely melt the deposited powder which resulted in some unmelted titanium powder particles that were seen in the microstructure as shown in Fig. 4.10a. Some of these unmelted titanium power particles were removed during the sample preparation thereby leaving some of the spherical impressions that are seen in this sample. The microstructure of the sample produced that was produced at a laser power density of 50/mm^2 is shown in Fig. 4.10b and it is characterized by fine martensitic alpha microstructure. The reason for the formation of this type of finer martensitic alpha microstructure was because of the relatively faster solidification and rapid cooling due to the smaller melt pool created at such lower power density. The microstructure produced at very high laser power density of 240 J/mm^2 was found to consist mainly of Widmastätten alpha grain microstructure. The reason for this could be as a result of the generation of larger melt pool size produced at such high laser power density that makes the melt pool to take a longer time before solidification that promoted the formation of the Widmastätten alpha microstructure that is coarser due to the high cooling rate. The martensitic alpha microstructure is harder and brittle while the Widmastätten alpha

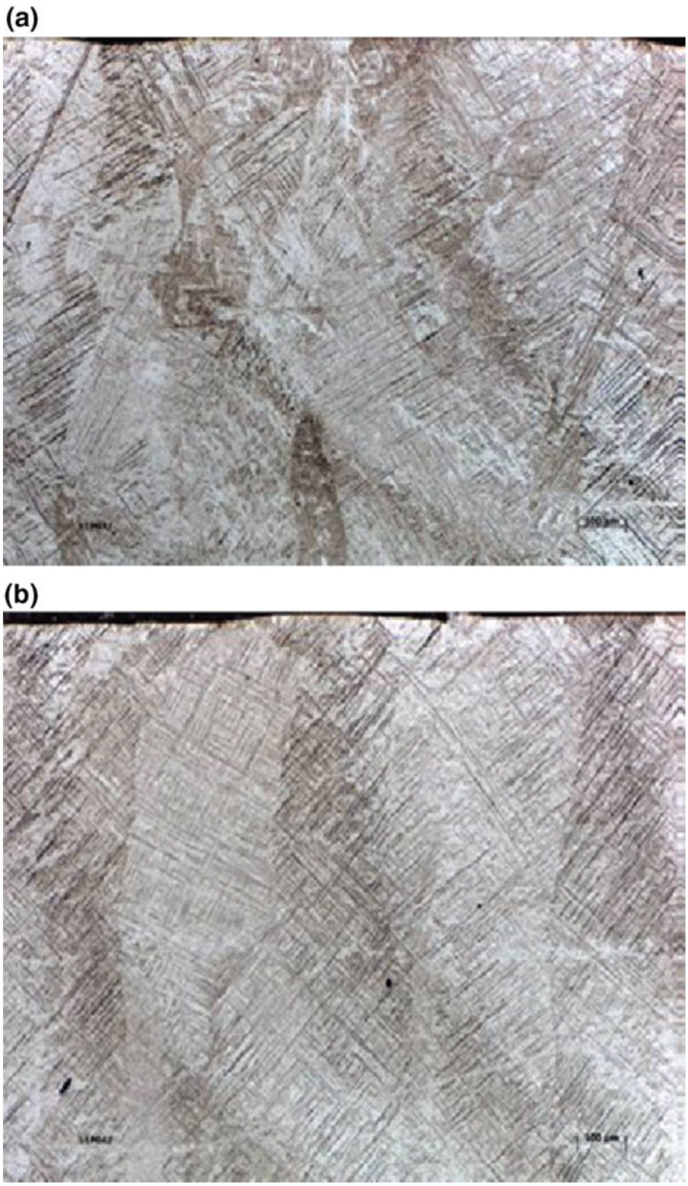

Fig. 4.9 Macrostructures of LMD Ti6Al4V specimens at a laser power of **a** 380 W **b** 470 W [5]

microstructure is softer and more ductile. This study also further confirms the role that the laser power played in the laser metal deposition process. By simply controlling the laser power in the laser metal deposition process, it is possible to create part that is hard and brittle or part that is softer and ductile.

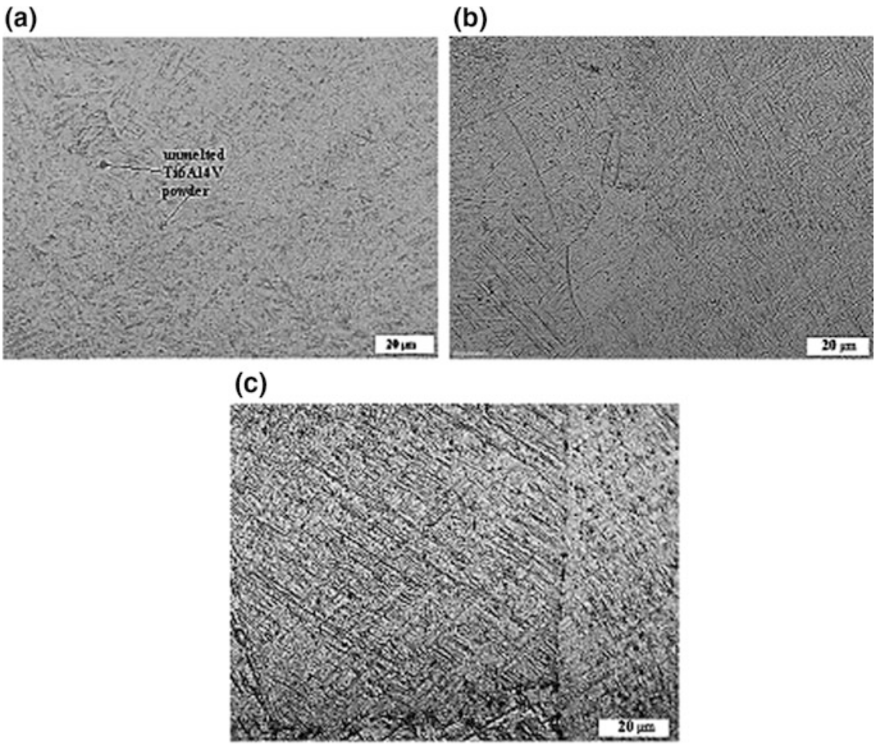

Fig. 4.10 Micrograph of samples at laser density of **a** 18 J/mm2, **b** 50 J/mm2, and **c** 240 J/mm^2 [4]

Mahamood et al. [14] also conducted investigation on the influence of laser power on the microstructure produced during the production of Ti6Al4 V using the laser metal deposition process. The laser power was varied between 0.8 and 3.0 kW.

The study showed that, as the laser power was increased; the microstructure changed from fine martensite to thick Widmastätten grain structures as shown in Fig. 4.11. The reason is similar to the explanation given earlier in this section. Also, the higher the laser power, the lower the quantity of columnar prior beta grain structure that is seen in the microstructure.

Also, the higher the laser power, the lower the quantity of columnar prior beta grain structure that is seen in the microstructure. A high density of columnar prior beta grains are seen at low laser power because of the smaller melt pool produced and higher solidification rate which does not permit much of grain growth in the heat affected zone. Thereby making the number of prior beta grains that grows epitaxially on the grains in the heat affected zone to be more. The low density of columnar prior beta grain structure observed at higher laser power was as a result of

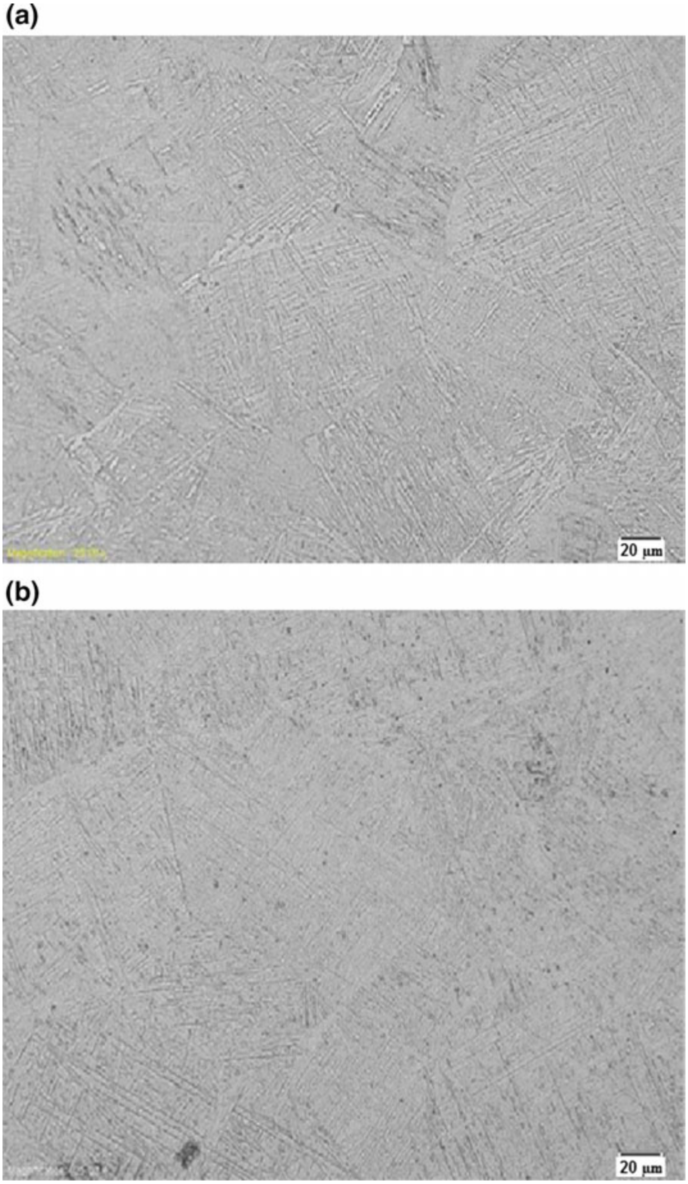

Fig. 4.11 Microstructure of sample at a laser power of **a** 1.6 kW **b** 3.0 kW [14]

larger melt pool and lower solidification rate that permitted more grain growth in the heat affected zone and hence fewer large grains on which the melt pool nucleate and grow epitaxially.

4.2.4 *Effect of Laser Power on the Mechanical and Tribological Properties*

It can be seen from the previous section how laser power affects the microstructural properties of the materials processed using the laser metal deposition process. There is a direct relationship between the microstructure of material and the evolving properties. Also, a number of research has been conducted to map the laser power with the resulting mechanical and tribological properties of materials processed using the laser metal deposition process. Some of these research works are analyzed in this section.

Mahamood et al. [4] conducted a study on the influence of laser power density on the microhardness property of titanium alloy produced with laser metal deposition process. The laser power was varied from 18 to 320 J/mm^2 and the microhardness was studied. The result showed that the microhardness was initially increased as the laser power density was increased and then becomes smaller as the power density was further increased as shown in Fig. 4.12. The microhardness value increased initially when the laser power density was increased and began to reduce when the laser power density was increased beyond 80 J/mm^2. The rate at which the microhardness was reducing when the laser power density was increased beyond 80 J/mm^2 was lower when compared to the rate the microhardness was increased when the laser power density was increased from 18 to 80 J/mm^2.

The reason for this observations was credited to the changes seen in the microstructures at these laser power densities. The insufficient melting at the low laser power density that produced unmelted powder particles could be responsible for the low microhardness values at low laser power density which increased as the laser power density was slightly increased. As the laser power density was increased beyond the 80 J/mm^2, the melt pool created was started to become larger and larger, thereby promoting the formation of coarse Widmastätten alpha grains structure which are softer and ductile. The formation of these Widmastätten grain structure was responsible for the dropping in the microhardness values at higher laser power density as the Widmastätten grains becomes more and more coarser as the laser power density was increased. It was concluded that depending on the service requirement of the part being produced using the laser metal deposition

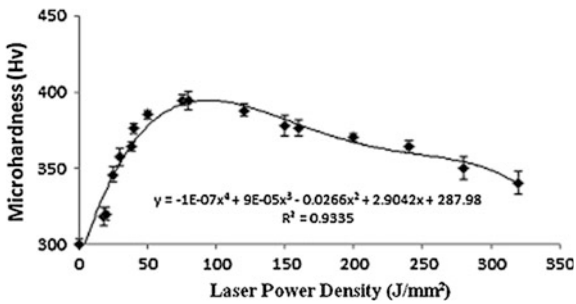

Fig. 4.12 Plot of laser power density against microhardness [4]

process in terms of microhardness desired, the laser power density can effectively be controlled in order to achieve the desired part properties.

A similar study was conducted by Mahamood et al. [15] where the influence of laser power on the resulting microhardness and wear resistance properties of Ti6Al4V/TiC composite produced using the laser metal deposition process were investigated. The laser power was varied between 0.4 and 3.2 kW. The Ti6Al4V/TiC composites were deposited at a 50 W% Ti64 and 50 W% TiC composition ratio. The deposition of the composites were achieved by placing the two powders of Ti6Al4V and TiC powder in a separate powder feeder hoppers in each hoppers and the two powders were deposited simultaneously. The results of this study showed that the laser power has a significant influence on the microhardness and the wear resistance properties of the composite produced. The microhardness and the wear resistance were found to initially increased when the laser power was increased from 0.4 to 2.0 kW and then started to experienced a decrease when the laser power was further increased beyond the laser power of 2.0 kW as shown in Fig. 4.13a, b respectively. The reason for these behaviuor was as a result of improper melting of the TiC carbide particles at very low laser power which was seen to aggravate the wear behaviour. The size of these TiC powder began to reduce as the laser power was increased. The smaller size of unmelted TiC powder particles are beneficial for the improvement in wear behaviour because they become fine powder through rubbing against the wear surfaces and against other unmelted TiC powder particles. The fine powder produced during this wear process help to form a powder lubricant in between these rubbing surfaces that will help to reduce the wear action and hence improved wear resistance property. Certain percentage of small size unmelted TiC powder particle are desired in order to improve wear resistance property. As the laver power was further increased, the TiC powder becomes more and more fully melted thereby removing the reinforcing purpose that the unmelted TiC served in the wear process and the more of dentritic TiC that are produced at higher laser powers are hard and brittle which could further aggravate the wear action through tearing and cutting of the surfaces during the wear process.

Ju et al. [5] investigated the influence of laser power on the mechanical properties of titanium alloy produced using the laser metal deposition process. The laser power was varied from 380 to 570 W. The influence of these laser powers on the microhardness, the yield and the ultimate tensile strengths of the fabricated parts were studied. The results showed that the increase in laser power produced better microhardness, yield strength and ultimate tensile strength which when compared to those of cast and annealed wrought material were found to be superior to them.

The improved in these properties was associated to the disappearance of porosity in the deposited samples as the laser power was increased.

Another similar study that was conducted by Bayode et al. [16] showed that laser power has a great influence on the microhardness properties in laser metal deposition process of 316 L stainless steel. In the study, the laser power was varied from 1.8 to 2.4 kW. The result revealed that with increase in the laser power, the microhardness of the components was found to decrease. The reason was attributed

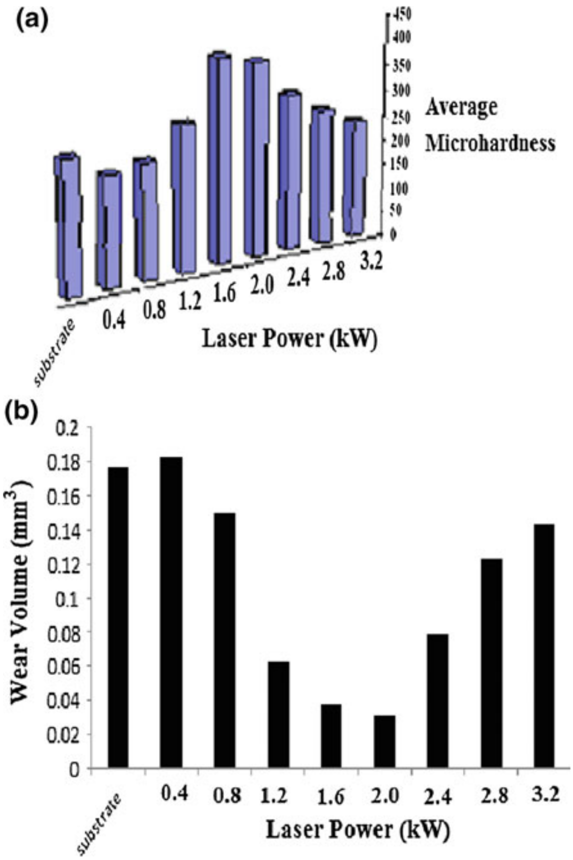

Fig. 4.13 The bar chats of the **a** average microhardness **b** wear volume [15]

to the grain structure coarsening as the laser power was increased. Laser power has also been reported to have a great influence on the material utilization economy [16, 17]. It can be concluded from all these studies that laser power can be controlled to effectively control the developed microstructure which will in turn control the properties that could result from the laser metal deposited material.

4.3 Scanning Velocity

The scanning velocity is another important processing parameter in the laser metal deposition process. It provides the length of time at which the laser beam interacts with the substrate and the deposited materials. The scanning velocity is achieved in the laser metal deposition process either by moving the laser head against a substrate placed on a stationary building platform, or by moving the substrate placed on a computer numerically controlled five axis table against a fixed laser head.

However the movement is achieved in the deposition process, the scanning velocity determines how long the laser and the materials being processed interact. A number of research work has reported the influence the scanning velocity has on the properties of the laser-deposited materials. Low scanning velocity; indicate that the laser and the materials interact for a longer period of time. A too low a scanning velocity could result in high dilution of the deposited material and the substrate, or it could even result in the evaporation of the materials being processed which is not desirable in the laser metal deposition process. However, too high a scanning velocity which produce a very short interaction time between the laser and the material being processed, could result in an incomplete melting of the deposited materials or even no melting at all. It can be seen that the scanning velocity has a influence that is inversely proportional to the influence the laser power has in the laser metal deposition process as was earlier explained in this chapter. The laser power is related to the scanning speed in what was described as laser power density through the formula according to Sentikumara et al. [18] as given in Eq. 4.1

$$\mathrm{E}\left(\mathrm{J/mm}^2\right) = \mathrm{p/dv} \tag{4.1}$$

Where: E is the laser energy density in J/mm^2, p is the laser power in W, v is the scanning velocity in mm/s; and d is the laser-beam diameter in mm.

It can be seen from the Eq. 4.1, that the energy density is directly proportional to the laser power and inversely proportional to the scanning velocity and the beam diameter. What this means is that, the laser energy density can be increased or decreased simply by either increasing or decreasing the laser power, or by reducing or decreasing the scanning velocity. Change in laser energy density can also be achieved by changing the laser beam diameter.

The influences of scanning velocity on various properties of laser metal deposited materials are analyzed in this section.

4.3.1 *Effect of Scanning Speed on the Surface Finish*

Mahamood and Akinlabi [19] investigated the influence of scanning speed on surface finish produced in laser metal deposition process of titanium alloy. The laser power and the powder flow rate were maintained at 3.0 kW and 2.88 g/min respectively, and the scanning speed was varied between 0.01 and 0.05 m/s. The results in this study showed that, the surface roughness increased as the scanning speed was increased. This is shown in Fig. 4.14a with the curve fitted graph shown in Fig. 4.14b. This was attributed to the phenomenon similar to the influence laser power has on surface roughness, which is inversely proportional to the scanning speed influence. The surface roughness is lower at lower scanning speed because, the laser material interaction time is higher at higher scanning speed thereby producing effective material melting, creation of larger melt pool and hence slower rate of solidification which promoted the lower surface roughness observed. The surface

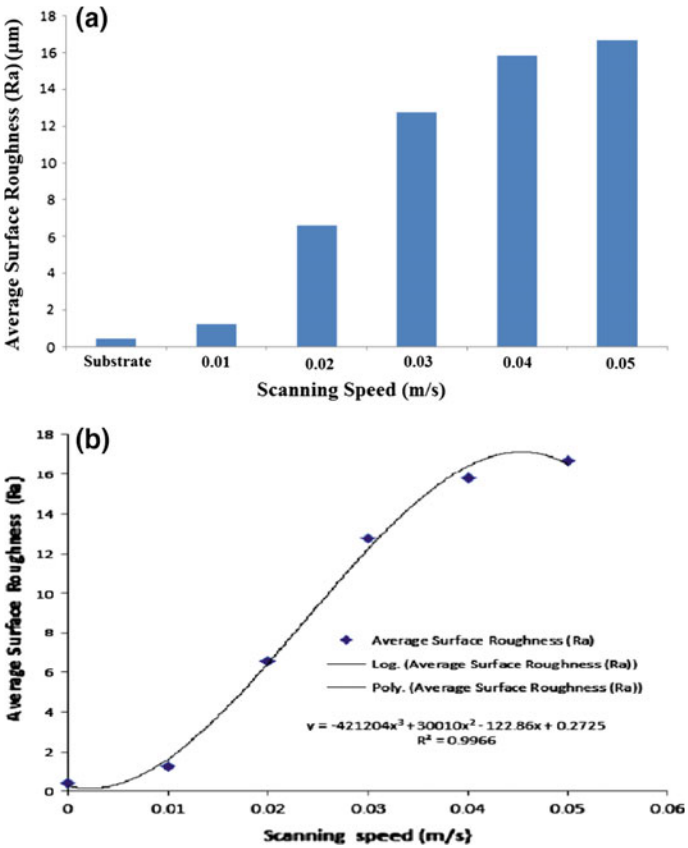

Fig. 4.14 **a** The bar chat of the average surface roughness against the scanning speed **b** graph of the average surface roughness against the scanning speed [19]

roughness is higher at higher scanning speed on the other hand, because, the laser material interaction time is shorter causing probably improper melting of the deposited material.

Also, the shorter laser material interaction time results in the creation of smaller melt pool which tend to solidify rapidly and creating scales on the surface of the deposited track apart from improper melting of the deposited material which could also contribute to the increased surface roughness. The study concluded that there is need to properly optimize the laser metal deposition process parameters through the right combination of process parameters in order to achieve the desired properties. This study was also suggested for use in repair application as well as in surface modification process using the laser metal deposition process.

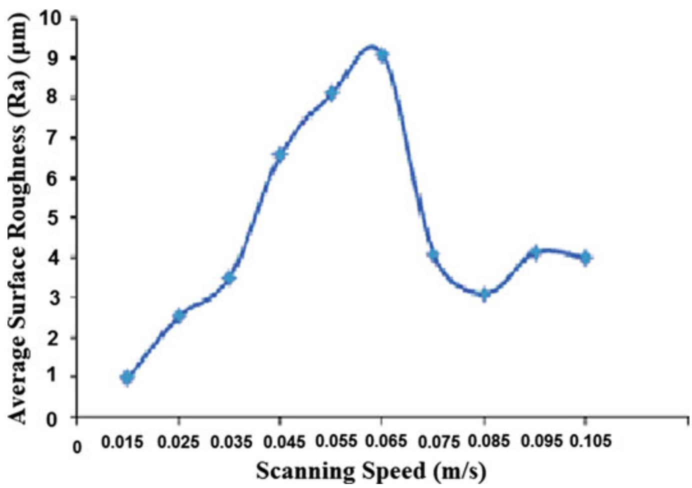

Fig. 4.15 Surface roughness profile against the scanning velocity [3]

A similar study was also conducted by Mahamood et al. [3] on titanium carbide-titanium alloy composite, by varying the scanning speed between 0.015 and 0.105 m/s. The result also showed that the least surface roughness was observed at lowest scanning speed of 0.015 m/s, although a nonlinear relationship was found as shown in Fig. 4.15. The average surface roughness was found to initially increase as the scanning speed was increased and started to decrease as the scanning speed was further increased.

The smoother surface observed at low canning speed was as a result of proper melting of the TiC powder due to the larger laser-material-interaction time. As the scanning speed was increased, the laser-material-interaction-time began to reduce thereby causing more and more unmelted TiC powder to be seen and hence increase in surface roughness value. The surface roughness value was seen to reduce as the scanning speed was increased beyond 0.065 m/s, as seen in Fig. 4.15. The reason for the decline in the average surface roughness value at these higher scanning speed was attributed to the little time available for both material delivering as well as melting of the material that was responsible for the low quantity of the unmelted TiC as compared to the large quantity that were seen at much lower scanning speed. This can be explained by the decline in the composite thickness as the scanning speed was increased as shown in Fig. 4.16.

The quantity of powder delivered at higher laser power is smaller as a result of the little time available at higher scanning speed, The reducing surface roughness seen beyond the scanning speed of 0.65 m/s was not due to more melting of powder as was the case at low scanning speed, but it was due to less powder particles that were being deposited that resulted in the population reduction of the unmelted TiC particles.

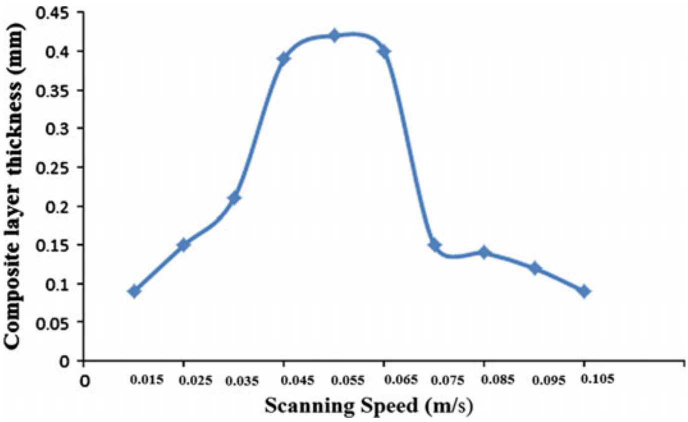

Fig. 4.16 Graph of layer thickness against the scanning speed [3]

4.3.2 Effect of Scanning Speed on the Microstructure

The scanning speed has also been reported to have influence of the microstructure of the part produced using the laser metal deposition process. The microstructural formation begins the moment the molten material started to solidifies. The type of microstructure produced depends on the size of melt pool created during the deposition process which of course determines the rate at which the melt pool solidifies. Low scanning speed promote the formation of large melt pool because of the high laser material interaction time. Larger melt pool on the other hand makes the solidification rate to be slower which promotes the formation of certain kind of microstructure that impact the evolving properties of the deposited material. Based on this, the influence of the scanning speed on the on the resulting microstructure of materials during the laser metal deposition process needs to be carefully understood so as to control it in order to produce the desired metallurgical, mechanical as well as tribological properties.

A study conducted by Mahamood et al. [20] on the influence of scanning speed that was varied between 0.005 and 0.095 m/s, on the resulting microstructure in laser metal deposition of titanium alloy showed that the microstructure changes as the scanning speed was changing as shown in Fig. 4.17.

Erinosho et al. [13] studied the effect of scanning speed on microstructure produced during laser metal deposition of titanium copper alloy as shown in Fig. 4.18. The microstructures were seen to consist of dendrites and acicular structures. The dendritic arms seen in the microstructure were found to be made up of the primary, secondary and the tertiary arms.

The dendrites were found to increase in thickness as the scanning speed was increased. Also the primary dendrite arms were seen to grow thicker while the tertiary arms grow shorter as the scanning speed was increased as shown in Fig. 4.18.

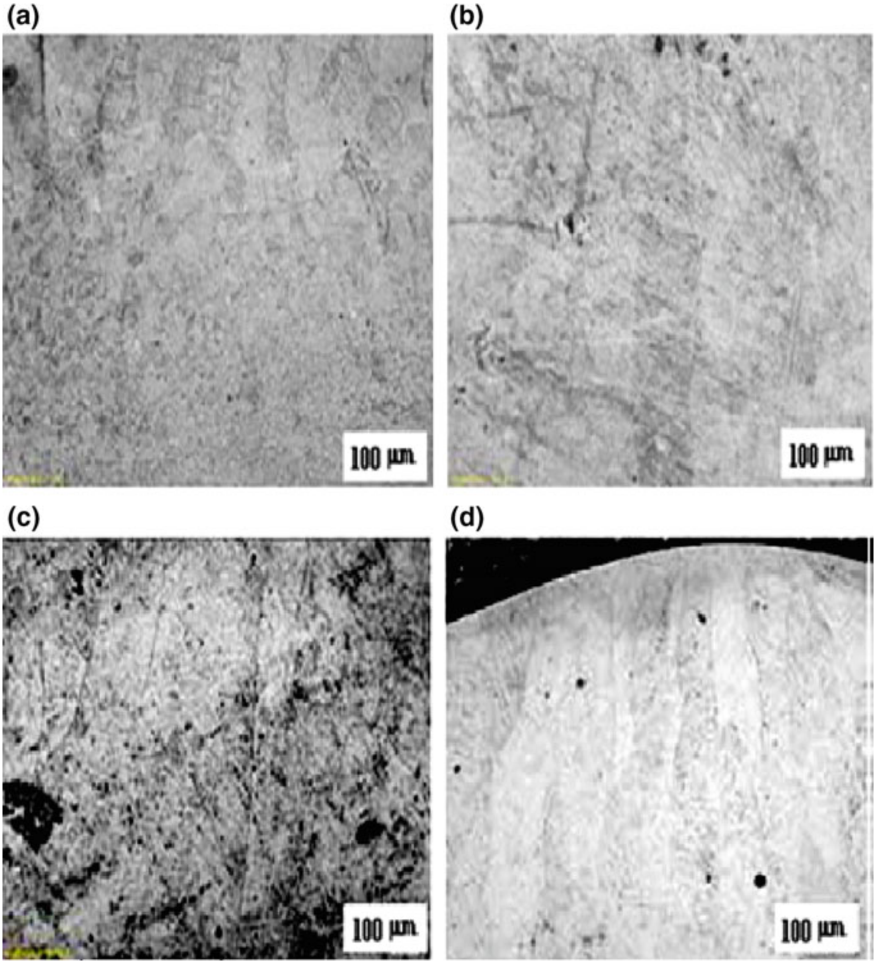

Fig. 4.17 The macrostructure of the samples at scanning speed of **a** 0.005 m/s **b** 0.015 m/s **c** 0.025 m/s **d** 0.035 m/s [20]

The microstructure formed at higher scanning speed shows snowflakes of dendrites which were formed next to the acicular microstructures with the dendrites structure disappearing gradually and the acicular microstructures formed at the interface of Cu composite and substrate became stronger with sharp edges. The rapid cooling associated with high scanning speed could be attributed to this type of microstructural formation. The rapid cooling could also be responsible for the cracks observed at the higher scanning speed shown in Fig. 4.18e.

Mahamood et al. [3] also investigated the influence of scanning speed on the microstructure produced during the laser metal deposition process of titanium carbide-titanium alloy composite. The size of the unmelted TiC particles were seen

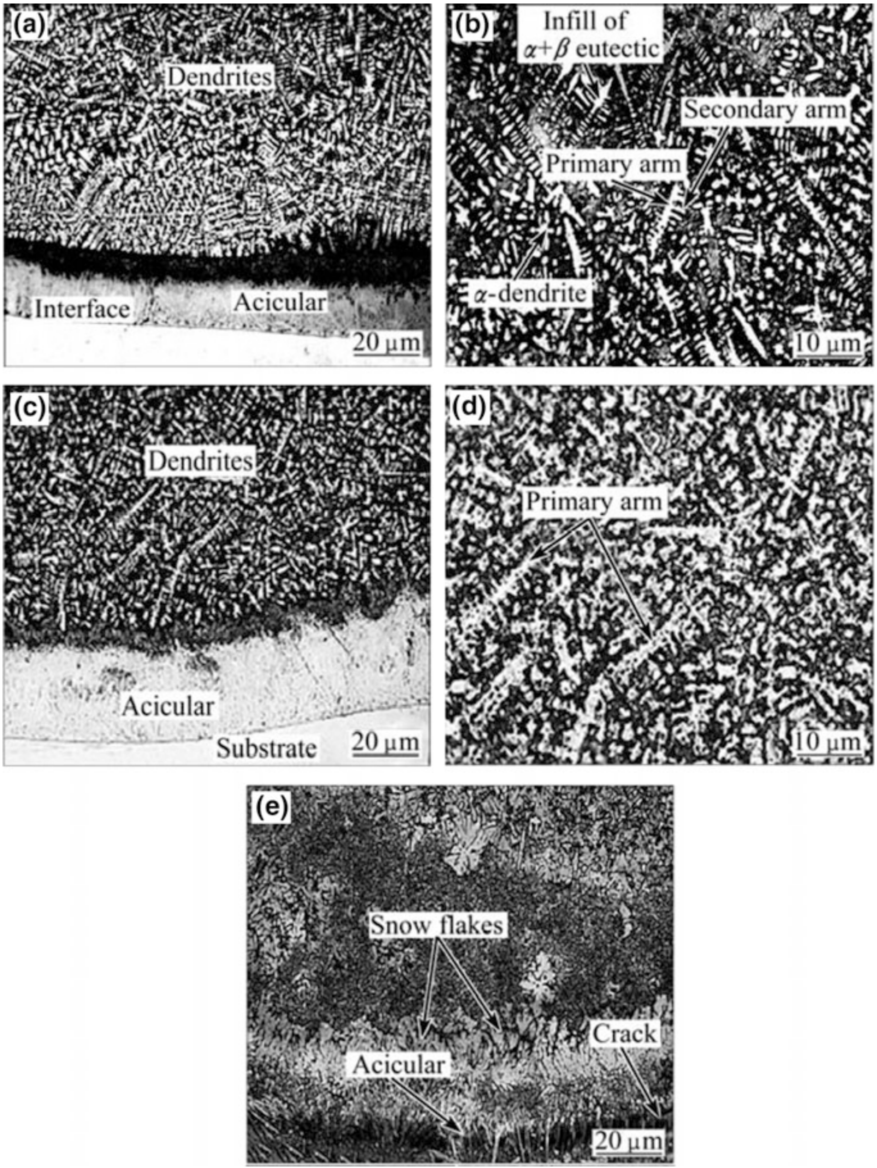

Fig. 4.18 Microstructures of samples at scanning speed of **a** 0.1 **b** 0.1 at higher magnification **c** 0.3 **d** 0.3 at higher magnification **e** 0.5 m/s [13]

to increase as the scanning speed was increased. This was attributed to low laser material interaction time at higher scanning speed which is responsible for the improper surface melting of the TiC powder particles. The size of unmelted TiC powder particles are smaller at low scanning speed as a result of adequate time that

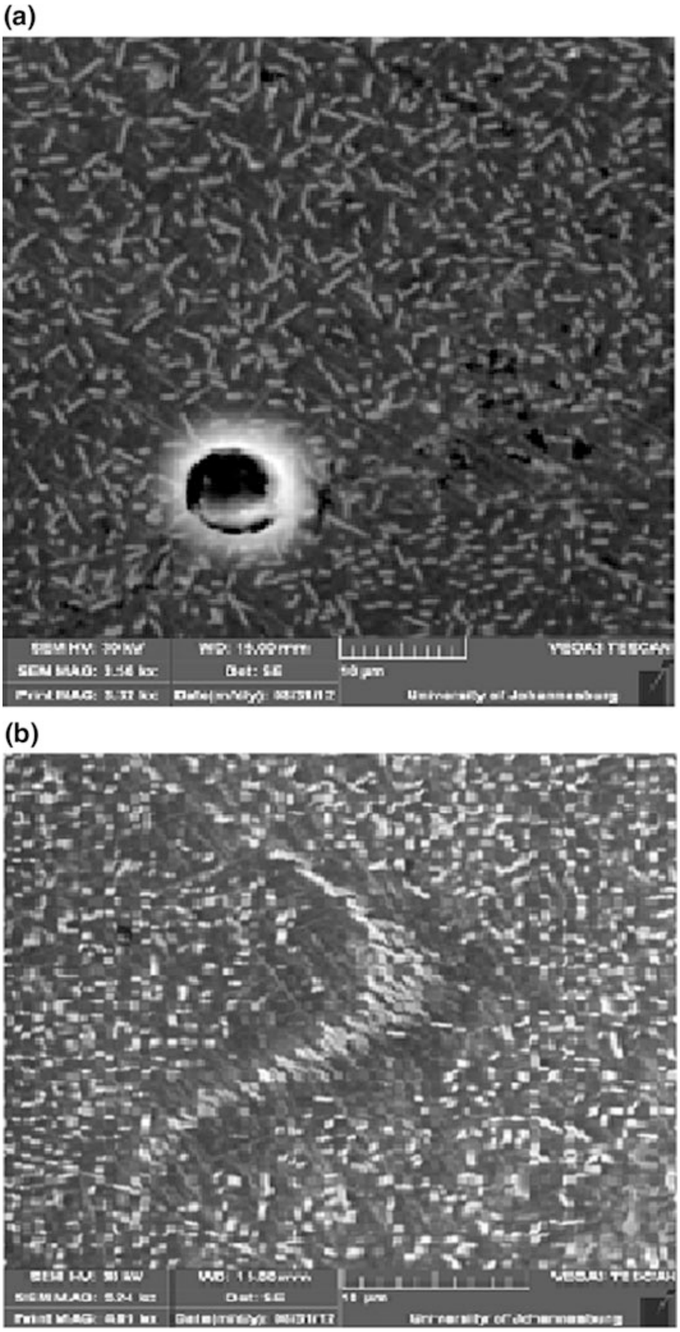

Fig. 4.19 The SEM micrograph showing secondary carbide in samples at scanning speeds of **a** 0.035 m/s, and **b** 0.065 m/s [3]

existed for the complete melting or more surface melting of the particles. The secondary carbides was also observed in the microstructures as shown in Fig. 4.19. They were formed as a result of the solid-state precipitation taking place during cooling. The secondary dendritic TiC were found to evolve from the primary dendritic TiC as shown in Fig. 4.20. which made the primary dendritic TiC to reduce both in quantity and in size, while the secondary TiC were found to be increasing as the scanning speed was increased. The reason for this microstructural evolution was given as a result of the lower laser–material interaction time at higher scanning speed which caused the solidification rate to becomes faster and favour the precipitation of these microstructures.

The microstructure observed in later metal deposited samples are usually different depending on the location in the track or layer region. The microstructure closer to the substrate for instance typically formed columnar grains because of the way heat is rapidly conducted away by the substrate. These columnar grain structures can be stretched across the deposited layers through the epitaxial growth process. The mid part usually experience slower cooling rates and promotes the

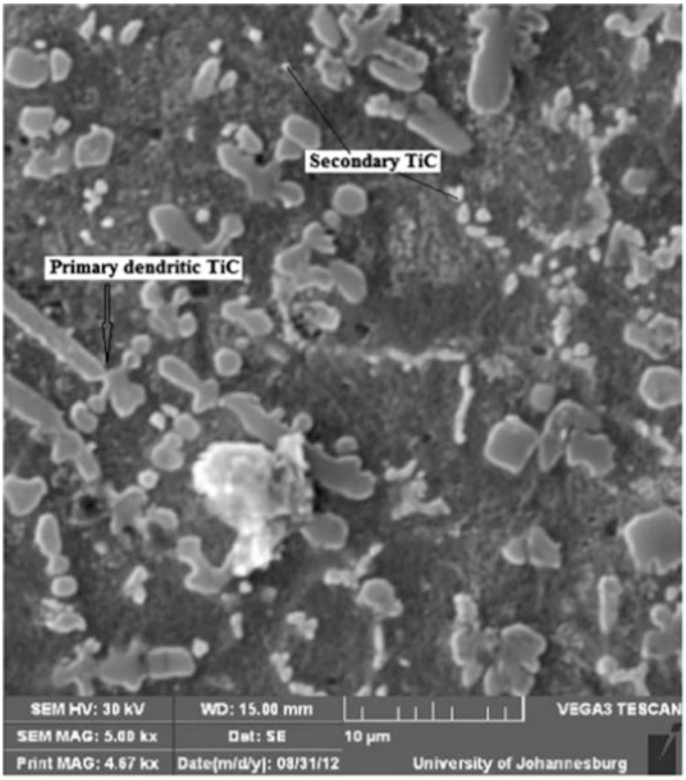

Fig. 4.20 Micrograph of sample at scanning speed of 0.055 m/s showing primary dendritic and secondary carbide [3]

formation of microstructures such as the Widmanstätten or basket woven microstructure or even the secondary dendrites.

