

Numerical modelling of the gas-powder flow during the laser metal deposition for additive manufacturing

Quanren ZENG^a, Yankang TIAN^a, Zhenhai XU^{a, b}, and Yi QIN^{a, 1}

^a*Centre for Precision Manufacturing, Department of Design, Manufacture and Engineering Management, University of Strathclyde, Glasgow, G1 1XJ, UK*

^b*National Key Labfor Precision Hot Processing of Metals & School of Materials Science and Engineering, Harbin Institute of Technology, Harbin 150001, China*

Abstract. As one of the most popular additive manufacturing (AM) technologies in the aerospace industry, laser metal deposition (LMD) employs moving laser to melt the coaxially ejected metal powders near the laser focal point, forms a molten pool on the substrate and consequently traps the powders and solidifies the tracks to construct the components with complex geometry layer-by-layer. The mechanical properties and functionality-related performance of the deposited components by LMD depend on the factors such as metal powder's material/shape, supply status of powders and gas, laser-related manufacturing parameters. According to these influencing factors, there are 4 sub-processes to be modelled in sequence to realize holistic LMD modelling: (1)CFD simulation of the gas-powder flow; (2)laser-powders interaction; (3)formation of molten pool due to laser irradiation with mass and heat addition; (4)solidification of molten pool with deposited metal powders and formed solid track. In this paper, gas-powder flow within the internal passages of laser deposition head and then ejecting from the nozzles' tips were modelled and analyzed to give a well-depicted image of the related key physics during the LMD process. An in-depth study of the gas-powder flow in LMD via numerical simulation could give a better understanding of subsequent formation mechanism of molten pool and deposited tracks, which will eventually offer more controllable and optimized processing parameter sets to improve the functionality-related performance of LMDed parts.

Keywords. additive manufacturing(AM), laser metal deposition (LMD), gas-powder flow, molten pool formation, solidification, deposited solid track

1. Introduction

Laser metal deposition (LMD) is a promising additive manufacturing technology for the fabrication of the near net shape parts with streams of metal powder for some high performance applications in the aircraft & aerospace, high performance automotive, medical device, nuclear industry^[1]. Many physical phenomena and influencing factors involve in the LMD additive manufacturing process and all of them will have direct or indirect effect on the microstructure and material properties of the final deposited parts^[2-4]. A full control of these influencing factors and processing variables such as laser power, scanning speed, powder density, powder feed rate, size distribution and other processing variables, is required to achieve high-quality deposited parts. However,

¹ Corresponding Author, Prof Yi Qin, DMEM, University of Strathclyde, UK; qin.yi@strath.ac.uk

choosing the reasonable and robust processing variable set via experiment is obviously time consuming and expensive^[5]. This to some extent hinders the LMD AM process from being wider used in practical production. A more expecting alternative is to develop a reliable numerical model which could serve to identify proper processing variable set for producing crack free and reliable parts by using LMD.

2. Description/breakdown of LMD process

In LMD, as shown in Fig.1, metal powders firstly flow within the deposition head ducts and are accelerated and becomes a fully developed flow before being ejected out from the nozzles' tips; then the powder jets interact with the laser beam near the laser focus plane prior to deposition on the substrate, which is melted due to the laser irradiation and forms a molten pool trapping the incident powder jets; the melted or trapped powders keep depositing and adding into the molten pool on the surface of the growing layer and the molten zone finally solidifies and forms the tracks/clads when the laser beam moves away. According to these physical phenomena and procedures, there are 4 sub-processes could be modelled in sequence and then coupled to realize holistic LMD modelling: (1) CFD simulation of the gas-powder flow^[4]; (2) laser/metal powders interaction^[6]; (3) formation of molten pool due to laser irradiation with addition of powder mass and heat; (4) solidification of molten pool with deposited metal powders and formed solid track.

