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2D modelling of clad geometry and resulting thermal cycles during laser cladding

Wei Ya[a,b,*], B. Pathiraj[a], Shaojie Liu[c]

[a] University of Twente, Laboratory of Mechanical Automation, P.O. Box 217, 7500 AE Enschede, The Netherlands
[b] Materials innovation institute (M2i), P.O. Box 5008, 2600 GA Delft, The Netherlands
[c] University of Twente, Production Technology, P.O. Box 217, 7500 AE Enschede, The Netherlands

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ABSTRACT

A 2D thermal model of laser cladding process based on mass and energy balance is built incorporating the powder efficiency and solved with the finite element software COMSOL MULTIPHYSICS® v4.4. Powder efficiency was used as one of the input parameters. Powder efficiency was determined with weight measurements before and after laser cladding on thin DIN 2393 steel plates. Powder efficiency was also calculated from the clad area measured with binary image processing technique applied on cross section micrograph. The powder efficiency obtained from these two methods is in good agreement. The changes in powder efficiency with cladding process conditions were analysed in detail. The effect of input energy on the powder efficiency and dilution were correlated. The powder efficiency increases with energy input to a maximum value, beyond which the increase is marginal. The dilution continues to increase within the tested effective energy levels. Two methods were used to validate predictions of the thermal model. The positions of the melt depth and depth of the HAZ are measured from optical micrographs and from the hardness profiles. The depths were computed by tracing the melting temperature and the Ac_3 temperature of the substrate material against the isotherms generated in the numerical simulations. The agreements in general were good. Thermocouples were inserted in the substrate materials at different locations and depths to record the temperature changes during laser cladding of 11 overlapped clad tracks. Measured and simulated temperature cycles with time agree within 5% of error. The developed powder efficiency based model is able to predict accurately the clad geometry and thermal cycles during the laser cladding process.

1. Introduction

Laser cladding is a metal deposition process employed for surface repair and to apply a functional coating. The coating process is achieved by either pre-placed powder or blown powder techniques which are compared by Steen and Mazumder (2010). The blown powder technique is applied in this research, which is schematically shown in Fig. 1. During laser cladding, the surface of the substrate is melted by laser irradiation and a melt pool is created. The powder is either injected into the melt pool with a co-axial or an off-axial nozzle using an inert carrier gas. A powder stream is formed once the powder particles exit the nozzle tip. Both the powder stream and laser beam are focused on the same surface area of a substrate. The powder becomes molten and is captured by the melt pool, after which it mixes with the substrate material. Metallurgical bonding takes place between the coating material and substrate by the solidification of the melt pool. Shielding gas (such as argon, nitrogen and helium) is used to protect the melt pool against oxidation. A clad track is produced on the substrate surface when the laser beam and powder stream are travelling together with respect to the substrate. In practice, a surface is cladded by overlapping several clad tracks (then called as clad layer).

Analytical and numerical models have been developed to simulate the laser cladding process. Lalas et al. (2007) presented an analytical model to predict the clad geometry. Nenadl et al. (2014) established an analytical model to predict the geometry of a single clad track and the overlapped clad layer, which were validated with experimental data. Toyserkani et al. (2004) developed a 3D model to predict the clad layer shape with a Nd:YAG pulsed laser and performed experiments. The effective energy density and powder density were used to evaluate the clad geometry under different processing conditions. Experimental results of cladding pure iron on a mild steel substrate were used for validation. Tabernero et al.

* Corresponding author at: University of Twente, Laboratory of Mechanical Automation, P.O. Box 217, 7500 AE Enschede, The Netherlands.
E-mail address: w.ya@utwente.nl (W. Ya).

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(2014) recently presented a model to simulate the clad geometry by combining several previously developed sub-models, which takes into account the effects of the powder mass flow, power attenuation by powder stream (Tabernero et al., 2012) and the melt pool formation (Ukar et al., 2010). In one of their sub-models, Ukar et al. (2010) validated the thermal predictions by comparing the predicted isotherms (the melting temperature, T_m, isotherm and the austenitizing temperature, Ac_3, isotherm) to the corresponding cross sections. DIN 1.2379 tool steel was used in their the validation experiments. Many researchers have combined numerical modelling with experimental results to define processing windows for industrial applications (Gedda, 2000; Hung and Lin, 2004). The various relationships between laser power, cladding speed, powder feeding rate, dilution, temperature distributions and stress profiles, etc., have been studied numerically. Fu et al. (2002) derived a group of equations to calculate the temperature distribution on the surface of a substrate, considering the effects caused by a powder stream/cloud. In their model, they studied convected and absorbed laser energy due to attenuation by the powder. Costa et al. (2002) simulated the tempering of steel parts produced by laser cladding. They established the relationship between the temperature distribution and the hardness profile within the tempered zone. Cho et al. (2004) reported the importance of latent heat effect in modelling laser cladding processes and developed an improved numerical analysis algorithm using Abaqus™ software. Smaller size of melt pool, lower maximum temperature and narrower heat affected zone were predicted when latent heat effects were taken into consideration. Costa et al. (2002) also studied the influence of thermal cycles on the resulting microstructures, when cladding ten overlapped clad tracks of AISI 420 on AISI 420 tool steel substrate. Solid state phase transformation was simulated to evaluate the relationship between the processing conditions and microstructures. Santhanakrishnan et al. (2011) reported an experimentally validated thermo-kinetic hardening model which can predict cross-sectional temperature history. Hofman et al. (2011) presented a model to predict clad geometry and found a relationship between dilution and melt pool width in their study. It is interesting to note that Brückner et al. (2007) used a simple one dimensional analytical model to evaluate stress and strain. According to them, it is very difficult to understand in detail the mechanism of strain and stress evolution in laser cladding and their dependence on the processing conditions. However, the phenomena can be described well by a rather simple 1D analytical model. Brückner (2012) further developed their model into 2D and 3D FEM models. Thermo-mechanical behaviours in laser cladding is simulated in their models. After comparing the simulation results from the 2D and 3D models, the authors concluded that their results were similar and that a 2D model represents the cladding process quite well.