The thermal cycles that result when depositing materials layers after layers can also trigger the formation a number of metallurgical phenomena that produce constantly changing microstructures that could eventually result in a complex forms of microstructures because of the thermal history experienced at various parts of the deposited sample. The formation of microstructure such as fine Widmanstätten alpha or basket weave or colony structures or even lamellae microstructures are usually due to the rapid cooling rates or solidification rate at higher scanning speed.

4.3.3 Effect of Scanning Speed on the Mechanical and Tribological Properties

The scanning speed has a great influence of the mechanical and tribological properties of laser metal deposited parts as a result of the influence of the processing parameters on the melting of the deposited material and the solidification rate that influence the microstructural formation. Chen et al. [21] investigated the effect of scanning speed on the microhardness, wear resistance and fracture toughness properties of laser metal deposition of titanium alloy composite coating. The scanning speed was varied between 5 and 20 mm/s. The results showed that the average microhardness was increased as the scanning speed was increased. Also, the wear resistance increased with the increase in scanning speed. The reason for these observations were attributed to the microstructural development as the scanning speed was increased. The microstructures were found to consist of a number of blocky particles and cellular dendrites which were seen as uniformly distributed reinforcements as shown in Fig. 4.21. The microstructure changed from thick to fine as the scanning speed was increased. The reinforcements were also seen to be increased in volume fraction as the scanning speed was increased. The study of the constituent of the phases showed dendrite and interdendritic phases (S2). The dendrite phase (S1) were shown to be TiNi while the interdendritic phase (S2) was found to be (Ti, Cr) $_{2Ni}$ solid solution. The high microhardness at high scanning speed was as a result of the TiNi–Ti2Ni dual-phase intermetallic alloys present in the microstructure. The higher yield strength and the higher wear resistance observed at higher scanning speed was as a result of the combination of TiNi alloy's special ductility behavior and high hardness of the Ti2Ni intermetallic alloy.

The study conducted by mahamood et al. [3] also confirms that the microhardness increased as the scanning speed was increased as shown in Fig. 4.22. The increase in microhardness as the scanning speed was increased was as a result of improper melting of the TiC powder particles. The wear resistance was however not having a linear relationship with the scanning speed as the microhardness.

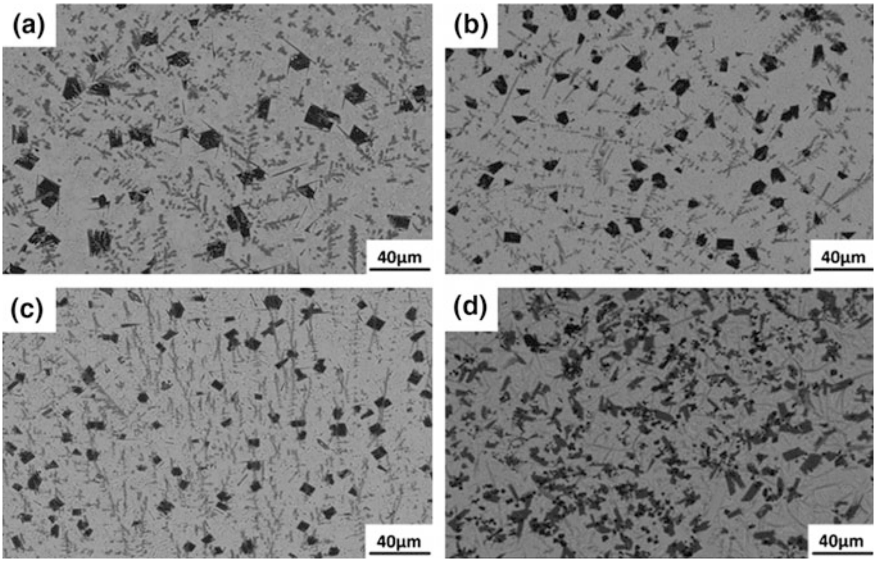

Fig. 4.21 SEM micrographs of the coatings, **a** 5 mm/s **b** 10 mm/s **c** 15 mm/s and **d** 20 mm/s [21]

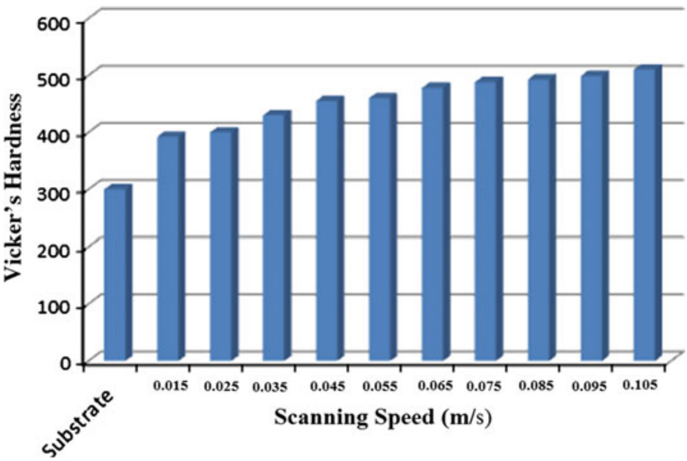

Fig. 4.22 The bar chat of the microhardness [3]

The wear resistance was found to increase initially as the scanning speed was increased and then started to decrease as the scanning speed was increase beyond 0.065 m/s. The reason for this could be explained thus: the increase in the average size of the unmelted carbide as the scanning speed was increased does not help to improve the wear resistance behaviour. During the wear process, the unmelted carbides of considerable sizes are removed and ground between the contacting

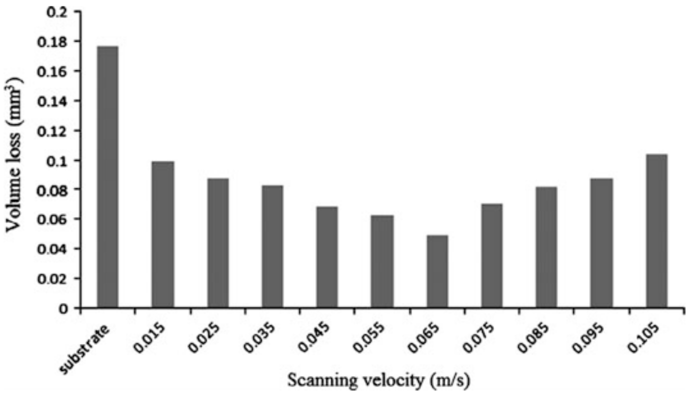

Fig. 4.23 The bar chat of wear volume against the scanning velocity [3]

surfaces. The unmelted carbide particles are reduced into fine powder as the wear action progresses and help to for a powder lubricant between these rubbing surfaces and help to inhibit the effect of wear action. On the other hand, if the size of the unmelted carbide is too large like those seen at much higher scanning speeds, it becomes difficult to grind them to form the powder lubricant that helps to improve the wear resistance property. The larger unmelted carbide particles would further aggravate the wear process because it would cut and tear off the rubbing surfaces. This cutting would further destroy the surfaces in the rubbing action which would further aggravate the wear action (Fig. 4.23).

4.4 Powder or Wire Flow Rate and Gas Flow Rate

The powder or wire flow rate is another important laser metal deposition process parameter. It represents the amount of material in grams leaving that is leaving the delivery nozzle in a unit time. A number of study in the literature showed that the material flow rate has a considerable influence on the properties of the deposited sample which include the physical, metallurgical, chemical, tribological and mechanical properties [22–24]. The material flow rate also has a great influence on the overall economy of the laser metal deposition process [17, 25]. The material flow rate needs to be effectively controlled in the laser metal deposition process as too large a material flow rate could result in improper melting of the deposited powder or even no melting at all. The available energy density determines the rate at which the material can be delivered. Too low a powder flow rate is also not very useful in the laser metal deposition process because if the available energy density is high and the powder flow rate is too low, vaporization of material could result which is not desirable in the laser metal deposition process. On the other hand, if the material flow rate is too large, the available energy density may not be sufficient to properly melt the deposited material which would result in poor material utilization and poor properties of the deposited sample. There is need for the utilization of the optimal powder flow rate in any laser metal deposition process so as to achieve the desired physical, metallurgical and mechanical properties, and with optimum material utilization efficiency. Material flow rate also has a great influence on the material distribution and density of the deposited part.

The gas flow rate is another important laser metal deposition process parameter. It is the powder carrier gas flow rate. The powder is delivered through the carrier gas which are inert gases that are used to protect the powder from the environmental attack especially reactive materials. The gas flow rate also need to be adequately adjusted depending on the project at hand although the gas flow rate does not have much effect on the resulting properties of the deposited samples but too low a gas flow rate could result in improper protection of the material being deposited if it is a highly reactive material. Also, too high a gas flow rate could be detrimental to the laser metal deposition process because it could result in the blowing away of the powder from the point where the powder will be melted (melt pool area) [19]. The gas flow rate has also been reported in the literature to have influence on the properties of the deposited part [26–28].

4.5 Laser Beam Diameter and Overlap Percentage

The laser beam diameter is also an important laser metal deposition process parameter that determines the resolution obtainable from a laser metal deposition process. Beam diameter is also known as the laser spot size and it is the size of the laser beam measured at a given focal distance. It is measured at a plane that is perpendicular to the laser beam axis and it is measured in millimeters. The laser sport size has a great influence on the energy density in the laser metal deposition process. The laser spot size is inversely proportional to the laser energy density and depicted in Eq. 4.1. A very small spot size will provide a very large laser energy density. This is similar to what can be observed by changing the size of the orifice in a water tank. By reducing the size of the orifice will cause the pressure in the water coming out of the orifice to be increased. By reducing the laser spot size, the pressure in the laser is greatly increased which is termed the energy density in the laser metal deposition process. The laser spot size also determines the layer

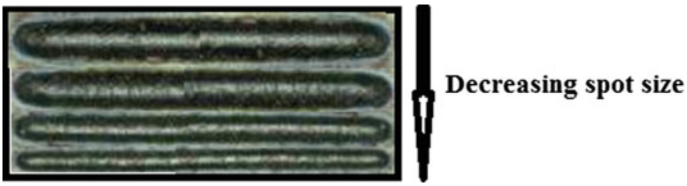

Fig. 4.24 Change in track width with increasing laser spot size

thickness that is produced during the laser metal deposition process as shown in Fig. 4.24. If very fine detail needs to be deposited, the laser spot size must be very small. The laser spot size also has a great influence part quality and the deposition efficiency in laser metal deposition process as was reported in the literature [29–31].

Overlap percentage is another important process parameter in the laser metal Deposition process. The overlap percentage is the percentage of the preceding track that is covered by the succeeding track. Overlap percentage is very important in the deification achievable in the laser metal deposition process. The proper overlap percentage need to be selected during laser metal deposition process to avoid inter-track as well as interlayer porosity. The shape of a single track deposit in the laser metal deposition process is dome in shape and a certain overlap percentage is necessary to prevent porosity between tracks which has great influence on the final density of the part produced [32].

4.6 Summary

Laser metal deposition process is an important additive manufacturing process that is useful in the production of functional part and in the repair of high valued parts that were not repairable in the past. Processing parameters play an important role in the evolving physical, metallurgical, mechanical and tribological properties of the deposited parts. The key processing parameters in the laser metal deposition process was analyzed in this chapter. The process parameters that were analyzed are the laser power, scanning speed, powder flow rate, gas flow rate, laser beam diameter and the overlap percentage. The influence of each of these processing parameters on the properties as well as the economy of the laser metal deposition process were greatly explored. It was seen in the chapter that these processing parameters needs to be optimized based on the desired properties from the deposited part.

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Chapter 5
Laser Metal Deposition of Metals and Alloys

Abstract Laser metal deposition process has evolved over the past two decades and it has provided the needed solution into a number of engineering problems. The capability of this additive manufacturing technology to produce end used parts directly from metals and alloys is one of the attractive features of this manufacturing process. Laser metal deposition process can be used to create parts without the need for expensive and time wasting tooling. This technology helped to build near net shape components simply by adding materials layer after layer using the three dimensional (3D) model data of the part to be built. Laser metal deposition process is a true green manufacturing process that is capable of reducing material and energy wastages, help to reduce component lead time, and can also help to reduce carbon footprint through product remanufacturing capability. Any complex part that is difficult or prohibitive to be fabricated using the conventional manufacturing processes can readily be made using the laser metal deposition process. In this chapter, the use of laser metal deposition process for the processing of metallic materials and alloys are discussed. The current research activities and the future research direction are also presented.

Keywords Additive manufacturing · Copper · Laser metal deposition process · Stainless steel · Titanium alloy

5.1 Introduction

Laser metal deposition (LMD) process is an important laser additive manufacturing technology that is used to fabricate three dimensional (3D) parts or object through incrementing the materials in a layer-wise manner directly from the part's 3D computer aided design (CAD) data [1]. The CAD data is used to generate motion control program which will form the laser path during the deposition process. The laser will follow the motion planned that has been generated to melt and deposit the injected powder located coaxially with the laser. This process is used to produce successive layers of the solidified melted powders which then form a solid mass

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representing the desired CAD model of the part that is being built. The laser metal deposition process have been proved to be feasible for producing parts and components from most metal and alloys with the fabricated part possessing properties that approaches or even exceeding in some cases the properties of conventionally processed materials.

The main driving force for the development of the LMD process is its importance in many applications and the limitless in the type of materials that can be processed using this technology. Also, the weight and cost saving achieved using the LMD process is another important factor in the development of this technology. That is, the building of complex part in a single manufacturing step which eliminates the need for additional production time as well as extra materials needed for joining parts if produced through the conventional manufacturing process. The possibly of producing internal cavities and over-hangs without the need to join various parts together. Also because LMD process is a tool-less process, difficult to process materials such as titanium and its alloys, the refractory materials, and high temperature alloys through the traditional manufacturing methods can readily be manufacture using this process. The ability of the laser metal deposition process to handle more than one material at the same time makes it possible to produce composite materials and functionally graded compositions, this is discussed in the next chapter. Another attractive feature if the laser metal deposition process is its ability to repair high valued parts which were used to be discarded in the past, this is also discussed in Chap. 7. Different types of metals and alloys have been processed using the laser metal deposition process as was reported in the literature [2–8]. Some of the research work using laser metal deposition process for fabricating metals and alloys are presented in this chapter. For this process to be commercially accepted and used more in industries especially in the production of critical parts in the aerospace industries, the technologies need further development through more research to solve some of the unresolved issues such as poor surface finish that makes it necessary to carry out a secondary finishing operation on some deposited parts. This and other future research need on this technology is also presented in this chapter.

5.2 Laser Metal Deposition of Metal-Alloys

Laser metal deposition process has been proven through a number of research works that fully dense parts can be produced with mechanical properties that are closed to or even superior to the properties achievable from the conventionally processed materials [9–11]. A number of industries such as aerospace and medical industries have used laser metal deposition process for the fabrication of aerospace parts and biomedical implants from materials such as commercially pure titanium, steels, titanium alloys, cobalt alloys, aluminium alloys and nickel alloys. Laser metal deposition process was reported by Hedges [12] for the fabrication of hip implants using titanium alloy grade (V). The tensile property and the fatigue behaviour of the implant were found to match those of the wrought materials. Laser metal deposition process has also been used to develop novel alloy materials which were impossible to produce using the conventional process which the thermodynamic principle has limited their manufacturability. Example of novel alloy developed using the laser metal deposition process was the burn-resistant beta Ti alloy developed by Wu et al. [13] for the fabrication of turbine blades.

Yu et al. [5] studied the recent progress on the use of laser metal deposition of titanium alloy- Ti6Al4V parts. The study showed that the yield strength and the ultimate tensile strength of the parts produced using the laser metal deposition process to be superior to those produced using casting process and annealed wrought material. The microstructures of the fabricated parts (as shown in Fig. 5.1) were seen to show prior columnar beta grains which consist of acicular martensite. In the study, a real-time monitoring and control of the laser metal deposition process was conducted in order to minimize the heat accumulation and the dilution between the substrate and the deposited material. The control of heat accumulation was as a result of the influence it has on the properties of fabricated parts, such as the microstructure and the oxygen content level. Titanium has high affinity for oxygen at high temperature. Martensite phase microstructures were observed due to the rapid cooling of the melt pool that is common to laser metal deposition process. The microstructure consists of prior beta grain structure that grows epitaxially. It changes from thin to coarser as the laser power was increase as shown in Fig. 5.1. The mechanical property: the hardness of the fabricated parts was found to be 360 ± 10 HV which is higher than the microhardness value of a forged plate. Also, the yield strength and the ultimate tensile strengths were found to be about 976 and 1099 MPa respectively, which are also superior to the cast and an annealed wrought material. Although the elongation of the laser metal deposited material was found to be lower (4.9 ± 0.1). Figure 5.2 shows an example of parts produced using the laser metal deposition process. Figure 5.2a is a turbine blade made from INCONEL718 while the inlet tube made from an aluminium alloy is shown in Fig. 5.2b.

In a similar study conducted by Xue et al. [10] the manufacturing of functional part made of Ti–6Al–4V and Inconel 625 alloys components for a space robot manipulator using laser metal deposition process. The properties of the Ti–6Al–4V parts produced was found to also exhibited yield strength, tensile strength and Young modulus of about 1062, 1157 MPa and 116 GPa, respectively, which are also higher than those of the as-cast and annealed wrought alloys. A number of research works has demonstrated that the properties of laser metal deposited metals are at least equal to or even exceeds those of the parent material as shown in Fig. 5.3. The Pictorial diagram of Laser metal deposition process is shown in Fig. 5.4.

Mazumder et al. [14] studied a more difficult alloy for laser deposition, chromium-molybdenum die steel, H13. It is a difficult alloy to deposit because of its susceptibility to cracks and high residual stress as a result of continuous heat accumulation during the deposition process and the continual martensitic transformation. H13 alloy is an important die alloy in the tooling industry. The use of

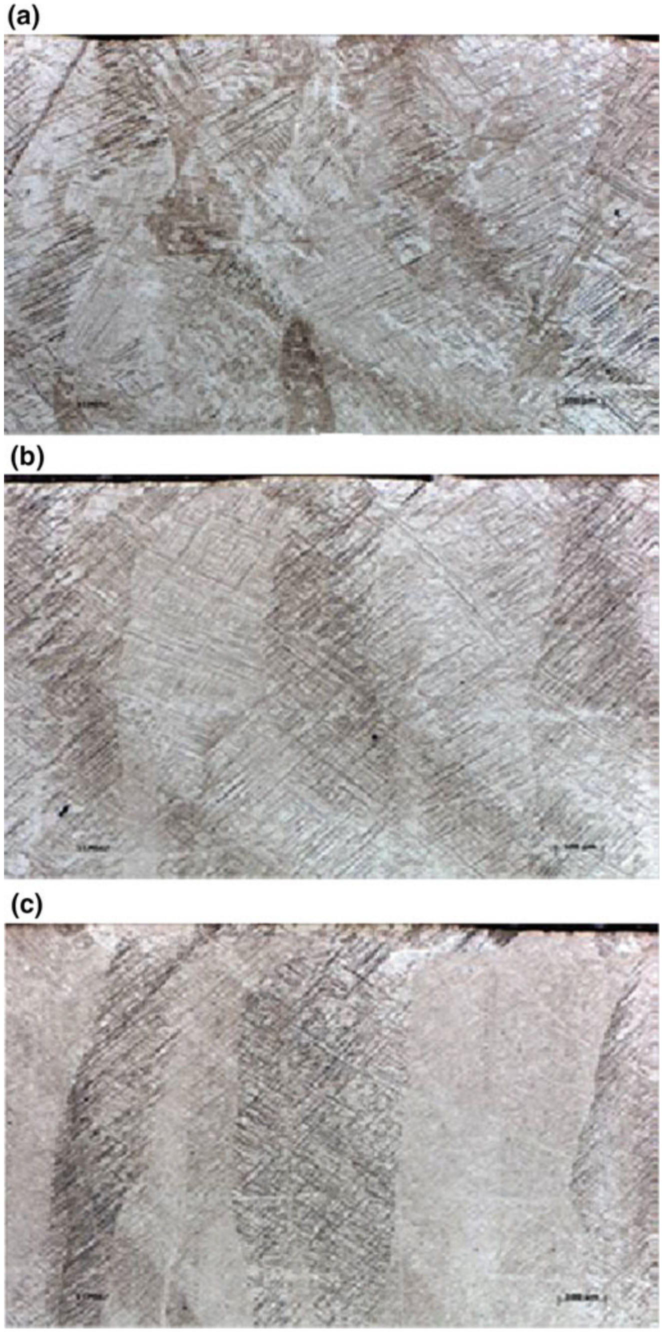

Fig. 5.1 Macrostructures of LMD Ti6Al4V specimens using different laser power; **a** 380 W **b** 470 W **c** 570 W [5]

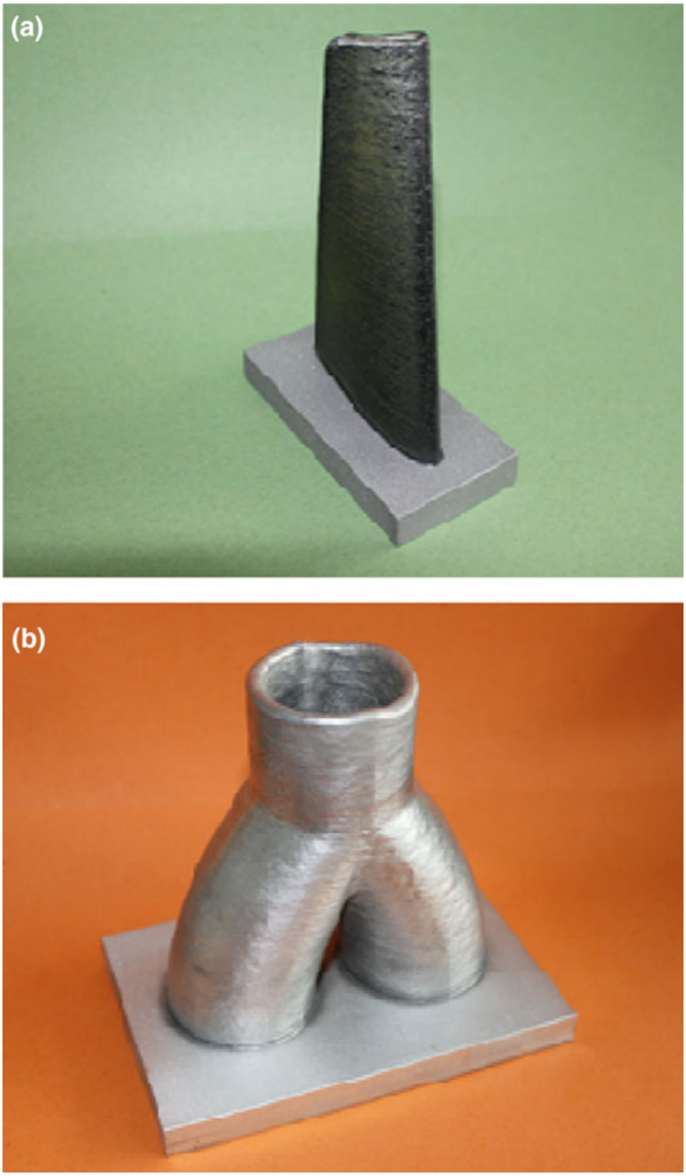

Fig. 5.2 **a** Turbine blade made from INCONEL718. **b** Inlet tube made from AlMg5 [36]

laser metal deposition process in the tooling industries cannot be over emphasized, It enables flexibilities in die design because, an existing die design can be modified by depositing materials on an existing tool without having to start from the scratch. In their study, the H13 steel was deposited on a wrought H13 and heat treatment

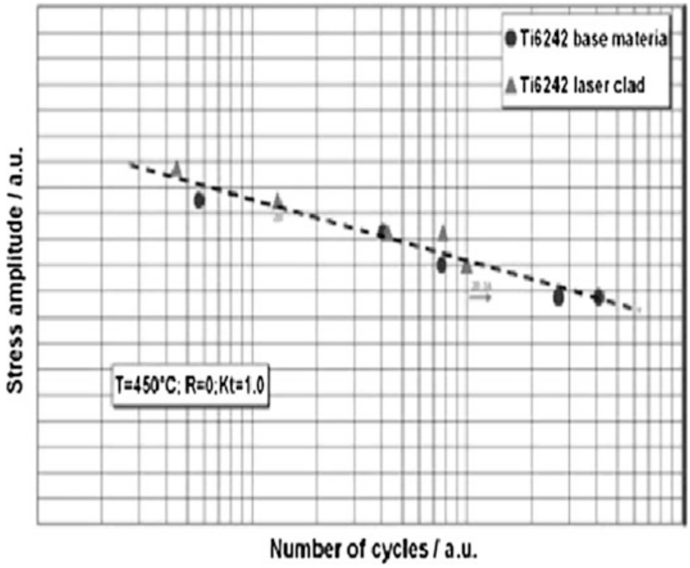

Fig. 5.3 High cycle fatigue tests result of laser deposited titanium alloy as compared to the parent material [37]

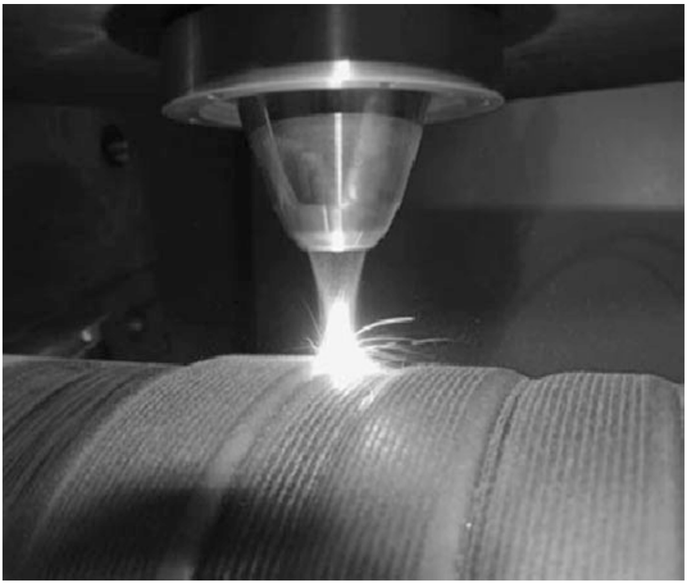

Fig. 5.4 Pictorial diagram of laser metal deposition process [37]

was performed on both the as deposited part and the wrought part (substrate). Two sets of deposited samples were produced: one at high laser power, high scanning speed and the other one at low laser power, low scanning speed which are called coarse and fine deposition respectively. Two types of heat treatments were conducted on the deposited samples and the substrate material. The first set of samples were tempered at a temperature range between 375 and 650 °C for two hours while the second sets of samples were austenitized at a temperature of 1.010 °C, then quenched in oil, and tempered for at a temperature range of between 400 and 650 °C for two hours. The results of the mechanical test carried out on the samples showed that the properties of the deposited samples matched those of the parent material or even better as shown in Fig. 5.5. The microstructure was observed to be refined at higher scanning speed as shown in Fig. 5.6. The study also showed that the residual stress can be controlled by carrying out stress relief intermittently while depositing multi-layer components. This method has been used to produce dies shown in Fig. 5.7 and was proved to have low residual stress. High residual stress is responsible for the production of cracks which can be eliminated through this method.

The thermal stability of Inconel 625 powder deposited on Inconel 625 substrate to form a three dimensional (3D) object using the laser metal deposition process was investigated by Dinda et al. [15]. The microstructure and mechanical properties

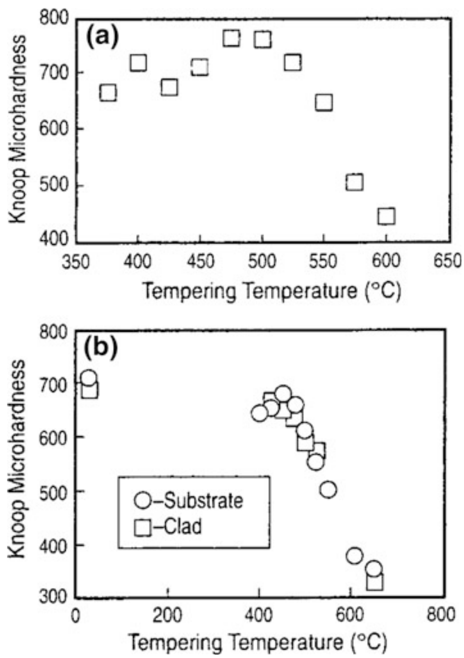

Fig. 5.5 **a** Tempering response the deposited H13 samples. **b** Tempering response of austenitized deposited H13 samples [14]

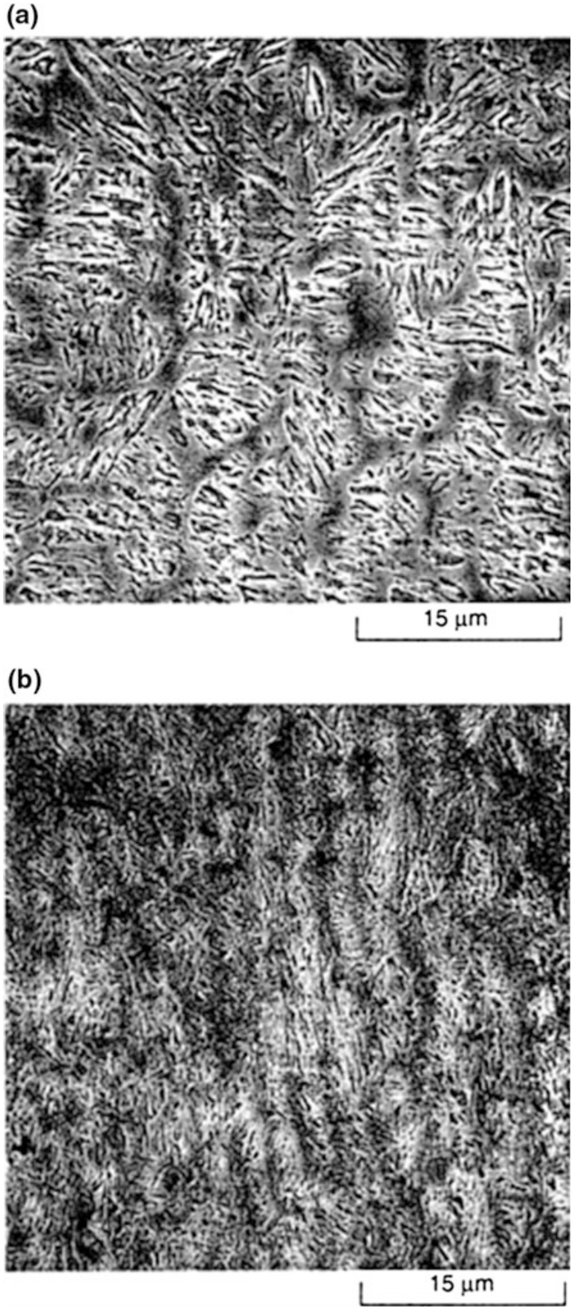

Fig. 5.6 Scan electron micrograph of laser deposited samples at **a** laser power of 3 kW and scanning speed of 152 cm/min **b** laser power of 2 kW and scanning speed of 330 cm/min [14]

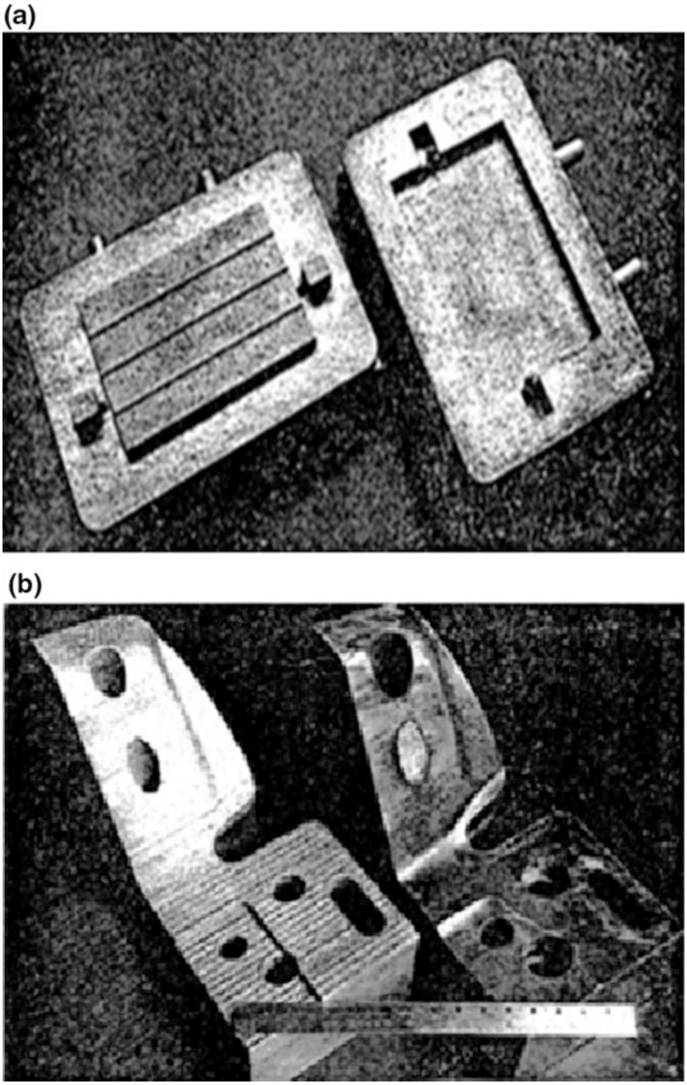

Fig. 5.7 **a** Injection molding die with embedded copper chill block and cooling channel. **b** Trimming die [14]

were studied. The microstructure was found to consist of columnar grains which are dendritic in nature and grew epitaxially from the substrate towards the surface of the deposit as shown in Fig. 5.8.

The thermal stability of the evolved microstructure was studied by annealing the as-deposited samples at temperature range between 700 and 1200 °C for one hour and then cooled down in still air under argon gas environment. The results showed

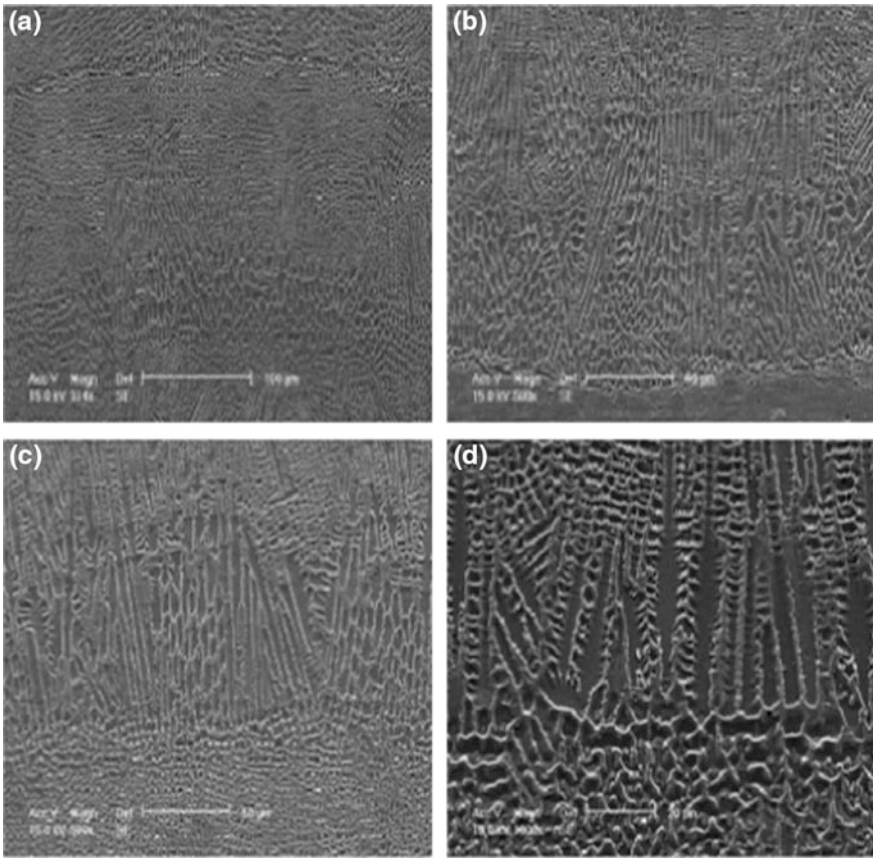

Fig. 5.8 The micrograph of a sample at different locations of the sample showing the dendritic and epitaxial growth [15]

that, as the annealing temperature increases, the microstructure changed from dendritic to a mixture of recrystallized microstructure which are more of equiaxed and dendritic microstructures. The dendritic microstructure was found to disappeared completely from the microstructure at the annealing temperature of about 1200 °C and was replaced by recrystallized and equiaxed grains structure. The microhardness was also found to decrease as the annealing temperature was increased. This is evident from the microstructural observation; the dendritic grains are hard while equiaxed are softer. The phase growth and mechanical properties of laser metal deposited 316 stringers with high aspect ratios were investigated by Sankaré [16]. Two different types of stringers were produced using the laser metal deposition process namely: high aspect ratio of 100 mm high and 25 mm breadth; and a low aspect ratio of 25 mm high and 100 mm breadth. The result of this study reveal that the sample with the higher aspect ratio showed some defects such as pores and cracks. The ultimate tensile strength and the yield stress and elongation were high. The internal pores and cracks were found to be responsible for the low modulus of elasticity. It was concluded that the fabricated stringers could be used in mechanical construction. The influence of laser power on the properties of commercially pure titanium using laser metal deposition process was investigated by Nyoni and Akinlabi [17]. The properties that were studied are the microstructure, microhardness, wear and the corrosion resistance behaviour. Increase in laser power was found to increase the wear resistance behaviour. The reason for this was attributed the increase in dilution between the deposited powder and the substrate material which helped to increase the Al and V elements in the deposit. The microstructure showed fine martensitic grains structure at lower laser power while at higher laser power, Widmanstätten alpha grains were observed. The biocompatibilities of the fabricated samples were also studied. The atomic absorption spectroscopy analyses confirmed there was no leaching happening during the test that showed that the samples are biocompatible. This is confirmed in the microstructure of the sample after the test was conducted for 14 days as shown in Fig. 5.9.

A similar study was conducted by Mahamood and Akinlabi [8]. The influence of laser power on the microstructure and the microhardness property of laser metal deposited titanium alloy. The aim of the study was to help in the development of close loop control for the laser metal deposition process that could be useful for the fabrication of new part as well as in the repair of worn-out part. The microstructure showed from fine to coarse globular primary alpha from low to high laser power. Globular grains are the grain growth that occurred at the substrate due to heat transferred to the substrate from the melt pool region to the substrate.

Globular grains are shown in Fig. 5.10a. At lower laser power, the microstructure consists mostly of martensite and less Widmastätten alpha micro Widmastätten structure (see Fig. 5.10b) while the microstructure changed to more of Widmastätten as the laser power was increased. Also, the average microhardness was found to initially increase as the laser power was increased which then decrease as the laser power was further increased beyond 2.2 kW.

Microscopic banding was also observed in the microstructure which was usually attributed to the remelting of the previous layer by the succeeding layer in multi-layer deposition but was observed in the single track experiment in this study. The layer band observed was attributed to shrinkage that could occur during the solidification process in the deposition process.