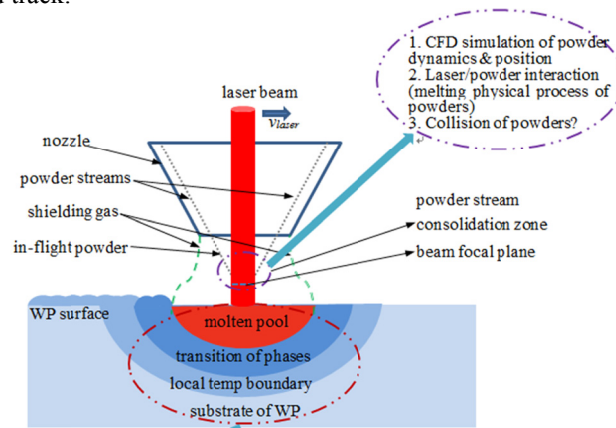


Fig. 1 Schematic diagram of holistic LMD process^[1]

This research mainly focused on the first sub-process of modelling gas-metal powder flow in LMD; and a 3D CFD model which could accurately simulate the details of gas-powder flow status of LMD process was established and analyzed.

3. Numerical Modelling of gas-powder flow for LMD

The gas-powder flows in the nozzles' ducts and within the interaction zone between the nozzles' tips and the substrate are not a simple one-phase turbulent flow. In fact, this flow can be characterized as a two-phase flow, in which the primary phase is the turbulent inert gas and the secondary phase consists of the metal powder particles. The

behavior of particles suspended in a turbulent flow depends on the properties of both the particles and the flow. Turbulent dispersion of both the particles and the carrier gas can be handled by the concept of eddy diffusion energy in some range of the particle size distribution. The interaction of the particle and gas could be solved by two-way coupling the discrete and continuous phase until the solutions in both phases achieve a kind of stable balance^[7-9]. To realize the simulation and analyze powder flow behavior involved in the powder feeding system of the LMD deposition head, especially the turbulence phenomenon for the gas-powder flow, a numerical model has been developed based on the nozzle setup shown in Fig.2(a).

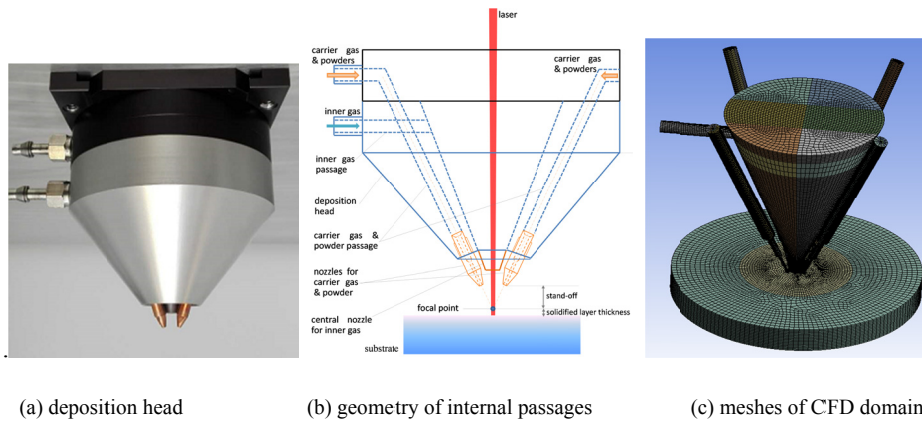


Fig.2 The practical laser deposition head and its internal geometry with passages

