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Research Paper

Process mechanisms based on powder flow spatial distribution in direct metal deposition

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ABSTRACT

Direct Metal Deposition (DMD) is becoming increasingly attention-attracting technology for new component manufacture and repair. However, fundamental process understanding is not yet comprehensive. Without considering the realistic spatial distribution of powder flow, some important process conditions have been neglected in layered deposition, such as the initial stand-off distance of nozzle, scanning direction (orientation of nozzle), change in stand-off distance through process and stability of multi-layer deposition. This then limits the efficacy of deposition strategies which serves to limit the industrial uses of DMD. In this paper, a realistic model was built for the simulation of multi-layer deposition, using real spatial powder flow concentration. Then, the influences of the orientation of nozzle, the stand-off distance of nozzle and single-step rise on geometric characteristics are investigated. It is showed that the stand-off distance of nozzle significantly affects the geometric characteristics of the deposited layer thickness, while the influence of the orientation of four-tip nozzle on deposition can largely be neglected. Furthermore, the stability of multi-layer deposition was discussed, and the steady condition was obtained by analyzing relation among single-step rise, maximum deposited layer thickness and stand-off distance of nozzle. This also allows a deposition strategy to be optimized for the purpose of manufacturing given procedure. The approach taken here is also verified by experiments with the strategies proposed by simulation.

1. Introduction

Additive manufacturing methods which make use of Directed Energy Deposition are becoming increasingly commonplace for new component manufacture and repair. As an extension of laser cladding strategies, Direct metal deposition (DMD) technology is a promising additive manufacturing technology and capable of producing complex geometries in high value materials. Many investigations for this technology have been reported in the literature. Kamran et al. (2015) and Li et al. (2017) developed graded metal materials using this technology. Liu et al. (2013) focused on microstructural characterization of laser melting deposited (LMD). Panagiotis (2014) investigated in detail finite element techniques for modeling metal deposition heat transfer. Zhong et al. (2016) developed high deposition rate laser metal deposition technology.

Understanding the influence of process conditions is critical in order to facilitate the use of this technology. Li et al. (2003) and Zhang et al. (2007) investigated experimentally the influences of the process parameters on geometric characteristics of single-layer clad with lateral and coaxial powder feeding, respectively. Gharbi et al. (2013) focused the study on understanding the influence of the main process parameters on the surface finish quality in direct metal deposition (DMD). Although these investigations were benefit for the improvement of process, the applications are limited due to a lack of understanding for basic process. Some models of process have also been developed to investigate geometric characteristics of the deposit. Liu and Li (2007) established a model of cross-section clad profile in coaxial single-pass cladding, based on powder mass concentration in a Gaussian distribution at the substrate surface, and demonstrated close agreement with single-pass deposition results. Tabernero et al. (2014) also consider powder mass flow distribution on the melt pool area and built a simulation model of clad geometry by a mass balance entering the melt pool. The model can predict the 3D shape of single and multiple clads while considering overlapping effects on typical laser material deposition process

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parameters. These models have not yet been applied to multi-layer deposition. Toyserkani et al. (2004) built a 3-D transient finite element model of laser cladding based on the powder feed rate to melt pool area. Developing this, Alimardani et al. (2007) developed a 3D dynamic numerical approach for temperature and thermal stress distributions in multilayer laser solid freeform fabrication processes and showed the modeling approach enhanced the accuracy of experimental results due to considering the influence of nonplanar surfaces during a multilayer deposition. But this model did not consider the spatial distribution of powder mass flow, so the dynamic interaction between powder flow and melt pool have been ignored. Pinkerton and Li (2004a) built a model of multi-layer deposition of thin wall, and investigated the influence of deposition point standoff variation. Due to the assumption that powder flow diverge throughout, the effect of convergence of powder flow was neglected. To date, most research has focused on single-layer clad situations, and the powder flow has been considered as a simplistic surface distribution to melt pool area which is distinct from real world powder flow with spatial distribution. Indeed, important process conditions, which are related to the spatial distribution of powder flow concentration, have been neglected in layered deposition, such as the initial stand-off distance of nozzle, scanning direction (orientation of nozzle), change in stand-off distance through process and stability of multi-layer deposition. These serve to affect seriously the geometric characteristics of the deposit. Especially, during actual multi-layer deposition, if the layer thickness might not agree with the single-step rise, ΔZ, the change of nozzle stand-off distance and powder concentration on deposited surface will significantly affect the subsequent deposition process. This is a primary concern for users of DMD processes. Therefore the relationship between the single-step rise, ΔZ, and the actual deposited layer thickness are important for multi-layer deposition.

In this work, a realistic growth model is built based on spatial distribution of powder flow concentration to assess the influence of the key process parameters (including the orientation of powder streams and the initial nozzle and substrate surface). The matching relationship between the single-step rise and the actual deposited layer thickness will also be discussed in detail. Finally, the selection strategy is proposed and exemplar components are presented which make use of the improved process conditions.

2. Process modeling

2.1. Description of single-layer deposition

During DMD, a laser beam scans over a substrate surface (or a previously deposited layer) and creates a melt pool, into which feedstock powders are injected. These are propelled by an inert gas through a powder delivery nozzle. The deposited layer is formed due to the interaction between the powder flow and the melt pool, as shown in Fig. 1(a). Here, to simplify process analysis, it was assumed that all of the particles injected into the melt pool were instantly melted, and only contributed to the volume growth at the substrate in situ, without considering spreading and convection phenomenon. Thus, according to conservation of mass, the deposition growth at any point in the melt pool can be regarded as the volume increment of the powder injected into a given point per unit time.