Mahamood et al. [18], in a related study, investigated the influence of the laser power and the scanning speed on the microhardness of the Laser Metal Deposited Titanium-alloy using full factorial design of experiment. The result of this study revealed that the higher the laser power causes the microhardness to be reduced. On the other hand, as the scanning speed was increased, the microhardness was increased. The full factorial design of experiment (DOE) used in this study helped to establish the statistical relationship the two processing parameters. The main effect plot of laser power on the microhardness is shown in Fig. 5.11a, and the main effect plot of the scanning speed on the microhardness is shown in Fig. 5.11b. The

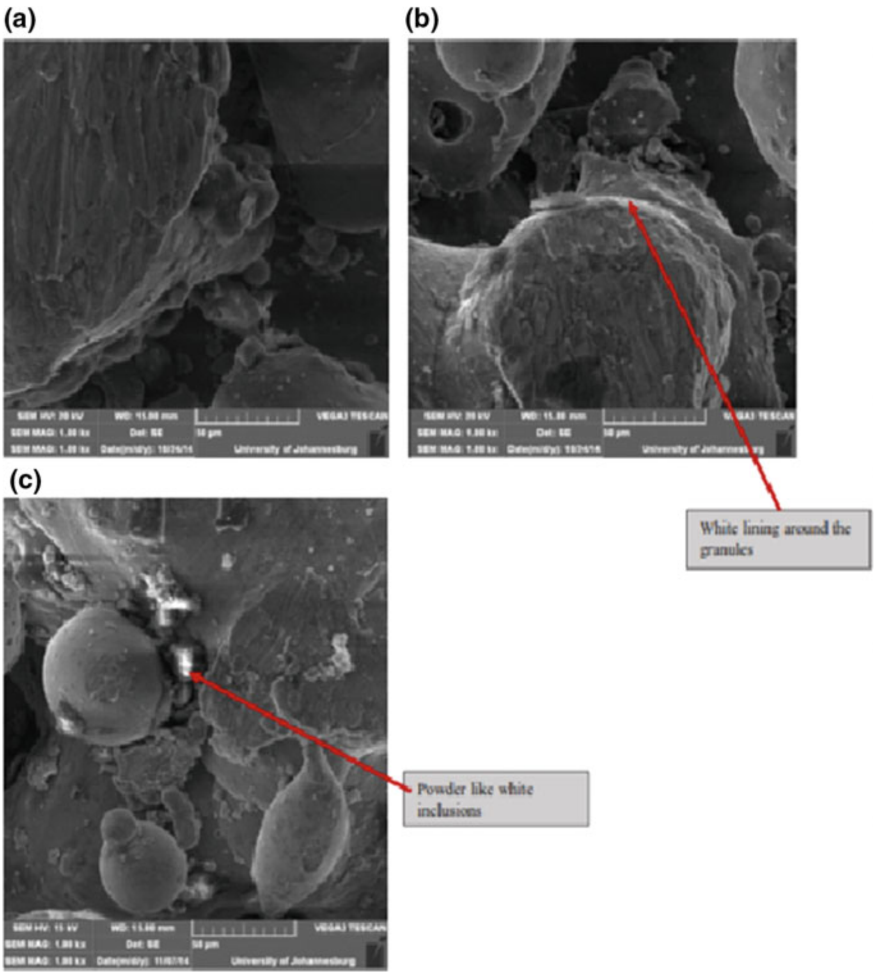

Fig. 5.9 Biocompatibility analysis of the samples deposited at 400 W Deposit at: **a** zero hours; **b** 5 h; and **c** 14 days immersion [17]

relationship between laser power, scanning speed and microhardness is represented by Eq. 5.1.

$$M = +388 - 22A + 20.5B + 10.5AB \tag{5.1}$$

Where M is the average microhardness, A is the laser power and B is the scanning speed.

The graph of predicted value against the actual experimental data is shown in Fig. 5.12a. This graph showed that the developed equation is a true representation of the relationship between the microhardness, laser power and scanning speed. The

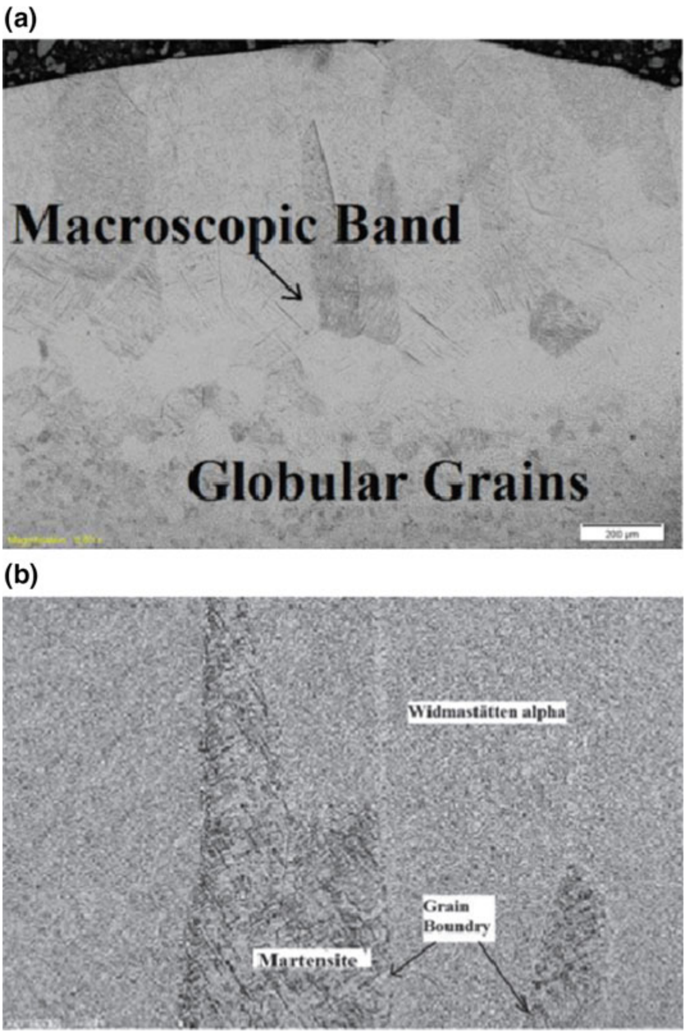

Fig. 5.10 **a** Optical micrograph of a sample produced with Nd: YAG laser power of 1.4 kW showing globular grains in the HAZ. **b** Optical micrograph of a sample produced with Nd: YAG laser power of 2.6 kW showing the martensite and Widmastätten grains [8]

interaction between the laser power and scanning speed is shown in Fig. 5.12b. There is a very strong interaction between the laser power and the scanning speed. It was concluded that the laser metal deposition process require proper control of the processing parameters in order to control the developed properties such as microhardness and the microstructure.

Kobryn et al. [19] investigated the influence of process parameters on macrostructure, microstructure, porosity, and build height of laser metal deposited

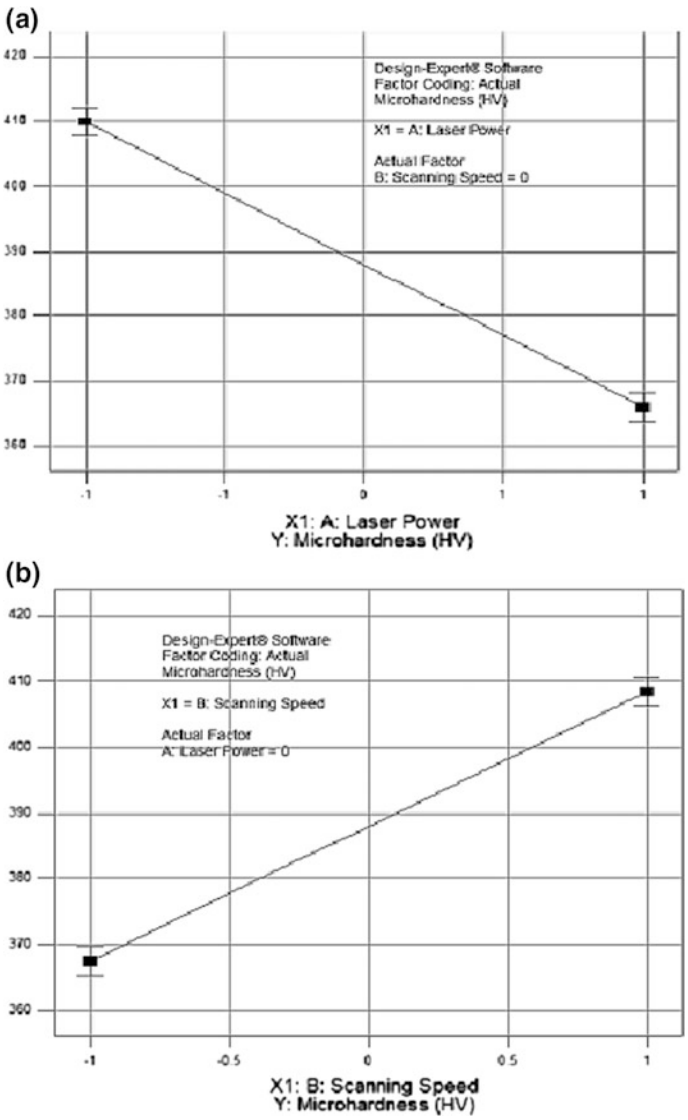

Fig. 5.11 The main effect plot of microhardness against **a** laser power, **b** scanning speed [18]

titanium alloy, Ti6Al4V. The microstructure of the laser metal deposition process is characterized by columnar grains as shown in Fig. 5.13a, b. Due to high temperature gradients that is characterized by the process and the high cooling rates. The study showed that the width of the columnar grains decreases with increasing scanning speed. Local banding was observed in the microstructure as shown in Fig. 5.13c.

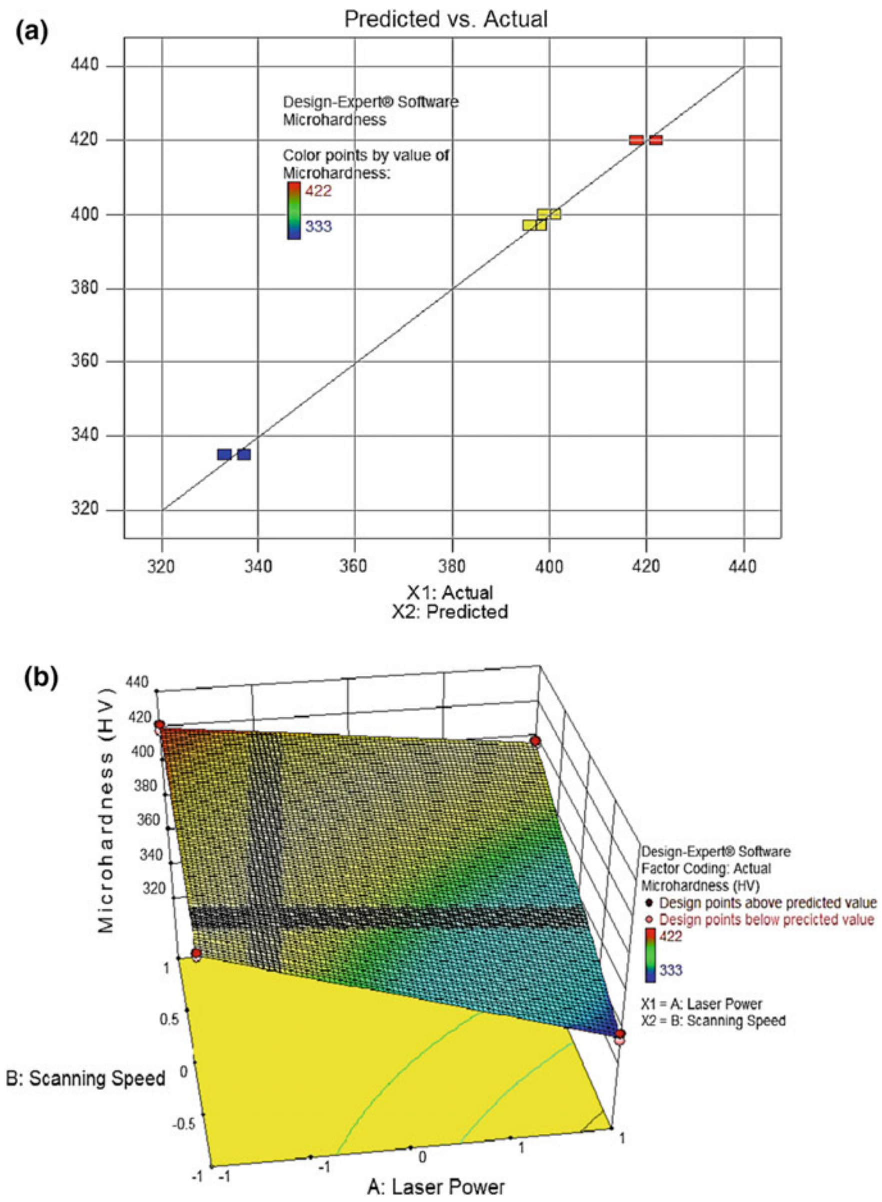

Fig. 5.12 **a** Graph of Predicted against the actual experimental data. **b** The surface plot of the microhardness against the laser power and the scanning speed [18]

The banding was attributed to local changes in the number of fine and equiaxed alpha grains in the microstructure as shown in Fig. 5.13d. This increase in the number of alpha grains was as a result of the reheating of previous layer. Also,

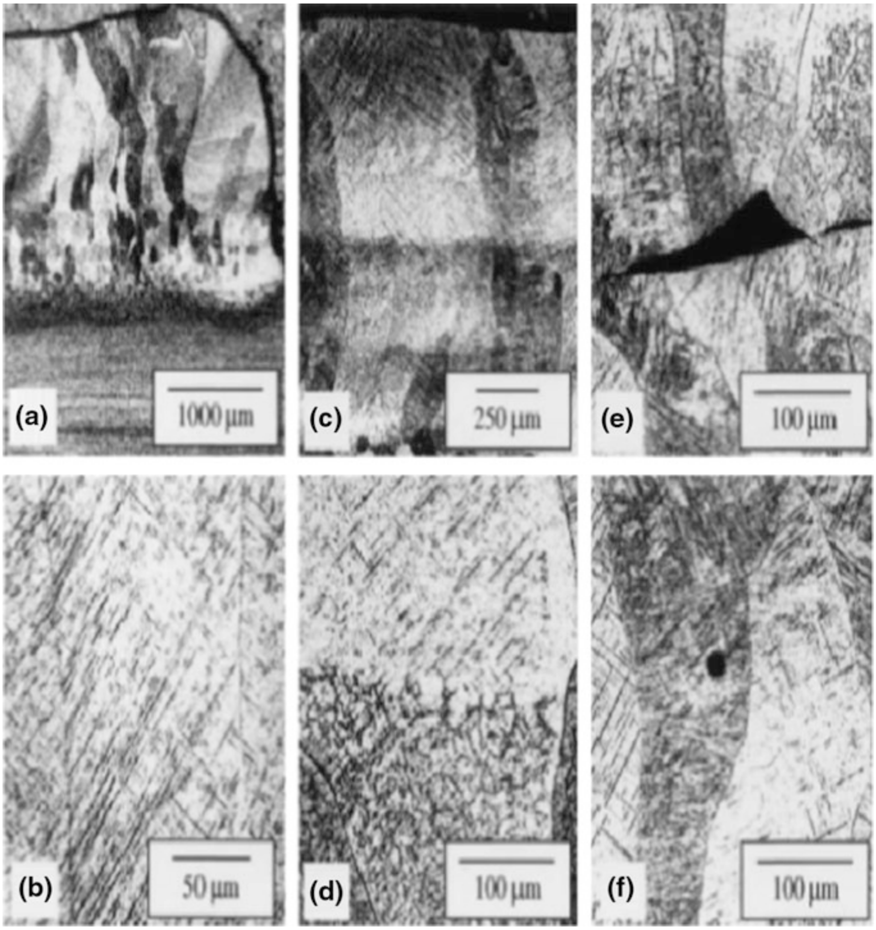

Fig. 5.13 Metallographic observations for laser-deposited Ti-6Al-4V: **a** macrostructure, **b** microstructure, **c** macrostructural banding, **d** microstructure transition across a band, **e** lack-of-fusion porosity, and **f** gas porosity [19]

increasing the laser power and scanning speed result in reduction in Lack-of-fusion and gas porosity as shown in Fig. 5.13e, f. The build height was found to decreases with increasing scanning speed.

Bagheri et al. [20] also studied the influence processing parameters- laser power, powder feed rate and scanning speed, on the microstructure, hardness and tensile strength of laser metal deposition of Ti-6Al-4V components. The results of the microstructure extermination showed that the scale of columnar grains increases with decrease in the scanning speeds with all other processing parameters maintained constant. Also, the size of the alpha and beta grains laths increases with increasing laser powers and decreasing scanning speeds. The ultimate tensile strength and yield strengths of the laser metal deposited samples were found to be more than those of the parent material. The powder flow rate and the gas flow rate influence on the properties of laser metal deposited titanium alloy. The physical properties that were studied are: the track dimension, the Microhardness and the metallurgical property. The study revealed that as the powder flow rate was increased, the track width and the track height were also increased. On the other hand, as the gas flow rate was increased, the track width and the track height decreased. The average Microhardness was found to decrease with an increase in the gas flow rate while the microhardness was found to increase as the powder flow rate is increased. A number of studies were dedicated to study the influence of heat treatment on these properties.

In a study conducted by Yao et al. [21], the influence of heat treatment on the mechanical property of laser metal deposited titanium alloy was investigated. The influence of heat treatment on the microstructure and uniaxial compressive strength under the quasi-static and dynamic loading were investigated. The microstructural investigation and the compressive test were conducted on both the as-deposited samples and the heat treated samples. The compressive test was conducted at room temperature between 10^{-3} and 3000 s^{-1}. The mechanical behaviors of the two sets of samples such as flow stress, strain hardening rate, strain rate sensitivity and fracture mechanism were investigated in that study. The fracture mechanism was also analyzed. The results showed that the microstructure of the as deposited samples of the titanium alloy- Ti6Al4V consists of the usual columnar prior beta grains that grows epitaxially from the substrate. Beta grains were also observed along the grain boundaries. The microstructures of the heat treated samples are made up of Widmanstätten lath alpha phases that are parallel to each other as shown in Fig. 5.14. The microstructure, basket-weave α laths, and the primary α phase grains became coarser and shorter as a result of heat treatment which occurs due to recrystallization. Also, there are large numbers of acicular secondary alpha phase precipitation produced in the prior beta phase during heat treatment. The heat treatment has helped to improve the yield strength and the compressive strength of the laser metal deposited samples- Ti-6Al-4V alloy. On the other hand, the plasticity property of the heat-treated samples was found to decrease when compared to the as-deposited samples. Also, there is a considerable strain softening observed in the heat-treated samples at a strain rates of 1500 and 3000 s^{-1}. The study conducted on the Microstructure observations indicated the samples at these strain rates revealed the appearance of adiabatic shear localization which could be attributed to the reason for the strain softening observed. The adiabatic shear band is also observed during the dynamic loading of the heat treated samples that is characterized by equiaxed nano grain structures that were produced during recrystallization. The deformation twins were found to occur in the heat-treated samples during the quasi-static loading experiment. The study of the fractured samples revealed that the high dislocation density that existed within the adiabatic shear band while the deformation twin was restricted in the microstructure of the heat treated samples. Also, the twining-induced rotational dynamic recrystallization could be responsible for the mechanism of crack initiation and propagation of the adiabatic

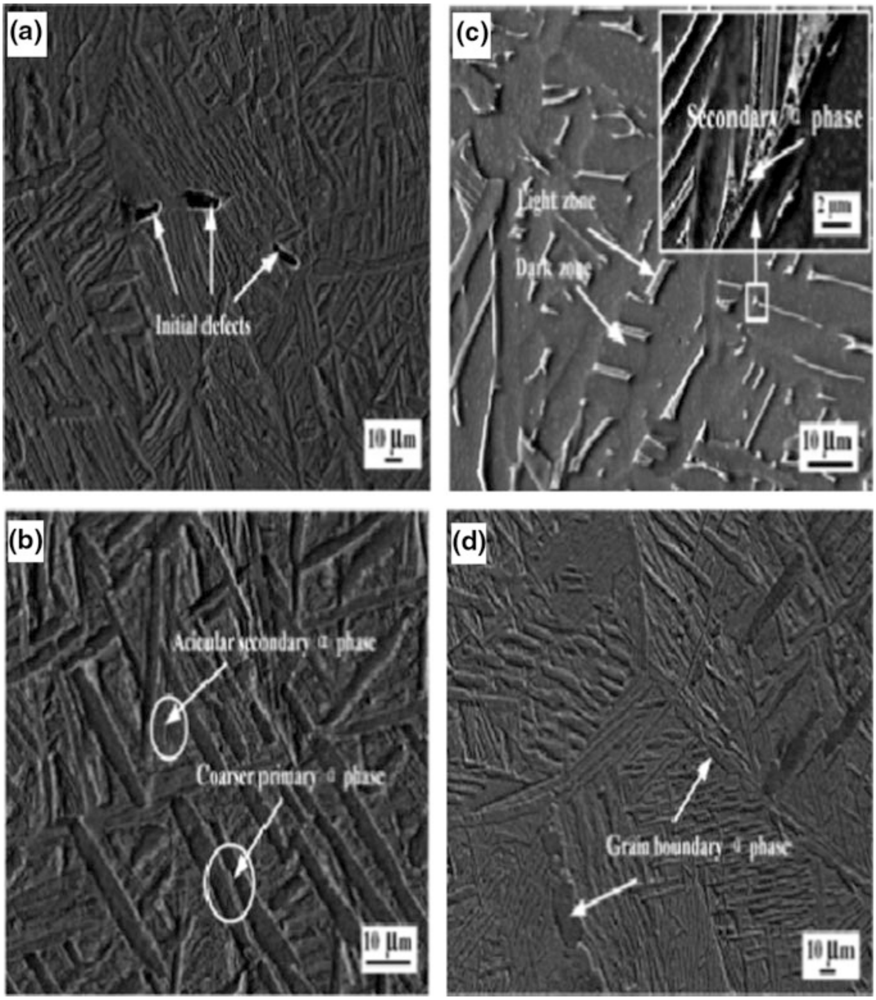

Fig. 5.14 Microstructure of the heat-treated Ti-6Al-4V alloy **a** the defects on the side surface, **b** and **c** side view by SEM (for **c** light zones are β phase, the dark zones are α phase), **d** top view by SEM [21]

shear band in the heat-treated samples during dynamic deformation. It was concluded that the improvement in the strain rate sensitivity was as a result of the fine nano size secondary alpha phase grains observed in the prior beta grains observed in the microstructure of the heat treated samples. The coarse alpha grains are responsible for the poor plasticity property of the heat-treated samples.

Also the heat treatment can help to suppress the strain rate sensitivity of the laser metal deposited Ti6Al4V alloy but it produced the higher susceptibility of adiabatic shear localization to some extent. Also, heat treatment cause larger shear band than the as-deposited samples, with parallel deformation twins in quasi-static loading condition.

Lu et al. [22] studied the influence of annealing temperature, annealing time, cooling rate, and aging treatment on properties of laser metal deposited Ti6Al4V. The formation mechanisms of the sub-critical annealed special bi-modal microstructure were also investigated. The laser metal deposited samples were sub-critically annealed at temperatures of 955, 985, 990 and 995 °C for 30 min and then cooled in air. This experiment was used to study the influence of the annealing temperature on the properties. To investigate the influence of the annealing time on the properties, the anneal times of 30, 45 and 60 min at 990 °C were used for the investigation. Also, the annealed specimens at a temperature of 990 °C for 30 min were aged at 550, 570, 600, and 700 °C for 2 h and then air cooled to study the influence of aging temperature on the properties of the laser metal deposited samples. The result of the microstructural observation showed a type of bimodal microstructure that consists of coarse crab-like primary alpha and fine lamellar transformed beta which was obtained through the sub-critical annealing process. By increasing the annealing temperature up to the beta transus temperature, the crab-like morphology of the primary alpha becomes more pronounced. The annealing treatment was found to have a high influence on the volume fraction of the primary alpha grains, its size and aspect ratio. The aging treatments also have significant influence on the volume fraction and aspect ratio of primary alpha grains and on the width and volume fraction of the secondary alpha. The aspect ratio of the coarse crab-like primary alpha decreased from about 5 to 3.5 as the aging temperature was increased from 550 to 700 °C, as shown in Fig. 5.15. The area fraction of the primary alpha grains decreased from 34 to 29% as the aging temperature was increased from 550 to 700 °C. The secondary alpha laths tend to increase in size with increasing aging temperature as shown in Fig. 5.15. The microhardness properties of the sub-critically annealed samples are higher than that of the as-deposited and annealed samples. The microhardness was found to initially increase and then decreases as the aging temperature was increased beyond the aging temperature of 600 °C.

Amanda et al. [23] studied the microstructure, the mechanical properties, fatigue behavior, and the failure mechanisms of laser metal deposited titanium alloy. Also, the effect of porosity on the fatigue behavior of laser metal deposited Ti6Al 4V was investigated. A series of fully-reversed strain-controlled fatigue tests were conducted on the laser deposited samples for both in the as-built and heat-treated conditions. The fractured surfaces of fatigue specimens were studied to understand the failure mechanism, and the influence of defects such as porosity on the fatigue behaviour. The fatigue lives of the as-built laser metal deposited samples were found to be shorter than those of wrought samples with the presence of porosity attributed to the shorter fatigue lives. Heat treated samples were found to have improved fatigue lives. The presence of different shape and sizes of pores helped to promote the more unpredictable fatigue behavior of the as-built and annealed parts as shown by the fracture mechanism presented in Fig. 5.16.

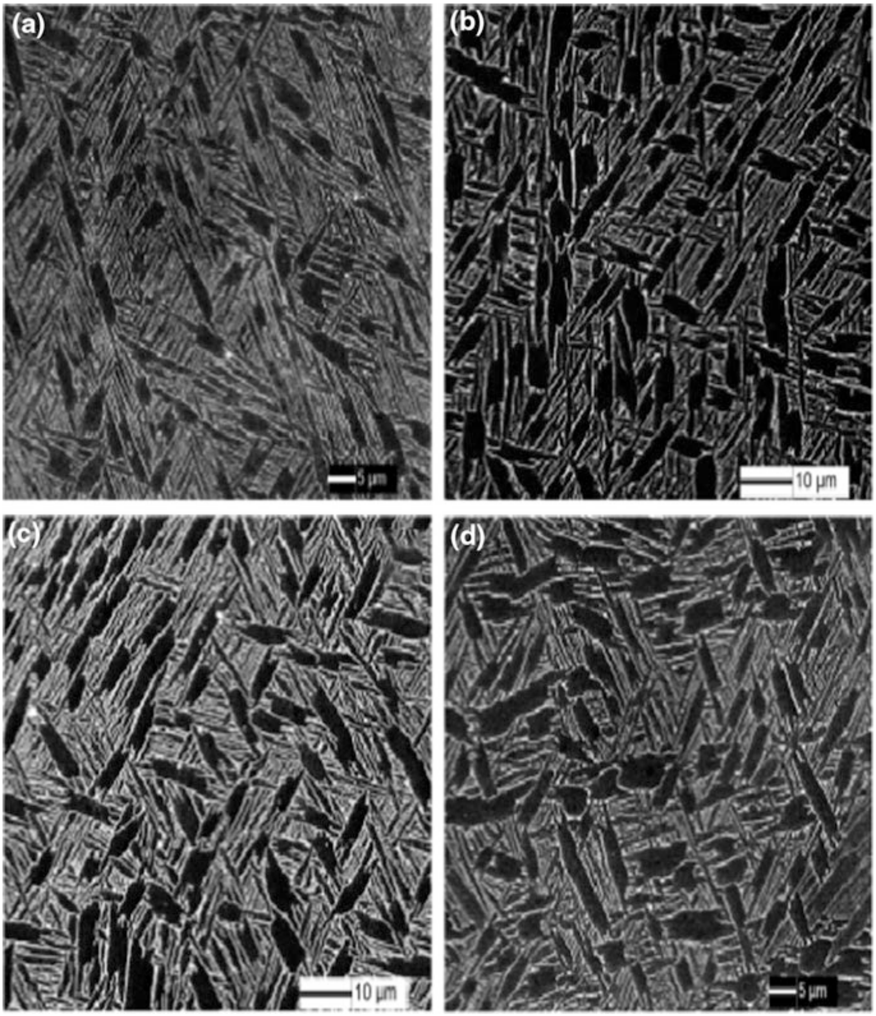

Fig. 5.15 SEM micrographs showing the typical microstructures of laser melting deposited Ti–6Al–4V after anneal treatment at 990 °C for 30 min followed by post-anneal aging at 550 °C (**a**), 570 °C (**b**), 600 °C (**c**) and 700 °C (**d**) for 2 h. [22]

Since porosity is the main contributory factor to the fatigue behavior, then the process parameters should be properly controlled to reduce or eliminate porosity. It has been proved in the literature that processing parameters have a significant influence in porosity during the laser metal deposition process [24]. The study concludes that quantity of pores, shape, size, and location will impact the fatigue behavior of as-deposited samples as well as the annealed parts. Larger, irregular shaped pores closer to the outer surface will seriously affect the fatigue life. The presence of pores makes the fatigue life less predictable during the high cycle

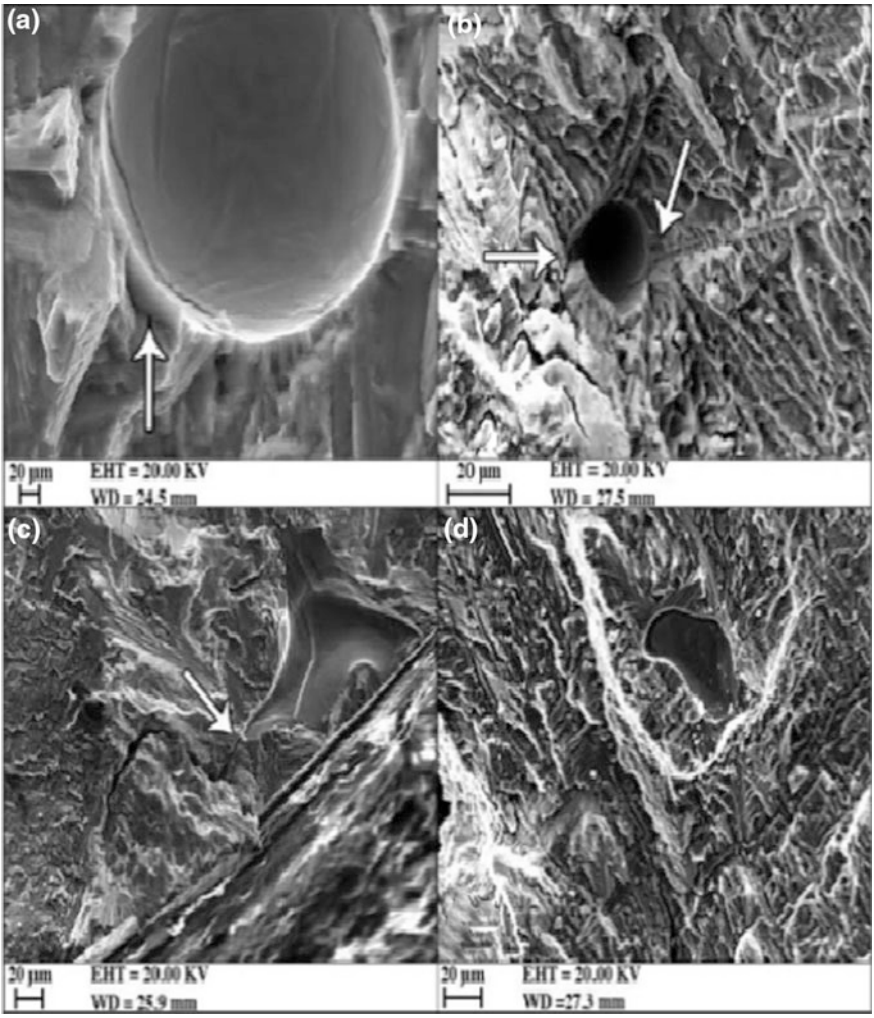

Fig. 5.16 **a** Porosity resulting from gas entrapment, as evidenced by the smooth lip protruding from the fracture surface of a fatigue specimen, **b** pore serving as a crack initiation site, **c** crack initiation and propagation off the tip of an irregularly shaped pore, and **d** two pores merged together to form a larger pore, observed on the fracture surfaces of as-built LENS Ti–6Al–4V fatigue specimens [23]

fatigue tests. Heat treatment tends to improve the fatigue lives of the laser metal deposited samples. Hence, it is important to properly optimize the processing parameters of laser metal deposition process so as to reduce or eliminate porosity which will help to improve the fatigue life. There are a number of studies on the fatigue behaviour of laser metal deposited parts and the readers can consult the following references for further reading [25–29].

The influence of processing parameters on the economy of laser metal deposition process was studied by Mahamood et al. [30]. The influence of laser power on the material utilization efficiency in laser metal deposition process. The laser power was varied to understand its effect on the layer height, layer width, material efficiency and metallurgical integrity. The result showed that increasing the laser power result in higher material utilization efficiency. A similar study was conducted by Mahamood et al. [31], the influence of scanning speed on material efficiency in laser metal deposition process of titanium alloy. The results showed that for the set of processing parameter used in that study, the optimum scanning speed for maximum material utilization efficiency is approximately 0.045 m/sec. Another study conducted on the four important processing parameters in laser metal deposition process for material utilization efficiency was carried out by Mahamood and Akinlabi [32]. The influence of processing parameters, the laser power, the scanning speed, powder flow rate and gas flow rate, on the material utilization efficiency in laser metal deposition process using full factorial design of experiment. The results showed that the optimized process parameters for optimized material utilization were found to be laser power of 3.2 kW, scanning speed of 0.06 m/s, powder flow rate of 2 g/min and gas flow rate of 3 l/min. The use of scrap such as chips or swarf as deposited material in laser metal deposition process has been explored in the literature by Mahmood et al. [33–35]. This study is an important one towards recycling of waste material in the machining industry. This is important not only for the economy of the laser metal deposition process but also for saving energy and also in saving the environment. The machining waste has been proved to be useable for the fabrication of solid three dimensional components. Mahmood et al. [33] investigated a way of reconstituting machining waste-chips/swarf, into a solid structure using laser direct metal deposition process. Laser metal deposited samples were produced from carbon steel machining chips using three different size ranges of the chips. The influences of particle sizes on the properties of the deposited samples were studied. The properties of the deposited samples were studied. The microstructure, hardness and physical properties of the deposited material were investigated for both recycle chips and original powder particles. recycle chips and original chip particles were both studied in order to compare the results. The results revealed that it is possible to reproduce three dimensional components with full density, fine microstructure and no significant contamination using irregular size and shape of particles. The result showed that as the particle size increases, the deposition tracks height decreased while the width increased. Increase in particle size results in decrease in hardness for both original and recycled chips. The hardness was higher with the recycled chips than with the original particles. The results of the microstructure extermination are shown in Fig. 5.17. The microstructure of the sample produced with smallest original chips (sampleO1) is shown in Fig. 5.17a. The microstructure consists of tempered martensite grains structure with dispersed cementite particles in the matrix of ferrite. The microstructure of the smallest recycled sample R1 was similar to what was observed in the original chips shown in Fig. 5.17a but with smaller grain size as shown in Fig. 5.17b. The microstructure of the larger original chips (O2) is shown in

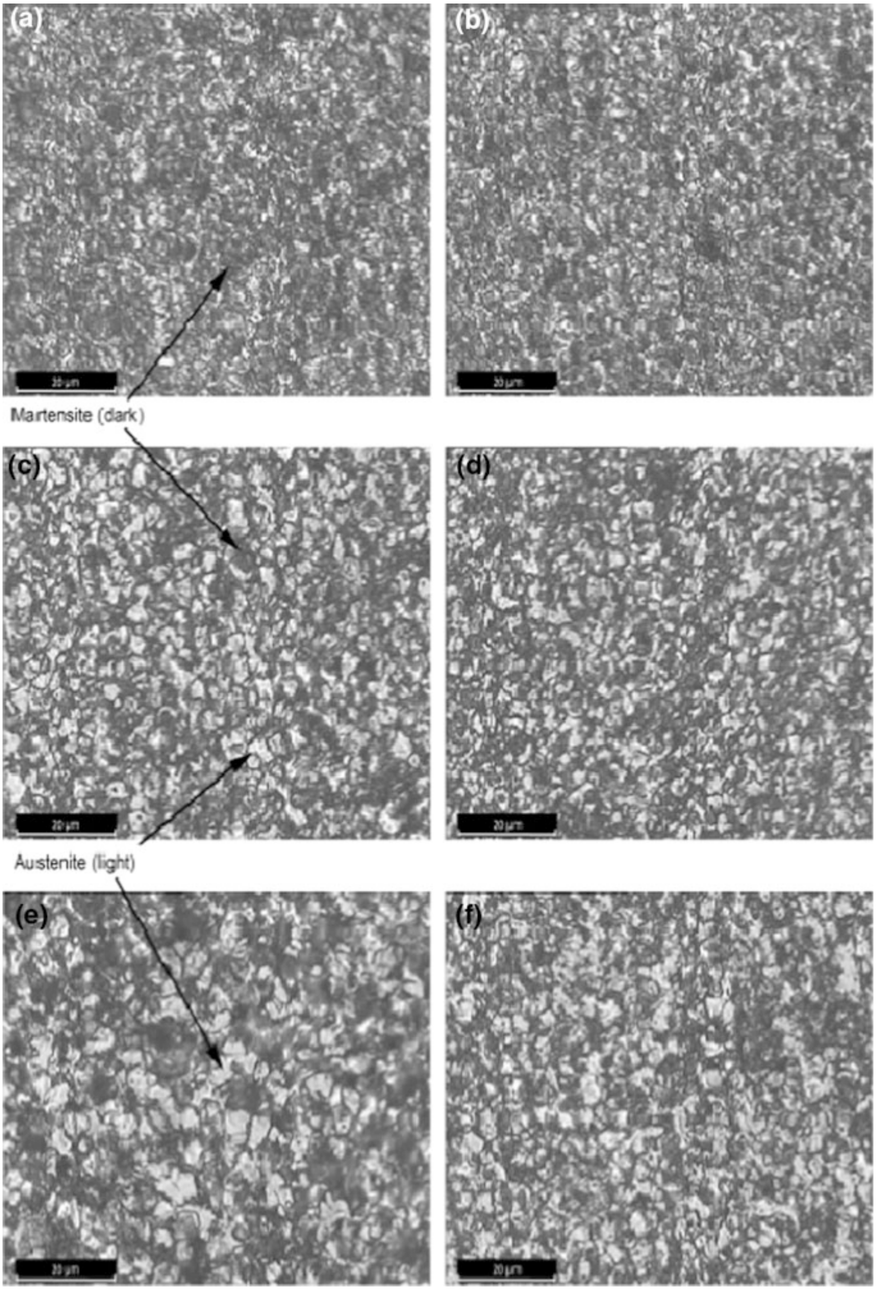

Fig. 5.17 Microstructure of clad samples: **a** O1, **b** R1, **c** O2, **d** R2, **e** O3 and **f** R3 [33]

Fig. 5.17c. The microstructure consists of tempered martensitic grains structure. The microstructure of recycle chips (R2) is shown in Fig. 5.17d with a smaller grain size and martensite grains structure. The whitish phase shown in Fig. 5.17d is the retained austenite.

The microstructure of the largest original chips (O3) is shown in Fig. 5.17e. austenite concentration is more pronounced in the microstructure. Figure 5.17f shows the microstructure of the largest recycle chips. The grain sizes are found to increase with increase in chip sizes. This study shows that the machining waste can be effectively used as deposition material in laser deposition and this could also help as an important recycling method.

5.3 Summary

Laser metal deposition process is an important additive manufacturing process for the fabrication of three dimensional parts as well as for repair of high valued components. The flexibility of laser metal deposition process with its ability to handle more than one material simultaneously makes the process also suitable for the fabrication of composite and functionally graded materials. Laser metal deposition for metals and alloys are presented in this chapter. A number of research works has been carried out in this field and some of these works are presented in this chapter. Laser metal deposition of composites and functionally graded materials are the focus of the next chapter.

