Progress of the Modelling of a Direct Energy Deposition Process in Additive Manufacturing

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Abstract. The development speed and application range of the additive manufacturing (AM) processes, such as selective laser melting (SLM), laser metal deposition (LMD) or laser-engineering net shaping (LENS), are ever-increasing in modern advanced manufacturing field for rapid manufacturing, tooling repair or surface enhancement of the critical metal components. LMD is based on a kind of directed energy deposition (DED) technology which ejects a strand of metal powders into a moving molten pool caused by energy-intensive laser to finally generate the solid tracks on the workpiece surface. Accurate numerical modelling of LMD process is considered to be a big challenge due to the involvement of multiple phase changes and accompanied mass and heat flows. This paper overviewed the existing advancement of additive manufacturing, especially its sub-category relating to the DED. LMD process is analyzed in detail and subsequently broken down to facilitate the simulation of each physical stage involved in the whole process, including powder transportation and dynamics, micro-mechanical modelling, formation of deposited track and residual stress on the substrate. The proposed modelling considerations and a specific CFD model of powder feeding will assist in accurately simulating the DED process; it is particularly useful in the field of aerospace manufacturing which normally has demanding requirement on its products.

Keywords. additive manufacturing(AM), laser metal deposition (LMD), direct energy deposition (DED)

1. Introduction

In engineering, additive manufacturing (AM) refers to a process in which objects or parts are built up and finally produced by means of adding, depositing and consolidating material (typically powder or filament) on to a substrate layer by layer. This term, AM, reflects its processing strategy and is defined to differentiate itself with the conventional material removal or subtractive process, such as machining, forming or casting. Rapid prototyping (RP), rapid manufacturing (RM), layer manufacturing, solid freeform fabrication (SFF) and more recently recognized industrial version of 3D

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printing, are usually taken as the synonyms of AM to some extent. Since being available from the mid of 1980s and then mainly used to fabricate displayed models and prototypes, AM technology has already developed for more than 20 years[1–2]. It was popular because of its desirable attributes such as easy generation of complex geometry, arbitrary configurations, efficient material use and possibility of material function design[3]. Nowadays, AM is becoming one of the most fast-developing advanced manufacturing techniques both in the fields of academic and industry due to the recent innovations in materials and accessibility of commercial high-energy system using both laser or electron beam to melt materials[4]. Easy access to various commercial AM devices really gives this technology a more flexible customization route and a kind of "on-demand" manufacturing mode which could drastically reducing waiting times and product stocks. It is totally different with the large-scale production mode and will definitely open up new product market and upgrade conventional manufacturing technologies. Some researchers[5] therefore reckoned that AM and its relating technologies will bring us with the "renaissance in manufacturing". Some other even regarded that AM technology which involves a comprehensive integration of materials science, mechanical engineering, and laser technology, is already starting an important revolution in manufacturing industry[6].

2. Advance in Additive Manufacturing

AM is a comprehensive process encompasses many specific technologies. These technologies involved could be classified into 7 categories according to the techniques used to deposit layers and the ways in which the deposited layers are bonded together to form the track[7]. In terms of ASTM F42 committee's suggestions, the 7 categories are[7]: 1) vat photo polymerization (e.g. Stereolithography, SLA); 2) material jetting (e.g. multi-jets modelling, MJM); 3) binder jetting (e.g. 3D printing, 3DP); 4) material extrusion (e.g. fused deposition modelling ,FDM); 5) powder bed fusion (e.g. SLS, SLM, EBM); 6) sheet lamination (e.g. laminated object manufacturing, LOM); 7) directed energy deposition (e.g. LMD/LENS, EBAM).

Table 1. Process categories, corresponding technologies and materials for existing AM processes[7]

Process category	Specific technology	Corresponding Materials
(1) Vat photo polymerization	Stereolithography (SLA)	UV curable resins
(2) Material jetting	MJM (multijet modeling)	waxes, ceramics, UV curable resins
(3) Binder jetting	3DP (3D printing)	waxes, composites, polymer, ceramics, metals
(4) Material extrusion	FDM	thermoplastics
(5) Powder bed fusion	SLS, SLM, EBM(electron beam melting)	waxes, thermoplastics, metals metals metals
(6) Sheet Lamination	LOM	Paper, metals, thermoplastics
(7) Directed energy deposition	LMD/LENS EBAM	metals metals

Table 1 lists the category names, corresponding technologies and materials to be dealt with for these 7 categories of AM processes. It is also possible to divide AM processes into 4 main categories only based on the materials dealt with, e.g. liquid, filament/paste, powder, or solid sheet[8]. After intensive research and development in the areas of materials, processes, software, equipment, and integration, AM has been used directly and indirectly to produce prototype parts with suitable material properties for evaluation and testing, as well as to make tools, dies, and molds. Currently, the direct fabrication of functional end-use products is becoming the main trend of AM technologies, in particular, for metallic products[9].