A moving powder coordinate system (x, y, z) is used with a stationary substrate, as shown in Fig. 1(b). The symmetric center of nozzle tips on the exit plane and the direction of laser scanning velocity v_b were set as the coordinate origin o and x-axis, respectively. When the processing head (interaction system of the melt pool and powder flow) passes through a point $W(x_i, y_i, z_i)$ with the deposition height of h_i, the powder flow mass concentration at that point was considered to be $C(x_i, y_i, z_i)$. Therefore, a mass increment dM at a point W within an infinitesimal time interval dt is;

$$dM = C(x_i, y_i, z_i)v_p dxdydt \tag{1}$$

where v_p is the speed of the powder particles. Therefore, the volume increment dV can be given as;

$$dV = \frac{C(x_i, y_i, z_i)v_p dxdydt}{\rho_p} \tag{2}$$

where p_p is the density of the powder material (a single powder species is assumed), and the height increment dh_i of the position W can be obtained as;

$$dh_i = \frac{C(x_i, y_i, z_i)v_p dxdydt}{dxdy\rho_p} = \frac{C(x_i, y_i, z_i)v_p dt}{\rho_p} \tag{3}$$

After time dt, the translation of processing head is given by $v_b dt$. The coordinate of the point W would therefore change from (x_i, y_i, z_i) to $(x_{i+1}, y_{i+1}, z_{i+1})$, and

$$\begin{aligned} x_{i+1} &= x_i - v_b dt \\ y_{i+1} &= y_i \\ z_{i+1} &= z_i - dh_i \end{aligned} \tag{4}$$

As a result the powder flow mass concentration at this position can be expressed as

$$C(x_{i+1}, y_{i+1}, z_{i+1}) = C(x_i - v_b dt, y_i, z_i - dh_i) \tag{5}$$

Substituting Eq. (4) into Eq. (5), the deposition height increment of the point W within time dt can be represented as

$$dh_{i+1} = \frac{C(x_i - v_b\ dt,\ y_i,\ \ z_i - dh_i)v_p\ dt}{\rho_p} \qquad i = 0, 1, 2, \ldots \tag{6}$$

Based on this iterative relation, once the powder flow mass spatial distribution and the melt pool boundary are obtained, deposited growth at any point on a single-layer deposition path can be described.

2.2. Defining the powder flow mass spatial distribution

In this study, a coaxial nozzle was used with typical powder feed situation. This consisted of four tips uniformly orientated about the optical axis of the laser. The relation of orientation of nozzle tips and scanning direction is shown in Fig. 2(a). Powder flow mass spatial distribution can be obtained from an effective model developed using analytical methods. This model has also been previously developed and validated (Tan et al., 2012, 2016). The powder flow mass spatial distribution of a four-tip coaxial nozzle $C(x, y, z)$ can be given as;

$$C(x, y, z) = C^{13}(x, y, z) + C^{24}(x, y, z) \tag{7}$$

$$\begin{aligned} C^{13}(x, y, z) =& \frac{m_p}{4a^2\pi v_{p0}\{l + z\csc\varphi - [x + (S_f - z)\cot\varphi]\cos\varphi\}^2} \\ &\times\exp\left[-\left(\frac{\sqrt{\{[x + (S_f - z)\cot\varphi]\sin\varphi\}^2 + y^2}}{a\{l + z\csc\varphi - [x + (S_f - z)\cot\varphi]\cos\varphi\}}\right)^2\right] \\ &+\frac{m_p}{4a^2\pi v_{p0}\{l + z\csc\varphi - [-x + (S_f - z)\cot\varphi]\cos\varphi\}^2} \\ &\times\exp\left[-\left(\frac{\sqrt{\{[-x + (S_f - z)\cot\varphi]\sin\varphi\}^2 + y^2}}{a\{l + z\csc\varphi - [-x + (S_f - z)\cot\varphi]\cos\varphi\}}\right)^2\right] \end{aligned} \tag{7-1}$$

$$\begin{aligned} C^{24}(x, y, z) =& \frac{m_p}{4a^2\pi v_{p0}\{l + z\csc\varphi - [y + (S_f - z)\cot\varphi]\cos\varphi\}^2} \\ &\times\exp\left[-\left(\frac{\sqrt{\{[y + (S_f - z)\cot\varphi]\sin\varphi\}^2 + x^2}}{a\{l + z\csc\varphi - [y + (S_f - z)\cot\varphi]\cos\varphi\}}\right)^2\right] \\ &+\frac{m_p}{4a^2\pi v_{p0}\{l + z\csc\varphi - [-y + (S_f - z)\cot\varphi]\cos\varphi\}^2} \\ &\times\exp\left[-\left(\frac{\sqrt{\{[-y + (S_f - z)\cot\varphi]\sin\varphi\}^2 + x^2}}{a\{l + z\csc\varphi - [-y + (S_f - z)\cot\varphi]\cos\varphi\}}\right)^2\right] \end{aligned} \tag{7-2}$$

where $C^{13}(x, y, z)$ is the powder flow mass concentration from nozzle