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Chapter 6
Laser Metal Deposition of Composites and Functionally Graded Materials

Abstract This chapter deals with the fabrication of composites materials consisting of metals and ceramic or metal-metal composite materials. The flexibilities offered by the laser metal deposition process allow the use of more than one material at the same time during the deposition process. This important process makes it possible to fabricate parts with two dissimilar materials which could be difficult to produce with any other manufacturing process. Functionally graded materials can also be produced with laser metal deposition process. A number of composite materials and functionally graded materials produced using the laser metal deposition process has been investigated and reported in the literature. Laser metal deposition process are also used to produce composite coatings and functionally graded material coatings on other material in order to improve the surface property of such base materials. Some of these studies are presented in this chapter. The properties of these laser deposited composite materials and functionally graded materials are also presented.

Keywords Additive manufacturing · Functionally graded materials · Laser metal deposition process · Microhardness · Wear

6.1 Introduction

The revolution of the advent of additive manufacturing technology comes with a very high impact when it comes to fabrication of one of its kind products and products with special designed properties. Laser metal deposition process, an additive manufacturing technology, is a flexible manufacturing process that is capable of fabricating three dimensional (3D) objects directly from the 3D computer aided design (CAD) model of the object by adding materials layer after layer. Multiple materials can also be used simultaneously with this additive manufacturing process to fabricate parts with composite materials or functionally graded materials in a single manufacturing process. This means that, part that is designed to have specific properties can be produced using laser metal deposition process and in one manufacturing run. This is different from what is achievable using the conventional

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manufacturing process, which could involve that the desired material with the required properties be first produced, and then the desired part is then made from the bulk material in a series of manufacturing processes. The laser metal deposition process is still fairly new, and the physics of the process needs to be understood in order that the properties of the part (made of composite materials or functionally graded materials) produced can be understood as well. In order to understand the process, a number of research work has been conducted and reported in the literature on laser metal deposition of various composite materials as well as functionally graded materials. Some of the earlier studies are for the establishment of the capability of using the laser metal deposition process for the fabrication of composites and functionally graded materials [1, 2]. Processing parameters play an important role in the resulting properties of the laser metal deposited composite materials and a number of investigations are also dedicated to these studies [3]. In this chapter, research works on the use of laser metal deposition process of composite materials such as titanium alloy composite, TiC/Inconel 718 composite, and TiC/H13 tool steel composite are presented. Some of the composite materials produced using the laser metal deposition process are in the form of surface coating for improving surface properties of the base material especially for wear resistance or corrosion resistance. Some of this and other studies are also presented in this chapter.

6.2 Laser Metal Deposition of Composite Materials

The flexibility provided by the laser metal deposition process makes it possible to fabricate 3D parts that are made with composite materials in a single manufacturing process. Part requiring special surface properties such as composite coating can also be produced using the laser metal deposition process and also in one manufacturing run. The use of laser metal deposition process for the production of 3D composite material and fabrication of composite coating are presented in this section. The use of laser metal deposition process has helped in the production of composite materials that could not be produced through other manufacturing process which could be restricted with the thermodynamic phenomena. For example, when composite material is produced using the powder metallurgy process, the sintering temperature is usually carefully selected such that the material with the lowest melting temperature in the constitute materials will be partially melted. This would be used to bind the composite material together. If the sintering temperature is made too high, segregation will occur. The material with the lowest melting point will be fully melted and the liquid will be separated from the solid with the one with higher density settling down at the bottom of the mold. There is no such limitation in the laser metal deposition process. This is made possible because all the constituent materials are brought together and melted in small quantity simultaneously making it possible to fully melt all the constituent materials if so desired without having to worry about segregation of or thermodynamic limitations. The rapid solidification of the process also make it possible to produce some non-equilibrium phases which could not be achieved if other manufacturing processes are used. The rapid solidification of the process also favour in situ composite formation [4–7]. This unique properties of the laser metal deposition process has made it possible to produce composite with novel composite materials which were not possible to be produced in the past. A number of research work has been done to demonstrate this capabilities of this novel manufacturing process for the production of composite materials. As a relatively new manufacturing process, a number of research work are directed towards the quantification of the process and establishment of the relationship between the process parameters and the evolving properties of the composite produced. Some of these research work are presented in this section.

Earlier research works are used to demonstration of the capability of the laser metal deposition process for the fabrication of composite materials [8]. The composite material of Ti6Al4V and TiC were produced using the laser metal deposition process. The composite produced were made to contain various volume fractions of TiC in the matrix of the titanium alloy-Ti6Al4V using Ti6Al4V wire and TiC powder. The schematic diagram of the Laser metal deposition process is shown in Fig. 6.1.

The produced composite material were characterized in terms of the microstructure, the wear resistance and the tensile properties were measured with their Young's moduli. The study was aimed to investigate the possibility of using the laser metal

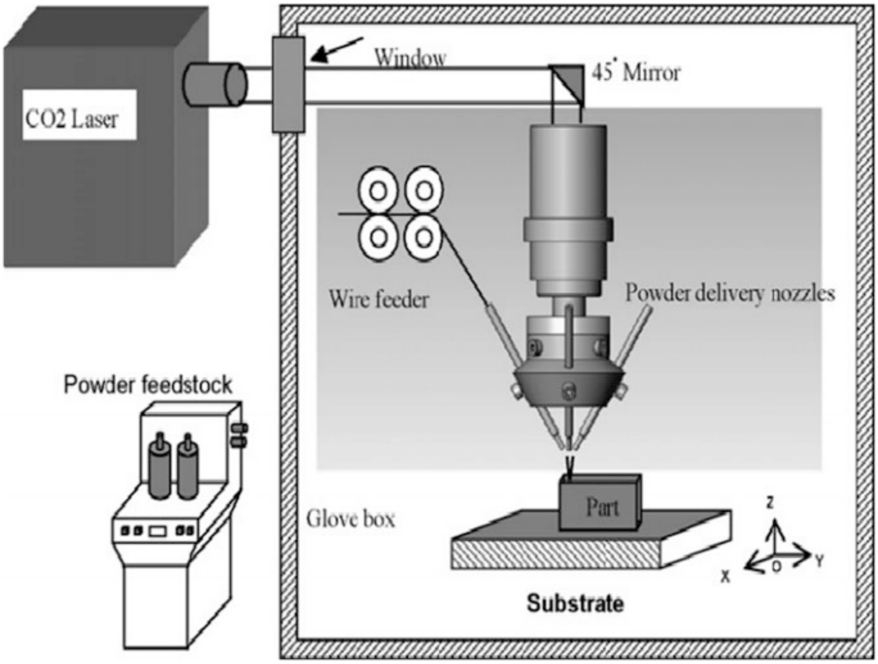

Fig. 6.1 Schematic diagram of laser metal deposition process with simultaneous powder and wire feed [8]

deposition process for the fabrication of composites materials from both powder and wire stock material composite samples with various compositional ratios were produced at optimum processing parameters which were earlier established using various fixed compositions along their length. The variation in the compositional ratio of the composite was used to assess the success of the laser metal deposition process through studying of the mechanical and tribological properties of the different composites. The results showed that the laser metal deposition process can be used to fabricate composite materials. The microstructural extermination of the substrate material- Ti6Al4V which was used to compare the composite materials was seen to be made up fine laths of beta grains in the matrix of coarse alpha laths with different orientations and with a basket weave microstructure. This type of microstructure is common with any laser metal deposited Ti6Al4V [9–11]. The microstructure of the deposited composite materials showed the varying volume fraction of the TiC in the matrix of the Ti6Al4V as shown in Fig. 6.2.

The volume fraction of the eutectic TiC increases with the deposition height as seen in Fig. 6.2a–c. Some secondary carbides that are produced through solid-state precipitation during the solidification process are also seen in Fig. 6.2d. The

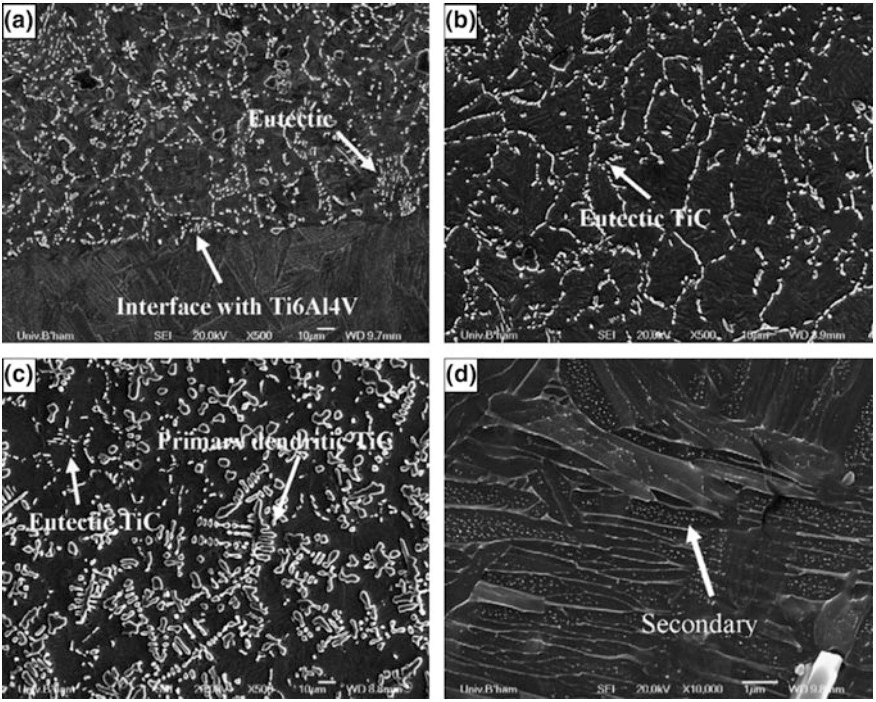

Fig. 6.2 Scanning secondary electron micrographs taken from a sample of TiC reinforced compositionally graded Ti6Al4V. **a** The interface between the composites and the Ti6Al4V. **b** TiC feed rate of 0.14 g/min. **c** TiC feed rate of 0.44 g/min. **d** High magnification microstructure showing fine secondary TiC taken from the region where the feed rate of TiC was 0.44 g/min [8]

mechanical property of the laser metal deposited Ti6Al4V/TiC composite were found to be improved and greater than those of the parent material of Ti6Al4V. The tribological property of the composite material were also found to be improved. A similar study conducted by Pouzet et al. [12] where titanium composite with various volume fractions of TiB and TiC were deposited using laser metal deposition process. The composite produced does not only contain only the elemental constituents materials but it also contain phases produced in situ during the laser metal deposition process. The microstructures of the various composites produced are shown in Fig. 6.3. The mechanical properties of the composites are improved when compared to the parent material-Ti6Al4V. Processing parameters has also

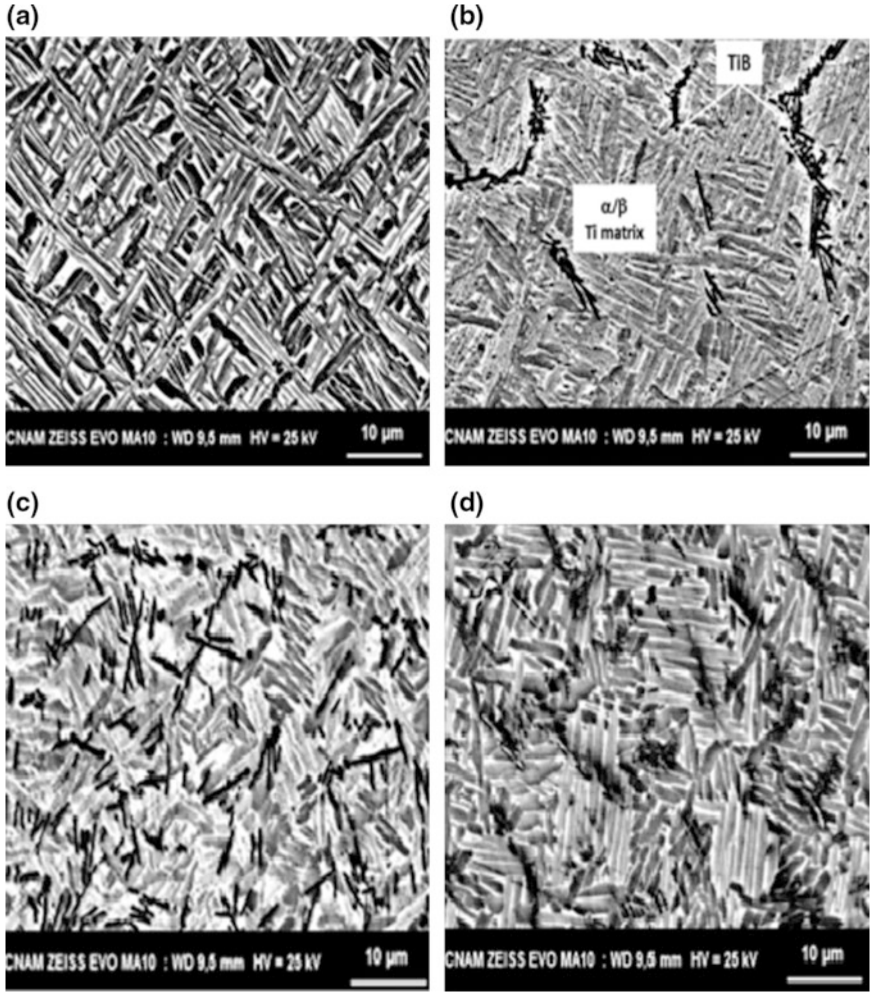

Fig. 6.3 SEM microstructures of Ti-6Al-4V composites for **a** Ti-6Al-4V **b** 0.5% B_4C, **c** 1.5% B_4C, **d** 3% B_4C [12]

been found to have great influence on the properties produced using the laser metal deposition process. Mahamood et al. [13] studied the influence of processing parameters on wear resistance behaviour of Ti6Al4V/TiC composite using the laser metal deposition process. The effect of laser power and powder flow rate on the wear resistance property of the Ti6Al4V/TiC composite was investigated. The laser power was varied between 1.5 and 3.0kW while the powder flow rate was varied between 2 and 4 g/min while the scanning speed and the gas flow rate were kept constant. The study showed that the wear resistance of the composite increased when the laser power was increased. The powder flow rate has a reverse influence on the wear resistance property of the composite.

The decrease in powder flow rate was found to increased the wear resistance properties. The microstructure of the composite consists of unmelted carbide (UMC), re-solidified carbide and dendritic TiC as shown in Fig. 6.4. The presence of these three grin structures are responsible for the improved wear resistance properties observed in the composites. The ratio of these structures were found to change with change in the processing parameters which is responsible for the varying wear resistance properties observed at varying processing parameters. Crack behaviour of composites of tungsten carbide using laser metal deposition process was studied by Wang et al. [14]. The study of crack behaviour of composite materials is an important one because it helps to understand the performance and failure behaviour of the composite materials.

The effect of processing parameters on the properties of titanium alloy composite produced using laser metal deposition process was investigated by Zheng et [15]. The composites were prepared using powder of Ti6Al4V and a varying volume fractions of Nickel nanocoated TiC particles. The study reveal the presence of intermetallic compound phases and resolidified TiC particles in the microstructure which were attributed to the thermal load accumulation during the deposition process. The processing parameters were found to play an important role on the evolving microstructure and the developed mechanical properties of the composites. The photograph of the deposited samples with varying weight percent of the TiC/Ni composites are shown in Fig. 6.5. The microstructure of the sample with 10% TiC/Ni composite is shown in Fig. 6.6a and that of the sample with 20% TiC/Ni is shown in Fig. 6.6b. Re-solidified carbide particles and un melted carbide particles are seen in the microstructure. The higher magnification micrograph of the sample is shown in Fig. 6.7. The intermetallic of Ti-Ni is seen in the microstructure stronger interface bonding between the TiC particles and matrix are observed and the strength of the composite is higher when compared to those of the monolithic parent material. The high strength was attributed to the presence of Ti-Ni intermetallic phases as well as the reinforcing power of the TiC in the deposited composites. Also, the Ti-Ni intermetallic compound formed in the composite as well as grain size refinement of the Ti6Al4V occurring during the deposition process.

A similar study was conducted by Xu et al. [16] where WC particulate reinforced Ni3Al intermetallic matrix composite coating produced using laser metal deposition

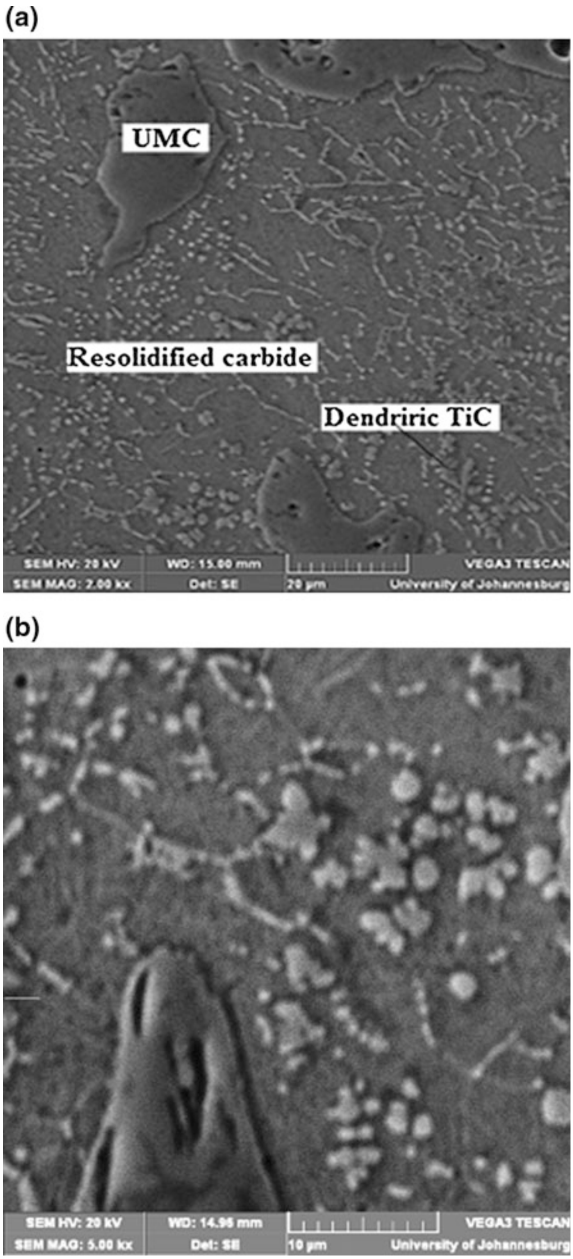

Fig. 6.4 The SEM micrograph of sample at high laser power and low powder flow rate **a** at low magnification **b** at higher magnification [13]

process with powder of Ni/Al composite and blended with WC powder. The composite coating produced was found to be of an excellent metallurgical quality and good interfacial bonding with the substrate (see Fig. 6.8).

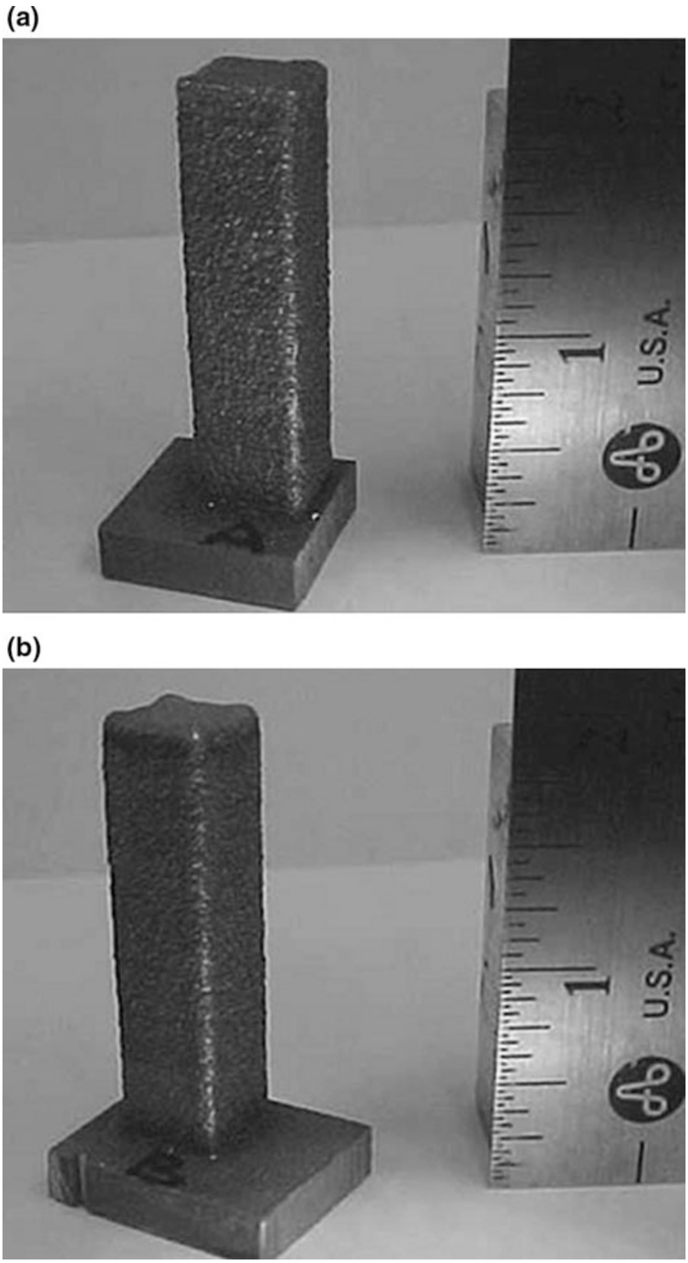

Fig. 6.5 Photos of laser-deposited Ti6Al4V+ TiC/Ni cubic samples with LENS **a** Ti6Al4V+ 10 wt pct TiC/Ni and **b** Ti6Al4V+ 20 wt pct TiC/Ni [15]

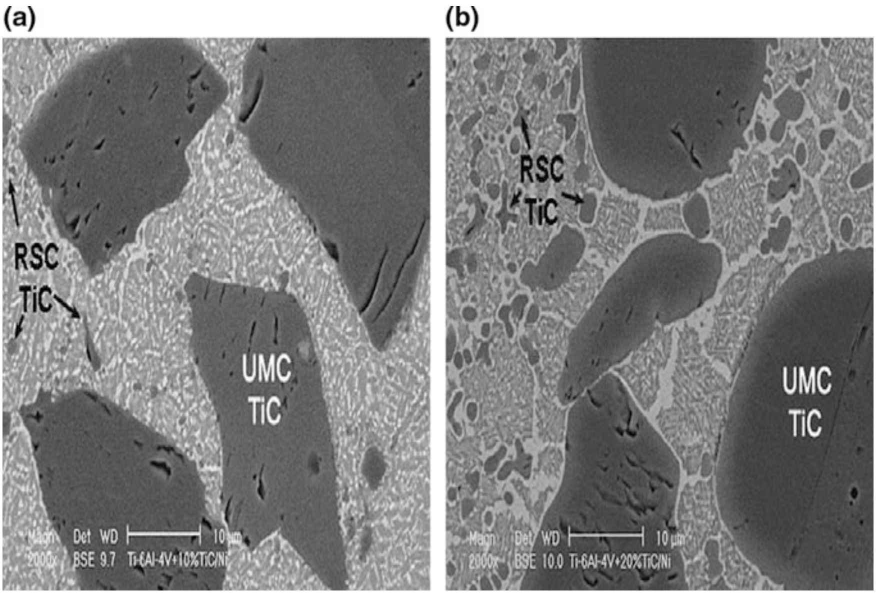

Fig. 6.6 SEM (BSE) micrographs of the LENS-deposited Ti6Al4V+ TiC/Ni MMCs **a** Ti6Al4V+ 10 wt pct TiC/Ni and **b** Ti6Al4V+ 20 wt pct TiC/Ni [15]

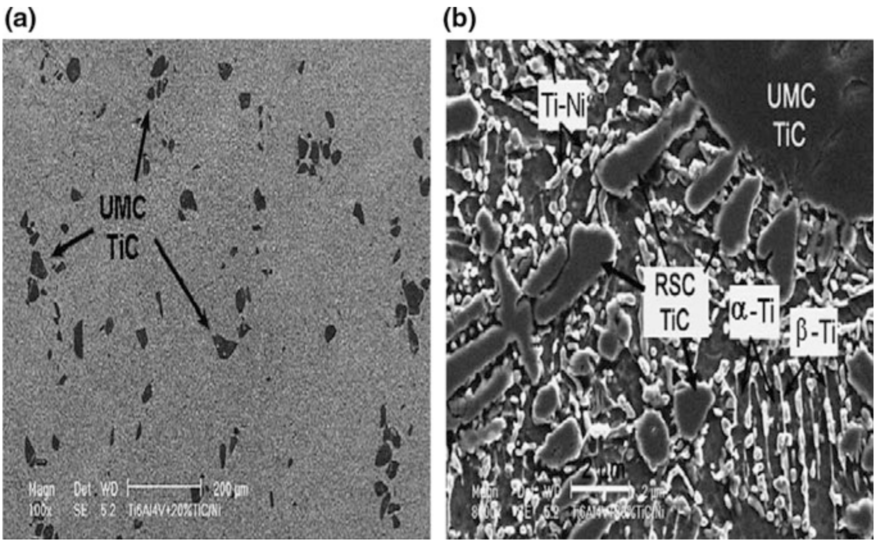

Fig. 6.7 SEM micrographs of etched LENS-deposited Ti6Al4V+ 20 wt pct TiC/Ni MMCs **a** Lower magnification micrograph. **b** Higher magnification micrograph [15]

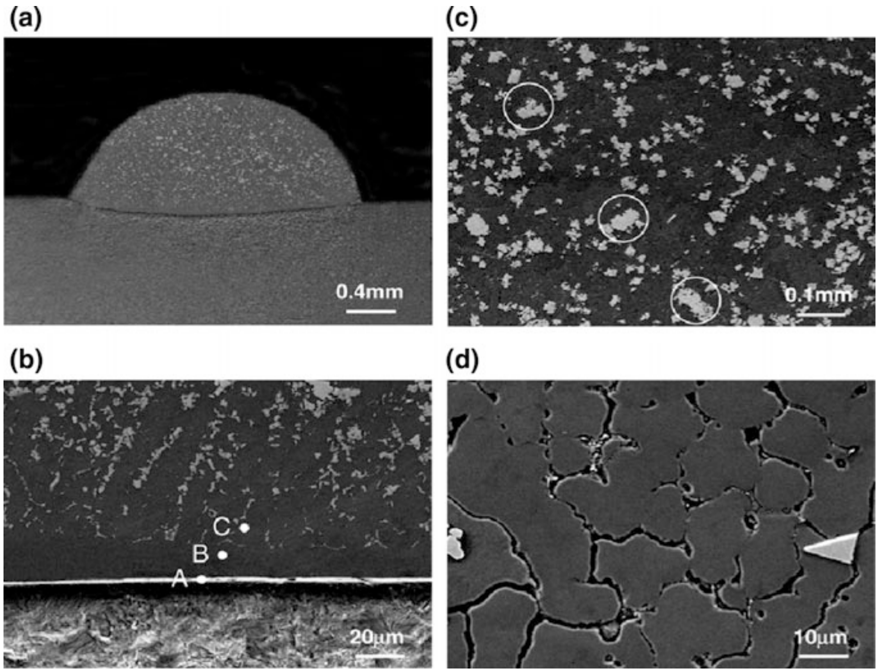

Fig. 6.8 SEM micrographs of morphology and microstructure of the composite coating fabricated by laser powder deposition: **a** The entire cross sectional morphology, **b** Interface between the coating and the substrate and the adjacent microstructure, **c** whole microstructure, and **d** the matrix microstructure [16]

The microstructure of the composite coating is made up of γ grain structure. Also, Ni Al Fe W intermetallic are formed in the microstructure and WC are dispersed showing different morphologies as shown in Fig. 6.9.

The result of the average microhardness of the composite coating is much higher than those of the Ni3Al alloys without WC particulate reinforcement. The dilution between the substrate and the deposited powder causes iron, Fe, to be transferred into the coating from the substrate, thereby helps to improve the ductility of the composite and it also facilitate bonding of the deposit with the substrate. The iron content was found to decrease with an increasing distance from the substrate while Nickel and Aluminium content were found to increase with increase in distance from the interface. This is desirable because it helped to reduce stress concentration between the interface and the deposit, thereby preventing residual thermal stress that causes cracks. Other researcher works that investigated the laser metal deposition process for the production of composite coatings include [17–24]. Hong et al. [17] investigated the influence of laser power on the microstructure, microhardness and wear resistance properties of TiC/Inconel 718 composite coatings using laser

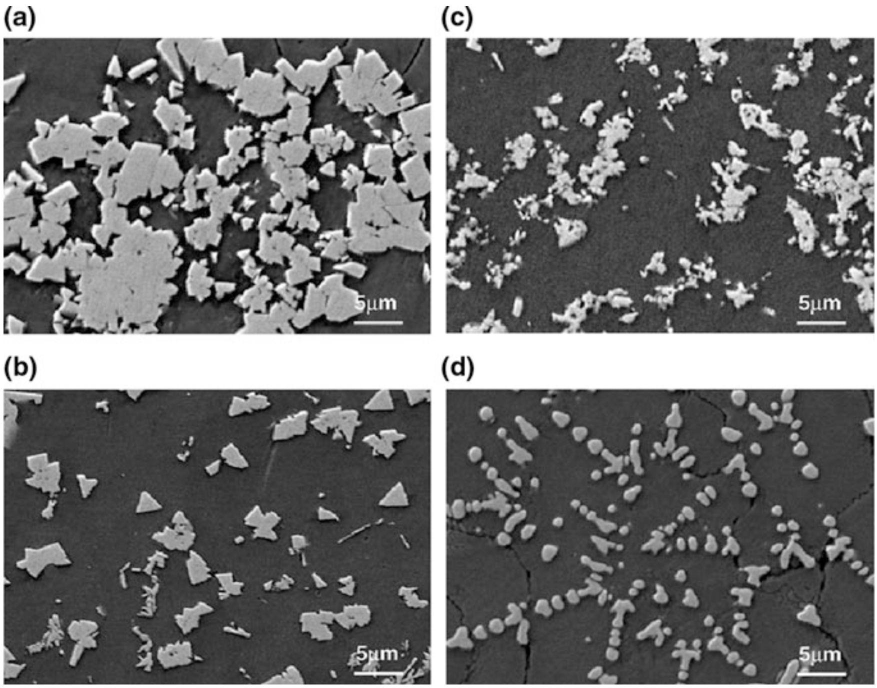

Fig. 6.9 SEM micrographs of WC particulate morphologies in the composite coating fabricated by laser powder deposition: **a** Separated incompletely and undissolved WC particulates, **b** separated completely and undissolved WC particulates, **c** separated completely and dissolved partially WC particulates, and **d** dissolved completely and precipitated [16]

metal deposition process. Ma et al. [18] studied the formation process of titanium/nickel composite coating using the laser metal deposition process. The laser metal deposition of functionally graded materials are discussed in the next section.

6.3 Laser Metal Deposition of Functionally Graded Composite Materials

Laser metal deposition process has also been proven to have the capability of producing functionally graded materials. The process can be used to make part that is made up of functionally graded materials directly from the 3D CAD model of the part and in one manufacturing run. Some of the earlier research work were conducted to demonstrate the capability of producing functionally graded materials using the laser metal deposition process. Liu and DuPont [25] were able to fabricate crack-free functionally graded material of TiC/Ti composite using the laser metal deposition process- laser engineered net shaping (LENS). The functionally graded material was produced by changing compositions from 100 vol% Ti and 0 vol% TiC to approximately 5% Ti and 95 vol% TiC. The composite was produced by simultaneously delivering each of the materials from different powder feeders. The study revealed that the laser metal deposition process can be used to produce functionally graded materials. The micrograph of the functionally graded material shown in Fig. 6.10. It can be seen in the micrograph that the microstructure is continuous and without sharp interface.

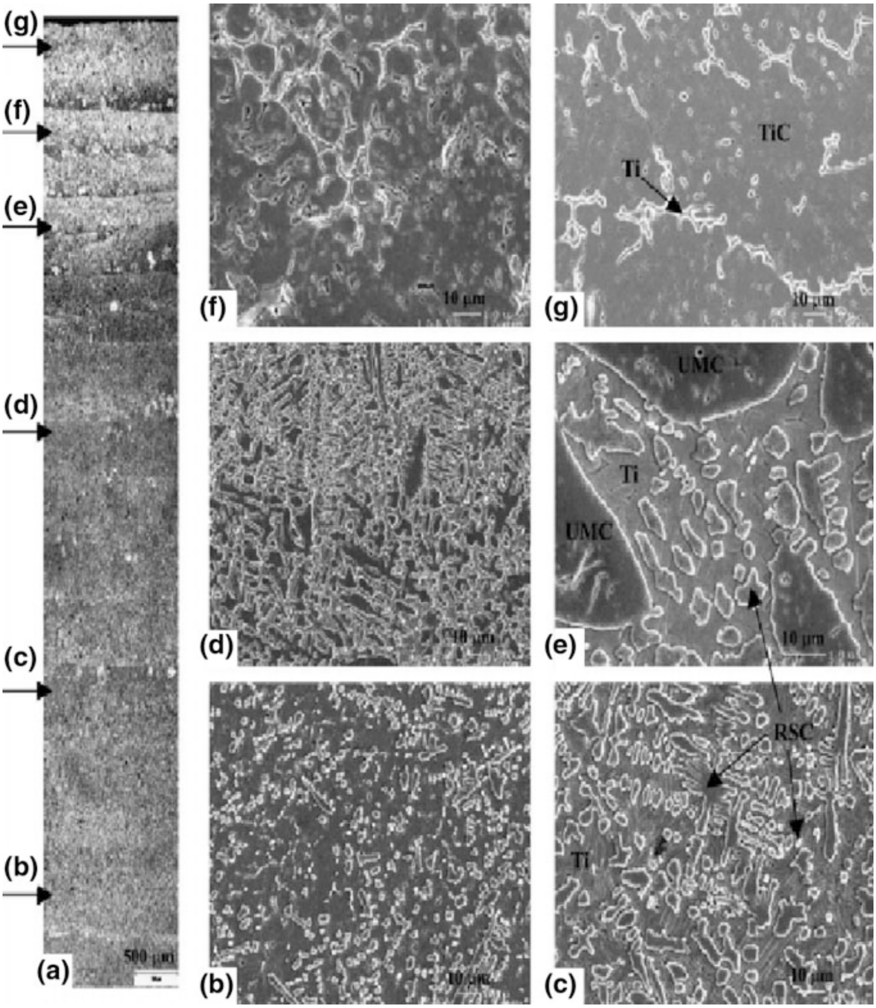

Fig. 6.10 Microstructures of the FGM deposit: **a** LOM photomicrograph of the deposit; **b**–**g** SEM photomicrographs with increasing TiC contents in different locations (UMC and RSC denote unmelted and re-solidified TiC carbide respectively) [25]

The crack free achieved in the deposited functionally graded material was attributed to the reduction in the thermal stresses that is made possible through the plastic deformation in the ductile substrate material, the thermal stress can be significantly reduced while improving the ductility through the gradual variation of the constituent materials of the FGM making the crack formation to be prevented. The microhardness was found to increase from 200 Vickers hardness number (VHN) on the Ti side to about 2300 VHN on the TiC layer. The hardness was found to increase gradually which is one of the advantage of FGM which unlike in the traditional composite material, the hardness value will spike from the lowest to the highest value resulting in higher stress concentration and hence cracking. The study concluded that through the delivering of the constituent materials through separate hoppers and by properly controlling the powder flow rate as well as the processing parameters, LENS, a laser metal deposition process can be used for the fabrication of functionally graded materials without any crack.

Wang et al. [26] in a related study fabricated functionally graded Ti6Al4V/TiC composite using the laser metal deposition process. A combination of powder and wire of TiC and Ti6Al4V respectively were used in this study. The wire and the powder materials were delivered into the melt-pool simultaneously by varying the powder flow rate and the wire feed rates. The results show a varying composition of the TiC in the matrix of the Ti6Al4V. Unmelted TiC were seen in the regions with higher TiC ratio while there was complete melting of the TiC powder in the regions with lower TiC content where primary TiC, eutectic TiC and secondary TiC are seen in the microstructure as shown in Fig. 6.11. The tribological properties of the FGM produced were found to be improved due to the presence of the varying compositions of the TiC powder that serves as reinforcement in the composite. The optimum TiC content that give the optimum tribological behaviour was found to be about 24 vol% of TiC.

Figure 6.11a shows the microstructure of the layer at 100% Ti6Al4V consisting of coarse alpha laths at various orientations with a small fraction of very beta laths seen at the interface and forming a basket weave microstructure. Figure 6.11b shows the interface between the 100% Ti6Al4V and 5% TiC which is seen to be continuous with the TiC evenly distributed. The transition is basically smooth. The gradual increase in the TiC content is also seen in the micrographs in Fig. 6.11c–i.

