Investigation of Additive Manufacturing Process by LMD Method, Affecting Process Parameters on Microstructure and Quality of Deposition Layers

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Received: 17 March 2021 - Accepted: 04 June 2021

Abstract

Additive manufacturing (AM) is a general name used for production methods which have the capabilities of producing components directly from 3D computer aided design (CAD) data by adding material layer-by-layer until a final component is achieved. Included here are powder bed technologies, laminated object manufacturing and deposition technologies. These technologies are presently used for various applications in engineering industry as well as other areas of society, such as medicine, aerospace, architecture, cartography, entertainment. Laser metal deposition (LMD) using powder as an additive is an AM process which uses a multi-axis computer numerical control (CNC) machine to guide the laser beam and powder nozzle over the deposition surface. The component is built by depositing adjacent beads layer by layer until the component is completed. LMD has lately gained attention as a manufacturing method which can add features to semi-finished components or as a repair method. LMD introduce a low heat input compared to arc welding methods and is therefore well suited in applications where a low heat input is of an essence. For instance, in repair of sensitive parts where too much heating compromises the integrity of the part. It has been found that the most influential process parameters are the laser power density, scanning speed, powder feeding rate and powder standoff distance and that these parameters has a significant effect on the characteristics of the material such as microstructure.

Keywords: Additive Manufacturing (AM), Laser Metal Deposition (LMD), Process Parameters, Power Density.

1. Introduction

Additive manufacturing (AM) techniques are used in various industries to create physical prototypes as well as end-use parts. Additive manufacturing processes refer to layer by layer joining of materials to make end-usable products. The benefits of AM over traditional manufacturing include (i) complex part manufacturing without excess tooling needs, (ii) reduced number of processing steps and (iii) minimal requirement for post-processing. While all AM processes involve layer-based generic approach starting from CAD model generation to post-processing/finishing of built parts, they essentially differ in the processing strategy by means of (i) the materials that can be used and their initial properties, (ii) how the layers are created, and (iii) how the layers are bonded to each other. Such differences will eventually determine the accuracy of build part, its properties and performance [1]. This development can be attributed to the opportunities AM offers. To this end, several digital methods for designing printable parts and for planning AM processes have been developed. In addition, file formats to store and exchange the resulting data have emerged [2].

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It should be mentioned that, over the past 2 years major aerospace and other manufacturers such as General Electric (GE) have opened advanced manufacturing and additive manufacturing centers in various parts of the world (2016–2017). In addition, facilities for producing precursor products, especially metal and pre-alloyed powders have been constructed [3]. In the international standard ISO/ASTM 52900, AM is defined as a “process of joining materials to make parts from 3D model data, usually layer upon layer”. It is an alternative to conventional manufacturing processes, in which, for example, material is formed in molds or subtracted by milling. There are numerous ways in which units of material can be joined together to form a part. Different types of materials are being held together by different types of atomic bonds for instance, metallic materials are typically held together by metallic bonds. The type of bonding provides the most fundamental conditions for how that type of material can be joined in an additive process. Besides the type of material, the joining operation is also dependent on in which shape the material is delivered to the system, and how it is distributed. For additive manufacturing processes, the feedstock, the bulk raw material that is fed into the process, can typically come in the form of powder, filament and sheet. Dependent on the shape, the feedstock may then be distributed layer by layer in a powder bed, deposited by a nozzle, applied as layers in a sheet stack, deposited through a print head, or applied as a liquid, paste or slurry in a vat. In respect to the great possibilities for variation in different types of materials, different types of feedstock and means of distribution of the feedstock, there is large number of possible principles that could be used for additive manufacturing processes. However, while there are significant research and development activities in this area world-wide, far from all potential solutions have been realized in a working process, and fewer still have reached the market [4].

The parts are fabricated in a single operation where the basic geometric shape and basic material properties of the intended product are achieved in a single operation simultaneously. Removal of the support structure and cleaning may be necessary. Fig. 1. represents overviews of AM processing principles for metallic materials [4].

