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Modelling of coating thickness distribution and its application in offline programming software

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Cold spray technology exhibits various advantages such as potential applications like additive manufacturing and dimensional recovery of damaged parts. For the purpose of coating thickness control and reduce extra machining work, it is essential to optimize robot trajectory, operating parameters and spray strategy for a desired coating thickness distribution. In this study, a numerical model of single coating profile based on standard experimental results was established, which included the effects of spray angle, nozzle traverse speed as well as scanning step. Meanwhile experimental studies of cold spray on effects of spray angle and nozzle traverse speed were carried out to validate the numerical model. Based on the coating profile model, coating thickness model was developed to estimate the coating thickness distribution by taking into account the nozzle trajectory on the substrate. With the help of these models, an add-in program "ProfileKit" is developed and integrated in the offline programming software RobotStudio™, which enables the simulation of coating profile in 2D and coating thickness simulation in 3D. A trapezoid cold sprayed coating was deposited by changing scanning step to confirm the profile model in this study and to validate the simulation results by ProfileKit.

1. Introduction

Among various spray technologies, cold spray has drawn more and more attention due to its low porosity, high adhesion strength and low particle oxidation. In this process, particles in solid state with relatively low temperature are accelerated to high velocity ranging from 300 to 1200 m/s by heated and compressed driving gas through a converging-diverging nozzle, deposited onto substrate or layer already deposited [1–3]. Differing from traditional thermal spray processes where molten or semi-molten particles deposit at a low velocity, cold sprayed particles with low temperature and high velocity upon impact can avoid the occurrence of particle oxidation as well as local thermal residual stresses [4]. Due to its features of high deposition efficiency, high adhesion strength, low oxidation and low residual stress, cold spray is considered as an effective technology of additive manufacturing (AM) or 3D printing [5–8]. Compared with other additive manufacturing technologies like selective laser melting (SLM) and direct metal deposition (DMD), the small heat transfer in cold spray process can mostly retain the microstructure and mechanical and chemical properties of feedstock powders. Meanwhile, the controllable spray jet by the nozzle mounted at the robot provides more degree-of-freedom to the process, which enables fabrication of complex forms and coating deposition on free-form workpieces [5].

Nowadays, most additive manufacturing or dimensional repairs realized by cold spray are achieved by machinery on the cold sprayed block coating, which causes great amount of unavoidable material waste. Less attention is focused on the design of as-sprayed coating shape or coating profile control with high accuracy. For the purpose of effective additive manufacturing by cold spray, it's of great importance to find out the dependence of operating parameters such as spray angle, nozzle traverse speed, scanning step and standoff distance on coating thickness distribution. So far, there have been a series of studies focusing on the coating deposition model in cold spray as well as thermal spray process. Djurić et al. [9] developed a metal spray deposition model to simulate the spatial mass flux distribution produced by the nozzle. The deposition efficiency was included by transferring the non-linear inverse problem to a boundary-value problem. Rayment et al. [10] investigated the distribution of temperature and temperature variance on the substrate by using the same model, which aimed at the path planning optimization as well as the elimination of the thermal residual stress and distortion of the sprayed steel shell. Duncan et al. [11] also used the numerical model developed by Djurić to optimize the path separation in spray coating, which used the sampling theory to transfer the problem into the spatial frequency domain. However, the studies mentioned above have not included the influence of off-normal spray, which has become common cases due to the compromise on workpiece geometry or spray strategy. Fasching et al. [12] achieved

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a coating thickness distribution with low standard deviation by optimizing robotic trajectory, which was realized by using a nozzle spray-tilting model. Similarly, Leigh et al. [13] evaluated the effects of spray angle on coating profile by various coating properties like micro-hardness, tensile adhesion strength of the plasma sprayed coating.

In this study, a numerical model of coating profile based on Gaussian distribution was developed and then added to the offline programming software. The numerical model includes the facts of various spray parameters, such as spray angle, scanning step and nozzle traverse speed, while three groups of experiment by cold spray were made to validate the numerical model. Afterwards, the coating thickness model was integrated to the offline programming software RobotStudio™ as a module in the software "Thermal Spray Toolkit" (TST) [14,15]. It enables the coating thickness simulation based on the operating parameters in spray process, robot trajectory and robot kinematic data obtained by process simulation. Combined with other modules in TST such as trajectory generation [15–17] on different kinds of substrate surface, users are able to improve the spray strategy, robot trajectory as well as the operating parameters according to the results of coating thickness simulation and robot kinematic data.