As shown in Fig.2(a), the typical construction of a real laser deposition head is a conical metal structure with 4 copper powder nozzles facing to a focal point and 1 main central nozzle for gas and laser passing through coaxially. its detailed geometry with internal passages and ducts are given in Fig.2(b). Fig.2(b) also shows the schematic diagram of how the laser deposition head deliver powders with assistance of gas.. The gas-powder mixture is firstly injected into the inlets of laser deposition head and reaches a fully developed flow while travelling through the passages and ducts inside the deposition head and nozzles. Once the gas-powder flow is sprayed out from the 4 nozzles' tips, 4 gas-powder mixed jets will firstly flying without interactive actions and then intersect with each other to form a small circular focused spot which show the maximus powder mass concentration of the gas-powder flow. Fig.2(c) shows the domain are discretized by different level of meshes to both consider the improvement of overall calculation speed and the required accuracy at some local critical areas with complicated geometry (such as the nozzle tip and focus plane) Some assumptions are taken for modelling of the gas-powder flow: (1)gas-powder mixture is treated as a steady-state turbulent flow with a constant velocity and pressure distribution at the inlets; (2)the powder particles volume fraction is less than 10% and the one-way coupled discrete phase modeling (DPM) is adopted; (3)the heat transfer by laser radiation is temporarily neglected; (4)the particle size is assumed to be spherical and with an average diameter of 100um. .

For the deposition simulation, a 25L/min argon jet is supplied and ejected from the inner gas nozzle to protect the laser optics from the rebounding particles and to shield the melt pool. The TiAl powders were delivered to the melt pool by using carrier gas (argon) via 4 nozzles which are spaced equally around the inner gas nozzle. The total

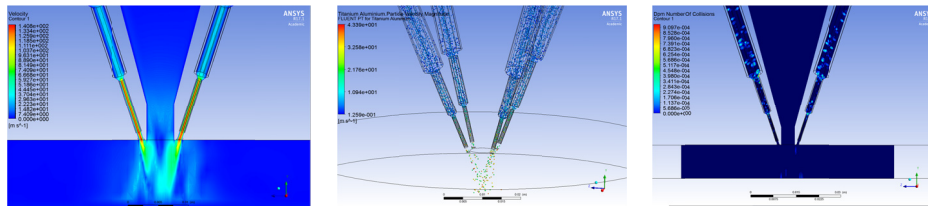
flow rate of the carrier gas for the 4 nozzles is 5 L/min. These 4 nozzles are installed around the main inner gas nozzle and point to the melt pool which could make the carrier gas-powder jets be trapped to the melt pool. The diameter of the nozzle tip/outlet is 1.17mm. Each of the nozzles is tilted 65 degree from the substrate surface. The initial conditions for CFD simulation of gas-powder flow are given and listed in Table 1.

Table 1 Material properties & processing parameters used for numerical simulation of LMD

Inputs for CFD	Value	Inputs for CFD	Value
pressure of inner gas at inlet	300 MPa	average diameter of powders	100um
Inner gas density (Ar)	1.67 kg/m ³	powder density (TiAl)	3910kg/m ³
Inner gas flow velocity (Ar)	0.118 m/s	powder flow rate (inlet)	2.55 (g/min)
Inner gas flow rate (Ar)	416.7 mm ³ /s	powder flow velocity (inlet)	0.118m/s
pressure of carrier gas at inlet	300 MPa	dia of central nozzle (outlet)	6.4mm
carrier gas density (Ar)	1.67 kg/m ³	number of powder nozzles	4
carrier gas flow(Ar)	0.588 m/s	dia of powder nozzles(outlet)	1.17mm
carrier gas flow rate (Ar)	83.3 mm ³ /s	Stand-off distance	9.5 mm

4. Results and discussion of CFD simulation

There are many output variables from CFD simulation, in which particle velocity, particle mass concentration, DPM number of collision and trajectory of powders after being ejected from the nozzles, are the main variables of interest that will directly affect the further sub-processes of deposition and solidification of molten pool in LMD. If powders have sufficiently large velocity and cannot be absorbed or trapped by the molten pool on the substrate, then the rebounding velocity of powders is another output variable may need to pay attention to.