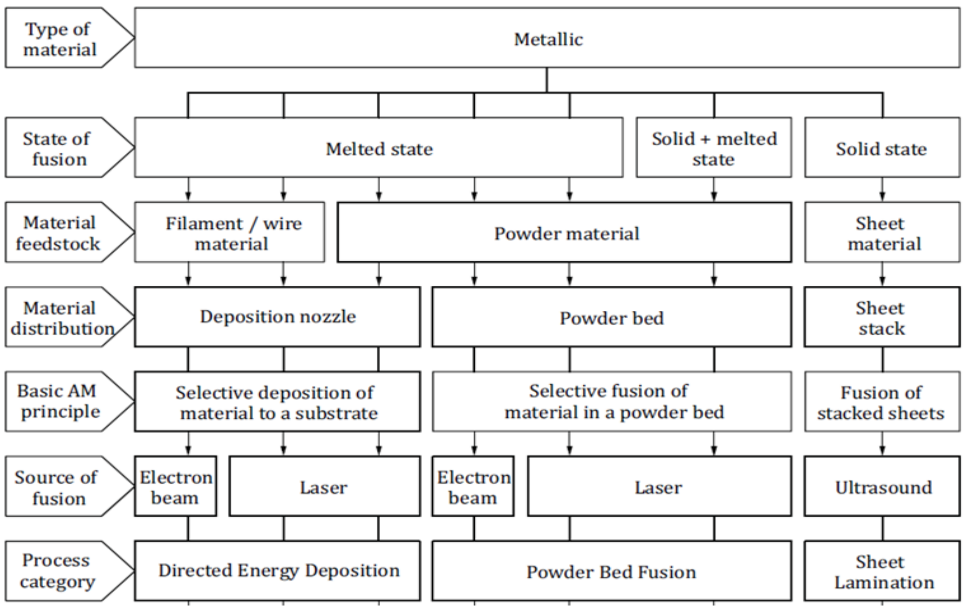

Fig. 1. Overview of single-step AM processing principles for metallic materials [4].

Table. 1. The comparison between different types of additive manufacturing processes – by authors.

AM	Process	Energy Source	State Of Starting Material	Layer Creation Technique	Application	Advantage	Disadvantage
Direct Energy Deposition (DED)	LMD	Laser Source	Powder / Wire	On-demand Powder injection and melted by laser	Metal Part Repair, Tooling, Functional Part	Layer can be fabricated in any orientation, variety of materials in powder form can be processed, Large components can be manufactured and Higher deposition rates are possible	Geometrical accuracy is lower, Stair-stepping effect can limit geometrical accuracy and Post-processing operations may be required
	DMD	Laser Source	Powder / Wire		Tooling, Functional Part		
	LENS	Laser Source	Powder / Wire		Tooling, Functional Part		
Powder Bed Fusion (PBF)	SLM	Laser Source	Powder	Laser scanning	Tooling, Functional Part	Good geometrical accuracy, No support structures are required, Suitable for the processing of metallic materials and Produced components are near fully-dense, suitable for functional use.	Size of produced components is limited by the dimensions of the enclosing chamber, Availability of materials is limited, Slow build-up rate and Machining may be required for accurate dimensioning and improving surface finish
	EBM	Electron Beam	Powder	Electron Beam Scanning	Tooling, Functional Part		
	DMLS	Laser Source	Powder		Tooling, Functional Part		

According to Fig. 1. the process category is classified into three groups, including direct energy deposition, powder bed fusion and sheet lamination. It can be also stated that, direct energy deposition can be indicated as Laser metal deposition (LMD).
Table. 1. Denote the comparison between different types of additive manufacturing processes in Energy Source, State Of Starting Material, Layer Creation Technique, Application, Advantage and Disadvantage. According to this table, process LMD can be used to reconstruct and repair sensitive and expensive parts, and by doing so, those parts can be used again. For example, process LMD can be used to repair gas turbine blades that cannot be used in gas turbines due to mechanical impact fractures or local corrosion. Another advantage of the LMD process is the unlimited size of the parts, which is very important and practical.

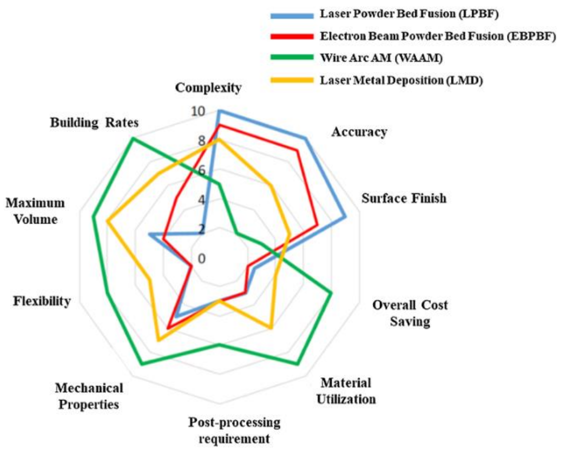

Fig. 2. Comparison framework among different metal AM technologies used in the aerospace industry [5].