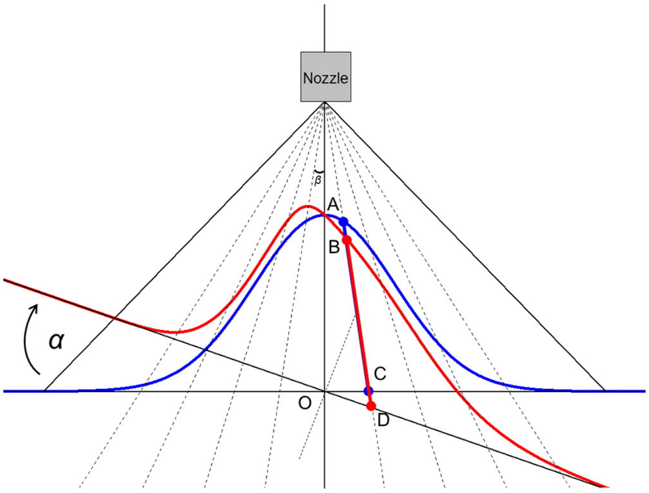

Fig. 1. Schematic of coating profile in perpendicular (blue line) and off-normal (red line) spray cases. The substrate is inclined clockwise in off-normal spray case. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

2. Modelling and experimental details

2.1. Single coating profile modelling

According to the central limit theorem, the averages of random variables can be considered normally distributed when the amount of variable is sufficiently large. Thus, in the case of thermal spray process, the feedstock jet distribution out of nozzle as well as the coating thickness distribution on substrate surface can be approximated by the mathematical expression of Gaussian distribution. As a result, for the coating deposited by thermal spray process, its thickness distribution also known as coating profile can be expressed by Gaussian approximation [18] as the equation below. Coating profile has been frequently used for coating thickness distribution in spray process, which can be experimentally measured from the cross-section of the coating deposited by single nozzle path [12].

$$\varphi = \zeta(\theta)\int_0^{T}\Big(\int \frac{A}{\sigma\sqrt{2\pi}}e^{-\left(\frac{(x-\mu_x)^2}{2\sigma^2}+\frac{(y-\mu_y)^2}{2\sigma^2}\right)}dxdy\Big)dt \tag{1}$$

Where A is the amplitude factor in relation with the feedstock flow rate obtained from experimental result, σ is the standard deviation of coating profile, (μ_x, μ_y) is the center coordinate of coating profile on substrate surface and $\zeta(\theta)$ is the deposition efficiency in function of the spray angle. The values of each variable are obtained through experiments for a certain powder/substrate material system and spray parameters.

Generally, the spray angle is 90° in order to obtain a maximum deposition efficiency and coating quality. However, in the real spray process, due to the limits of workpiece geometry and working condition, the off-normal spray usually appears as a compromise on spray strategy. In this study, the effects of spray angle are included in the numerical model through mathematical transformation. As shown in Fig. 1, for perpendicular spray case, the coating profile is conical and symmetric with the central line of nozzle. In the off-normal spray case, the substrate is inclined clockwise according to the nozzle. The coating profile in off-normal cases can be deducted by transforming the perpendicular spray model in the Cartesian coordinate system to the polar coordinate system. The spray cone in polar coordinate system is divided into a series of rays with constant interval angle. Exemplary rays in polar coordinate are indicated as dash lines in Fig. 1. In the polar coordinate system, any point on coating surface in the perpendicular spray case can be described by two variables. As illustrated in Fig. 1, one is the deflection angle β between each ray and the central line, and the other one is the spray length AC at this angle between the impacting point C on the substrate and the point A at coating profile. Thus, it is able to describe the coating profile as a function of the deflection angle and the corresponding spray length.

Due to the fact that mass distribution out of nozzle is constant during nozzle inclination, an assumption can be made that the spray length at each deflection angle is constant during inclination. Thus, the coating profile of off-normal spray can be established by spray length at each deflection angle in the standard model in perpendicular case. For example at the deflection angle of β as indicated in Fig. 1, the spray length AC at perpendicular spray case has the same value as BD at off-normal spray cases. The impacting point at each deflection angle is obtained by perspective projection through the nozzle exit point at the substrate surface. As a result, by applying the spray length at each deflection angle, it can obtain the corresponding points at the coating surface within the inclined spray cone area. The coating profile for off-normal spray cases is given in Fig. 1, where off-normal coating profile is marked as red, and perpendicular one is marked as blue.

As shown in Fig. 2a, exemplary coating profiles at different spray angles from 90° to 50°that is obtained by the methodology above without accounting deposition efficiency are given, where the nozzle is inclined anticlockwise according to the original point, standoff distance is 30 mm. It is found that for off-normal spray cases, as spray angle is decreasing from 90°, the mass distribution is gradually concentrated on the left side, and its asymmetry becomes more evident. Due to the decrease of spray angle, particles are dispersed on a larger area, which causes the decrease of maximum coating profile height and increase of coating profile width as it is observed in Fig. 2a. The effects of spray angle on deposition efficiency will be presented in the following parts by experimental data. In order to evaluate the coating profile asymmetry with spray angle, the parameter of skewness, which is usually used to characterize the symmetry of the probability distribution of a set of random values, was applied and its variation is given in Fig. 2b. For the spray angle of 90°, the skewness of the coating thickness distribution is zero, which indicates the perfect symmetric distribution. With the decrease of spray angle, the skewness increases, which indicates the asymmetric distribution as well as the fact that the coating profile is gradually concentrated on the same direction of nozzle rotation. The skewness variation with the spray angle has a good consistency with the coating profile variation in Fig. 2a.

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