(a) velocity of gas-powder (two phase) (b) velocity of powder(discrete phase) (c) DPM number of collisions

Fig.3 CFD simulation result of the velocities of gas & powder

The velocity of gas-powder flow is shown in the Fig.3(a). We could see the max velocity of the gas-powder flow is still within the nozzle ducts especially near the outlet of nozzles. It is because the inlet pressure and flow rate of gas are supplied constantly while the sectional area near the nozzle is at the minimum. The magnitude of the velocity for the dispersed powders is shown in the Fig.3(b). The particles are accelerated in the passages and ducts of nozzles stage-by-stage. After the particles being ejected out from the nozzles, their velocities keep increasing and reach the maximum magnitude (around 40m/s) before they collide with each other near the focus. The collision of particles means the possibility that powder will collide with each other due to the blown gas. As shown in Fig.3(c), the collision are most likely to be happened

within the internal ducts especially at the position where its sectional area has a abrupt change. But after the powders are ejected out from the nozzles, they are less likely to collide until four jets of the powders from the 4 nozzles concentrate on the focus leve. This means that the powders ejected from the nozzles will fly with less possibility of collision until they are intersected with each other near the focal point.

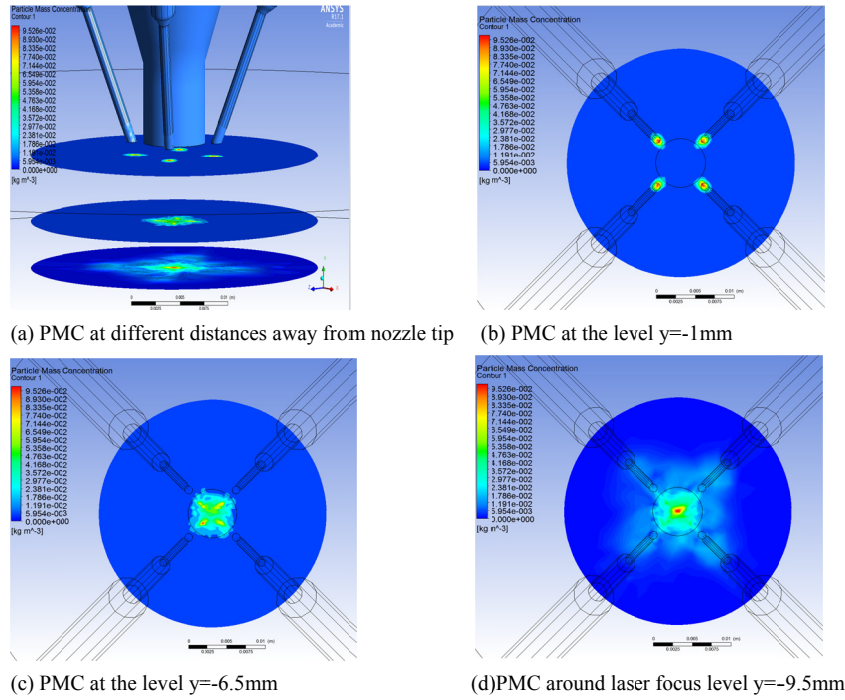


Fig. 4 Particle mass concentration at different locations away from the outlet of nozzle

Particle mass concentration is a variable that describe the density of particles on a specified plane or in a specified volume. It could give the straightforward impression where the particles are more likely to gather. Fig. 4(a) shows the simulated result of variation of particle mass concentration along the stand-off distance of LMD. After ejecting out from the nozzles, there is a clear trend that the 4 jets of particles are travelling to and concentrating on a point of intersection. At the level of $y=-1\text{mm}$ (Fig. 4(b)), the particle mass concentration of the 4 jets are separate and discrete. When the jets travels to the level of $y=-6.5\text{mm}$ (Fig. 4(b)), the boundary of 4 jets is becoming blurred. When the 4 jets travels to the level of $y=-9.5\text{mm}$ (Fig. 4(c)), the highest particle mass concentration of the 4 jets seem to converge at the middle of the domain. If the focal point of a laser beam is just at this location, then the highest laser power heat could be employed to melt the densest cloud of particles. Matching the laser beam focal point and the position of the convergent highest particle mass concentration is extremely important for full fusion of the depoisted substrate and particles and consequently generation of crack-free and high-quality depoisted tracks. The Fig.4(d) shows a larger influencing area of particle mass concentration than that of Fig.4(b) and (c). It is mainly because that it is near the focal point and some particles will collide and even bounce back once comes into contact with the substrate.