Fig. 2. compares various types of metal additive manufacturing processes which applied in the aerospace industry. As can be seen, different factors in the manufacturing process, such as flexibility, surface finish, overall cost and production volumes, are considered in this diagram. In a general view, each AM technology can be compared with the others [5].
LMD is a novel manufacturing method that has a great potential to reduce material waste through near net shape production as well as to add value to a manufactured component.
LMD either uses powder or wire as feedstock material. To distinguish between these two methods LMD-p and LMD-w will be used when referring to the powder method and wire method, respectively.
LMD-p has a relatively low deposition rate and is most suited in producing small components; add on features on semi-finished components or as a repair method. LMD-p introduce a low heat input compared to arc welding methods and is therefore well suited in applications where a low heat input is of an essence. For instance, in repair of sensitive parts where too much heating compromises the integrity of the part by e.g. microstructural degeneration or by deviations in the dimensional precision caused by residual stresses. This method is the main focus in this paper [6].
The main advantages of LMD-w compared to the LMD-p method is a higher deposition rate, less porosities in the deposited material and better surface finish. However, this comes at the cost of higher heat input. Additionally there is an inherent challenge in LMD-w when it comes to controlling the process.
The process is sensitive when it comes to coupling the wire; laser and deposition surface together and small variations in the surface or wire feed rate can cause problems in the process. Additionally, LMD-w is a directionally asymmetrical process which further complicates the control of the process. In LMD-w components are built by depositing adjacent beads in layers, as described in Fig. 4. The weld torch supplies the wire to the melt pool created by the laser.
The wire can be heated by the use of electricity through the weld torch while the actual melting of the wire is done using the laser [6]. Here is the great differentiator that makes LMD processes suitable for large components where high buy-to-fly (BTF) ratios make conventional manufacturing extremely expensive because of the material costs. Table. 2. represents some examples of BTF ratios achieved for various aerospace components [7].

Table. 2. The weight of billets, the weight of final parts, and Buy-to-Fly (BTF) ratios of aerospace components [7].

Component	Billet (kg)	Finished product (kg)	BTF Raito %
Intercase	182	30	6.1
Simple duct flange 1	67	11.1	6
Simple duct flange 2	67	7.7	8.7
Complex duct flange 1	149	7.7	19.4
Complex duct flange 2	207	10.3	20.1
Large blisk	810	97	8.4
Wing Rib	657	18	37

Lastly, and only by LMD, it is possible to add material to repair damaged or worn metal components. Effectively, this could be com-pared to CNC welding or cladding processes but would have to be complemented by sophisticated metrology and design tools in order to be effective. Therefore, repair of parts using AM would only be feasible in planned and repeatable scenarios, and where scrapping the part would have a bigger impact in terms of value or spare part availability [8].

2. LMD Process with Powder

2.1. Deposition Process

In LMD, a melt pool is created on the surface of the printed structure using a laser, an electron beam, or an electric arc. At the same time, metal powder or wire is added to the melt pool in order to generate an additional layer [9].

LMD is an AM process which uses a multi-axis computer numerical control (CNC) machine or robot to guide the laser beam and powder stream over the deposition surface.

The component is built by depositing adjacent beads layer by layer until the component is completed, as illustrated in Fig. 3. There are some different nozzle types which provide the powder either off-axis though an external nozzle or coaxially where the powder is provided ax symmetrical to the laser beam [6].

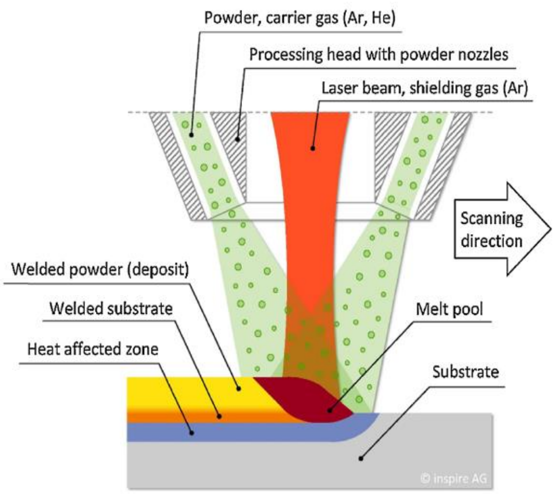

Fig. 3. A cross section of a coaxial LMD nozzle [10].

2.2. Equipment in LMD

Nozzle: There are mainly two types of nozzles in LMD: coaxial nozzles and off axis nozzles. The coaxial nozzles that show in Fig. 4. have the advantage of being directionally independent since there is symmetry between the powder and laser. With an off axis nozzle the powder is fed from the side which means that the efficiency of the deposition process will vary with changes in the deposition direction.

With a coaxial nozzle the powder enters the laser beam above the surface which has an effect on the laser attenuation and distribution at the deposition surface as well as the powder temperature before entering the melt pool [6].

Powder feeding subsystem: The powder feeding subsystem is responsible for the uniform and controllable transfer of metal powder to the melting zone.