A similar study was also conducted by Wilson and Shin, [27] where functionally graded titanium carbide and Inconel 690 was fabricated using the laser metal deposition process. The FGM was produced by varying the volume percentage of TiC from 0 to 49%. The influence of the TiC concentration on the evolving microstructure and properties of the functionally graded material was thoroughly investigated. The result revealed an evolution in the microstructure with the TiC content of over 30% gave rise to a refined microstructure of finely dispersed crystalline phase and with smaller grain sizes as shown in Fig. 6.12a, b. The evolution of dendritic TiC was also observed as shown in Fig. 6.12c, d. The grain sizes and dendritic arm spacing were found to decrease as the TiC content was increased. The grains changed from columnar grains to equiaxed grains as the TiC content was increased. The microhardness and wear resistance behaviour of the

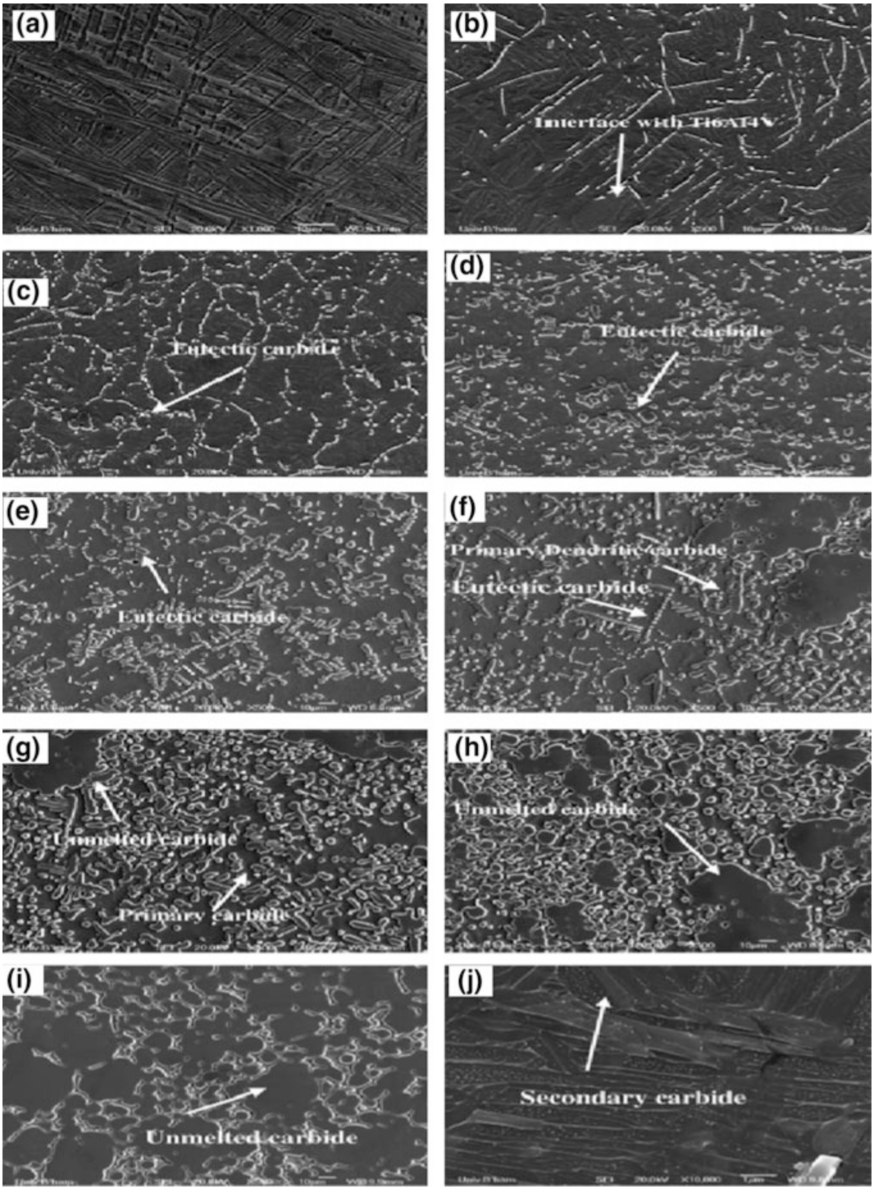

Fig. 6.11 Microstructure of compositionally graded Ti6Al4V–TiC showing various sections in the FGM [26]

FGM increased as the TiC content was increased. The Hardness value was found to increase to about 145% of the base material-Inconel 690, as the TiC content was increased. The wear volume also shown an improvement of about 42% when the TiC content was increased to 40 vol%

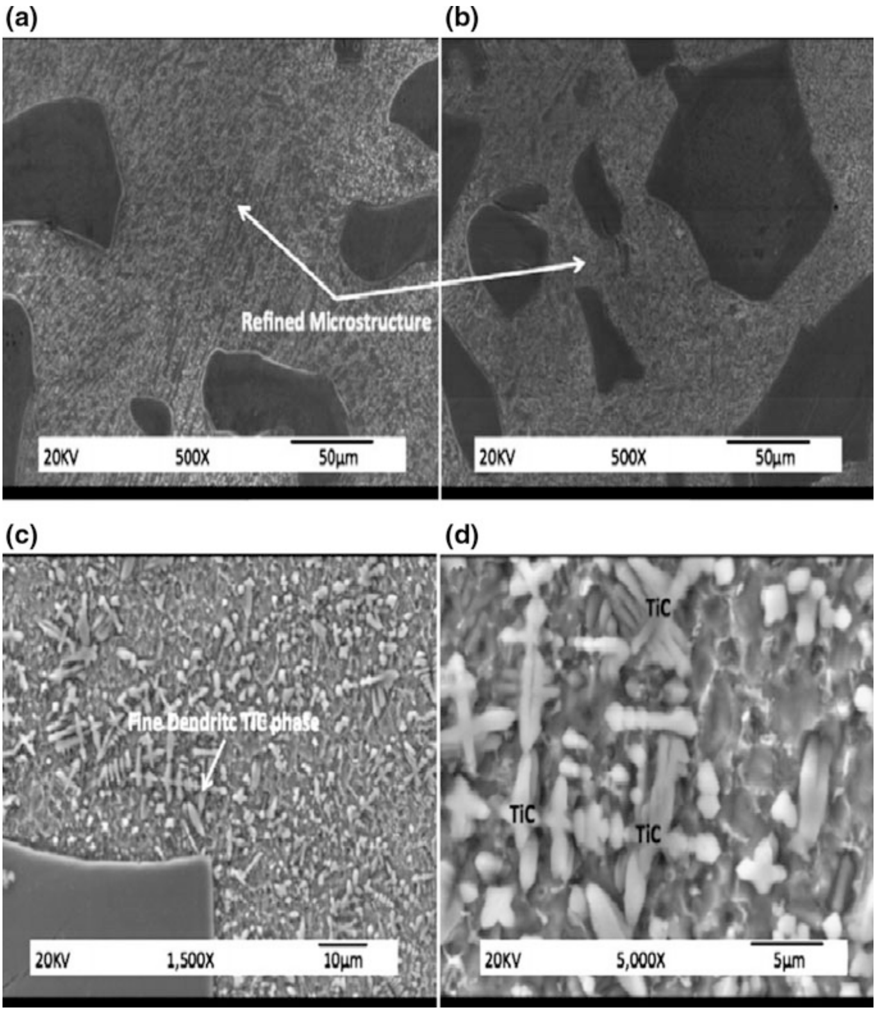

Fig. 6.12 Micrograph of the Inconel 690/TiC FGM showing the refined microstructure and secondary dendritic TiC phases [27]

Mahamood and Akinlabi [28] investigated properties of Ti6Al4V/TiC functionally graded material produced using laser metal deposition process. The functionally graded material was produced using the optimized process parameters for each of the composition ratio of the constituent materials in the FGM. The optimised process parameters were obtained from a model that was earlier developed by the authors. Each of the layer that made up the FGM was deposited at these predetermined optimized process parameters.

The properties of the produced functionally graded material was compared with the substrate and functionally graded material that was produced at constant process

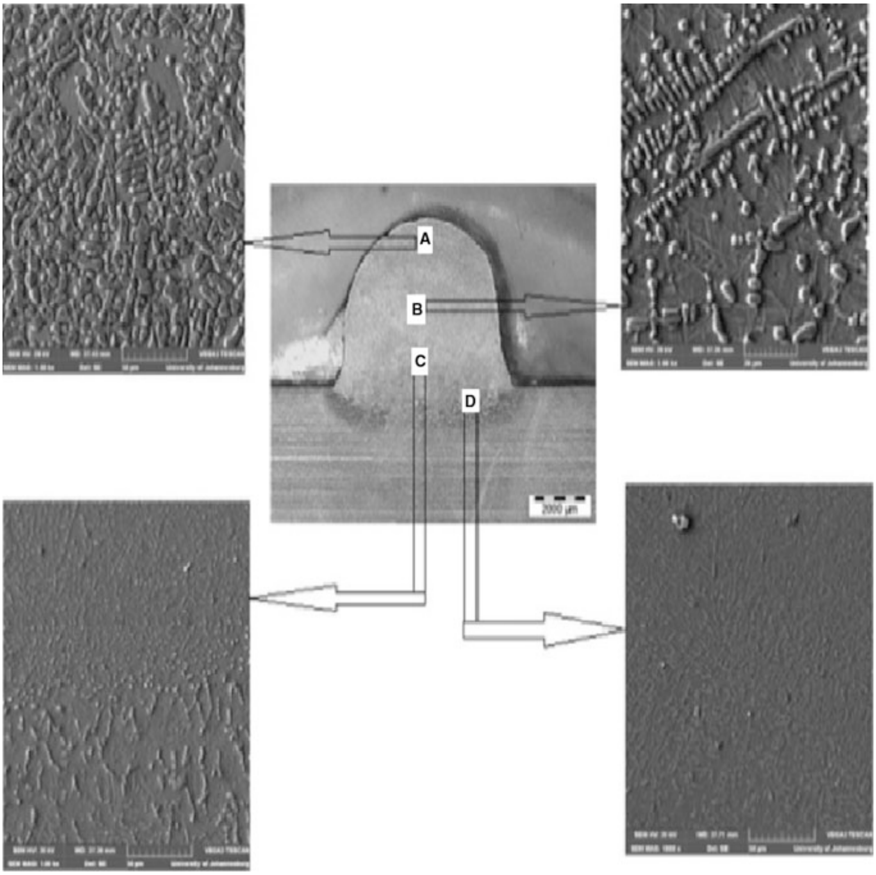

Fig. 6.13 SEM micrograph of the sample produced at optimized-processing parameters, showing the top (*A*); middle (*B*); lower level (*C*); and the dilution region (*D*) [28]

parameters. The microstructure of the FGM produced at optimized process parameters showed a smooth transition from layer to layer as shown in Fig. 6.13. The results show that the FGM that was produced using the optimized has better properties when compared to the one produced at constant processing parameters.

The optimized functionally graded sample has the best wear-resistance behaviour when compared with both the substrate and the FGM produced at constant process parameters. The microhardness of the FGM produced with optimised process parameters was also found to be improved and as high as four times that of the substrate as shown in Fig. 6.14.

The study concluded that the properties of FGM can further be improved by producing each layer of the FGM using optimized process parameters.

Carroll et al. [29] carried out experimental and thermodynamic studies of building a functionally graded material 304L stainless with Inconel 625 using the

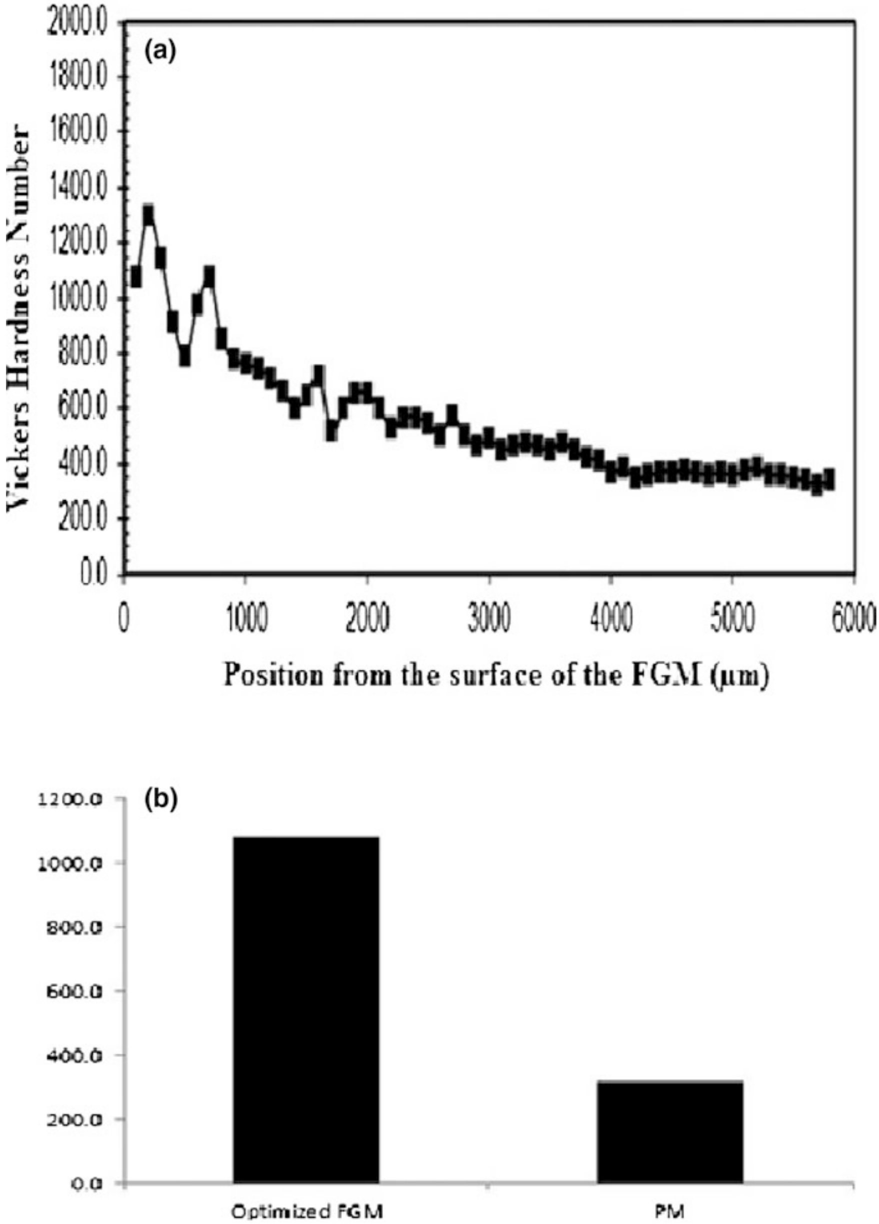

Fig. 6.14 **a** The microhardness of the optimized FGM across the section of the sample; **b** the bar chart of the average microhardness of the optimized FGM and that of the substrate material [28]

laser metal deposition process. The authors investigated the evolved microstructure, phases and chemical composition, as well as the microhardness. The result showed the presence of secondary phases within crack region in the FGM. These secondary phase compounds were found to contain transition metal carbides. The experimental results were compared with the theoretical modelling of a functionally graded material produced using laser metal deposition process. The microstructure of the fabricated FGM showed a smooth transition from one compositional region and another as shown in Fig. 6.15. The microstructure consists of cellular dendrites and columnar dendrites. These dendritic structure although continuous from one layer to the next but in different orientations seen in Fig. 6.15. The cracks that are observed in the microstructure were attributed to the secondary phase particles that are formed during the fabrication process. The thermodynamic model was used to predict the stability of a refractory metal monocarbide and the EDs analysis showed that the cracks contain Mo and Nb. The study showed that the thermodynamic calculation and the experimental analysis showed good agreement with one another. The study also demonstrated the feasibility of fabricating components with graded materials using laser metal process since the cracks observed on the FGM was as a result of developed secondary phases, the study suggest the need to incorporate in the design of FGM for possible secondary phases that may be formed during the fabrication process and the potential variation in properties that could result from it. The hardness of the deposited base alloys are higher than those of wrought material while the microhardness was found to initially decrease with increase in Iconel 625 and begin to increase as the Inconel 625 was further increased.

Bobbio et al. [30] also studied functionally graded material of Ti6Al4V and Invar 36 produced with laser metal deposition process. The authors use both the experimental and computational analysis to study the FGM produced. The microstructure, chemical composition, phases, and microhardness were studied with respect to position in the FGM. The results showed the presence Intermetallic phases (FeTi, Fe2Ti, Ni3Ti, and NiTi2) which were found to be responsible for cracks observed in the FGM. The microstructure of the Ti6Al4V region of the FGM are shown in Fig. 6.16a and b while the microstructure of the Invar 36 region of the FGM are shown in Fig. 6.16c and d. Columnar grains that grow in the build direction, are in both regions. The higher magnification images showed fine alpha-lath microstructure in Fig. 6.16b while cellular structure are seen in Fig. 6.16d. The thermodynamic calculations that was based on the phase diagram was used to predict the these phases which were found to be in good agreement sparks of high microhardness were observed in the FGM which were attributed to the presence of the secondary phases of intermetallic that were formed during the fabrication process. This study concludes that computational work is needed to predict and design the FGM appropriately in order to advance the development of functionally graded materials. A number of other studies on functionally graded materials as well as modelling has also been reported and the readers can consult these materials for further readings [31–34].

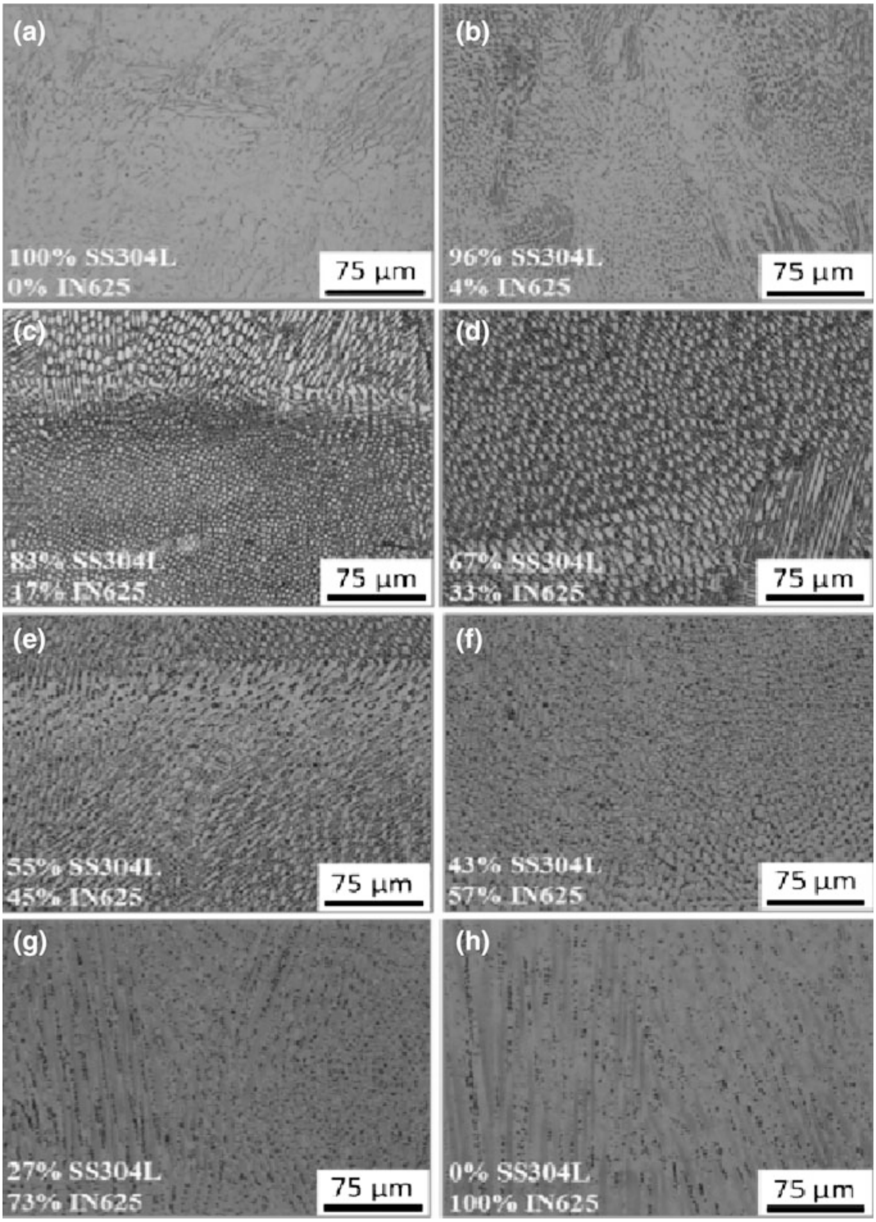

Fig. 6.15 Microstructure of gradient zone from 100% SS304L (**a**) to 100% IN625 (**h**) [29]

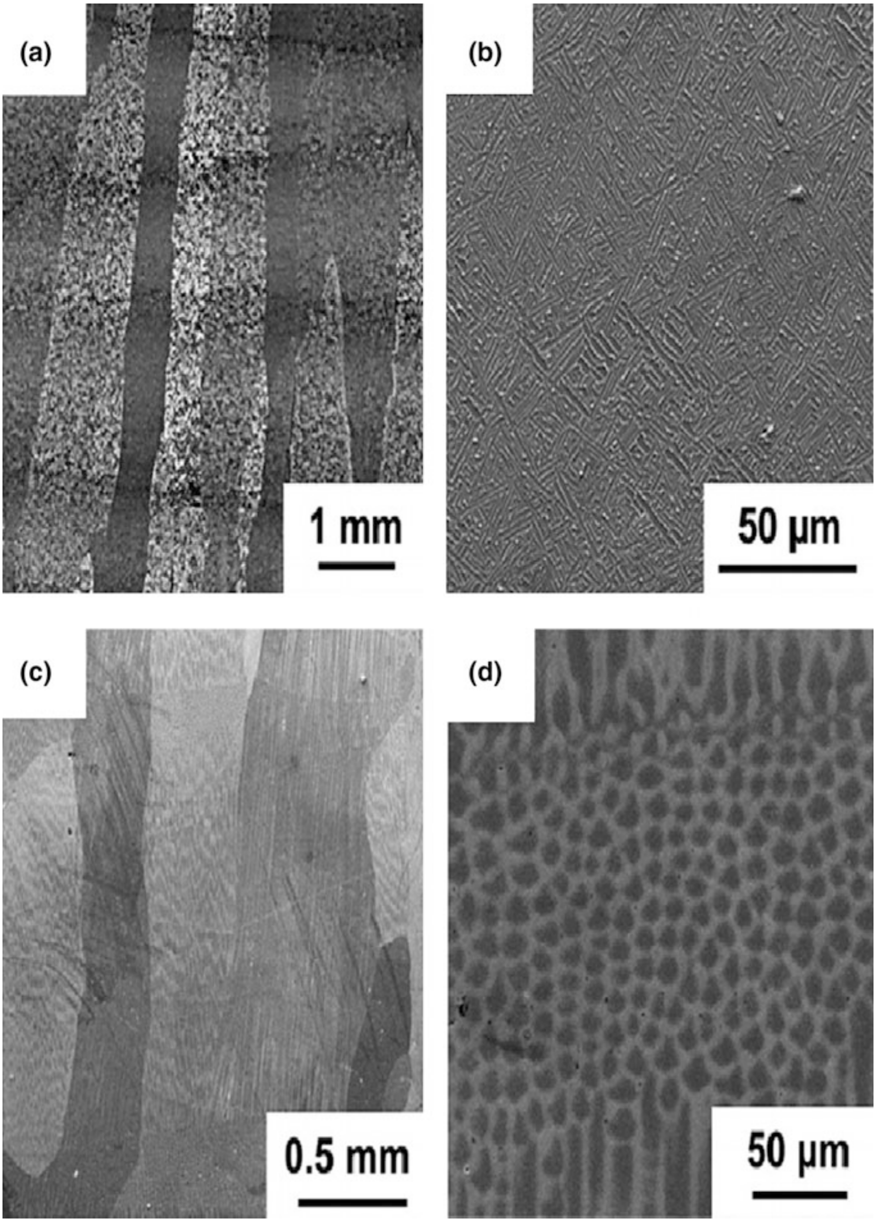

Fig. 6.16 Micrograph of the pure Ti6Al4V region (**a**) and (**b**) the pure Invar region of the sample (**c**) and (**d**) [30]

6.4 Summary

The use of laser metal deposition process for the fabrication of composite materials and functionally graded materials has been presented in this chapter. The flexibility offered by the laser metal deposition process that allows the use of more than one material during the fabrication process has made it possible to use the process for the fabrication of parts with composite and functionally graded materials. The production of metal-metal composite materials, metal ceramic composite materials and functionally graded materials of metal–ceramic materials have been presented some of the results of current research are also analyzed. The next chapter will focus on the areas of application of laser metal deposition process and the use of laser metal deposition process in repair of high valued engineering component.

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Chapter 7
Areas of Application of Laser Metal Deposition Process–Part Repair and Remanufacturing

Abstract Laser metal deposition process is an important additive manufacturing process with a number of capabilities such as the ability to fabricate three dimensional (3D) part directly from the 3D computer aided design profile of the part; the ability to repair worn out parts of very high value that were not repairable in the past; and the ability to build a new part on an existing part that are metallurgically bonded to the old part. This important capability of the laser metal deposition process (ability to add new part on an existing part) is what has positioned this important additive manufacturing process in product remanufacturing and this is a unique laser metal deposition capability. Product remanufacturing is an important aspect of manufacturing that helped to improve material life cycle and helped to reduce scrap. In this chapter, repair, remanufacturing and surface modification applications areas of laser metal deposition process are presented.

Keywords Additive manufacturing · Aerospace · High value repair · Laser metal deposition · Product remanufacturing · Surface modification

7.1 Introduction

Laser metal deposition (LMD) process is an additive manufacturing technology that can be used to produce three dimensional (3D) object by adding materials, wire or powder, directly from the 3D computer aided design (CAD) of the part [1, 2]. Laser metal deposition process can also be used in the repair of high valued parts that were prohibitive or not repairable in the past [3, 4]. Some parts are too small that repairing such part using the conventional process could result in damage of the parts especially because of the large heat affected zone. Laser metal deposition process produce very low heat affected zone because of the laser that is used as the energy source and the properties of laser that made it to be applied only to the needed area as a result of its high directionality and coherency. The success of using LMD for effective repair can also be attributed to the rapid cooling of the process that prevent the melt pool from staying too long which is responsible for the low

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heat affected zone. The high resolution that is also achievable with the laser beam makes it possible to create miniaturize parts and repair of such part with high precision using the laser metal deposition process. Another unique property of LMD process is its capability to produce a new part on an existing part with high metallurgical integrity. These important characteristics of the LMD process have helped to position the technology in product remanufacturing [5–7]. Design modification is also made possible with this technology without having to start from scratch and without having to turn an existing machine or equipment into scrap. This additive manufacturing technology gives designers the flexibility to modify an existing design with ease.

In this chapter, the capabilities of LMD process are explored and some of the research works in these application areas are also presented. Laser metal deposition process holds a lot of promises for the manufacturing industries and has the capability to reduce scrap and hence helped to reduce global warming. This is because, the end of life of any material can considerably be increased with the possibility of changing an existing obsolete design to a new one making material utilization to be very high and hence reduce scrap. Advantages of using laser metal deposition process include: the ability to produce near net-shape part requiring minimum finishing operations, the ability to use metals and ceramic materials simultaneously to produce part made with composite materials and compositionally grade materials [8–11] and the capability of building part with no build-up size restriction as well as the flexibility of changing the part design without having to start from the scratch. The uses of laser metal deposition process in part repair, product remanufacturing, surface modification and in the fabrication of new 3D part are explained in this chapter. The use of laser metal deposition process for the application of hard wear resistance surface materials to components such as drilling components for the oil drilling industry, where hard materials such as tungsten carbide is coated onto the cylindrical-shaped component. This coated material needs to be metallurgically bonded to the surface of the component to provide the needed protection for the component. Also, laser metal deposition process is used to apply wear resistance coating on wear-resistant blades for digging operations in the agricultural industry. These topics are covered in detail in this chapter and the chapter is concluded with summary.

7.2 Laser Metal Deposition Process in Repair

Laser metal deposition process, owing to its flexibilities has been demonstrated to be capable of repairing high valued parts as well as repairing such part with composite or even functionally graded material which helps to extend the service life of the components being repaired. The flexibilities in its ability to use multi materials are responsible to this capability found with laser metal deposition process. A number of industries that are already benefiting from this technology for the repair of their high valued components include: in mould and tool industries, aerospace, and automotive industries. In this section, some of the repair works that has been carried out successfully using the laser metal deposition process both industrially [12] and through research works are explored.

The laser metal deposition process has been successfully implemented especially in the repair of aircraft turbine blades as well as for the repair of very high-value part -blisk [13]. In the past, the blades on these parts cannot be replaced because they were manufactured from a single block and they were produced as a single unit part. Any slight damage to any part of the blade no matter how small would render the entire turbine wheel and the blisk useless. Laser metal deposition process has proven its ability in being able to repair these high valued components and it's been able to reconstruct the damaged edges or broken tips to its original geometry and material properties [13, 14].

The marine industry is another industry that benefits immensely from the repair offered by the laser metal deposition process [15]. For example, LMD Process can be used to restore damaged piston ring grove to its original geometry The laser metal deposition process provide the needed good accessibility to the tight geometries and it offers high precision with no damage to the base material. Difficult to reach geometries can be accessed using the laser metal deposition process as a result of the ability to effectively control the laser beam to only the needed area (directionality). Another key property of laser metal deposition process is its ability to produce better material properties to the repaired part making it more attractive as this will further help to extend the life of the repaired component more than the new part.

A number of research works has been conducted in the literature on the use of laser metal deposition process for repair of components and parts, some of this research works are presented in this section. Nowotney et al. [16] carried out research on the repair of worn-out gun barrel due to erosion, using the laser metal deposition process. The objective of this research work was to develop an effective repair method for the damaged gun barrel and to develop the right material that can be coated on the surface of the gun barrel that will help to extend its service life. The result of this study showed that the laser metal deposition process can effectively be used to repair damaged component using proper process parameters. Of all the materials tested in this study for proper wear resistance, the composite material system of a CoCrMo filler alloy and a TiC hard coating was found to have better wear resistance properties. The pictorial diagrams of the laser head with coaxial powder and the deposition process used in this study is shown in Fig. 7.1.

The feasibility of effecting repair on sintered tool and die using laser metal deposition process with wire was conducted by Capello et al. [17]. The sintered tool and die made of steel is characterized by porosity that becomes a challenge. The porosity needed to be reduced to the barest minimum in order for the deposited material to be strongly bonded with the sintered tool or die material. The authors first carried out laser re-melting of the porous surface before the proper deposition process. The laser surface re-melting was to ensure that the superficial layer of the base material becomes fully dense. Also the authors study the influence of processing parameters on the deposit shape and base material porosity. This study was

(a)

(b)

Fig. 7.1 **a** Coaxial powder nozzle of the internal diameter deposition head for omnidirectional welding operation. **b** Process of direct laser material deposition on inner surfaces [16]

important to ensure proper bonding of the first layer of the deposited material and the porous base material. The results of this investigation were then used to produce multilayer deposit and the microstructure and the microhardness properties of the multilayer pad produced were studied. To understand the influence of surface re-melting on the sintered base material, the two samples were (with surface re-melting and without surface re-melting) produced and the results were compared. The study revealed that laser metal deposition using wire can be used to repair sintered tools and die. The laser surface re-melting was found to be detrimental to the repair process as it was seen to increase porosity in the base material as well as in the deposited material. The porosity in the deposited material was attributed to the porosity in the base sintered material which can be reduced by grinding as demonstrated in Fig. 7.2.

The use of laser metal deposition for repair of different milled damaged groves (v-groove, u-groove, and u-groove with angled side wall) has been investigated by Graf et al. [18]. Stainless steel and Ti6Al4V were used in this study and the influence of processing parameters on the microstructure and the heat affected zone were studied. The study showed that the laser metal deposition process can be used to carry out repair of milled groove of U or V shaped groove without defect and with good side wall fusion as shown in Fig. 7.3. The study also concluded that titanium alloy could be deposited without the need for trailing inert gas if low heat input is used which results in shorter cooling times. The investigation was also able to develop an automatic repair strategy without manual adjustment that produced deposition with defect-free layers. They concluded that laser metal deposition process can be used for an automated repair process.

The influence of process parameters on the geometric dimension of weld bead in laser metal deposition process for repair using a full factorial design has been pursued by Graf et al. [19]. The laser power (p) was varied between 800 W and 1.7 kW, the laser spot diameter (d) was varied between 1.2 and 1.8 mm, the scanning speed (v) was varied between 320 and 680 mm/min and the powder flow rate ($\dot{m}$) was varied between 5 and 11 g/min. The result of this study is summarized in Fig. 7.4. The bead width and height was found to vary with varying process parameters as shown in Fig. 7.4.

The laser power was seen to greatly influence the bead width while the bead height is significantly influenced by the scanning speed and powder flow rate.

A similar study was conducted by Pinkerton et al. [20] where the potential problem of using the laser metal deposition process for repair of rectangular and triangular shaped grooves with the influence of processing parameters on the groove geometry studied using design of experiment. H13 hot-work tool steel components are used in this study. The influence of processing parameters on the deposition rate, microstructure, porosity, size of the heat-affected zone, and microhardness were investigated. The results showed that the higher the line energy, the higher the possibility for cracks development as shown in Fig. 7.5. There are small cracks observed around the fusion region in Fig. 7.5d as a result of high line energy which are mostly caused by thermal stress concentration from rapid cooling at this region.

The results also showed that solid deposits with fine microstructure and with good metallurgical bond with the substrate can be achieved. Porosity was seen as a problem with the two shapes. The porosity seen on the vertical side walls of the square groove was attributed to improper accessibility of the wall by the laser beam that prevents the proper melting of the deposited powder. The lowest point on the V-slot was also seen to be prone to porosity. The increase in the laser power and powder flow rate was observed to cause an increase in the porosity.

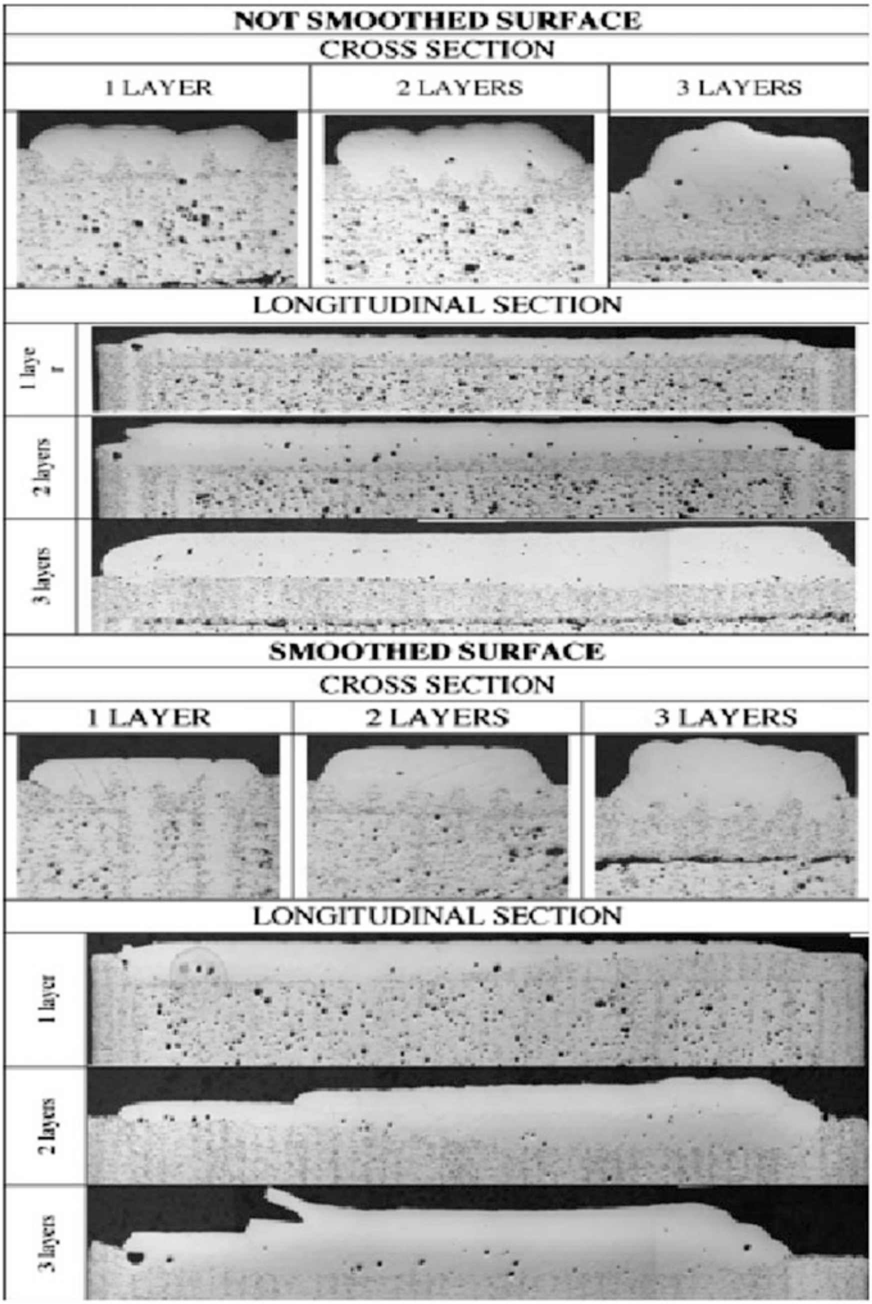

Fig. 7.2 Micrograph showing the reduction of porosity through grinding [17]

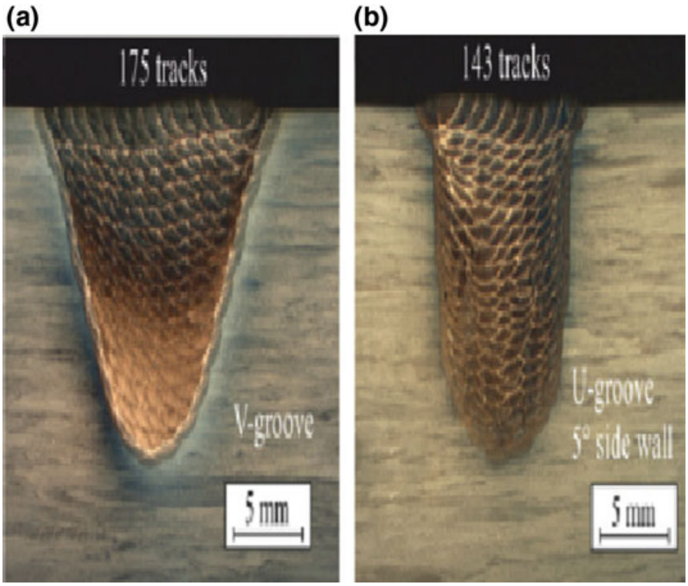

Fig. 7.3 Micrograph of cross sections of rebuild grooves [18]

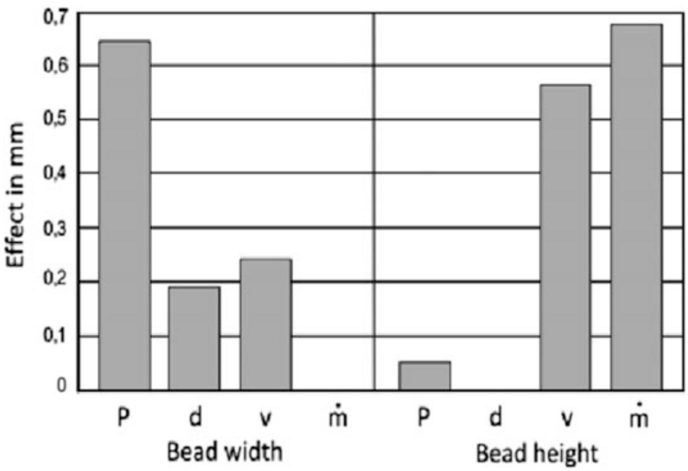

Fig. 7.4 Effect of welding parameters on bead width and height [19]

Qi et al. [21] also use design of experiment to develop a geometry-based adaptive tool path for laser metal deposition method for repair of turbine engine compressor and blisk airfoils (see Fig. 7.6) using Inconel 718 powder.

The study revealed that the most significant processing parameters that affect the deposition bead width are the laser power, the transverse speed, and beam defocus

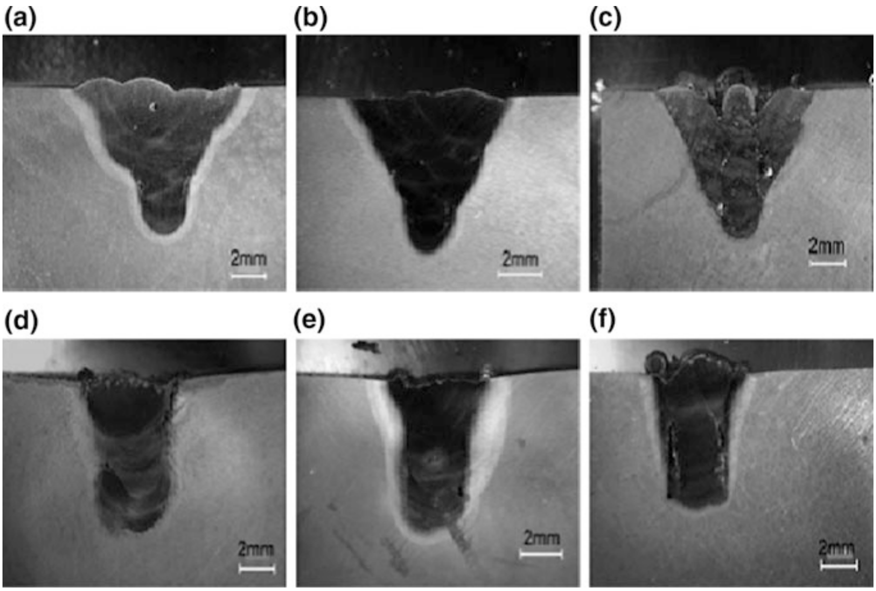

Fig. 7.5 Micrographs of cross-sections through selected samples prepared at a speed of 3 mm/s and a line mass of 0.237 g/mm: **a** V-type 1500 J/mm; **b** V-type 200 J/mm; **c** V-type 900 J/mm; **d** square 1500 J/mm; **e** square 200 J/mm; **f** square 900 J/mm [20]

distance. The bead height was mostly influenced by the powder flow rate, transverse speed, and the laser power. Transfer functions were developed from this model to correlate the processing parameters to the deposition geometry. A quadratic transfer function was developed for deposition bead width that has a 99.2% R-square in the studied process window. An adaptive deposition bead width was obtained by varying the laser power or travel speed according based on the developed transfer function. The deposition tool paths were generated with the varying bead width which is adaptive to the airfoil geometry so that a constant overlap ratio could be maintained. To demonstrate the effectiveness of the developed adaptive towpaths, the authors fabricated solid compressor airfoils and also used the tool paths to repair blisk blades that showed no lack-of-fusion porosity and with good dimensional accuracy as shown in Figs. 7.7 and 7.8 respectively.