5. Conclusions

LMD, based on blowing a powder stream into a moving laser-induced melt pool, is widely employed in the field of advanced manufacturing, such as rapid manufacturing, surface enhancement, tooling and repair. In LMDS, metal powders firstly travel in the laser deposition head, then eject out from the 4 nozzles, gradually converge into the focal point and get molten near or within the molten pool, and finally deposited as a track layer on the substrate. Modelling of LMD is difficult as it is characterized by multiple phase changes, mass and heat flows. In this research, the whole LMD process is analyzed and the gas-powder flow including powder conveyance and dispersion are detailedly investigate due to its direct influence on the subsequent track formation and residual stress on the substrate. The proposed CFD numerical model of gas-powder flow could be used to gain full insight into the powder deposition process and to analyze the influence of the geometrical & processing parameters such as the standoff distance, volumetric gas flow rate, and powder mass flow rate on the quality of the LMD. Also, the developed model provides important parameters for the calculation of the heat transfer boundary condition for the holistic LMD process once the laser radiation is added into the model.

Acknowledgement

The authors would like to acknowledge the support from EU H2020 project MMTECH (GA 633776) for the research reported in this paper.

References

- [1] Zeng, Q., Xu, Z., Tian, Y. & Qin, Y. Advancement in additive manufacturing & numerical modelling considerations of direct energy deposition process, in: Proceeding of the 14th International Conference on Manufacturing Research: Advances in Manufacturing Technology XXX. Goy, Y. M. & Case, K. (eds.). Amsterdam: IOS Press, p. 104-109 (ICMR, 6 Sep 2016)
- [2] V. Manvatkar, A. De, T. DebRoy, Heat transfer and material flow during laser assisted multi-layer additive manufacturing, *Journal of Applied Physics* **116** (2014), 124905
- [3] H. Qi, J. Mazumder, and H. Ki, Numerical simulation of heat transfer and fluid flow in coaxial laser cladding process for direct metal deposition, *Journal of Applied Physics* **100** (2006), 024903
- [4] S. Zekovic, R. Dwivedi, R. Kovacevic, Numerical simulation and experimental investigation of gas-powder flow from radially symmetrical nozzles in laser-based direct metal deposition, *Int. J. Mach. Tools Manuf* **47** (2007), 112-123.
- [5] M. Grujicic, Y. Hu, G.M. Fadel, D.M. Keicher, Optimization of the LENS rapid fabrication process for in-flight melting of feed powder, *J. Mater. Synth. Process.* **9(5)** (2001), 223-233
- [6] J.C. Liu, L.J. Li, Y.Z. Zhang, X.Z. Xie, Attenuation of laser power of a focused gaussian beam during interaction between a laser and powder in coaxial laser cladding, *J. Phys. D Appl. Phys.* **38(10)** (2005), 1546-1550.
- [7] H. Pan, F. Liou, Numerical simulation of metallic powder flow in a coaxial nozzle for the laser aided deposition process, *J. Mater. Process. Technol.* **168 (2)** (2005), 230-244.
- [8] H. Pan, T. Sparks, Y.D. Thakar, F. Liou, The investigation of gravity driven metal powder flow in coaxial nozzle for laser-aided direct metal deposition process, *Trans. ASME J. Manuf. Sci. Eng.* **128(2)** (2006), 541-553.
- [9] A.J. Pinkerton, L. Li, Modelling powder concentration distribution from a coaxial deposition from a coaxial deposition nozzle for laser-based rapid tooling, *Trans. ASME J. Manuf. Sci. Eng.* **126(1)** (2004), 33-41.