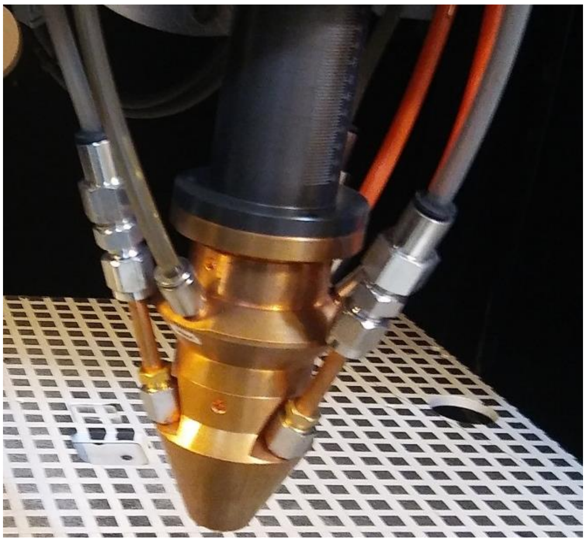

Fig. 4. Coaxial nozzle.

This system is equipped with a stirrer to improve the fluidity of the powder and can have a twin chamber with the ability to transfer two types of powder simultaneously and separately that illustrate in Fig. 5. It should be noted that this system transports metal powder with the help of carrier gas, which can be Argon, Nitrogen or Helium.

Fig. 5. Powder feeding subsystem.

Lasers: Many of the earliest AM systems were based on laser technology. The reasons are that lasers provide a high intensity and highly collimated beam of energy that can be moved very quickly in a controlled manner with the use of directional mirrors. Since AM requires the material in each layer to be solidified or joined in a selective manner, lasers are ideal candidates for use, provided the laser energy is compatible with the material transformation mechanisms. There are two kinds of laser processing used in AM; curing and heating. For heating, the requirement is for the laser to carry sufficient thermal energy to cut through a layer of solid material, to cause powder to melt, or to cause sheets of material to fuse. For powder processes, for example, the key is to melt the material in a controlled fashion without creating too great a build-up of heat; so that when the laser energy is removed, the molten material rapidly solidifies again [11].

The technical specifications of the laser system depend on factors such as the power of density, type of laser, the laser mode, the frequency and the wavelength.

2.3. Material and Powder Characteristics

Any powder material or powder mixture which is stable in a molten pool can be used for construction of parts. In general, metals with high reflectivity's and thermal conductivities are difficult to process, such as gold and some alloys of aluminum and copper. Most other metals are quite straightforward to process, unless there is improper atmospheric preparation and bonding is inhibited by oxide formation. Generally, metallic materials that exhibit reasonably good weld ability are easy to process. For powder feedstock, the powder size typically ranges from approximately 20–150 µm. It is within this range that powder particles can be most easily fluidized and delivered using a flowing gas. The interaction between powder and laser largely depends on the particle size of the powder grains. It has been shown that larger particles decrease the laser attenuation which leads to more laser power being available at substrate level [12]. Consequently the weld pool becomes wider and deeper with larger particles. Smaller particles heat up more quickly and thus have a higher probability of being completely molten when entering the melt pool. However, if the particles are too fine the shielding gas may blow them away. Additionally, if the particles are too fine and densely packed there is a risk of plasma forming [13].

The powder quality is an important factor when it comes to porosity in the LMD deposit. The powder used in LMD is mainly manufactured by either gas atomization (GA) or plasma rotation electrode process (PREP). Both methods produce spherical powder particles although the result and quality can vary greatly between suppliers and manufacturing method. GA powder has a well-established manufacturing process and high production rate which helps in keeping the cost down whereas PREP powder is more expensive. In general PREP powder has a more spherical morphology, a higher density and less satellites. GA has an inherent problem with entrapped gas inclusions in the powder particles from the manufacturing process which leads to increased porosity content in the deposit [14].

In LMD-p the powder has proven to have a large impact on the porosity content of the deposit. Low quality powder with high satellite content, porosity content and an uneven morphology result in more porosity [15]. The GA powder produced 25 times more porosity in the deposit compared to PREP powder [16].

2.4. Process Parameters

Most AM machines come pre-programmed with optimized process parameters for materials sold by the machine vendors, but LMD machines are sold as flexible platforms; and thus LMD users must identify the correct process parameters for their application and material. Table. 3. present the parameters with the most impact on the LMD process. Optimum process parameters are material dependent and application/geometry dependent. Important process parameters include track scan spacing, powder feed rate, beam traverse speed, power density, and beam spot size. Powder feed rate, beam power density, and traverse speed are all interrelated; for instance, an increase in feed rate has a similar effect to lowering the beam power.

Likewise, increasing beam power or powder feed rate and decreasing traverse speed all increase deposit thickness. From an energy standpoint, as the scan speed is increased, the input beam energy decreases because of the shorter dwell time, resulting in a smaller melt pool on the substrate and more rapid cooling [17].

Table. 3. LMD process parameters [17].