Bi and Gasser [22] investigated the feasibility of repairing a worn turbine blade knife edge using laser metal deposition process with effective melt pool control. The turbine blade is made of Ni-base super-alloy. A path-dependent process control strategy was used in this study to prevent hot-cracking and to also improve the dimensional accuracy of the deposition and the metallurgical properties of the deposited layers were studied. The study revealed that there was no any micro cracks in all the samples produced from the top of the deposit, middle and bottom as shown in Fig. 7.9. The microstructure of the bottom part is characterized by columnar dendritic microstructure that grows epitaxially from the base material

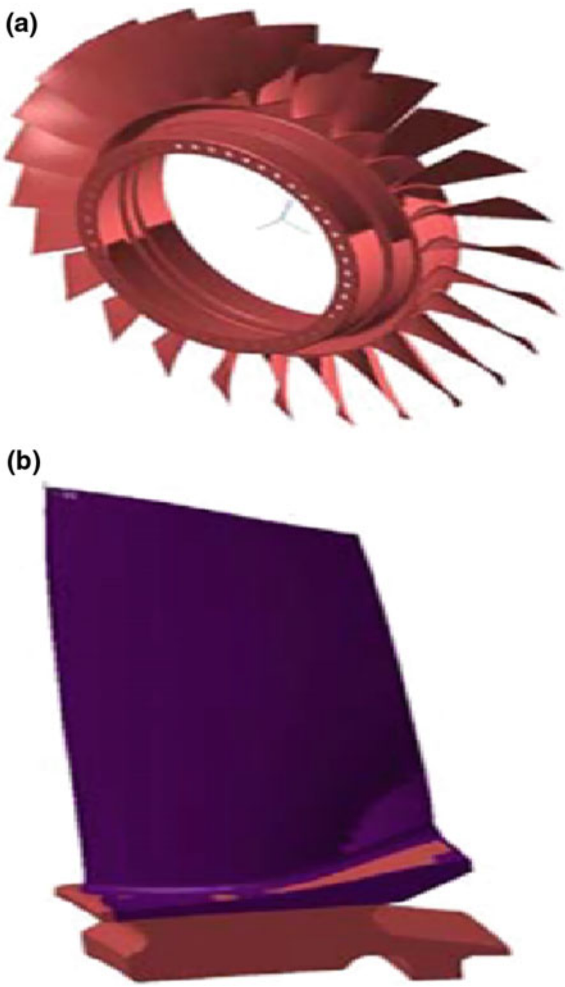

Fig. 7.6 **a** Integrally bladed rotor disk—blisk; **b** typical cross-sectional geometries of a blisk airfoil [21]

which was as a result of the heat sink by the base material. In the middle region, the microstructure is characterized by a mixture of cellular and columnar dendrite structures while the top layer is characterized by equiaxed microstructure with obvious second-dendrite arms due to rapid solidification happening on the surface.

The use of laser metal deposition process for repair has been widely studied and the process has been demonstrated to have a very high potential. The realization of repair using the laser metal deposition process is now effectively used in the industries for efficient repair of high valued components such as blisk in the aircraft engine [23] as in Fig. 7.10. The readers can consult the following references for further reading on the use of laser metal deposition process in repair applications [24–32]. The application of laser metal deposition process in remanufacturing is the focus of the next section.

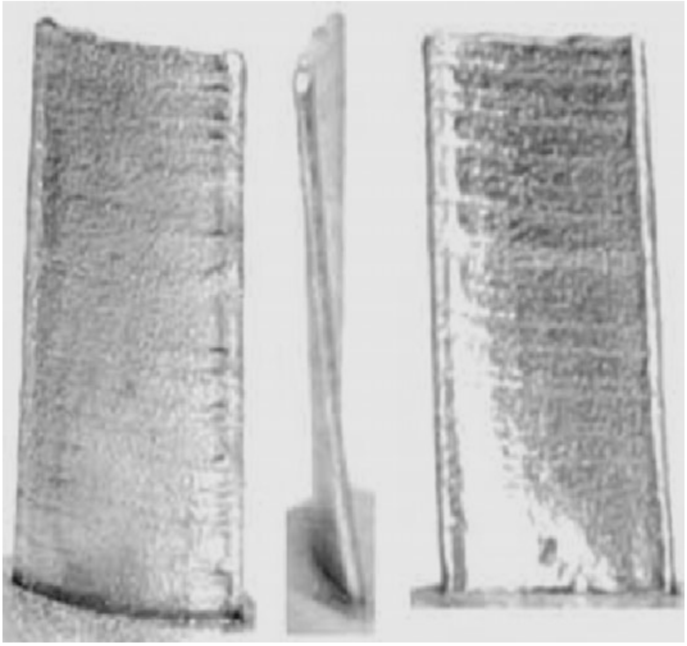

Fig. 7.7 High-pressure compressor airfoil sample made by adaptive tool path laser deposition [21]

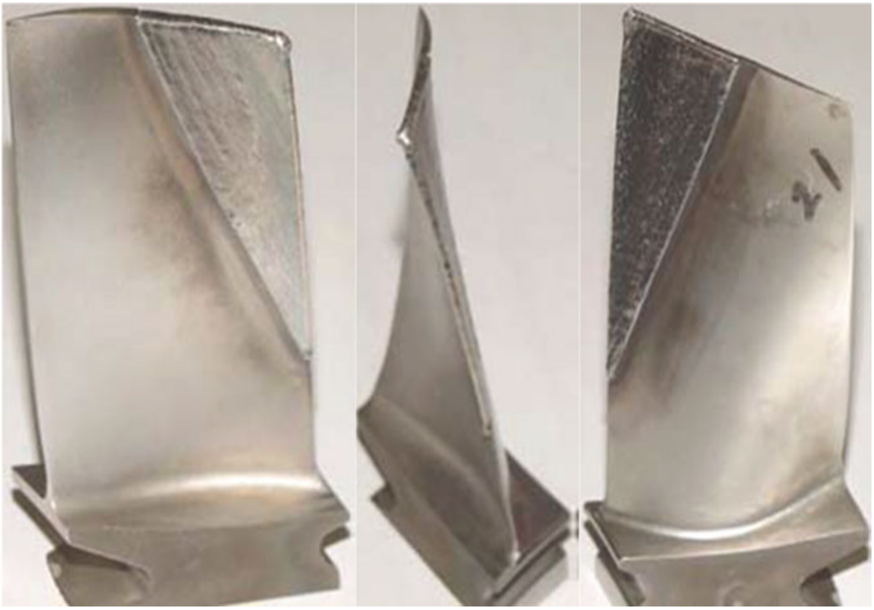

Fig. 7.8 Blisk airfoil repaired by laser powder deposition with adaptive tool path method [21]

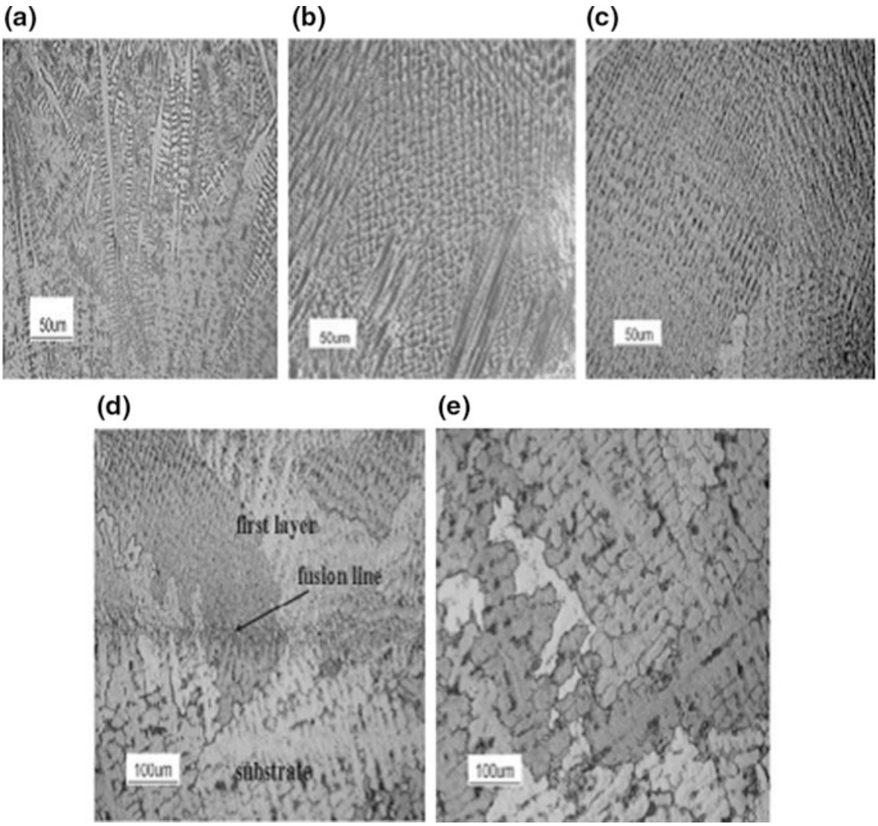

Fig. 7.9 Optical micrograph of the cross-section of the deposited thin wall at different location; **a** top; **b** middle; **c** bottom; **d** adjacent region between substrate and first layer; **e** substrate [22]

7.3 Laser Metal Deposition Process in Remanufacturing

The unique property of laser metal deposition process in its ability to build a new part on an existing part with strong metallurgical integrity is one of the major advantages of this important additive manufacturing process. With laser metal deposition process an obsolete equipment can be remanufactured with improved design and improved functionality. This can be achieved without having to turn an existing equipment into scrap thereby improving the material life cycle and also helped to reduce global warming as a result of reducing the need for material recycling process. Researches are still ongoing to further position this additive manufacturing process for efficient remanufacturing process. Some of the current research works in this field are presented in this section.

Wilson et al. [33] investigated the remanufacturing of a damaged turbine airfoils using laser metal deposition process and a semi-automated geometric reconstruction

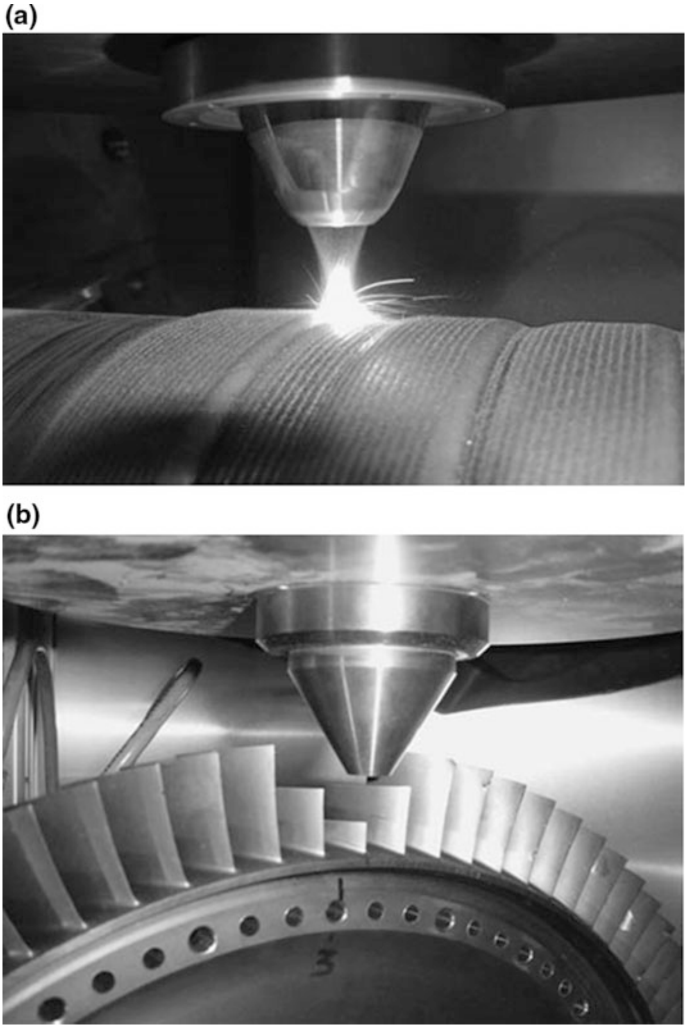

Fig. 7.10 **a** industry laser deposition process with coaxial powder supply. **b** Repair of damaged Titanium blisk using laser metal deposition process [23]

algorithm. Two types of restoration algorithms were used in this studied namely: the nominal and prominent cross section algorithm and the results are shown in Fig. 7.11.

The use of nominal algorithm results in better restoration because of minimal error exhibited by the algorithm. The results also showed the effectiveness of laser metal deposition in remanufacturing and how it can be used to remanufacture a wide range of part defects.

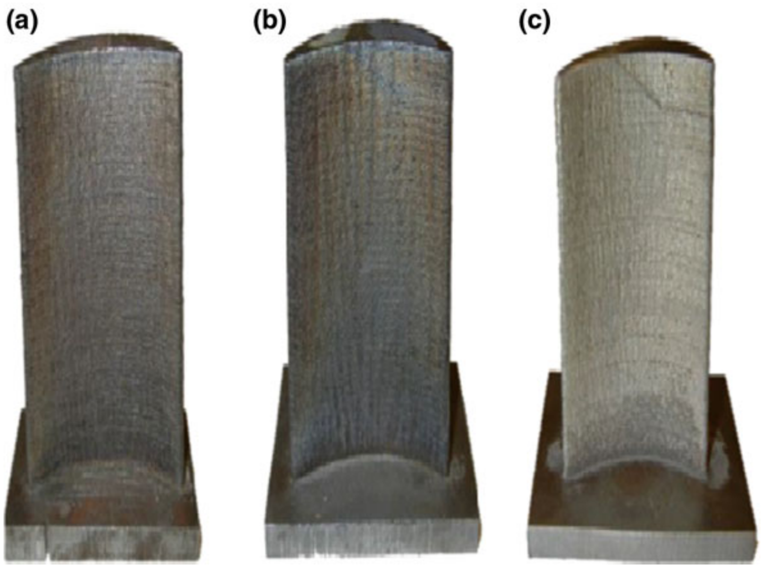

Fig. 7.11 Turbine blades built with the LMD Process. **a** Baseline undamaged blade, **b** nominal restored blade and **c** Prominent cross section restored blade [33]

A similar study was conducted by Lei et al. [34] on investigation of remanufacturing of a failed impeller blades (as shown in Fig. 7.12) using laser metal deposition process. The repair was carried out using FeCrNiCu alloy power. Mathematical model and experimental studies were conducted using finite element (FE) to determine temperature distribution and mechanical analysis. The microstructural analysis of the repaid impeller blade was studied as well as the mechanical properties.

The microstructure of the deposited layer showed a crack and pore free as shown in Fig. 7.13. The microhardness, and tensile property was found to be improved. The pictorial diagram of the remanufactured impeller blade is shown in Fig. 7.14.

The study concluded that the laser metal deposition process can effectively be employed in product remanufacturing. There is no doubt that laser metal deposition is a promising manufacturing technology for product remanufacturing that is economical and sustainable. Laser metal deposition process will help to extend end of life of material by adding value to materials that would otherwise be recycled. obsolete equipment can be redesigned and remanufactured using laser metal deposition process. The use of laser metal deposition process in surface modification is the focus of the next section.

Fig. 7.12 Failed open impeller [34]

7.4 Laser Metal Deposition in Surface Modification

The use of laser metal deposition process for the fabrication of surface coating of composite materials and functionally graded coatings with improved properties has also been explored in the literature [35]. Some applications required surface properties that is different from the bulk material, for example, in wear resistance applications. Wear is a function of surface properties of the material and to improve the wear resistance properties of such material there is need for surface modification which could be inform of deposition of harder and wear resistant material on the base material. Laser metal deposition process is an ideal candidate manufacturing process to achieve this purpose. Processing parameters has been proven to have significant influence on the properties of the coated materials using laser metal deposition process [11, 36–38].

The influence of laser power on microstructure, microhardness and wear resistance properties of laser metal deposited Ti6Al4V/TiC composite was studied by Mahamood et al. [36]. Ti6Al4V/TiC composites were deposited on the Ti6A4V substrate to improve the wear resistance property of the base material. Composition ratio of 50 W% Ti64 and 50 W% TiC were deposited at varying laser power between 0.4 and 3.2 kW while all other process parameters were kept constant. Each of the powders was placed in different hoppers from a powder feeder and the

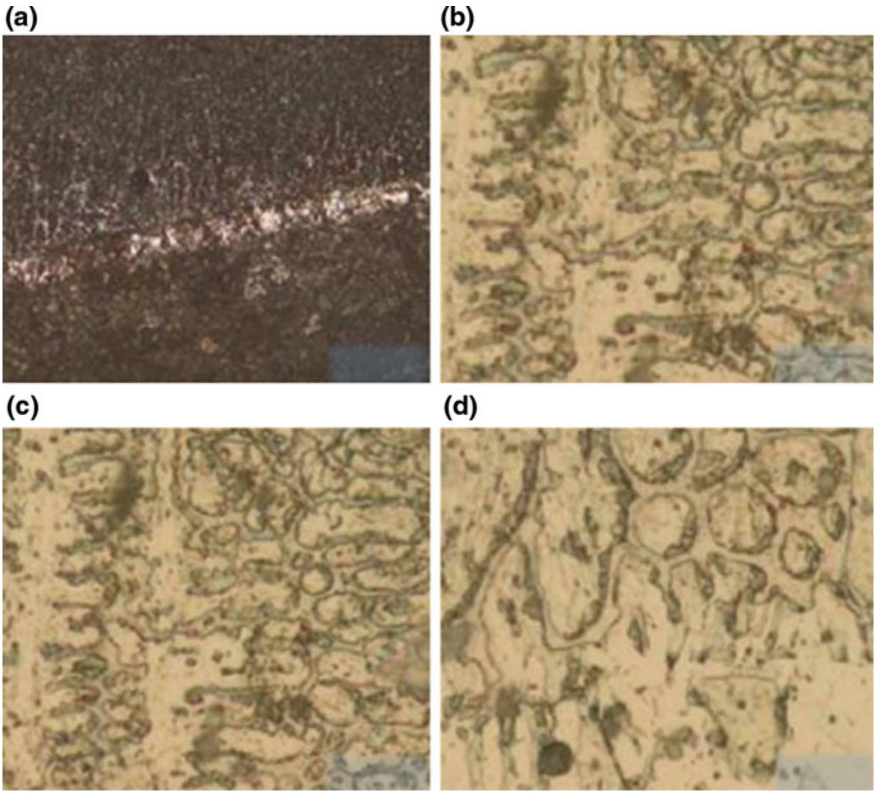

Fig. 7.13 Microstructure of cladding zone. **a** Interface of cladding and substrate. **b** Top cladding zone. **c** Middle cladding zone. **d** Bottom cladding zone [34]

Fig. 7.14 Remanufactured impeller [34]

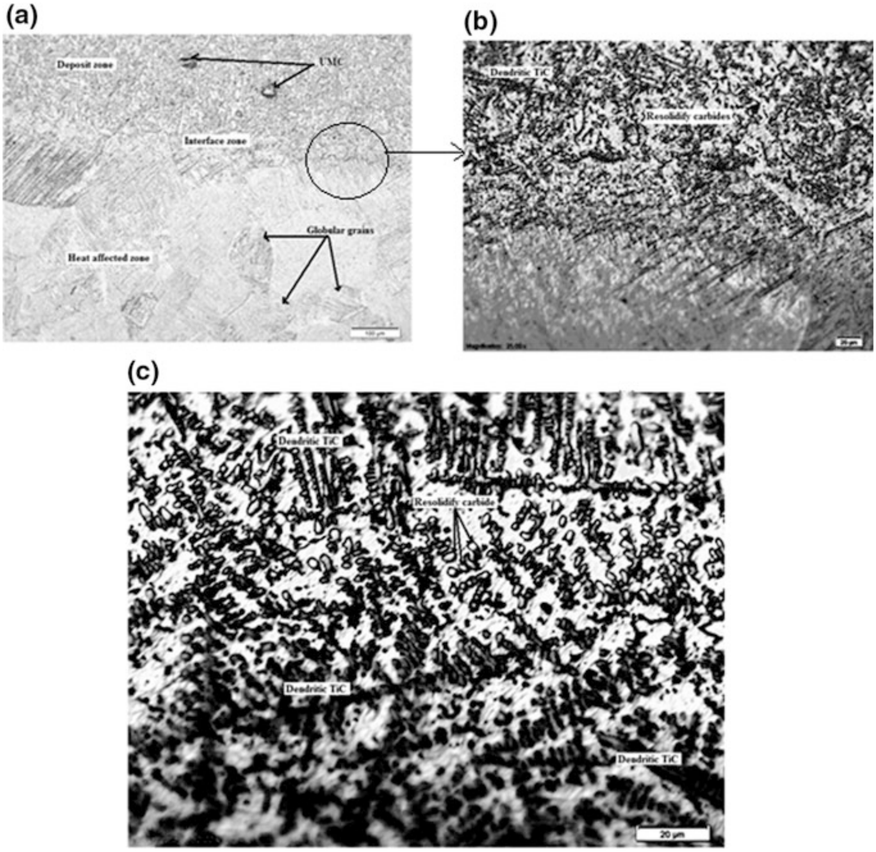

Fig. 7.15 Micrograph of the sample at laser power 1.6 kW showing **a** the deposit layer and the substrate **b** the interface between the deposit and the substrate and **c** the deposit area at higher magnification [36]

two powders were deposited simultaneously. The microstructures in the deposit zone were found to consist of unmelted carbide (UMC) resolidified carbide and dendritic TiC as shown in Fig. 7.15. The microhardness and the wear resistance properties were found to change with change in the laser power. The microhardness was found to increase initially and then decrease as the laser power was further decrease as shown in Fig. 7.16a and the wear resistance initially increased when the laser power was increased initially and then began to decrease as the laser power was further increased as shown in Fig. 7.16b. The study found the optimum laser power to be 2 kW for the set of processing parameters considered in the study.

The influence of scanning speed on the properties of laser metal deposited titanium alloy composite was also investigated by Mahamood et al. [37]. The result obtained in this study was found to be similar to what was obtained in [36]. The microhardness was found to increase with increase in the scanning speed while

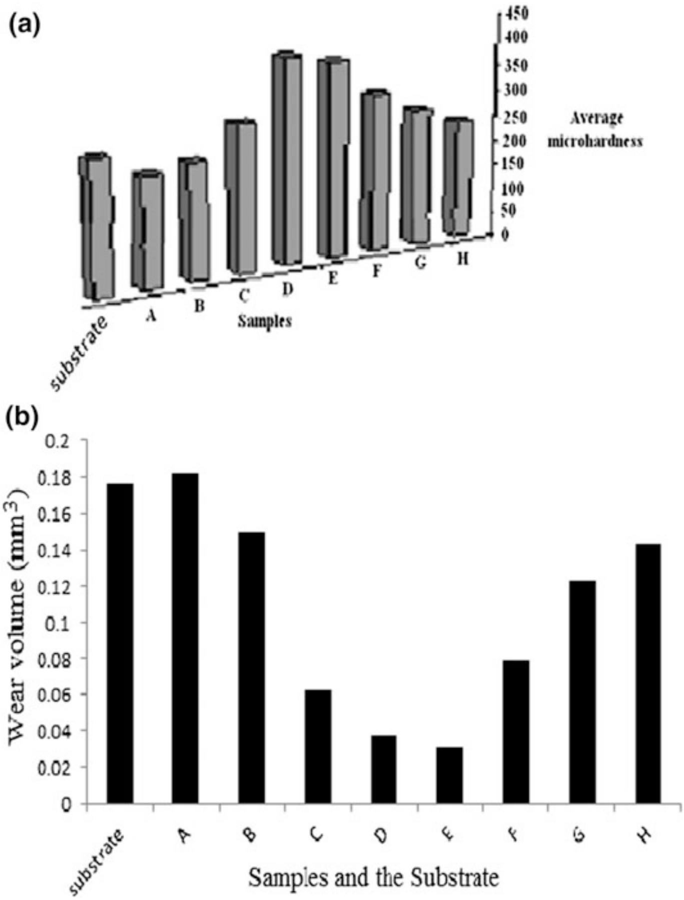

Fig. 7.16 The bar chats of the **a** microhardness and **b** wear volume against laser power (A-H representing 04–3.3 kW) [36]

wear resistance was found to initially increase as the scanning speed was increased as shown in Fig. 7.17.

Other studies on influence of processing parameters on properties of laser metal deposited composite coatings are presented in Mahamood et al. [11, 38].

Gu et al. [39] investigated the influence of TiC addition on the resulting properties of laser metal deposition pure Inconel 625 alloy and the TiC/Inconel 625 composites. The result of the study showed that the incorporation of TiC particles significantly changed the microstructure of Ni–Cr matrix phase with mostly columnar dendrites and cellular dendrites prevailing in the central zone of the deposited region. With the addition of nano-TiC particles, more and more of columnar dendrites were seen in the microstructure. The addition of nano-TiC particles caused the formation of the more refined columnar dendrites with well

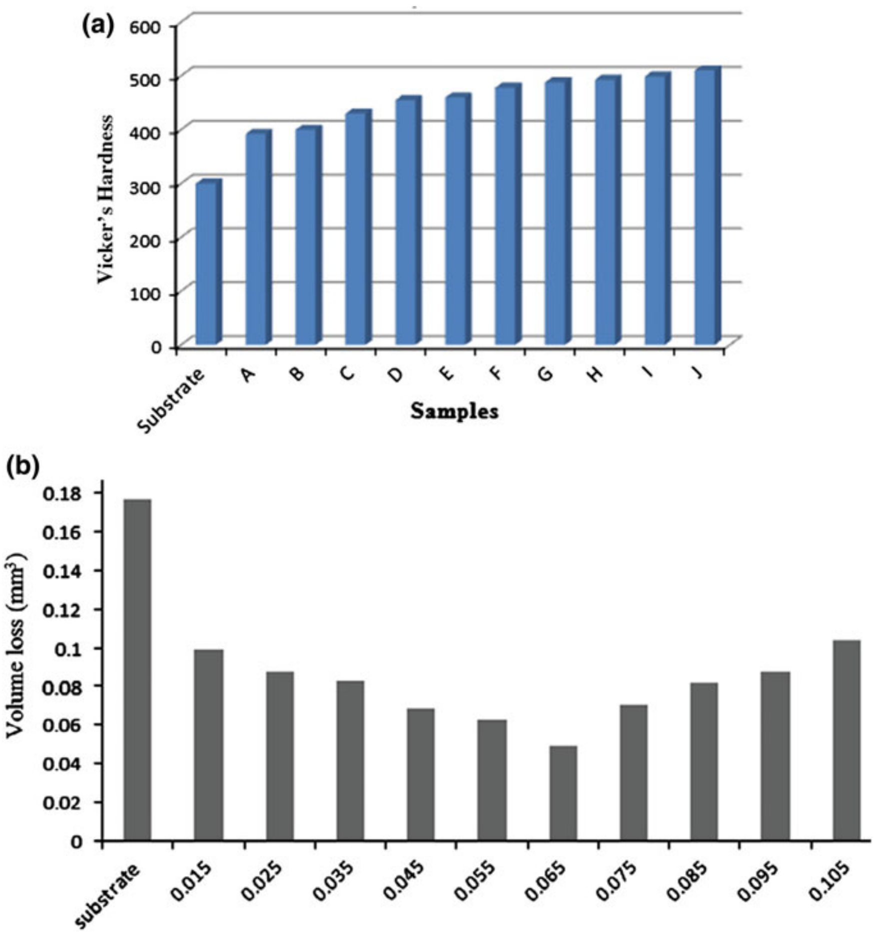

Fig. 7.17 Bar chart of the **a** microhardness and **b** wear volume against the scanning velocity (A-H is scanning speed from 0.015 to 0.105 m/s [37]

developed secondary dendrite arms. Increasing the quantity of the micro-TiC particles causes the columnar dendrites to become coarser and degenerated and the secondary dendrite growth is reduced. The cellular dendrites were found to be refined by the TiC particles. The addition of nano-TiC particles also resulted in significantly improvement in the microhardness, the tensile property, and the wear resistance properties

A similar study was conducted by Hong et al. [10]. The authors used the laser metal deposition process to deposit Inconel 718 metal matrix composites reinforced with TiC particles. The influence of the laser energy input per unit length on the properties of the deposited samples was studied. The study revealed that the deposited composites consists of γ Ni–Cr solid solution matrix, the intermetallic precipitation phase γ', and the TiC phases. The microstructures of the TiC reinforcing phase have a successive change as the laser energy input per unit length was increased. The microstructure changed from relatively coarsened poly-angular particles at low laser input energy per unit length due to the particles been melted on the surface to significantly refined TiC dendrites/particles at higher laser input energy per unit length which was as a result of fully melted TiC particles. The presence of TiC particles at both the lower and higher laser input energy per unit length helped to improve the microhardness and wear resistance performance of TiC/Inconel 718 composites. The use of laser metal deposition process for the production of functionally graded coatings has been studied by Mahamood and Akinlabi [8] and other researchers [40–44]. The readers can consult these references for further readings.

7.5 Summary

The areas of applications of laser metal deposition process have been presented in this chapter. Laser metal deposition process is an important additive manufacturing technology with lots of potentials and benefits. The use of this technology in repair, remanufacturing and surface modification has been dealt with in this chapter. The future of manufacturing highly rely on this manufacturing process because it will help in making good use of material for a longer time because of the repair capability it offers. A number of high valued parts that were not repairable before can now be repaired with this process. Also, an obsolete components can be remanufactured by modifying the design and with the capability of building a new part on an old part using laser metal deposition process makes this realizable without having to turn the obsolete equipment into scrap. Laser metal deposition process is also useful for extending the service life of component through surface modification by using the process to deposit more durable materials on the surface of the component.

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Chapter 8
Laser Metal Deposition of Titanium Alloy and Titanium Alloy Composite: Case Studies

Abstract Laser metal deposition process, an additive manufacturing process offer lots of advantages such as ability to produce three dimensional (3D) object from the 3D computer aided design of the object- meaning that whatever can be drawn using any CAD software can be manufactured; the ability to make part with composite and functionally graded materials- because it can make use of multi materials at the same time; and the ability to build a new materials on an old material with good metallurgical integrity. These important characteristics of the laser metal deposition process have made it the manufacturing technology of the future. This chapter presents case studies on laser metal deposition of titanium alloy-Ti6Al4V and its composite materials because of the role this materials play in key industrial applications. Also, laser metal deposition process is a relatively new technology and some of the process physics are yet to be fully understood. These case studies shed more lights on the use of this additive manufacturing process for Ti6Al4V and its composites, the influence of some processing parameters on the evolving properties and how such processing parameters can be controlled in order to tailor the properties of the component being fabricated.

Keywords Additive manufacturing · Laser metal deposition · Material characterization · Ti6al4v · Titanium alloy composite

8.1 Introduction

Titanium and its alloys are important materials in the aerospace, marine and petrochemical industries, to mention but few. The increase use of titanium and its alloys are base on the fact that, these materials have incredible properties that are required in a number of applications which include: excellent strength to weigh ratio, good corrosion resistance properties and these properties are often retained at elevated properties [1, 2]. In spite of these excellent properties of titanium and its

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alloys, processing these materials pose a lot of challenges especially during machining. It results in a lot of tool failure because of the interaction between the tool material and titanium and its alloys [3–5]. To keep the cost of processing these materials low, there is need for an alternative manufacturing process with the capability to offset some of the problems enchanter while processing these materials. The ideal manufacturing process that is tool less and contactless is laser metal deposition process.

Laser metal deposition (LMD) process, an additive manufacturing technology, that uses the important properties of laser (see Chap. 2) as its energy source to process materials with the application of laser energy only to the needed area. Traditional manufacturing technology such as machining, involves material removal which is referred to as subtractive manufacturing process, differs from laser metal deposition process which is an additive manufacturing process. Laser metal deposition process fabricates three dimensional (3D) parts by using the information generated by the 3D computer aided design (CAD) data to build the part by adding materials layer by layer [6, 7]. This mode of manufacturing is unique because it does not generate waste materials such as chips that become problematic to manage during the manufacturing of some materials using the subtractive manufacturing process. Managing and disposing such chips could be too expensive while machining difficult to machine materials such as titanium and its alloys. With the laser metal deposition process, there is no such problem; this is because materials are added up in order to fabricate materials and with proper process parameters control, material usage efficiency—that is the ratio of materials actually used up during the deposition process and the actual material being delivered during the process, can be very high [8–11]. The un-used materials can also be re-used making the process waste free.

Processing parameters such as laser power, scanning velocity, powder flow rate and gas flow rate (see detail about each of these parameters in Chap. 4) play important roles in the evolution of properties in materials produced using the laser metal deposition process as well as the economy of the process [8, 12–17]. Case studies of laser metal deposition of Ti6Al4V and Ti6Al4V/TiC composites are presented in this chapter and some of the influences of these processing parameters on the properties of the laser metal deposited materials are analyzed. Scanning speed is an important process parameter in the laser metal deposition process and it also determines the speed of the manufacturing process. Scanning speed has a number of influence on the physical, metallurgical as well as the mechanical properties of the deposited materials. A case study on the influence of scanning speed on the properties of laser metal deposited Ti6Al4V is presented in the nest section.

8.2 Case Study 1: Scanning Velocity Effect on Properties of Titanium Alloy Produced by Laser Metal Deposition Process

Ti6Al4V is an important material that is used in a number of industries including the automobile and aerospace industries because of its exciting properties. The major problem with titanium and its alloys is that, it poses a lot of challenges processing this material especially with machining processes. For this reason, it is very expensive to process because of a number of down time that is required to change the cutting tools and also the high cost of the cutting tool. The quest for alternative manufacturing process for difficult to machine materials lead to the use of additive manufacturing process which is a tool-less manufacturing method. Laser metal deposition process, an additive manufacturing technology, is an important manufacturing process that offers lots of advantages for producing three dimensional part as well as for repair of damaged parts. Laser metal deposition process is very sensitive to the processing parameters and it is capable improving the properties of materials. Fabricating moving parts for the aerospace, for example, will help to reduce the overall weight of the aircraft and also improve the fuel efficiency and hence help to reduce the carbon foot print of the aerospace industry. In this case study, the influence of scanning speed on the metallurgical and mechanical properties of laser metal deposited was investigated. Nd: YAG laser was used to deposit Ti6Al4V powder on Ti6Al4V substrate. The scanning velocity was varied between 0.005 and 0.095 m/s. The microstructures and microhardness of the samples were studied using the optical microscope Vickers hardness tester.

8.2.1 Introduction

Titanium and its alloys have a good combination of properties which include good corrosion resistance, high strength to weight ratio and the ability to retain these properties at elevated temperatures [18]. Titanium and its alloy find their applications in a number of industries because of these important properties. Ti6Al4V is an important titanium alloy with unique combination properties and structurally efficient for the fabrication of critical, high-performance parts which include automobile engine part, jet engine parts and airframe components [19]. However, titanium and its alloys are characterized as difficult to machine materials because of their chemical properties that make them be attracted to any material they come in contact with. This is why they react with cutting tool material causing damage to the cutting tool during machining operation. This has make machining titanium and its alloy very expensive to machine [3–5]. There is one of the reasons why there is need for an alternative manufacturing process for difficult to machine materials.

Laser Metal Deposition process is an important additive manufacturing technology which is a perfect alternative manufacturing process for processing titanium and its alloys because it is a contact-less manufacturing process [6]. Laser metal deposition process can be used to fabricate 3D parts directly from the 3D CAD image of the part no matter the complexity and it can be used to achieve repair of high valued component parts. Complex part can be made using the LMD process as a single unit part which helps in reducing the overall weight of such part thereby elimination the weight of the extra materials used in joining process. This weight saving results in fuel savings for the transportation industries. Customized parts can be produced using this, manufacturing process at near mass production rate and with high material efficiency as well as help to improve buy-to-fly ratio of aircraft [20, 21]. High valued parts that were not repairable in the past can now be repaired using the LMD process because of low heat affected zone associated with the process [22, 23]. A lot of research has been reported in the academic literature about the relationship of the processing parameters and the properties of Ti6Al4V produced with the LMD process [13–17, 24]. It has been shown in the literature that LMD process is a highly un-linear process in relation to the process parameters. This case study according to Mahamood and Akinlabi [24], sought to understand the behaviour of the LMD process with respect to variation of scanning speed. The influence of the scanning speed on the resulting microstructure and the microhardness are presented.

8.2.2 Experimental Procedure

Ti6Al4V powder, Ti6Al4V substrate, 4.0 kW Nd-YAG laser, argon gas, and improvised glove box are the materials that were used in this experiment. The Ti6Al4V substrate and the Ti6Al4V powder used in this experiment are of 99.6% purity. The Ti6Al4V powder is of particle size range of 150–250 µm. The substrate was sand blasted and cleaned with acetone prior to the deposition process. The laser metal deposition process was achieved with the experimental set-up shown in Fig. 8.1a which is available at the National Laser Center, in council for scientific and industrial research (CSIR), Pretoria South Africa. The set-up consists of a kuka robot carrying a 4.0 kW Nd-YAG laser with coaxial powder nozzles. The spot size of the laser was maintained at 2 mm and the focal length was maintained at a distance of 195 mm above the substrate throughout the experiments. The powder was delivered through the argon gas medium at a constant flow rate of 4 l/min. A glove box shown in the set-up was improvised and filled with argon gas to protect the deposited samples from the attack of oxygen and nitrogen. The laser beam create a melt-pool on the surface of the substrate while the Ti6Al4V powder was delivered onto the melt-pool through the coaxial powder nozzles. The laser left on its path a solid track of the Ti6Al4V as it moves along the substrate. The laser power and the powder flow rate were kept constant at 3.5 kW and 2 rpm. The scanning speed was varied between 0.005 and 0.095 m/s as presented in Table 8.1.

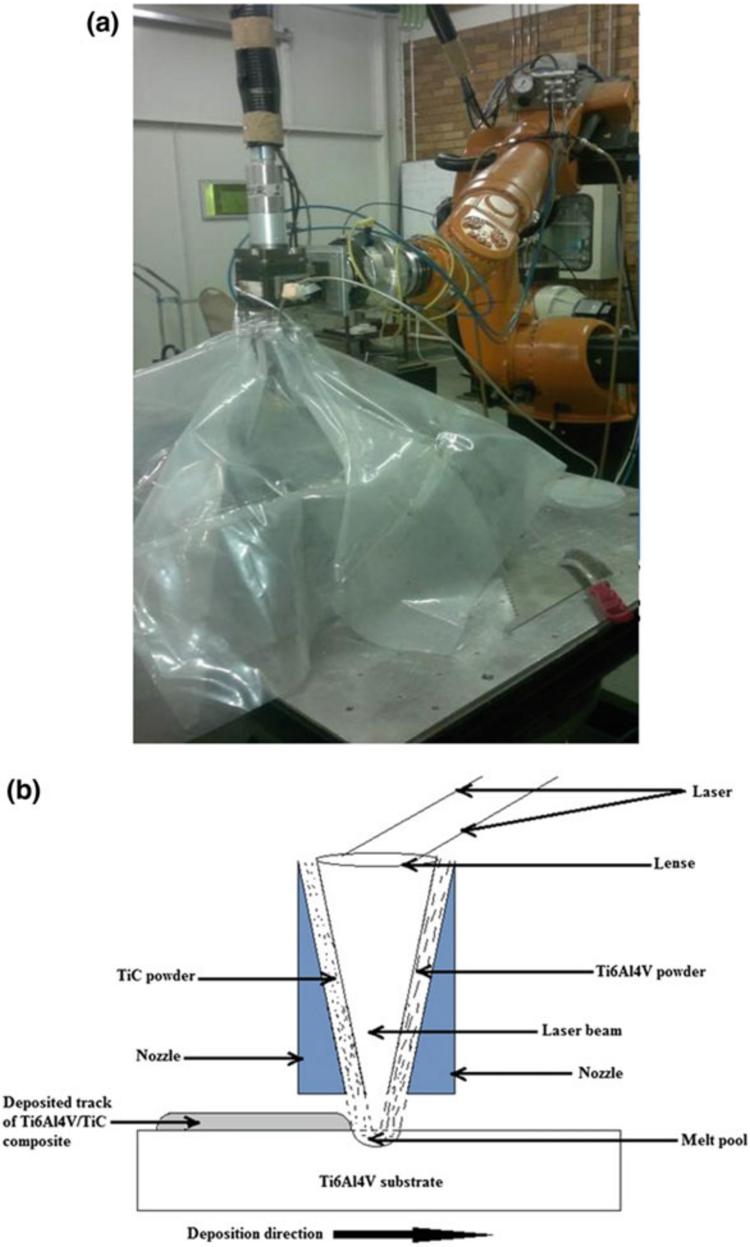


Fig. 8.1 **a** Pictorial diagram of the experimental set-up **b** Schematic of the LMD process [25]

Table 8.1 Experimental matrix

Sample designation	Scanning speed (m/s)
A	0.005
B	0.015
C	0.025
D	0.035
E	0.045
F	0.055
G	0.065
H	0.075
I	0.085
J	0.095

The experimental set-up and the schematic of the LMD process are shown in Fig. 8.1a, b respectively.

