Interaction of Laser beam, Powder Stream and Molten Pool in Laser Deposition Processing with Coaxial Nozzle

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Abstract. Powder-based laser deposition technology has widely used for parts coating, repairing and additive manufacturing. The quality and efficiency of laser deposition largely depends on the powder stream controlling. For some special laser deposition processing, such as ultra-high-speed laser cladding, inside laser cladding, FGM(Functionally Graded Materials) and MMC(Metal Matrix Composite) coating or parts manufacturing, the power stream controlling become more complex, because the powder melting behaviour is changed and varying proportion mix powder is used. In order to achieve the best feeding properties and highest powder efficiency aiming to different application requirement, the optimization of the nozzle geometry and controlling of powder flow are quite necessary. For this purpose, a comprehensive numerical model is developed to study the powder flow of coaxial nozzles, which include powder stream spatial distribution, flow rate, and trajectory. The powder stream convergence characteristics for different laser deposition application, and the interaction between laser beam, powder stream and molten pool are studied by numerical and experimental methods. The nozzle geometries, powder properties, and shield gas setting are optimized based on the understanding of the powder concentration distribution.

1. Introduction
Laser metal deposition (LMD) technology has been widely used in the industry for laser additive manufacturing, cladding or repairing the metallic parts. The supply of the metal powder is one of the key factors for the improvement of LMD quality and efficiency, and the coaxial nozzles are very popular in the laser cladding and repairing technologies[1][2]. It is important to establish a well-focused powder stream at the exit of the coaxial nozzle in order to obtain good quality and avoid waste of powders. Currently, the main challenges for powder-based LMD include the formation of defects, low surface finish quality, and spatially non-uniform properties of material. Such challenges largely caused by the limited knowledge of complex physical processes, such as powder stream concentration distribution, the molten pool physics, laser beam energy efficiency and so on.

Because the quality and efficiency of LMD greatly depends on interaction between laser, powder and molten pool. The powder flow structure below the nozzle tip, powder size, nozzle geometries and operating parameters should be optimized based on the well understanding of the complex heat and mass transfer mechanism during LMD process. Some simulation and experimental works have been done during past several years. In J. Lin’s work[3], a 2D axially symmetrical model of the two-phase turbulent gas-powder flow was used to investigate the influence of the nozzle arrangement and gas flow settings
on the powder concentration in the stream. Pulin Nie and O.A. Ojo[4] developed a coupled fluid-thermal-mechanical analysis to calculate the thermal history in a nickel-based alloy coating fabricated by the laser cladding with the goal of studying the dependence of laser deposited coating microstructure on powder size and process parameters, and the research indicated that powder in small size is favorable for obtaining fine solidification microstructure in the laser deposited coating. With the aim of improving the ratio between the trapped powder in the deposited area and the total injected powder, J.I.Arrizubieta and I.Tabernero[5] presented a new methodology for coaxial-continuous nozzle design based on a complete CFD model. The numerical model can predict particle flow, speed, powder concentration, etc. and design can be optimized using this input data. Based on the numerical simulation and image technologies, S.Zekovic and R.Dwivedi[6] investigated the influence of powder flow characteristics on the process stability and the process output. These previous researches are very useful for the better understanding of the powder flow phenomena from the coaxial nozzle.

The purpose of this work is to develop an analytical foundation for fundamental understanding of heat and mass transfer, molten metal flow and free surface evolution, and achieve the best feeding properties aiming to different application requirement with the coaxial nozzle. The numerical simulation and digital image are combined to investigate the powder convergence, molten pool physics and powder catchment efficiency.

2. Research methods
In this study, the trajectory and concentration of the powder carried by gas flow was investigated by using Ansys Fluent software. The discrete phase model was used in the CFD simulation based on the assumption that second phases that consist of spherical particles distributed in a continuous gas phase. The gas phase was computed by the standard k-ε turbulent flow model and the discrete phase was calculated by building particle track model and solving particle kinematics equations. The geometrical domain of the coaxial nozzle is determined in accordance with the dimension of the real nozzle, including the powder stream passage in the nozzles and the flying zone out of the nozzles, as show in figure 1. The molten pool was simulated by VOF method and the powder was coupled with the molten pool through the discrete phase model. With the high-speed and infrared camera, the interaction between powder stream, laser beam and molten pool were real-time monitored. The trajectory of powder streams during the flying procedure out of the nozzle tip, the effect of particles injection on the molten pool are comparatively analyzed by CFD model and vision sensing respectively, which provide a good insight into the process phenomena.