Parameter	Unit	Description
Power density	W	The power of the laser beam which fuses the powder with the substrate
Beam spot size	mm	The diameter of the laser beam
Scanning speed	mm/s	The traverse travel speed of the guidance system i.e. robot or CNC machine
Powder feed rate	g/s	The amount of powder which is fed into the melt pool

Scan patterns also play an important role in part quality. As mentioned previously, it may be desirable to change the scan orientation from layer to layer to minimize residual stress buildup [18].

Track width hatch spacing must be set so that adjacent beads overlap, and layer thickness settings must be less than the melt pool depth to produce a fully dense product. Some scanning pattern shows in Fig. 6. Sophisticated accessory equipment for melt pool imaging and real-time deposit height measurement for accurately monitoring the melt pool and deposit characteristics are worthwhile additions for repeatability, as it is possible to use melt pool size, shape, and temperature as feedback control inputs to maintain desired pool characteristics. To control deposit thickness, travel speed can be dynamically changed based upon sensor feedback. Similarly to control solidification rate, and thus microstructure and properties, the melt pool size can be monitored and then controlled by dynamically changing laser power density.

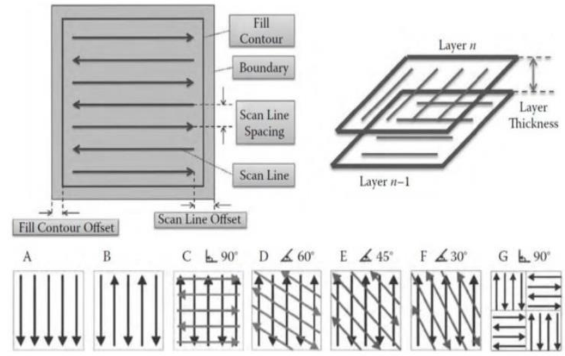

Fig. 6. some examples of scanning patterns [17].

Material properties, microstructural characteristics, defects and dimensional characteristics are heavily influenced by the process parameters, powder characteristics and substrate characteristics [17-19].
The laser power density is one of the most important process parameters in LMD. A higher laser power density has been shown to have a significant effect on e.g. the width of the deposit, penetration depth and surface finish. Additionally the laser power density affects the grain structure in the build [20-22]. A lower laser power density favours a columnar grain structure through an increase in temperature gradient. A too high energy density leads to a keyhole weld which is undesired since these types of welds have a high melt pool flow velocity and a plasma plume that would cause extreme disturbance in the powder flow [23].
The overlap of two adjacent deposits has been shown to have an effect on the grain structure, residual stress distribution and surface finish. A lower overlap leads to a more columnar grain structure due to a more pronounced gradient from the substrate. Additionally, the surface finish and dimensional precision of the build has been shown to be better with a lower overlap rate [24]. Furthermore, there is a higher residual stress in the overlap region of two adjacent deposits compared to the middle of a single deposit [25].
The purpose of the carrier gas is to transfer the powder from the powder feeder to the melt pool. Increase in carrier gas flow leads to a deeper and shorter melt pool. This could be an effect of the increase in powder particle velocity caused by the increased carrier gas flow rate [26]. The shield gas flow has also been shown to have some effect on the porosity content in the deposit. The shield gas also helps in preventing powder particles and spatter from repelling and damaging the laser optics [27].

3. Microstructure

LMD processes can involve extremely high solidification cooling rates, from 10^3 to as high as 10^5 C/s. High cooling rates can lead to several microstructural advantages, including: (a) suppression of diffusion controlled solid-state phase transformations; (b) formation of supersaturated solutions and nonequilibrium phases; (c) formation of extremely fine microstructures with dramatically reduced elemental segregation; and (d) formation of very fine secondary phase particles (inclusions, carbides, etc.). Parts produced using LMD experience a complex thermal history in a manner very similar to multi-pass weld deposits. Changes in cooling rate during part construction can occur due to heat buildup, especially in thin-wall sections. Also, energy introduced during deposition of subsequent layers can reheat previously deposited material, changing the microstructure of previously deposited layers. The thermal history, including peak temperatures, time at peak temperature, and cooling rates, can be different at each point in a part, leading to phase transformations and a variety of microstructures within a single component [28].
Parts made using LMD typically exhibit a layered microstructure with an extremely fine solidification substructure. The interface region generally shows no visible porosity and a thin heat-affected zone (HAZ). The deposited material generally shows no visible porosity, although gas evolution during melting due to excess moisture in the powder or from entrapped gases in gas-atomized powders can cause pores in the deposit. Pores can also result if excess energy is utilized, resulting in material vaporization and “key-holing.” Parts generally show excellent layer-to-layer bonding, although lack-of-fusion defects can form at layer interfaces when the process parameters are not properly optimized and insufficient energy density is utilized [28].
Residual stresses are generated as a result of solidification, which can lead to cracking during or after part construction. Residual stresses pose a particularly significant problem when dealing with metallurgically incompatible dissimilar material combinations. Formation of brittle intermetallic phases formed at the interface of dissimilar materials in combination with residual stresses can also lead to cracking. This can be overcome by suppressing the formation of intermetallics using appropriate processing parameters or by the use of a suitable interlayer. For instance, in several research projects, it has been demonstrated that it is possible to suppress the formation of brittle intermetallics when depositing Ti on CoCrMo by placing the focal plane above the CoCrMo substrate during deposition of the first layer, and depositing a thin