2.1. Directed energy deposition (DED)

As one of the 7 categories of AM processes, directed energy deposition (DED) is suitable for producing metal parts via the layer-by-layer deposition of molten metal powders or filament. It employs energy-intensive source (e.g. normally a laser or an electron beam) to generate a melt pool on the substrate into which metal powder or filament is injected [2, 4, 7]. The molten pool follows a specified route to move on and fill the top of substrate and progressively build up and deposit the part according to designed CAD geometry. Many AM technologies involve in this standard category, such as laser metal deposition (LMD), laser-engineering net shaping (LENS), direct metal deposition (DMD), Direct Laser Deposition (DLD), laser consolidation, laser cladding, laser deposition welding and powder fusion welding, many of which are trademarks of various machine manufacturers or research establishments. It is worthy to note that the local high-energy in DED process will affect the microstructure, deposited material properties, residual stress state and thermal-induced distortion of the final part.

2.2. Laser metal deposition (LMD)

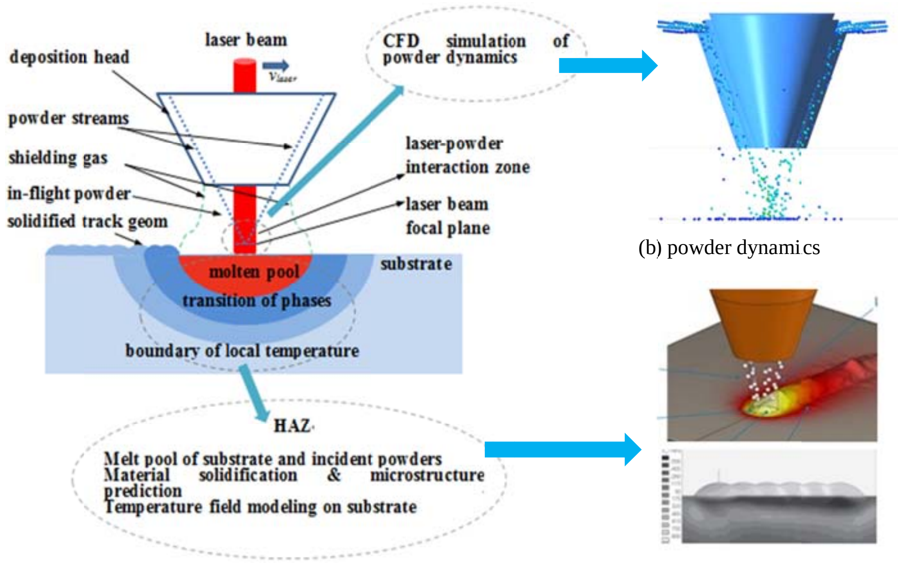
Laser metal deposition belongs to the AM category of DED. LMD involves a laser beam used to form a molten pool on a metallic substrate, into which powder is fed. The powder melts to which is fusion bonded and forms a deposited track on the substrate. This kind of laser based AM process generally has a complex non-equilibrium physical and chemical metallurgical nature, which is material and process dependent[2]. The current development focus of DED/LMD is to produce complex shaped functional metallic components, including metals, alloys and metal matrix composites (MMCs), to meet demanding requirements from aerospace, defense, automotive and biomedical industries. The influence of material characteristics and processing conditions on metallurgical mechanisms and resultant microstructural and mechanical properties of LMD processed components are highly desired to be clarified.

3. Numerical Modelling Considerations for LMD

To maximize the AM technology’s potential and study the above-mentioned influence of material deposition and processing condition of LMD on material and mechanical property, modeling and control of its process are of the priority. To better understand the physic phenomena during LMD, it is needed to use a combination of modelling methods to simulate different stages of LMD process.

For the LMD process, as shown in Figure 1, a high-power laser is used to melt metal powder supplied coaxially to the focus of the laser beam through a deposition head in LMD. The laser beam typically travels through the center of the head and is focused to a small spot by one or more lenses. The head is moved up vertically as each layer is completed. Metal powders are delivered and distributed around the circumference of the head by using a pressurized carrier gas. An inert gas is also used to shield the molten pool from atmospheric oxygen for better control of properties, and to promote layer to layer adhesion by providing better surface.