![Continuous coaxial nozzle](image)

Figure 1. The building procedure of powder stream FE model

3. Results and discussion
3.1. Powder stream structure with coaxial nozzle
When a continuous coaxial powder feed nozzle is used for LMD process, the powder is distributed in a conical ring-shaped cavity, forming a hollow powder cone which encloses the laser beam. Powder stream start from an annular shape on the nozzle exit to a Gaussian distribution near the powder stream focal plane (figure 2(a)). From the calculated results, we found that the powder flow with smaller range of particle sizes distribution has better convergent, and more uniform concentration distribution is achieved. The comparative analysis of different particles sizes range in figure 2(b) indicate that the smaller particles mostly distribute at the center of the powder spot, which due to it is easily affected by
the carrier gas flow than bigger size particles. The inner shielding gas also has the significant impact for the powder convergence. As shown in Figure 3, the powder focus plane downward when increasing the flow rate of inner shielding gas. It will lead to the change of powder catchment efficiency when the other parameters are fixed during LMD process.

(a) Concentration distribution along central axis   (b) Concentration distribution at powder focal plan

**Figure 2.** Influence of particle sizes on concentration distribution of powder stream

(a) Without inner shielding gas   (b) Gas flow rate 0.24 m/s   (c) Gas flow rate 1.2 m/s

**Figure 3.** Influence of inner shielding gas flow rate on continuous powder stream convergence

3.1.1. *Interaction between laser beam and particles.* When the powder particles move in laser field, they absorb the photons and their temperature increase. During to different times spent in laser and variation of laser intensity in the paths, particles reach the substrate with different temperature (figure 4). The temperature and melting state of particles are mainly affected by laser defocus distance, laser power and powder feed rate. With defocused laser beam irradiation means increasing the heating area, more particles are heated along the laser path. Higher powder feed rate means increasing the heated particles amount in constant time. Both approaches increase the temperature of powder stream. The heated particles by laser beam can be observed clearly by high-speed camera, as seen in figure 5.

**Figure 4.** Schematic of intersection between powder stream and laser beam

**Figure 5.** Influence of laser defocus and powder feed rate
3.1.2. Influence of powder particles impinging on molten pool. Powder catchment efficiency maybe affect by molten pool size and temperature, powder injection position, particles temperature and their motion velocity. Larger molten pool surface area results in increased powder catchment efficiency and more mass addition to the molten pool. The impinging of lower temperature powder stream changes the original temperature distribution and shape of the molten pool. A portion of thermal energy is returned to the cladding process by the heated particles. Temperature of the injected powder stream affect the molten pool shape and size. The powder particles add both mass and momentum to the melt pool. These additions affect the fluid temperature distribution and flow patterns in the molten pool. Powder velocity affect both the flow pattern and penetration of molten pool because of different particles impact force. Larger particles have greater impact force, resulting in an increase in flow rate of molten pool, and may even alter the flow pattern at the end of the pool.

![Image of molten pool](a) Image of molten pool  
![Temperature field](b) Temperature field  
![Flow field](c) Flow field  

**Figure 6.** Influence of powder particles impinging on molten pool

4. Summary

3D heat transfer, fluid flow and powder flow simulation are conducted to provide fundamental study for LMD processes, a good understanding of the correlation between powder stream, laser beam and molten pool is very helpful in solving many problems during LMD process.

For the trajectories control of particle, the wall collisions between particles and nozzle, the drag forces from carrier gas and particle sizes distribution should give a lot of consideration. Overheating of powder is closely depend on the proper powder size and laser energy. Improvement of the powder catchment efficiency not only relate to the molten pool size and mass deposition rate, but also powder stream heating and mass concentration.

Some novel developments like Ultra-high-speed cladding and graded materials additive manufacturing require the further understanding for the heat and mass transfer mechanism according to their special process characteristics.

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