coating of Ti using a low laser power and rapid scan rate. Subsequent layers are likewise deposited using relatively thin deposits at high scan rates and low laser power to avoid reheating of the Ti/CoCrMo interface. Once a sufficient Ti deposit is accumulated, normal process parameters for higher deposition rate can be utilized. However, if excess heat is introduced both during the deposition of subsequent layers or in subsequent heat treatment, equilibrium intermetallics will form and cracking and delamination occurs. In other work, CoCrMo has been successfully deposited on a porous Ta substrate when employing Zr as an interlayer material, a combination that is otherwise prone to cracking and delamination.

It is common for laser deposited parts to exhibit superior yield and tensile strengths because of their fine grain structure. Ductility of LMD parts, however, is generally considered to be inferior to wrought or cast equivalents. Layer orientation can have a great influence on % elongation, with the worst being the z direction. However, in many alloys ductility can be recovered and anisotropy minimized by heat-treatment without significant loss of strength in most cases [28].

4. LMD Benefits and Drawbacks

LMD processes are capable of producing fully dense parts with highly controllable microstructural features. These processes can produce functionally graded components with composition variations in the X, Y, and Z directions [29].

The main limitations of LMD processes are poor resolution and surface finish. Accuracy better than 0.25 mm and a surface roughness of less than 25 µm (arithmetic average) are difficult with most LMD processes. Slower build speed is another limitation. Build times can be long for these processes, with typical deposition rates as low as 25-40 g/h. To achieve better accuracies, small beam sizes and deposition rates are required. Conversely, to achieve rapid deposition rates, degradation of resolution and surface finish result. Changes in laser power density and scan rate to achieve better accuracies or deposition rates may also affect the microstructures of the deposited components, and thus finding an optimum deposition condition necessitates tradeoffs between build speed, accuracy, and microstructure [29].

Examples of the unique capabilities of LMD include:

- LMD offers the capability for unparalleled control of microstructure. The ability to change material composition and solidification rate by simply changing powder feeder mixtures and process parameters gives designers and researchers tremendous freedom.
- LMD is capable of producing directionally solidified and single crystal structures.
- LMD can be utilized for effectively repairing and refurbishing defective and service damaged high-technology components such as turbine blades.
- LMD processes are capable of producing in-situ generated composite and heterogeneous material parts.
- LMD can be used to deposit thin layers of dense, corrosion resistant, and wear resistant metals on components to improve their performance and lifetime. One example includes deposition of dense Ti/TiC coatings as bearing surfaces on Ti biomedical implants [29].

When contrasted with other AM processes, LMD processes cannot produce as complex of structures as powder bed fusion processes. This is due to the need for more dense support structures (or multi-axis deposition) for complex geometries and the fact that the larger melt pools in LMD result in a reduced ability to produce small-scale features, greater surface roughness, and less accuracy [30].

Post-processing of parts made using LMD typically involves removal of support structures or the substrate, if the substrate is not intended to be a part of the final component. Finish machining operations because of relatively poor part accuracy and surface finish are commonly needed. Stress relief heat treatment may be required to relieve residual stresses. In addition, depending upon the material, heat treatment may be necessary to produce the desired microstructures. For instance, parts constructed in age-hardenable materials will require either a direct aging treatment or solution treatment followed by an aging treatment to achieve precipitation of strengthening phases.

LMD processes are uniquely suited among AM process for repair and feature addition. As this AM process is formulated around deposition, there is no need to deposit on a featureless plate or substrate. Instead, LMD is often most successful when used to add value to other components by repairing features, adding new features to an existing component and/or coating a component with material which is optimized for the service conditions of that component in a particular location [30].

As a result of the combined strengths of LMD processes, practitioners of LMD primarily fall into one of several categories. First, LMD has been highly utilized by research organizations interested in the development of new material alloys and the application of new or advanced materials to new industries. Second, LMD has found great success in facilities that focus on repair, overhaul, and modernization of metallic structures. Third, LMD is useful for adding features and/or material to existing structures to improve their performance characteristics. In this third category, LMD can be used to improve the life of injection molding or die casting dies by depositing wear-resistant alloys in high-wear locations; it is being actively researched by multiple biomedical companies for improving the characteristics of biomedical implants; and it is used to extend the wear characteristics of everything from drive shafts to motorcycle engine components. Fourth, LMD is increasingly used to produce near net structures in place of wrought billets, particularly for applications where conventional manufacturing results in a large buy-to-fly ratio [30].