The models described in the literature use mass-energy balance equations. Such a balance is dependant on the powder efficiency (powder catchment). The clad geometry and dilution are influenced by powder efficiency. The changes in powder efficiency with process conditions are not investigated in works reported in literature, which has been analysed in detail in this research. A 2D thermal model to solve the clad geometry and heat conduction is built incorporating experimental results of powder efficiency tests.

The objective of this paper is to present a 2D thermal model of laser cladding that can predict the clad geometry and thermal distribution by taking into account the effects of powder stream density and powder efficiency on the clad geometry. The geometry of single or overlapped clad tracks is calculated as a function of the process parameters (laser power, cladding speed and powder feeding rate). The equations for conservation of energy and mass are solved in a coupled manner with the finite element software COMSOL MULTIPHYSICS® v4.4 (COMSOL). The geometry of the clad track is explicitly described using moving mesh, which takes into account mass addition, melting and solidification phase changes. The temperature dependant thermo-physical properties of the coating and substrate materials in the solid phase are used in the computation.

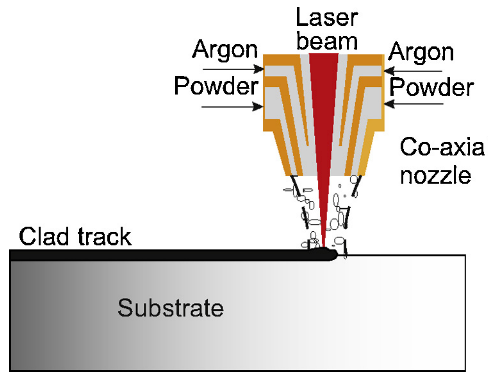

Fig. 1. A schematic overview of laser cladding with powder blown technique (co-axial nozzle).

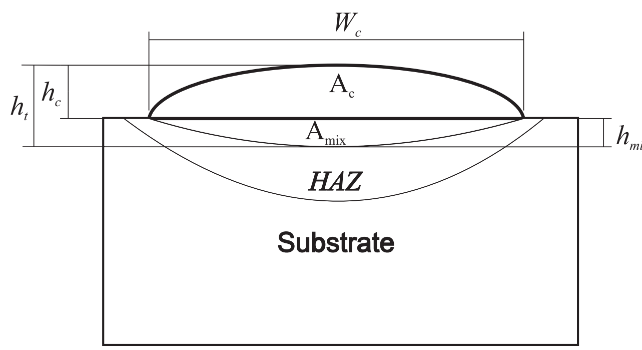

Fig. 2. A schematic view of the cross section of a single clad track.

2. Description of the developed thermal model

Table 1 lists the symbols uses in the model and their explanations. The developed thermal model is based on energy-mass balance and uses powder efficiency as one of the input parameters.

A schematic cross section of a clad track bonded on a substrate is shown in Fig. 2. It indicates the characteristics of a clad which include clad height (h_c), clad width (W_c), clad area (A_c) above substrate surface, mixing area (A_{mix}) below substrate surface, melt depth h_{mix} and heat affected zone (HAZ).

Dilution is defined as the mixing ratio between the coating and substrate materials. In principle, dilution refers to elements ratio of the mixing between substrate and the coating materials in the solidified melt. Schneider (1998) has shown that such elements ratio can be correlated to the clad geometry. Hence, the geometrical definition of dilution as defined by Abbas and West (1991) is used in this work. The dilution d is calculated from

$$d = \frac{A_{mix}}{A_{mix} + A_c} \times 100\% \approx \frac{h_{mix}}{h_{mix} + h_c} \times 100\%. \quad (1)$$

2.1. Governing equations

The energy balance (2) and mass balance equations (3) are as expressed as,

$$\rho_s C_{ps}{}' \frac{\partial T}{\partial t} + \rho_c V_m C'_{pc} \nabla T + \nabla T(-\lambda \nabla T) = Q_{abs} - Q_{loss}, \quad (2)$$