In addition, a series of simulation & modelling procedures are included in modelling of LMD which at least covers: (1) CFD modelling the powder flow and powder distribution; (2) micro-mechanics modelling of microstructures for deposited material; (3) thermal-mechanical modelling of the deposited track when solidification.



(a) schematics of LMD process (b) powder dynamics (c) solidified track geom[10]

Figure 1. Schematic diagram of LMD process & modelling zones definition

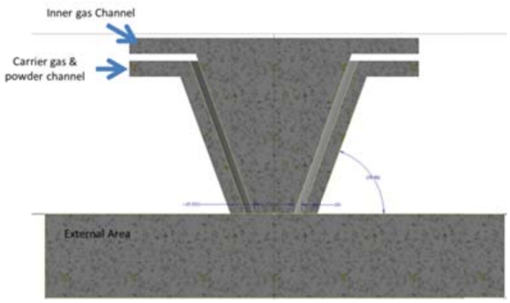
4. CFD modelling of powder feeding and ejection for LMD

In this research, CFD modelling procedure of powder feeding and ejection from the laser deposition are detailedly investigated among the whole modelling of LMD process. A typical construction of deposition head is shown in Figure 1; its geometry and the initial conditions for CFD simulation of powder feeding are given and listed in Table 2. Figure 1 also gives a schematic of how the powders move within the nozzle and then be ejected from the nozzle; while Figure 2(a) gives the extracted closed geometry for CFD simulation of the powder feeding.

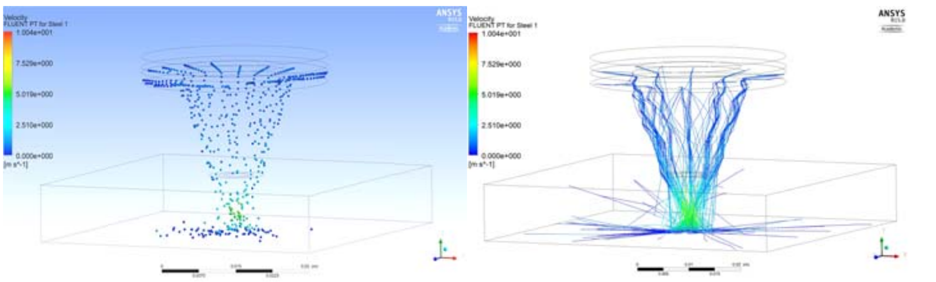
Table 2 Input parameters from CFD Simulation of powder feeding in LMD

Inputs for CFD	Value	Inputs for CFD	Value
average diameter of powders	100um	pressure of inner gas at inlet	2 bar
powder flow rate	100g/h	inner gas flow rate	6.67×10^{-5} m^3/s
powder flow velocity	0.118 m/s	inner gas flow velocity	0.471m/s
carrier gas flow rate	8.33×10^{-5} m^3/s	nozzle outer diameter	22.56mm
carrier gas flow velocity	0.588 m/s	material density	3910kg/m^3
pressure of carrier gas at inlet	8 bar	carrier gas density	1.67 kg/m^3

The outputs from CFD simulation are the powder dynamics (e.g. v, a, mv, E) and trajectory of powders after being ejected from head. If powders have sufficiently large velocity and not been absorbed by the molten pool on the substrate, then the rebounding velocity of powders is another output variable. Figure 2(b) and (c) show the CFD simulation results of powder dynamics and trajectories with the inner gas flow considered 3D powder dynamic and 3D powder trajectories according to the input parameters of CFD. The max velocity of powder is around 10 m/s.



(a) extracted closed geometry for CFD simulation



(b) powder velocities from CFD (c) powder trajectories from CFD

Figure 2. CFD simulation of powder feeding with powder velocity and trajectory as output

5. Discussion and conclusions

AM-related technologies are increasingly used in modern manufacturing as surface enhancement, rapid manufacturing, tooling and repair processes. LMD is based on blowing a powder stream into a moving laser-induced melt pool; modelling of LMD is difficult as it is characterized by multiple phase changes, mass and heat flows. In this research, the existing advancement in additive manufacturing, especially the category of DED is overviewed. The LMD process is analyzed in detail and subsequently broken down to 3 stages for further simulation of each physical procedure involved in LMD including powder conveyance and dispersion, molten pool dynamics and track formation and residual stress on the substrate. The proposed numerical modelling considerations and detailed CFD model of powder feeding will assist in accurately simulating the DED processes; it is particularly useful in the field of aerospace manufacturing which normally has demanding requirement on its products.

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