5. Applications

Biomaterial:
A recent report forecasts that the additive manufacturing industry will grow from $6.1 billion in 2016 to $21 billion by the year 2020. The biomedical market represents 11 % of the total AM market share today and is going to be one of the drivers for AM evolution and growth [31]. Some examples of AM method applications in medical components are illustrated in Fig. 7.

Biomedical applications have unique necessities:

- High complexity. Biomedical research is challenged by the complexity and innovative approaches. AM will allow the development of new biomedical implants, engineered tissues and organs, and controlled drug delivery systems [32]. AM flexibility allows for manufacturing extremely complex shapes by engineering novel materials [32].
- Customization and patient-specific necessities. Biomedical applications need to be patient-specific, from implants to drug dosage. AM presents great potential for patient-specific biomedical products, from hearing aids to biomedical implants and from customized orthotics to prostheses. AM is also used for planning surgeries, improving efficiency and effectiveness, and reducing the necessity of further operations to adapt the implant to the patient. AM will also be used for customizing drug dosage forms and releasing profiles [34-37].
- Small production quantities. AM is more cost-effective compared to traditional manufacturing methods for lower production volumes, which are typical in the biomedical industry. Moreover, it allows for manufacturing complex products without the necessity of preparing new tooling fixtures each time. AM can prototype parts faster than conventional manufacturing methods, such as moulding, forging and milling in a fraction of the time [38]. The development of numerical methods to design and incorporate complex geometrical features in the implants will facilitate the design of the macro-scale shapes and microarchitecture [39].
- AM has been used for prosthetics and orthotics, allowing customizations for both fitting the patient's anatomy and improving functional aspects [40].

Fig. 7. examples of medical components fabricated by AM method- by authors.

Aerospace:
The Wohlers' report shows that the aerospace industry accounts for 18.2% of the total AM market today and is considered one of the most promising fields in the future [31].
AM techniques are ideal for aerospace components as they have the following peculiar characteristics:

- Complex geometry. Complex shapes are necessary for integrated functions i.e., structural, heat dissipation and airflow. For example, GE Aviation is developing fan blade edges with optimized airflow [41]. Moreover, it is possible to simplify parts by combining multiple components, such as GE fuel nozzles [42]. Finally, functional electronics can be implemented (or printed) easily as AM parts [43].
- Difficult-to-machine materials and high buy-to-fly ratio. The aerospace industry uses advanced and costly materials, such as titanium alloys, nickel-based superalloys, high-strength steel alloys or ultra-high-temperature ceramics that are very difficult to manufacture and create a large amount of waste materials (up to 95%) [44]. AM reduces waste (down to around 10-20%) and provides complex shapes [45].
- Customized production. The aerospace industry is characterized by the production of small batches of parts. AM is more convenient economically than conventional techniques for small batches as it does not require expensive equipment such as molds or dies;
- On-demand manufacturing. Airplanes have a long working life of up to 30 years. Keeping old parts incurs a notable cost of inventory but AM is capable of manufacturing parts on demand, thereby reducing the maintenance time [46].
- High-performance to weight ratio. Aerospace components need to be lightweight and present high- strength and stiffness-to-weight ratios to reduce costs and emissions. For example, the cost of space travel to Low Earth Orbit (LEO) i.e., orbit around Earth at an altitude of 2,000 km is around $2,500 per kg [47].

Fig. 8. Airplane engine blade repair through LMD [48].

Both metallic and non-metallic parts for aerospace applications can be manufactured or repaired using AM such as aero engine components, turbine blades and heat exchangers (Fig. 8., Fig. 9.). LMD technology is used for manufacturing large structural components as it is less accurate than PBF (±1 mm accuracy versus ±0.05 mm) but much quicker (up to 10 times) [49]. For example, 'Norsk Titanium AS' manufactures titanium structural parts for the Boeing 787 Dreamliner using their in-house 'Rapid Plasma Deposition TM' process in which a titanium wire is melted in a chamber filled with argon gas [50]. This method resulted in a reduction of cost by $2 to $3 million per aircraft [51].

'Thales Alenia Space' in collaboration with 'Norsk Titanium AS' were able to reduce the buy-to-fly ratio in half with a lead-time reduced by six months. 'GKN Aerospace' developed the first advanced 'Ariane 6 nozzle (SWAN)' for the 'Vulcan 2.1' engine produced by 'Airbus Safran Launchers'. Large-scale LMD allowed the production of the 2.5 m diameter nozzle, which reduced the number of parts (from ~1,000 to ~100), costs (~40%) and production times (~30%) [52, 53].

High-performance aerospace components are made of expensive materials with advanced and complex manufacturing techniques [54].

