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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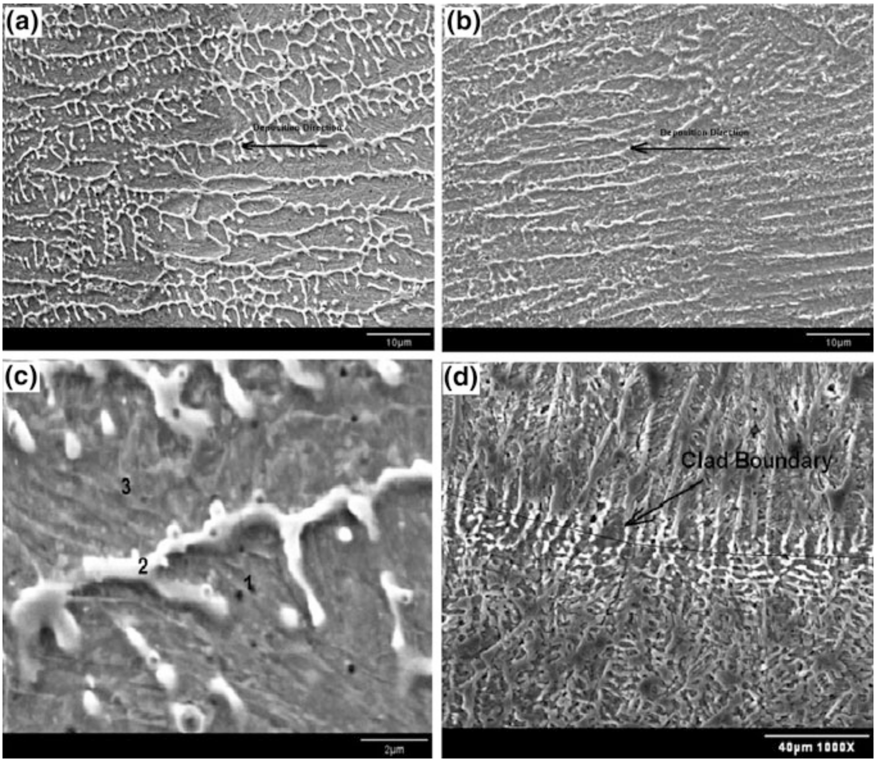

Fig. 9.1 SEM micrograph of deposited samples showing dendritic samples **a** upper deposited zone **b** lower deposited zone **c** between deposited layers **d** (**c**) at lower magnification [11]

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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