After the deposition process, the samples were cut across the deposition direction to reveal the cross section of the deposited samples.

The cut samples were mounted in hot resin, ground and polished following the standard metallurgical sample preparation for titanium and its alloys [21]. The microstructural samples were etched with Kroll reagent. Kroll's reagent consists of 100 ml of water with 3 ml of hydrofluoric acid and 4 ml of nitric acid. The etched samples were observed under Olympus BX51M Optical Microscopy (OP) that was equipped with an Olympus DP25 digital camera. The microhardness was measured using the Metkon Vickers hardness tester with a load of 500 g, dwelling time of 15 s distance between indentations kept at 15 μm following the ASTM standard [26].

8.2.3 Results and Discussion

The micrograph of the Ti6Al4V powder and substrate are shown in Fig. 8.2a and b respectively. The Ti6Al4V substrate is made up of alpha and beta grains that is typical of any Ti6Al4V. The alpha phase is shown as the lighter parts of the microstructure while the darker parts are the beta grain structure. The Ti6Al4V powder is spherically shaped because it is gas atomized. The microstructures of the samples deposited at 0.005 m/s and 0.055 m/s are shown in Fig. 8.3a and b respectively. The microstructure showed globular grains in the heat affected area. The globular grains are produced as a result of grain growth from the transmitted heat to this area from the melt-pool. The microstructure in the deposited zone is characterized by columnar grains which grow epitaxially on the globular grains as

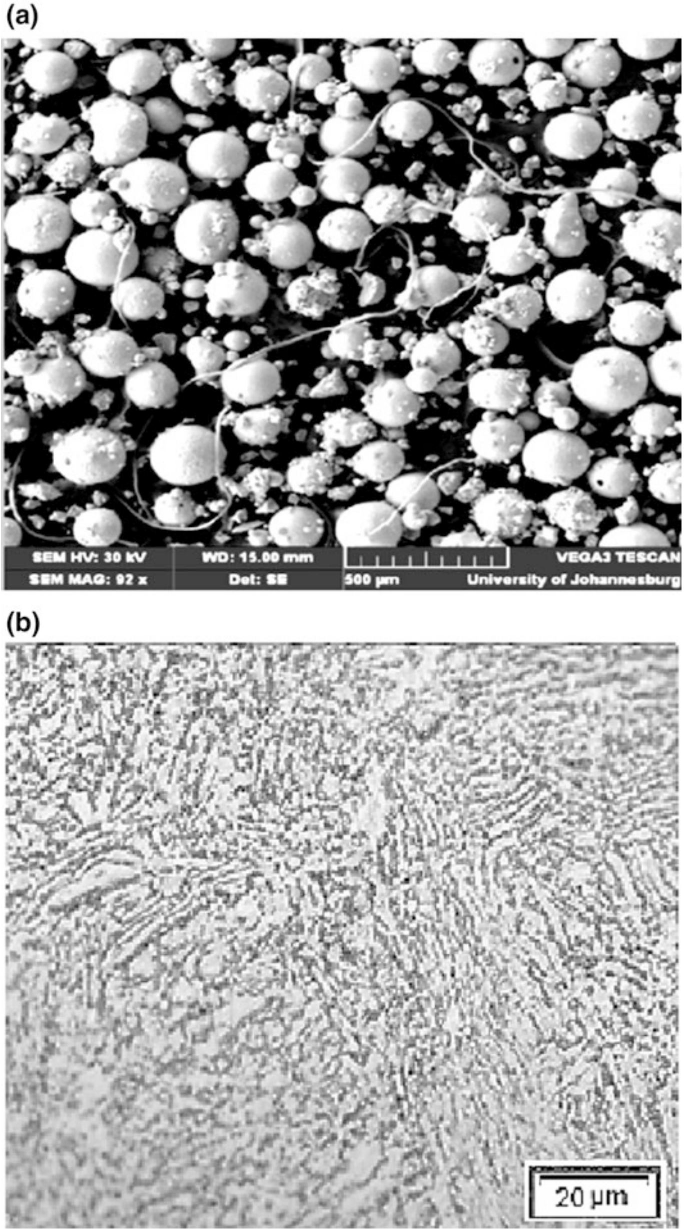


Fig. 8.2 **a** SEM micrograph of the Ti6Al4V. **b** Micrograph of the Ti6Al4V substrate

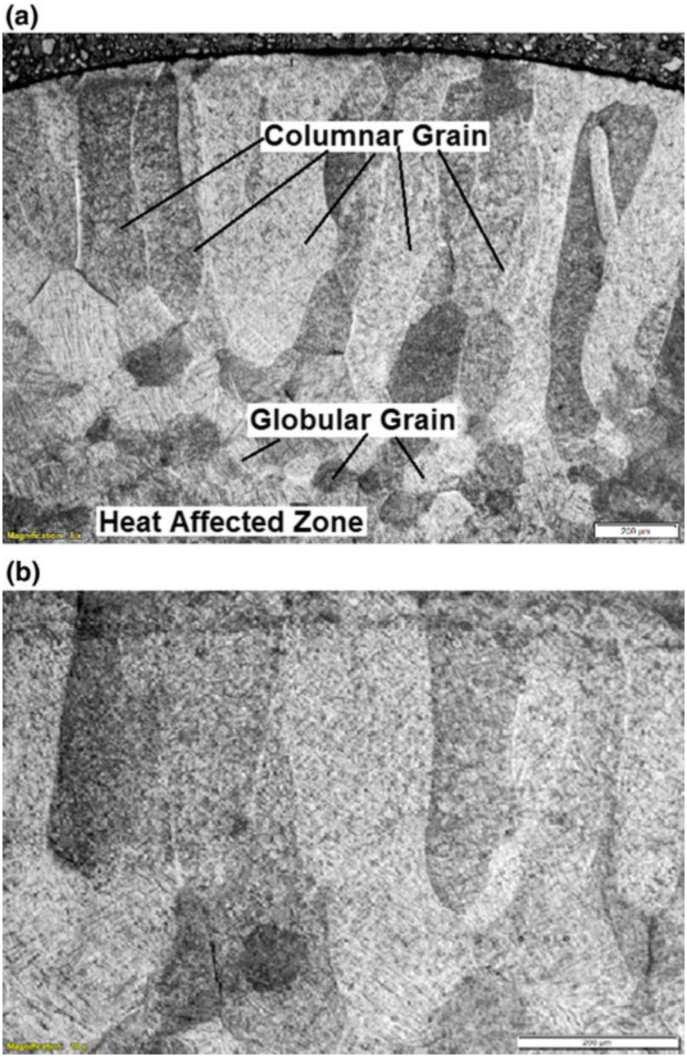


Fig. 8.3 Micrograph of the sample at the scanning speed of **a** 0.005 m/s and **b** 0.055 m/s

shown in Fig. 8.3a. The directional solidification of the melt-pool is responsible for the columnar grains. The substrate is cold and it act as heat sink that causes the columnar grains to be formed. The quantity of these globular grains was found to increase as the scanning speed was increasing. At higher scanning speed, the columnar grains are smaller in size as compared to those at the lower scanning speed as shown in Fig. 8.3b. This is because, the laser material interaction time is

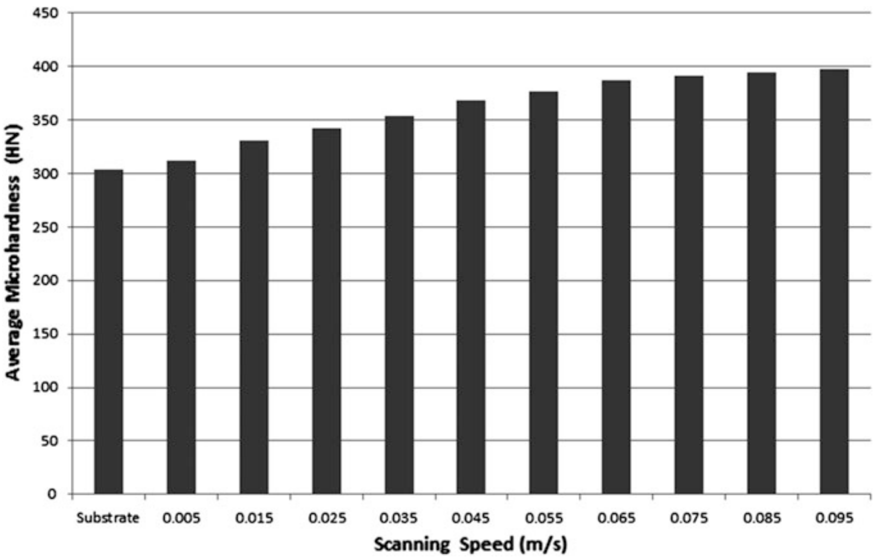


Fig. 8.4 Bar chart of the average Microhardness versus the scanning speed

longer at lower scanning speed that resulted in larger melt-pool formed. Larger melt-pool will result in the formation of larger globular grains that in turn form the larger columnar grains which are fewer in number at lower scanning speed.

On the other hand, at higher scanning speed, smaller melt-pool are created which solidified much quickly and hence causing little grain growth. This was why the globular grains formed at this higher scanning speed to be smaller and hence smaller and larger quantity of columnar grains formed. Since the columnar grains grow epitaxially on the globular grains, hence the columnar grain have direct relationship to the globular grains as shown in Fig. 8.3a and b.

The results of the microhardness is shown in the bar chart presented in Fig. 8.4. The microhardness was found to increase as the scanning speed was increasing. At lower scanning speed, the solidification rate was slower which helps to promote the formation of the Widmanstatten alpha as shown in Fig. 8.5a and hence the lower microhardness at lower scanning speed. At higher scanning speed, on the other hand, the melt-pool formed is smaller and the solidification is more rapid that promotes the formation of the martensitic alpha as seen in the microstructure shown in Fig. 8.5b.

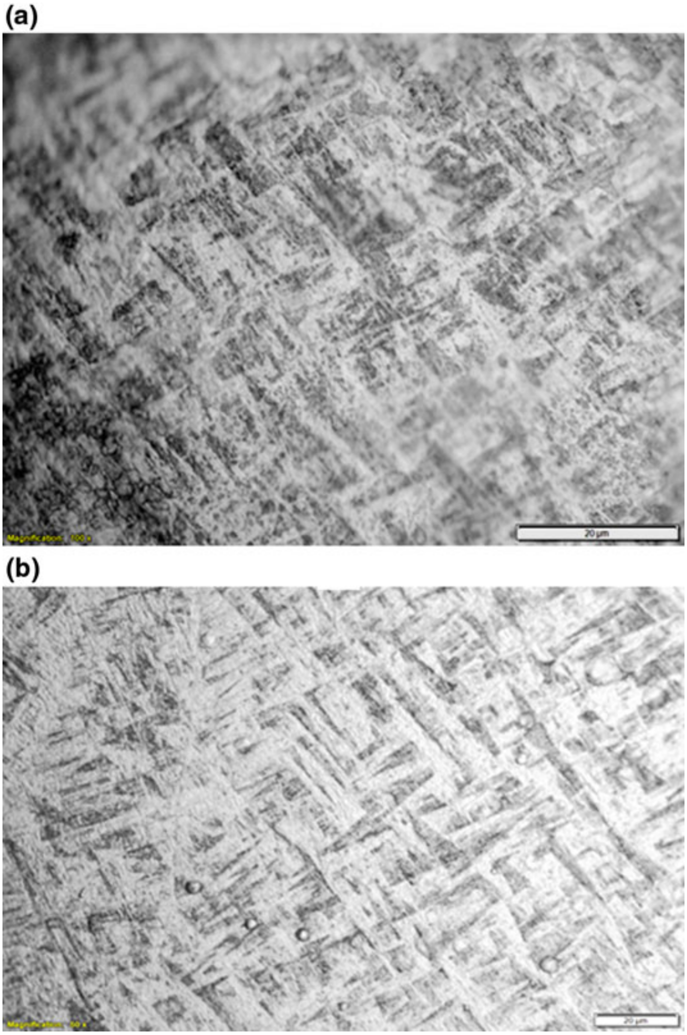


Fig. 8.5 Microstructure of sample at produced at scanning speed of **a** 0.025 m/s **b** 0.55 m/s

8.2.4 Conclusion

The excellent properties of the Ti6Al4V makes its application area to be on the rise. Repair of components that are made of Ti6Al4V will be required from time to time, therefore the laser metal deposition process, an important additive manufacturing technology will be needed in keeping these components in service for longer period of time. The influence of scanning speed on properties of laser deposited Ti6Al4V has been studied. The microstructure was found to change from Widmanstätten structure at lower scanning speed to martensitic structure at higher scanning speed. Also, the microhardness was found to increase as the scanning speed was increased. The average microhardness of all the samples were found to be higher than that of the substrate because of the relatively high solidification rate that is associated with the LMD process. I order to control the hardness property of the deposited parts, the scanning speed can be effectively controlled. The next case study is on the influence of processing parameters on properties of laser metal deposited Ti6Al4V/TiC composite.

8.3 Case Study 2: Effect of Laser Power on Laser Metal Deposited Ti6Al4V/TiC Composite

The flexibility offered by laser metal deposition process, ability to make use of different materials such as metals and ceramics, makes it possible to deposit metal matrix composite material. The use of laser metal deposition process for the production of composite materials results in properties that are phenomena because; the process is characterized by rapid solidification of the meltpool that helped to produce microstructures that could not be produced through other process. The thermodynamic limitation does not also affect composite materials processed using the LMD process because of the rapid solidification in the process. The process parameters of laser metal deposition process also have a great influence on properties of deposited composite materials. In this section, the effects of laser power on the laser deposited titanium alloy composite of Ti6Al4V/TiC are analyzed.

8.3.1 Introduction

Ti6Al4V is the most widely used titanium alloy in the industry and it is often referred to as the workhorse in the industry because of its excellent properties [27–29]. It has the highest strength to weight ratio of any known material and it has very good corrosion resistance properties. Despite all these excellent properties, Titanium is difficult to machine and its wear resistance property is poor [3, 4, 30]. The reason for the poor wear resistance behaviour of Ti6Al4V is that it reacts with any material it comes in contact with, which is responsible for its been difficult to machine. When this material is involved in the rubbing action with another material, it generates a high temperature. This is what leads to galling of the Titanium to the cutting tool material during machining operation that results to tool failure.

8.3.2 Wear Performance Behaviour of Ti6Al4V

The wear resistance behaviour of Ti6Al4V is poor and it has a very high coefficient of friction [31]. The reason for the poor wear resistance behaviour of Titanium has been attributed to the low thermal conductivity and the low strain hardenability of this material [32]. The high chemical reactivity of Ti6Al4V causes a strong adhesion with itself, or with other materials that it comes in contact with [33]. During the rubbing action of Ti6Al4V and material, they tend to adhere to the surface of the other material that results in very high friction. This high frictional forces cause lots of heat to be generated during the robbing action. The heat generated finds it difficult to escape out of the two surfaces because of the poor thermal conductivity of Ti6Al4V that then result in wear of the surfaces. That is why Ti6Al4V needs surface modification if this material will be used in application requiring rubbing action.

A number of surface modifications have been reported in the literature to improve the wear-resistance behaviour of Ti6Al4V. Hard wear resistance metal matrix composite materials are often deposited on the surface of Ti6Al4V using laser metal deposition process in the literature in order to improve its wear-resistance performance [34–37].

Metal Matrix Composites (MMCs) materials are engineering material, developed in order to improve the material's properties [38]. MMCs have better properties compared to other alloyed materials such as higher wear and fatigue resistance, higher deformation resistance, higher rigidity and better thermal shock resistance. It has been proved that the tribological properties of titanium alloys can be improved by reinforcing them with ceramics [39]. Titanium Metal Matrix Composite (TiMMC) is an important engineering material with excellent combination of properties that is used in applications such as the production of connecting rods and piston pins which gives a better fuel economy, reduced emissions, lower noise and vibration as a result of the weight reduction it provided [40]. Forming metal matrix composite reinforced with ceramic coating on the surface of Ti6Al4V has been proved to be very effective in improving the wear resistance behaviour of this important aerospace alloy. Wang et al. [41], investigated the effect of Titanium Carbide (TiC) volume fraction on the wear behaviour of Ti6Al4V/TiC composite. The composite for different volume fractions of the Ti6Al4V/TiC with 8, 15, 24 and 74 vol% TiC composites were produced at constant processing parameters. They found out that the wear resistance was not improved when the vol.% TiC was less than 15 vol% TiC. As the TiC volume fraction was increased beyond 15 vol% TiC, the wear resistance performance was increased.

Different ceramics has been used to reinforce Titanium and its alloy as MMC in the literature. Kim et al. [42] reinforced Ti6Al4V powder with Titanium carbide (TiC) to produce composites using powder metallurgy process. The TiC was developed using a gas–solid in situ reaction process. Titanium Carbide, Aluminum Carbide and Vanadium Carbide were produced during the chemical reactions. Of all the carbides formed during the chemical reactions, only Titanium Carbide was left after the sintering. The TiC/ Ti6Al4V composite formed showed higher hardness, higher elastic modulus, higher tensile strength, and better wear resistance than wrought Ti–6Al–4V alloys. Cui et al. [43] used a 2 kW Nd: YAG laser to synthesize Ti/TiN metal matrix composite coating to modify the surface of pure Titanium. The Ti/TiN metal matrix composite coating had higher hardness and better wear resistance, Joshi et al. [44] used mechanical activation process of reactive milling to produce Ti–TiO_2 composite powders from titanium powders. The microhardness was shown to increase with increasing milling time. Alman and Selamat et al. [45] also produced SiC/Ti6AL4V composite to modify the surface structure of a Ti6Al4V alloy using laser processing. Lapin et al. [46] studied the effect of various volume fractions of Al_2O_3 particles on property of Ti6Al4V. The yield stress was found to be increased with increasing volume fraction of Al_2O_3 particles. De Castro et al. [47] used arc-melting technique to produce Y_2O_3-dispersed titanium with Y_2O_3 (Zr_2O_3, R_2O_3 (R means rare element)) content ranging between 0.3 and 0.7 wt% was starting from Ti and Y_2O_3. A uniform nano-dispersion of Y_2O_3 particles were found in all the alloys. The Y_2O_3 nano-dispersion effectively strengthened these materials. Zhanga et al. [48] produced Ti6Al4V/TiC, Ti6Al4V/TiB and Ti6Al4V/TiC+ TiB by an in situ method. The microhardness was found to be improved with the TiC, TiB and the TiC+ TiB reinforcements and the microhardness does not really depend on the morphology of reinforcements.

The matrix alloy and the reinforcement material should be chosen based on their chemical compatibility and the ability of the matrix to wet the reinforcement [49]. TiC possesses desirable combination of properties that include: high hardness, high melting point, and excellent thermal and chemical stability making them to be useful in many wear resistance applications [50]. TiC particles are more compatible with Titanium and its alloy [51]. TiC has higher wetting and higher interfacial bonding with the matrix material [52]. It has been proved to be very stable thermodynamically in Ti6Al4V and bonds very well with the matrix [53]. Because TiC is thermodynamically stable in Ti6Al4V, the particle matrix interface that results is very stable [51]. This important property is absent in some other carbides like Silicon Carbide (SiC) because, there is chemical interactions between the SiC and Titanium which results in an unstable particle-matrix interface [53]. Other areas of application of Titanium MMC include: Aero engine compressor blades, combustion chamber, Throat, exit nozzle, engine valves and fins thrust, aero engines for compressor blades due to its higher elevated temperature resistance property [29, 54, 55].

A number of researches on the laser metal deposition of Ti6Al4V/TiC composite have also been reported in the literature [56–58]. Obiolodan and Strucker [59] used the LMD process to produce composites of 10 and 5w%TiC/Ti6Al4V on Ti6Al4V substrate. Popoola et al. [35] studied alloys of TiC/Ti6Al4V composite at various TiC compositions. Wang et al. [41] also deposited TiC/Ti6Al4V composite at different TiC compositions. Ochonogor et al. [60] studied the effect of the TiC ratio on the wear resistance performance of Ti/TiC composite, using laser metal deposition. In this case study, the influence of laser power on the properties of laser metal deposited Ti6Al4V/TiC composite is analyzed.

8.3.3 Experimental Method

The substrate material used was in this case study is Ti6Al4V alloy in annealed form. It was supplied by VSMPO-AVISMA Corporation in Russia. This alloy is 99.6% pure; and it contains approximately 6 w% of Aluminum, which is an alpha-stabilizing element and approximately 4 w% of Vanadium, a beta-phase stabilizing element. The chemical composition of the substrate material is presented in Table 8.2

The substrates were cut into a rectangular shape, with dimensions of 72 mm 72 mm × 5 mm. The substrate were sandblasted and cleaned with acetone before the deposition process. The purpose of sandblasting the substrate was to aid the laser-power absorption process, because a shining surface would reflect most of the laser beam. The powders used were Ti6Al4V and TiC powders. The particle size of the Ti6Al4V powder is between 120 and 350 μm. It is a spherically shaped gas-atomized powder. The TiC powder is of particle size range below 60 μm. The Ti6Al4V powder was supplied by F.J. Brodmann and Co., L.L.C., Louisiana. The detail of the material composition is given in Table 8.3. Atomized powders have a spherical shape and smooth surfaces. They exhibit low surface oxidation because of the reduced total surface area. The TiC powder used in this research is ball-milled powder, also supplied by F.J. Brodmann and Co., L.L.C., Louisiana. It has an irregular shape, which is characteristic of a ball-milled powder. The chemical composition of the TiC powder is presented in Table 8.4.

The laser metal deposition experimental set-up is the one shown in Fig. 8.1. The deposition was achieved by a Kuka robot carrying the laser head and coaxial powder nozzles. The substrate is fixed on the laser bed; while the robot moves the

Table 8.2 Chemical composition of Ti6Al4V substrate

Element	Al	V	Fe	C	N_2	H_2	O_2	Ti
W%	6.42	3.91	0.19	0.008	0.006	0.004	0.155	Balance

Table 8.3 Chemical composition of the Ti6Al4V powder

Element	Al	V	Fe	C	N_2	H_2	O_2	Ti
W%	6.20	3.90	0.18	0.008	0.005	0.005	0.150	Balance

Table 8.4 Chemical composition of the TiC powder

Element	C	O_2	N_2	Fe	Al	Na	Ti
%	19.5	0.28	0.4	0.045	0.03	0.026	Balance

laser, in order to achieve the deposition process. The various elements of the experimental set-up are described below. The laser used in this study was Nd: YAG laser with a wavelength of 1.06 μm and maximum power of 4.0 kW. The laser head was fixed on the end effector of the robot. The beam diameter was maintained at approximately 2 mm at a focal distance of 195 mm above the substrate. A glove box shown in Fig. 8.1 was improvised to prevent the deposited parts from environmental attack, such as Nitrogen and Oxygen. A transparent flexible plastic sheet was wrapped around the end effector in such a way that when the robot reached for the deposition process, the flexible plastic wrapping covers the box on the laser bed and the shielding gas was run to cover the deposit, and to protect it from the atmosphere, and to prevent oxidation. The powder feeder used in this study consists of two hoppers, as shown in Fig. 8.6. The two hoppers allow for the deposition of two powders simultaneously.

The nozzles from the hoppers were attached coaxially to the end-effector of the Kuka robot. The powders are protected by Argon gas. The hopper is calibrated in revolutions per minute (rpm). The two powders used in this study were placed separately in each hopper. Putting the powders in separate hoppers and delivering the powders simultaneously is more advantageous than premixing the powders. The problem of segregation is eliminated as a result of a density difference in the powders that were pre-mixed.

Fig. 8.6 Powder feeder

Table 8.5 Processing Parameters

S/N	Laser power (kW)	Scanning speed (m/s)	Powder flow rate (g/min)	Gas flow rate (l/min)
1	1	0.05	4	2
2	1.5	0.05	4	2
3	2.0	0.05	4	2
4	2.5	0.05	4	2
5	3.0	0.05	4	2

The laser power was varied between 1 kW and 3 kW; the remaining processing parameters were kept at fixed values in order to establish the influence of only the laser power. The processing parameters that are used in this study are presented in Table 8.5.

The laser metal deposition process was achieved by the robot moving the laser head towards the substrate, which was fixed inside the glove box. The laser heats up the surface of the substrate and creates a melt pool on the substrate. The powders are delivered into the melt pool through the coaxial nozzles, which were attached to the end-effector of the robot. As the melt pool solidifies, it forms a track of the deposited materials on the substrate. The photograph of the deposit is shown in Fig. 8.7. The deposit was allowed to cool before being removed from the glove box, because the Titanium could still react with the atmospheric oxygen if the deposit is hot and exposed to the atmosphere. After the deposition process was completed.

The surface roughness of the deposit and the wear track of the samples were measured with the stylus surface analyzer by Jenoptik, equipped with Hommelmap

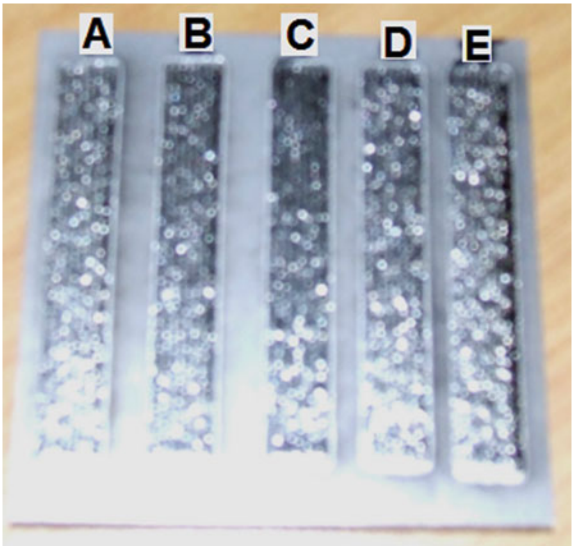
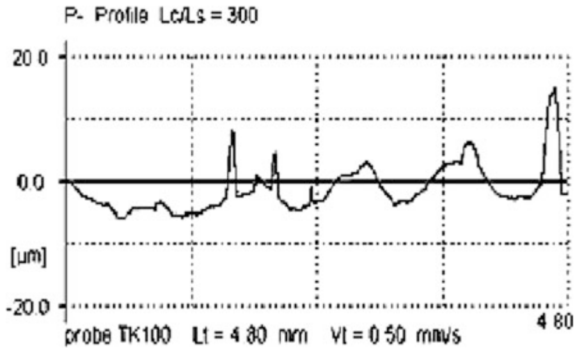


Fig. 8.7 Pictorial diagram of deposited samples

Fig. 8.8 Jenoptik surface profiler

Fig. 8.9 Surface profile of a deposited track with average roughness value of 1.0 µm [25]



6.2 software available at University of Johannesburg. The surface analyzer is shown in Fig. 8.8. The effective measuring length was 4.8 mm; the cut-off length was 0.8 mm; and the measuring range was 400 µm. A sliding speed of 0.50 mm/s was selected; five measurements were taken on each of the samples, and the arithmetic average of the 2D roughness profiles (Ra) was recorded for each sample of interest. The measuring condition used in the research was according to the 'BS EN ISO 4288:1998' standard [61]. The surface profile of a deposited track is shown in Fig. 8.9.

After the deposition process, the samples were prepared for microstructural characterization. The samples were cut in the perpendicular to the direction of scan to reveal the cross section. The substrate material was also cut to reveal the cross section using the Mecatome T300. Both the surface and the cross section of the

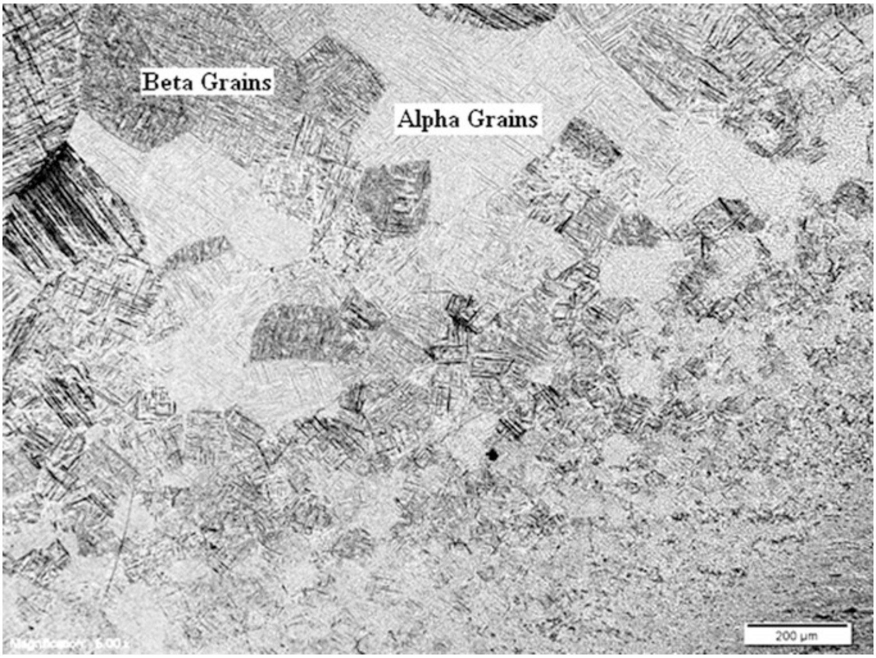


Fig. 8.10 An etched Ti6Al4V laser deposited sample

substrate were mounted in polyfast resin, using the Lecco PR 25 hot mounting press. The metallographic sample preparation was done, according to the standard metallurgical preparation of Titanium and its alloy, the ASTME3-11 standard [26]. The polished samples were etched with Kroll's reagent. The Kroll's reagent consists of 100 ml of water with 1-3 ml of hydrofluoric acid and 2-6 ml of nitric acid. This etchant colours the beta phase dark brown. Figure 10 shows an etched sample of Ti6Al4V showing the alpha (brighter) and beta (darker) phases.

The microstructural studies were carried out under Olympus BX51 M Optical Microscopy (OP) equipped with an Olympus DP25 digital camera. The microscope with magnifications from 50× to 1000× was connected to the computer system equipped with Stream software for image analysis. TESCAN Scanning Electron Microscopy (SEM) equipped with Oxford Energy Dispersion Spectrometry (EDS) was used, in order to take high magnification images of the samples.

The SEM has a resolution of 0.3 nm, magnification range from 5× to 300,000×, and an accelerating voltage in the range of 0.3–30 kV and the working distance between 15 and 25 mm. The purpose of using the SEM was to provide high resolution and high magnification images of the samples, in order to investigate the metallographic changes in the samples, as a result of the changing processing parameters. The energy dispersion spectrometry (EDS) helped to give quantitative and qualitative elemental analyses of certain regions on the imaged sample to obtain the elemental composition and distribution in the regions of interest. An Ultima IV

X-ray diffractometer (XRD) was used to study the phases in the samples. The XRD analysis was performed using MoKα radiations at a power setting of 40 kV and 4 mA.

The mechanical testing that were performed on the samples is the microhardness profiling. The hardness is the measure of the resistance of the material to permanent indentation. The size of the resulting indentation is an indication of the hardness of the material. The microhardness profile was taken on the cross-section of all the samples using the Metkon microhardness tester. A load of 500 g was used at a dwelling time of 15 s, and the distance between the indentations was kept at 12 μm, according to ASTM E384-11e1 standard [62].

The wear-resistance test was performed using a universal material tester UMT 2CETR tribotester with ball-on-plate arrangement under dry condition (no lubrication). The ball is a Tungsten Carbide sphere with a diameter 10 mm, at a load of 25 N, stroke length of 2 mm, and a reciprocating frequency of 20 Hz and for 1200 s. The coefficient of friction was measured for all the samples and recorded. The wear test was performed, according to ASTM G133—05(2010) Standard [63]. The wear surface was analyzed using the optical microscope, SEM and stylus surface analyzer (Jenoptik). The wear volumes were determined from information obtained from the wear-track surface profile, using the stylus surface analyzer and the optical microscope (that is, the cross-section of a wear track). As the stylus was

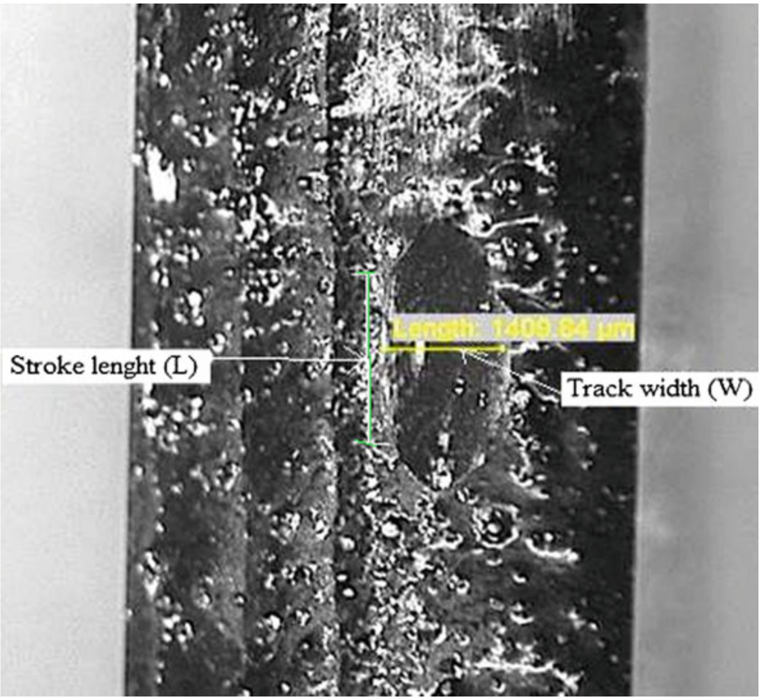


Fig. 8.11 Micrograph of a wear track showing the wear-track width and the stroke length

moved across the wear track, the vertical and horizontal positions of the stylus were recorded for the 2D wear profile of the track. An optical microscope was also used to measure the cross section, in order to ensure precision. Then the wear volume loss was obtained by using the formula proposed by Sharma et al. [64] in Eq. 8.1. An optical micrograph of a wear track is shown in Fig. 8.11.

$$V = L\left[r^2 \sin^{-1}\left(\frac{w}{2r}\right) - \frac{w}{2}\left(r^2 - \frac{w^2}{4}\right)^{1/2}\right] + \frac{\pi}{3}\left[2r^3 - 2r^2\left(r^2 - \frac{w^2}{4}\right)^{1/2} - \frac{w^2}{4}\left(r^2 - \frac{w^2}{4}\right)^{1/2}\right]. \tag{8.1}$$

where v is the wear volume in mm^3, r is the ball radius, w and L are the wear-track width and the stroke length, respectively. The wear volume was calculated by using Eq. 8.1.

8.3.4 Results and Discussion

The SEM micrograph of the Ti6Al4V powder and substrate are shown in Fig. 8.2. The SEM micrograph of the TiC powder is shown in Fig. 8.12. The TiC powder particle size analysis is shown in Fig. 8.13a it is in the range below 60 μm and it is

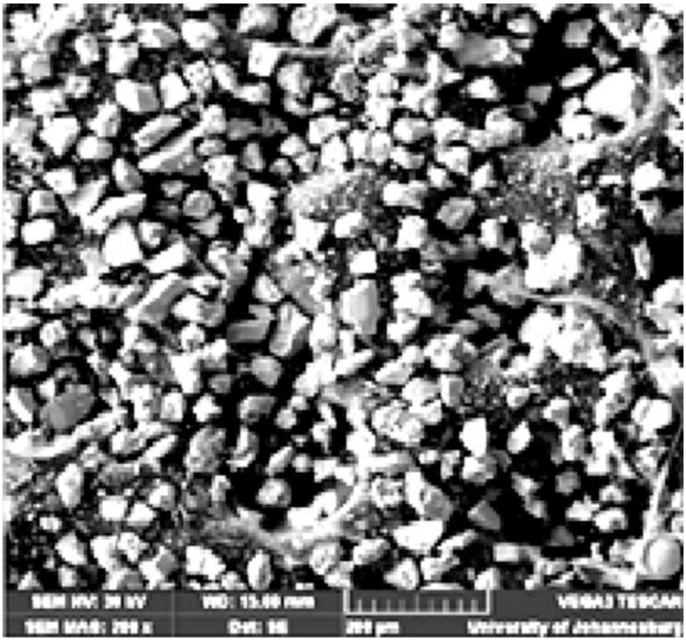


Fig. 8.12 TiC powder

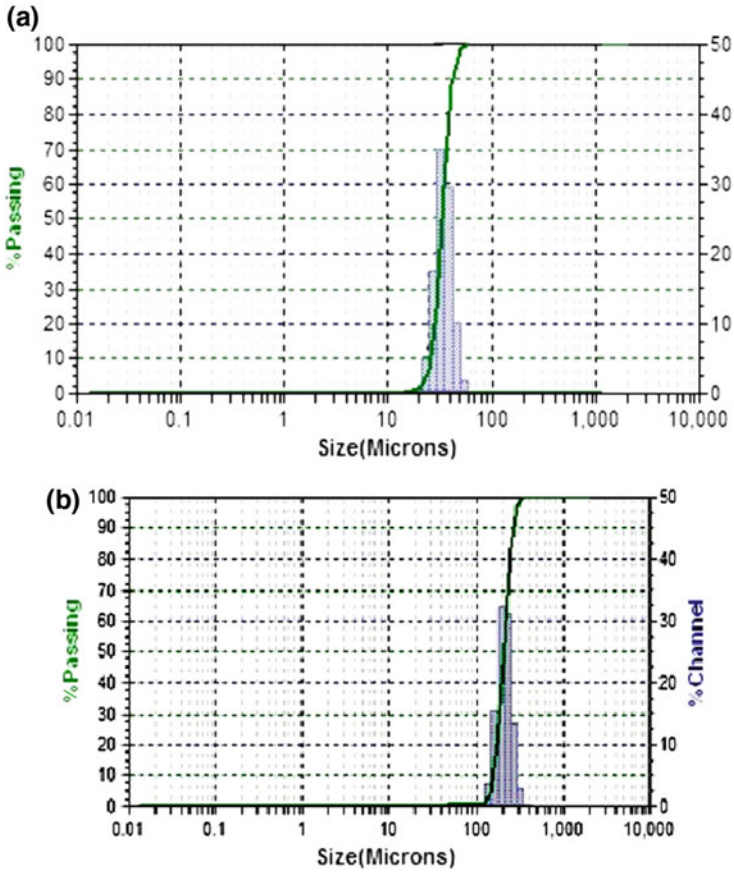


Fig. 8.13 Particle size analysis of **a** TiC powder **b** Ti6Al4V powder

characterized by irregular shape morphology that is typical of ball milled powder. The Ti6Al4V powder size is in the range of 150–350 μm. The particle size analysis is shown in Fig. 8.13b. The micrograph of the composite of the sample at a laser power of 1.6 kW is shown in Fig. 8.3. The macrograph of the deposited composite is shown in Fig. 8.14. The microstructure consists of Unmelted Carbides (UMC), dendritic TiC and re-solidified carbide. At low laser power, the microstructure consists of mainly unmelted TiC and some dendritic TiC. The melt pool created by the laser on the substrate makes the substrate to conduct the heat away as quickly as possible because the substrate is at room temperature; this causes the directional solidification as observed in the LMD process.