These parts are also subjected to corrosion, impacts, stress and repeated thermal cycles that can generate defects or cracks. As these parts are extremely expensive, replacement is more favorable than repair. On the other hand, AM technologies can repair high-value metal components with high precision and little generation of heat compared to conventional welding processes [55].

Fig. 9. LMD process for blade building [56].

A laser beam creates metallurgical bonds between the part (i.e., the substrate) and the added repair metal (i.e., the powder). This technique generates minimal distortions and can be used for complex and thin-walled aerospace parts. Also "non-weldable" materials or distortion sensitive parts can be repaired with AM [57].

In the most common approach, LMD machines spread and melt metal powder on the damaged area, while CNC milling machines improve the quality of the repair. Greater build capability, better accuracy and better surface finishing can be achieved by this method.

The added material presents better fatigue properties than the original wrought material with no distortion beyond dimensional limits. Moreover, this technique minimizes the degradation of mechanical properties caused by thermal stresses and can virtually repair any damage, even in non-visible zones. The cost for repair has been evaluated at 50% of the cost of remanufacturing the part [58].

Automatic systems are being developed to individuate the damage, align the original CAD files with the physical system (to evaluate the location for adding material) and repair the damaged components with AM and CNC machines [59].

The LMD process can also be used to make gas turbine components such as Sweiler and burners. It is possible that Siemens and General Electric are currently using this process to build and repair the equipment they need. Finally, it is necessary to mention the method of AM to use in aerospace, medical, industrial machine, electronics, military, motor vehicle, architecture, academic Institutions and others (Fig. 10).

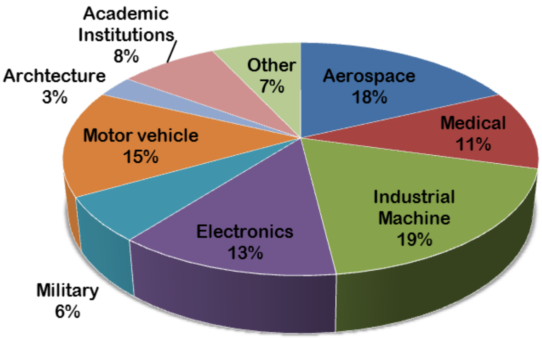

Fig. 10. AM market share [60].

6. Conclusion

LMD process focused region to heat a substrate, melting the substrate and simultaneously melting material that is being deposited into the substrate's melt pool. Unlike powder bed fusion techniques, LMD processes are NOT used to melt a material that is pre-laid in a powder bed but are used to melt materials as they are being deposited.

LMD process use a focused heat source (typically a laser) to melt the feedstock material and build up three-dimensional objects. Each pass of the LMD head creates a track of solidified material, and adjacent lines of material make up layers. Complex three-dimensional geometry requires either support material or a multi-axis deposition head.

The relationship between the LMD process parameters and material characteristics is highly complex. Process parameters optimized for one geometry may not mean a defect free result for another, different, geometry. As the heat distribution changes, localized heat build-up can cause the melt pool temperature to increase which in turn leads to a lower and wider deposit bead with more dilution as a result. A change in temperature distribution can lead to a different residual stress profile which in turn can lead to problems with the dimensional precision, cracking and/or deteriorated mechanical properties.

It is therefore important, in order for LMD to be a reliable manufacturing method, to predict and monitor the temperature history of the built material. This can be done by e.g. numerical analyses or online process control by temperature measurements. In order to reduce the heat build-up, a waiting time between deposit layers may be necessary. The waiting time affects the time-temperature profile of the deposition which consequently affect the microstructure of the material. In superalloys the heat build-up can also cause secondary phases to form in an uncontrolled manner which could cause cracking.

Longer waiting time between deposition layers leads to a lower temperature in the deposit which in turn results in a shorter cooling time for the subsequent deposition layers. With sufficient cooling the material may dwell in the brittle temperature range for a shorter period of time and thereby lowering its susceptibility to cracking. The effect of the waiting time will be more predominant with a higher build-up since the chilling effect of the substrate will be reduced.

An additional result of the lowered cooling rate is that the surface of the deposit has large tensile residual stresses, contrary to the effect of a heat treated material where compressive residual stresses are expected at the surface.

The distribution of residual stresses occurs when large residual tensile stresses are located at the surface of the deposit. Tensile residual stresses at the surface are undesirable since these will deteriorate the mechanical properties of the as-deposited samples.

Process LMD has benefits and drawbacks and will be used in various industries such as aerospace, biomaterial, power plants, etc., and as mentioned in the text, the possibility of reconstruction of complex parts is one of the most prominent features of this process.

Due to the rapid progress and development of the LMD process, as well as the increasing applications of this process in the production and especially the reconstruction of very sensitive and strategic parts such as turbine blades, this process is expected to find a special place in various industries and be very untying.

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