The grains of the substrate near the melt pool gain heat from the melt pool and results in grain growth, this forms a globular grains. The size of the globular grains reduced across the depth of the substrate because the grains far away from the melt pool gain less heat and hence less grain growth that results in smaller grain growth,

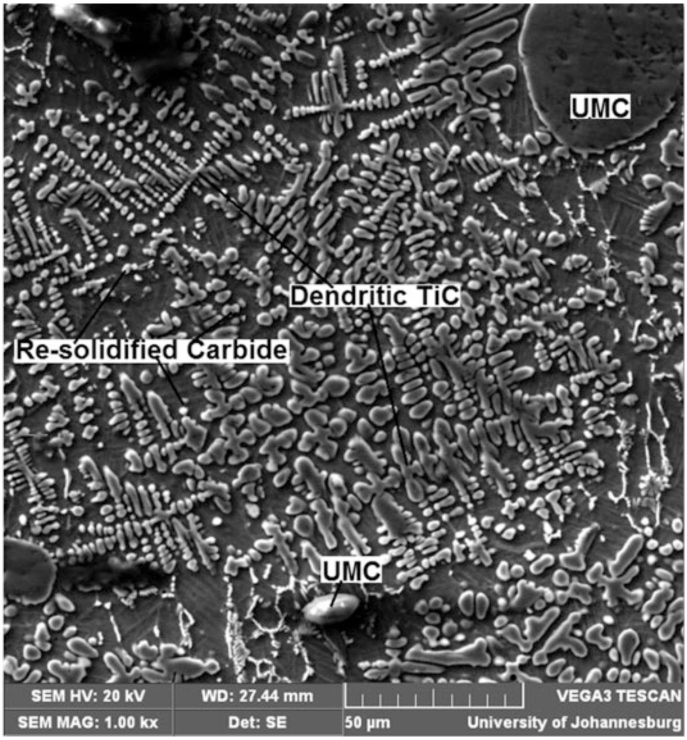


Fig. 8.14 SEM micrograph of sample at laser power of 1.5 kW

hence smaller globular grains. The rest of the structure grows epitaxially on the globular grains. The ratio of the unmelted carbide reduces as the laser power was increased. At a laser power of 2 kW the unmelted carbide disappeared and the microstructure consists of majorly dendritic TiC and re-solidified or secondary carbide as shown in Fig. 8.15. As the laser power was further increased, the microstructure consists mainly of dendritic TiC and re-solidified carbide with the dendritic arm reducing as the laser power was increased. The micrograph of sample produced at laser power of 3 kW is shown in Fig. 8.16. Comparing Figs. 8.15 and 8.16, it can be seen that the dendritic arm of the dendritic TiC arm in Fig. 8.15 is very long and the dendritic arm has almost disappear in Fig. 8.16 at very high laser power. The micrograph in Fig. 8.16 consists of mainly re-solidified carbide or secondary carbide.

At lower laser power, the deposited powders are not fully melted because the available laser power was not sufficient to fully melt the deposited powder. This is why there are unmelted carbides TiC found at low laser power as is seen in Fig. 8.14. As the laser power was increased more and more of the powders are melted. At moderately high laser power that is just sufficient to fully melt the deposited powders, the solidification is rapid and dendritic TiC are seen majorly in

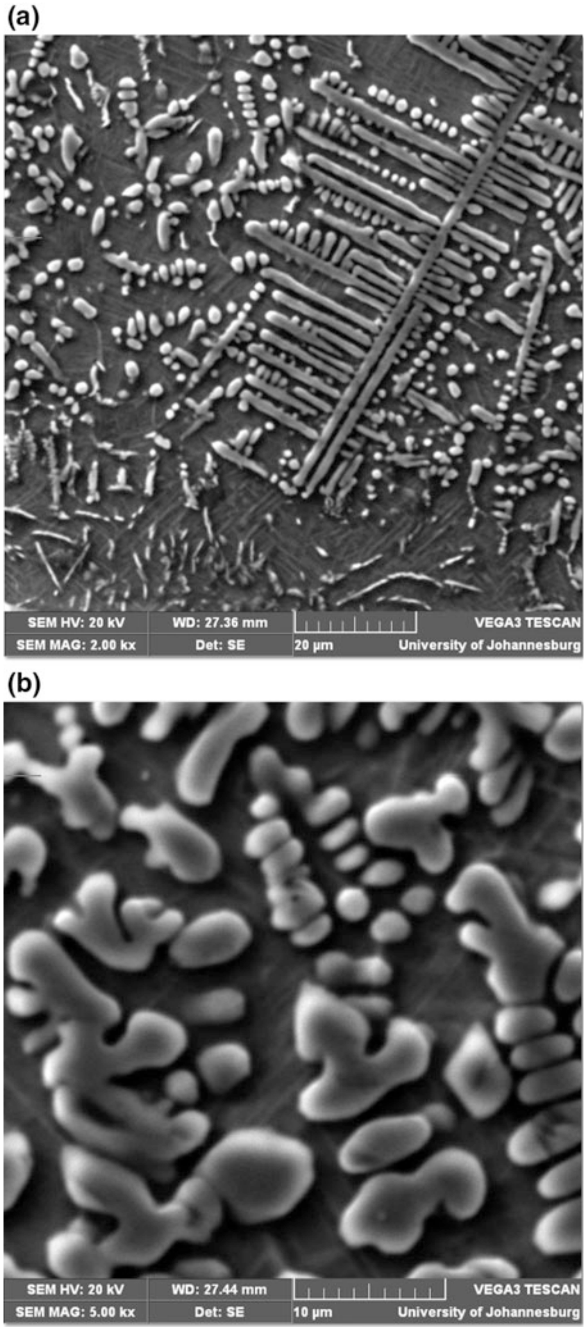


Fig. 8.15 SEM micrograph of sample produced at laser power of 2 kW **a** at low magnification **b** high magnification

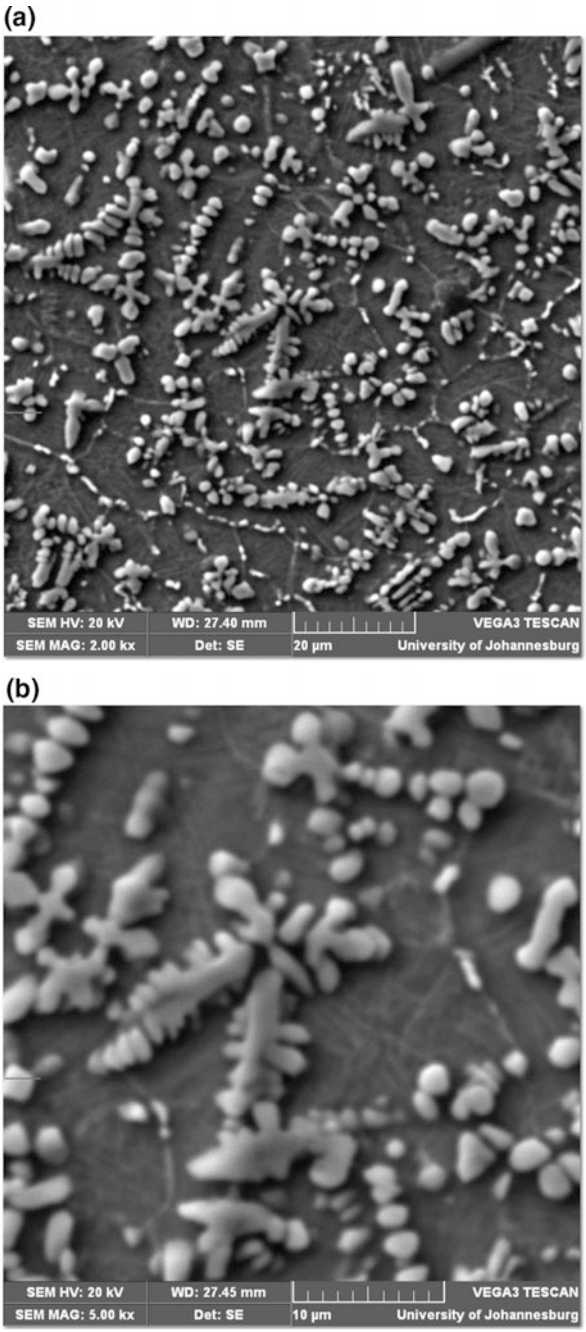


Fig. 8.16 SEM micrograph at laser power of 3 kW at **a** low magnification and **b** higher magnification

Table 8.6 Table of results

S/N	Laser power (kW)	Microhardness (HV)	Wear volume (mm^3)
0	Substrate	300.02	0.178
1	1	380.23	0.043
2	1.5	364.54	0.048
3	2.0	358.67	0.054
4	2.5	345.78	0.062
5	3.0	320.27	0.071

the microstructure with long dendritic arms. As the laser power was further increased beyond what was sufficient to fully melt the powders, this generated larger melt pool and the solidification is less rapid making more of re-solidified carbide or secondary carbide are more prominent at higher laser power. Less of dendritic carbides are seen and with low dendritic arms.

The microstructure has a direct relationship with properties. The results of the microhardness and the wear volume are presented in Table 8.6. The microhardness is found to reduce as the laser power is increased. The reason for this is not farfetched from the microstructural examination as was earlier explained.

The very high microhardness values observed at low laser power could be attributed to the higher quantity of the unmelted carbide that are seen in the microstructure due to improper melting of the powders thereby retaining some of the TiC carbide particles that are merely melted on the surface. As the laser power was further increased, the dendritic TiC grew bigger with longer dendritic arms which are also very hard. As the laser power was further increased, the dendritic TiC decreased and the secondary TiC further increased. The secondary TiC is softer there by given rise to a lower microhardness values.

The dry sliding wear test was result is presented in Table 8.6. The wear volume loss is found to increase as the laser power was increased. The analysis of the worn surfaces confirmed that the unmelted carbide found in the microstructure was responsible for the lower wear volume. The wear on the substrate is characterized by the ploughing grooves as shown in Fig. 8.17. The loose debris seen on the wear track are the work hardened Ti6Al4V particles that are produced during the rubbing action of the surface of the Ti6Al4V and the counter body. The wear mechanism is a combination of abrasion, adhesion and plastic deformation [25]. As the rubbing action continues, the frictional force between the two increased causing tearing of some of the surface material to chip off and with chips adhering to the surfaces.

The adhesion of the chip in the midst of rubbing action changed the wear mechanism from two body to three body wear mechanism causing generation of high temperature. The chips become work hardened and tear deep into the surface causing the ploughing ridges as seen in the Fig. 8.17. The wear tracks of the sample at a laser power of 3 kW and at 1 kW are shown in Fig. 8.18 and 8.19 respectively.

The unmelted carbide in the sample at a laser power of 1 kW helped to improve the wear resistance. The unmelted carbide got ground and reduced to fine powder that form protective coatings on the rubbing surfaces thereby reducing the wear

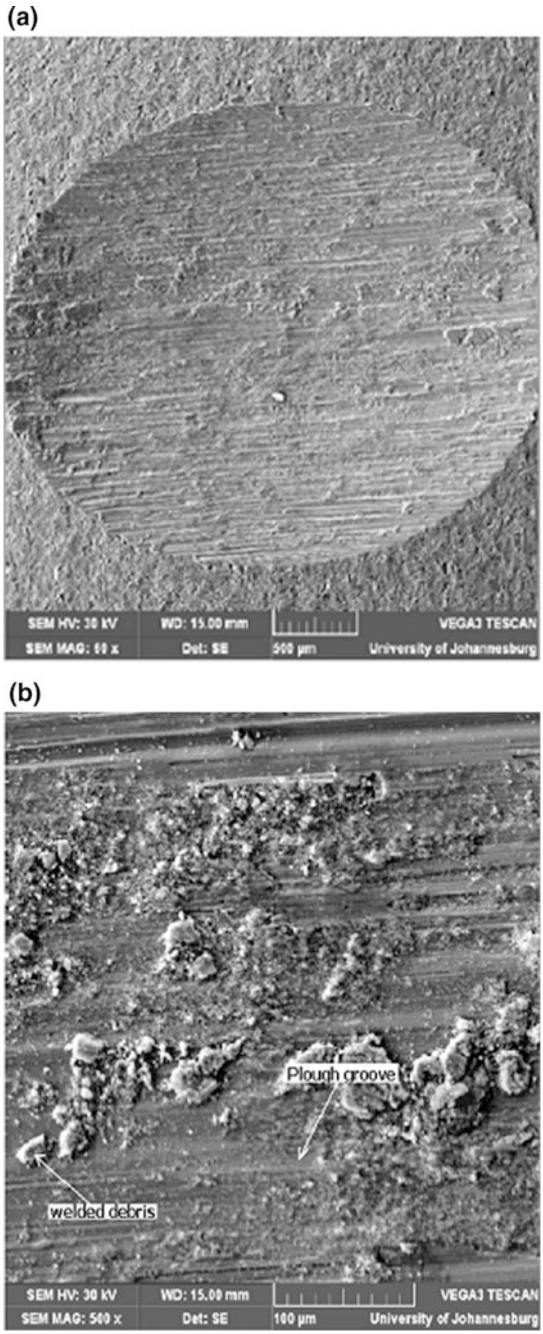


Fig. 8.17 The SEM micrograph of the wear track of the substrate at **a** low magnification and **b** higher magnification [25]

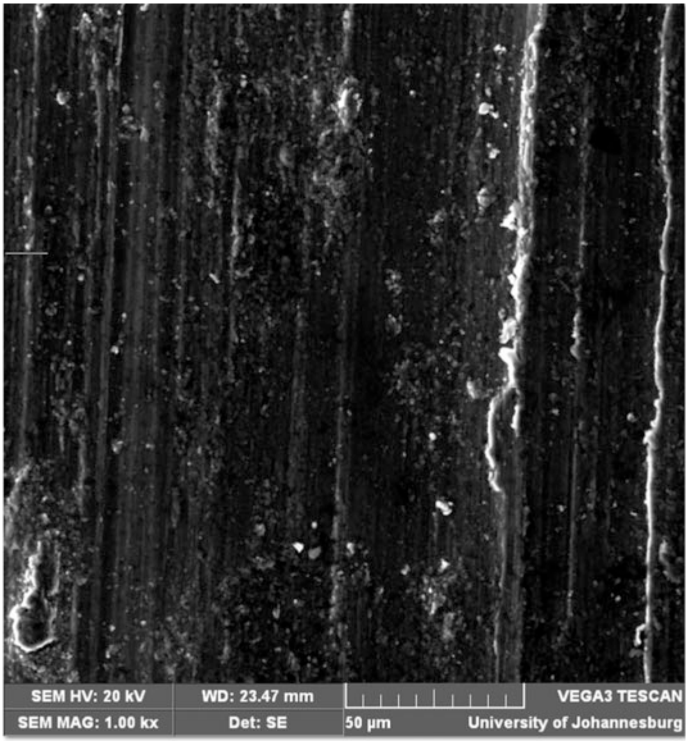


Fig. 8.18 SEM micrograph of sample at a laser power of 3 kW

action. The sample at a laser power of 3 kW showed wear track that is more aggravated because of the absence of the unmelted carbide particles. The wear track is much better than that of the substrate because the re-solidified carbides also help to improve the wear action.

8.4 Summary

The laser metal deposition of Ti6Al4V and Ti6Al4V/TiC composite has been presented in this chapter. The laser metal deposition process was seen to be very sensitive to processing parameters and it has been presented. Understanding the influence the processing parameter on the evolving properties will go a long way in controlling the properties of laser metal deposited materials. Also, an effective control system can be developed for the system to effectively control the properties of the deposited parts.

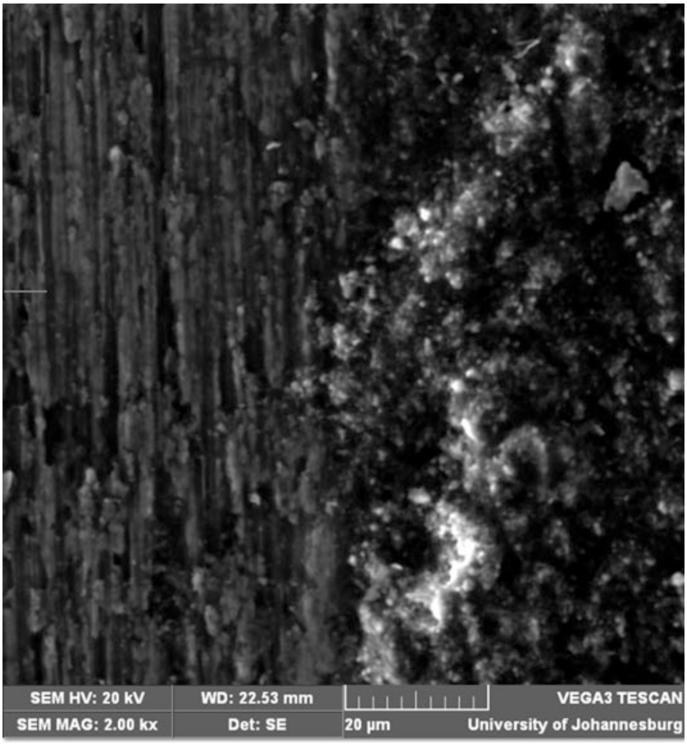


Fig. 8.19 SEM micrograph of the wear tracks of samples at a laser power of 1 kW

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Chapter 9
Research Advancements in Laser Metal Deposition Process

Abstract Laser metal deposition process is an additive manufacturing technologies that utilize laser as its source of energy to fuse and melt materials together layer after layer to produce three dimensional solid part. Laser metal deposition process has gain a lot of popularities in the research community since its inception because of the exciting properties of the power source 'laser' and because of the great potential of the process. Laser delivers heat energy in a coherent manner and with low divergence thereby making the intensity of the laser beam to be very high and can be controlled as required thereby concentrating all the intensity at a point of interest. Laser metal deposition process the capability to produce novel product that maybe difficult if not impossible to fabricate using the conventional subtractive manufacturing processes. Laser metal deposition process can help to extend the service life of parts through the innovative repair process. A number of industries have benefited from these exciting technologies which include: aerospace, automobile, medicine and jewelry. This technology is fairly new and it is a promising technology that may change the way machines are produced. The focus of this chapter is to analyze the progress in this important additive manufacturing technology in term of research efforts in this area and the current state of these technology.

Keywords Additive manufacturing · Direct metal deposition · Laser cladding · Laser engineered net shaping · Laser metal deposition · Laser powder deposition

9.1 Introduction

The laser metal deposition process is an important additive manufacturing technology that offers a number of solutions to the manufacturing industries such as the fabrication of functional parts as shown in Fig. 1 as well as in repair of worn-out parts. Additive manufacturing process has a lot of promise to revolutionized the manufacturing world [1–3] and has the potential to change the world we live in. With the advent of additive manufacturing technologies, a number of possibilities

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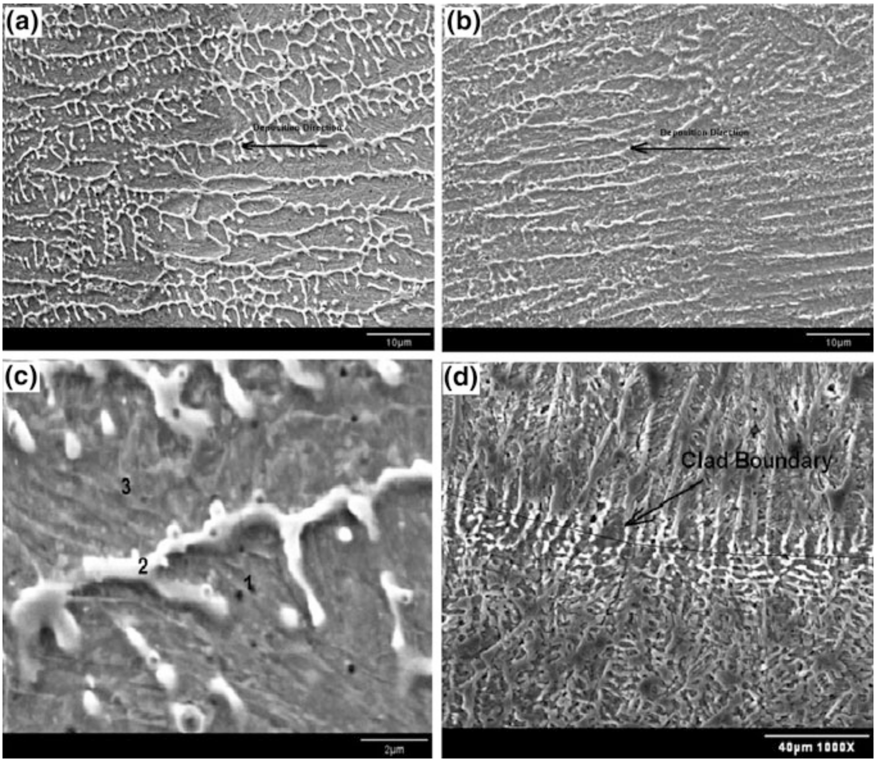

Fig. 9.1 SEM micrograph of deposited samples showing dendritic samples **a** upper deposited zone **b** lower deposited zone **c** between deposited layers **d** (**c**) at lower magnification [11]

has been brought to the manufacturing world. This manufacturing process has made it possible to fabricate parts on a micro and nano levels. Machines can now be produced as smaller and lighter as we want them to be and not being limited with how the machine will be fabricated. Laser metal deposition process comes with additional capabilities that other additive manufacturing do not possess. Laser metal deposition process can be use to add a new part on an existing part with good metallurgical integrity. This additional capability is one of the reasons why LMD process in an important manufacturing process. An obsolete equipment can be made new again with improved functionality by redesigning the equipment, removing the unneeded parts and adding the new designed part using the laser metal deposition process. Additive manufacturing technologies in general are very important due to the ability of the manufacturing process to reduce the energy intensive manufacturing processes and help to reduce global warming problem.

In this chapter, additive manufacturing is briefly described in order to bring to context the laser metal deposition process. The research efforts on the laser metal deposition process is then presented.

9.2 Additive Manufacturing

Additive manufacturing (AM) process also known as three-dimensional (3-D) printing [1] is an advanced manufacturing process that produces part directly from the computer aided design (CAD) model or image of the part to be made by adding materials layer by layer. According to the ASTM F-42 committee on additive manufacturing, Additive Manufacturing is defined as: "The process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing technologies" [1]. The principle of operation of additive manufacturing is such that the CAD model of the part to be made is converted to Additive-Manufacturing File (AMF) format [1]. The old file format is the standard triangulation language (STL) file. This old file format is not capable of defining some characteristics that are now present in the new file format. The AMF format is based on an open standard Extension Mark-up Language (XML). The AMF format is capable of describing in detail, the texture of the part, the colour, the curve triangles, the lattice structure, as well as the functionally graded materials. All these capabilities are absent in the old STL file format. The AMF format represents the 3-D surface assembly of planar and curved triangles that contains the co-ordinates of the vertices of all these triangles. After the conversion process, the AMF is sliced into two dimensional (2-D) triangular profile sections as defined by the geometry of the CAD model and the chosen build orientation. After the slicing is completed, the building of the part is commenced. The part is produced by adding the materials layer after layer until the building process is completed and the part is removed from the building platform. The finishing operations such as removal of support structures is then performed. Also, heat treatment can be performed on the part depending on the service requirement of the part. Any part that can be modelled digitally can be built using additive manufacturing process [1]. This provides a lot of flexibility for the design engineer, which enable the engineer to design part based on the functionality of the part as against based on the manufacturability of the part which was the practice when using the traditional manufacturing process. Also, the engineer can modify any existing design without having to start from the scratch, thereby saving the overall cost of production.

In AM processes, the machine uses the descriptions of the component to be created to build the component by adding material layer after layer until a 3D object is created. A number of raw materials are used in AM processes, they include: liquid, powder, wire, and sheet made from plastics, polymers, metals, alloys or ceramics. There are a number of advantages of additive manufacturing technologies when compared with the traditional or conventional manufacturing processes. In the traditional manufacturing processes, products are made by removing materials, especially in machining processes, in order to achieve the desired shape, this is referred to as subtractive manufacturing. Parts can also be created in traditional manufacturing methods by injecting molten material into a mold or by applying forces on heated or cold materials in order to achieve the desired shape. These traditional manufacturing processes are labour as well as energy intensive. Also, when a complex part is needed to be produced, the product designer has to break down the parts into smaller units in order for the part to be produced. The designers design the parts based on the ease of manufacturing such parts. These smaller parts are later assembled using extra materials from both, nuts rivet or filler materials in welding. All these processes are time consuming, laborious, and expensive. It also makes the component produced to be heavy because of all the extra materials used in joining the various parts together. However, additive manufacturing process is having an edge in this type of manufacturing demand by simply producing part through addition of materials directly from the CAD image of the required part and produce the part as a single unit, which is as against what is achievable in the traditional manufacturing route. Additive manufacturing technologies are used to produce models, patterns, tooling, prototypes, and functional parts using a variety of materials. Additive manufacturing technologies are used by a number of industries which includes: motor vehicles, aerospace, machinery, electronics, and medical products. Additive manufacturing process is grouped into two main categories depending on the energy source used in the system, namely: laser additive manufacturing and non-laser additive manufacturing. A number of additive manufacturing processes have appeared many of which are the same process but with different names. To ensure that standardization is achieved in additive manufacturing industry and because of how the same process is given several names which is not only confusing for a lay person but also cumbersome, additive manufacturing technologies was recently classified into seven classes by the international standard organization committee on additive manufacturing (committee F42) [1]. These seven classes of AM technologies are presented in Table 9.1.

Table 9.1 Classification of additive manufacturing

S/N	Class	Example of technologies	Process description
1	Vat photo polymerization	Stereolithography, digital light processing	Uses light source to cure layers of liquid material (photopolymer) in a vat as defined by the CAD model data
2	Material jetting	Poly jet, ink-jet thermo jet	Droplets of materials are cured by exposing them to the light according to the path dictated by the CAD data using a moving inkjet-print head to deposit material across a build area
3	Binder jetting	3D Printing, Ink-Jet Printing, S-Print, M-Print	Binding agents are used to consolidate powder material and traced according to CAD data using an inkjet-print head
4	Powder bed fusion	Selective laser sintering, selective laser melting, electron beam melting	Thermal energy is used to selectively fuse or melt powder preplaced on the build platform

(continued)

Table 9.1 (continued)

S/N	Class	Example of technologies	Process description
5	Material extrusion	Fused deposition modeling	Heated material is extruded following the path dictated by the CAD data
6	Sheet lamination	Ultrasonic consolidation, laminated object manufacturing	Sheets are bonded layer after layer and traced according to the path described by the CAD data
7	Directed energy deposition	Laser metal deposition, electron beam melting, laser powder deposition etc	Thermal energy is used to create a melt pool on the substrate, materials are introduced in the melt pool to fuse materials by melting them as they are deposited following the path dictated by the CAD data

Laser metal deposition process that belongs the directed energy deposition class of additive manufacturing technology is the focus of the next section.

9.3 Laser Metal Deposition Process

Laser metal deposition (LMD) process belongs to the directed energy deposition class of additive manufacturing and it is an AM technology that is more favoured because of the good properties delivered by the laser that enables the laser energy to be directed as required. Laser metal deposition process, like any other additive manufacturing can produce low-volume, customized, and complex part at no extra cost for complexity thereby allowing the production of any design of prototypes and parts comparatively cheaper than the traditional manufacturing processes. It reduces time to market of new product and also allows the satisfaction of customers whose demand is now moving from general product to more customized product. An important capability of LMD process that cannot be achieved by other classes of AM technology is that it can be use to repair high valued components that could not be repaired by any other manufacturing process [4, 5]. Laser metal deposition process allows the manufacturing of highly customized and complex parts; it also offers different industries a large number of opportunities in terms of verities of products they can achieve. The technology makes it possible to produce objects of any shape and any complex geometry at no extra cost. This technology will actually shift the way we design from the conventional product design which is manufacturing technique based design to part functionality based design. However, laser metal deposition process is yet to reach its full potential because of the stumbling blocks which are yet to be conquered because the technology is relatively new and the physics of the system is yet to be fully understood. The research efforts in this field are in the next section.

9.4 Research Progress in Laser Metal Deposition Process

A number of research work has appeared in the literature since the technology was invented. Laser metal deposition process has been found to be sensitive to the processing parameters and the process could be highly unstable. A number of this studies showed that the laser metal deposition process can be controlled by controlling the processing parameters. Some of these parameters and their influence on the properties of laser metal deposited materials have been investigated widely and some of this research works are presented in this section.

Laser power is an important processing parameters in laser metal deposition process. Shuklar et al. [6] studied the influence of laser power and powder flow rate on properties of laser metal deposited titanium alloy. The physical properties (deposition height and deposition width), metallurgical property and microhardness properties of the laser deposited titanium alloy-Ti6Al4V. The laser power was varied between 1.8 and 3.0 kW while the powder flow rate was varied between 2.88 and 5.67 g/min, while the gas flow rate and scanning speed are maintained at constant values of 2 l/min and 0.005 m/s respectively. The results showed that the deposition width was found to increase with increase in laser power. This could be attributed to increased dilution at higher laser power which is not desirable in the laser metal deposition process. Dilution needs to be kept low and it should also be enough to achieve the needed bonding between the substrate and the deposited layer or the previous layer. Proper control of laser power will help to achieve the required good metallurgical integrity and also minimize dilution that results in wastage of material and increase in weight of the component which is not required. A similar study was conducted by Mok et al. [7] and Brandl et al. [8]. Mok et al. [7] also studied the effect of laser power, scanning speed and wire feed rate on laser metal deposition of Ti6Al4V wire. The results showed that the processing parameters has great influence on the microstructure and hardness. Yu et al. [9] studied the influence of laser power on properties of laser metal deposited Ti6Al4V. The influence of laser power on the microstructure, the yield and ultimate tensile strengths of the fabricated parts are studied and compared with those of the cast and wrought materials. The results showed that the properties varied with the laser power. The laser deposited materials are also found to be superior to those of cast and annealed wrought material. Mahamood et al. [10] also studied the influence of laser power on the properties of laser metal deposited titanium alloy and also found a similar result.

Influence of process parameter on the properties on laser metal deposited tool steel was investigated by Choi and Chang [11]. The process parameters studied are the laser power, traverse speed and scanning speed while the properties that were studied are the hardness, porosity, microstructure, and chemical composition. The microstructure in the upper and lower of the deposited zone are shown in Fig. 9.1a and b respectively. The microstructure consists of dendritic structures that grows along the deposition direction and at perpendicular direction to the clad boundary with the substrate. Microstructure between two deposited layer is characterized by fine dendritic structure as shown in Fig. 9.1c, d which could be attributed to reheating of the previous layer by the new layer.

The EDX analysis of point 1 to 3 on the micrograph in Fig. 9.1c showed that point 1 is the composition of the as received powder. the Point 2 with fine dendritic structure and point 3 with inter-dendritic structure show a little difference in composition as compared to point 1 [11]. The results showed that the laser power, layer thickness and porosity are strongly affected by powder flow rate. The higher the powder feed rate, the higher the pore formation. This could be attributed to the fact that the available laser power was unable to properly melt the deposited powder thereby resulting in some powders that are not melted and hence creating porosity when the powder comes off. Also, the overlap percentage was also found to have a great influence on the porosity. The higher the overlap percentage, the lower the porosity. The microhardness was found to increase with increase in the scanning speed. A number of research has been conducted by the author and other researchers on the laser metal deposition process on titanium alloy, titanium alloy composite and functionally graded material of Titanium alloy composite and the readers can consult for further reading [6, 10, 12–36]. A number of research work on repair and remanufacturing using laser metal deposition process can also be consulted through these references [4, 37–57].

A large number of research work on the modelling of the laser metal deposition process has also been conducted towards the proper controller design for the system. There has been a considerable challenge in the accurate numerical modelling of the process because the process is a highly nonlinear one and with any nun linear system accurate system modelling is always very challenging. The nonlinearity of the process parameter on the evolving properties [30], the evolution of phase changes and the mass and heat flows in the system make it a very complex one. In order to further understand the process physics of the laser metal deposition process, there is need for proper modelling and simulation of the different stages of the process. Progress in the field of modelling the laser metal deposition process from the physical to the residual stress as well as repair in the laser metal deposition process has been presented by a number of researchers and the readers can consult the bibliography for further reading [58–125].

9.5 Summary

Laser metal deposition process, an important additive manufacturing process, has received an impressive attention from the research community because of great potential of this manufacturing process. A number of research work has appeared in the literature both from experimentally and analytical modelling of the process. The importance of modeling and simulation of the process cannot be overemphasized because of the benefit it has on the development of effective controller design for the system. The better the process is understood and adequately modelled, the simpler the controller design for the system becomes. Some of the research works on the laser metal deposition process are presented in this chapter and extensive bibliography are presented for the benefit of the readers.

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Chapter 10
Future Research Need and in Laser Metal Deposition Process and Summary

Abstract This book presents the laser metal deposition process, and advanced manufacturing process that belongs to a class of additive manufacturing technologies for the production of metals alloys and composite materials. The additive manufacturing technology was introduced and the brief background of the laser metal deposition process was also reviewed. The important energy source used in the laser metal deposition process is laser and it offers a number of capabilities that makes this manufacturing process to leave up what is expected. The laser was also reviewed in Chap. 2 of the book to bring to understanding of the reader and to know how important laser is in the laser metal deposition process. The processing parameters are of great importance in the laser metal deposition process and are also analyzed in this book. Areas of applications, case study and research advancement in laser metal deposition process are also presented. This chapter presents the future research direction in the field of laser metal deposition process and the chapter ends with the summary of the book.

Keywords Additive manufacturing · Alloys · Composites · Laser metal deposition · Metals · Titanium alloys

10.1 Introduction

Additive manufacturing (AM) technology is an advanced manufacturing technology that is promising to revolutionize the world [1]. Advantages and the promises of the AM technologies ranges from changing the way products are designed to how end of life of material is converted to renewable use. These capabilities does not only create flexibilities to product designers who's main focused will be diverted to the functionality of the product as against the manufacturability of the products but also help to extent the useful life of a product. Laser metal deposition process (LMD) is one of the AM technologies that are unique with combination of

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properties. This additive manufacturing technology has positioned itself to help to reduce global warming. The life of a material can be extended with LMD process through its ability to effectively carry out repair on broken part that would have been discarded in the past and recycled through an energy intensive process that increase the global warming effect. The laser metal deposition process is also very promising in taking care of legacy products whose original manufacture are no longer in business. In the past, any damage to such product could land them to recycling plant because of the unavailability of parts which would result in loss of investment and also increase in global warming effect. Legacy product can now be put to good use and even with better productivity because unproductive parts can easily be redesigned and replaced with improved design and then remanufactured using the laser metal deposition process [2]. The laser metal deposition process has helped to reduce the quantity of materials in the scrap yards because of its ability to add new material to old material with strong metallurgical bond. Materials that would have been considered scrap in the past because they cannot be repaired or because it is difficult or prohibitive to repair can now be brought back to their useful life and even with extended life using the laser metal deposition process [3–7]. New parts can also be fabricated directly from the three dimensional computer aided design information of the intended component through the addition of materials layer after layer [8]. Mass customization in also achievable with the laser metal deposition process [9–13]. The consumer goods are now moving away from the usual standardized product to more customized ones. Everyone is interested to have his or her own signature incorporated into the product being used and for manufacturing companies to remain competitive in the manufacturing world, they should be able to produce customize products at mass production rate. That is at a cheap rate and also on time. Laser metal deposition process is a promising manufacturing process in this regard. More than one customized product can be made simultaneously. If the drawing of the parts are arranged together on the same work space and loaded into the LMD machine, the parts will be made and completed at ones. A number of industries are currently benefiting from this exciting additive manufacturing process such as the aerospace, automobile and the petrochemical industries. A number of high valued parts have been repaired in these industries using the laser metal deposition process. New parts are also being manufactured using the laser metal deposition process. More critical parts could be made if some of the unanswered research questions are answered.

A number of research works has been done in the field of laser metal deposition process and more still needs to be done on the process in terms of research so as to be able to use the process to manufacture critical parts most especially in the aerospace industries. The future research need in the laser metal deposition process is presented in the next section and the summary of the book is also presented at the end of this chapter.

10.2 Future Research Need in Laser Metal Deposition Process

The laser metal deposition process is being increasingly used in the industries for building of new product, for surface modifications, in rapid tooling and repair processes. A number of issues are yet to be resolved with this technology. Modelling of LMD is difficult as it is characterized by multiple phase changes, mass and heat flows. The LMD process is analyzed in detail and subsequently and need to be considered in future research. System modelling and simulation is an important research area that needs to be greatly worked on. A proper modelling of the laser metal deposition process that truly represent the process physics will go a long way in the development of the feed forward and feedback controller that will help to effectively control the system to achieve desired physical, mechanical and tribological properties of materials processed using the laser metal deposition process. Also, more focused research and development are required in process repeatability, and efficient feedback and feed forward control will greatly help to achieve this in a laser metal deposition process. There is need for process parameter standardization and process calibration standards which will help various laser metal deposition process machines to produce identical products no matter the location of the machine or age of machine. More research is required to further understand the material behaviour during the laser metal deposition process. This include: the response of material to the rapid heating and cooling process which is the characteristics of this additive manufacturing technology. New materials need to be developed specifically for laser metal deposition process because using the existing materials will limit the novel material that can be developed using this novel manufacturing process. The thermodynamic limitation on the formulation of alloys can be override with laser metal deposition process and new materials can easily be formulated and developed through extensive research work. A new process- property relationship needs to be developed for the laser metal deposition process which will help in wider acceptability of this additive manufacturing process and a number of critical aerospace parts can be made using this process.

10.3 Summary

Laser metal deposition process, an additive manufacturing technology has been presented in this book. The book was introduced in chapter one where the background of the LMD process was presented. The advent of laser has really has really revolutionize the world because it has found its application in almost all areas of human Endeavour. The use of laser in material processing has been phenomenon. The properties of laser that have made it useful in all areas of human endeavor were explained in chapter two. Laser metal deposition process was presented in chapter three. The description of the LMD process was presented. The solidification mechanism and microstructural development in the in the laser metal deposition process are also presented in chapter three. Laser metal process is very sensitive to the processing parameters. The most significant processing parameters include the laser power, scanning speed, powder flow rate and gas flow rate. The influences of each of these processing parameters on the properties on the laser metal deposited materials are explained in chapter four. Different materials can be processed using the laser metal deposition process. Processing of metals and alloys are presented in chapter five. Laser metal deposition process is flexible such that it can process more than one material at the same time, making it possible to process composites and functionally graded materials. Laser metal deposition of composites and functionally graded materials are presented in chapter six. Laser metal deposition process can be used to produce three dimensional components directly from the three dimensional computer aided design digital image of the part. Laser metal deposition process can also be used to repair high valued parts that were not repairable in the past. The manufacturing process can also be used to produce hard wear and corrosion resistance coatings on an existing part to improve its surface properties and extend its service life. Application areas of laser metal deposition process are presented in chapter seven. Case study on laser metal deposition process of titanium alloy and titanium alloy composite are presented in chapter eight. The research progress in the laser metal deposition process is presented in chapter nine.

The future research need and summary is presented in this chapter. The book ends with the overall summary of the book.

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