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Geometric Modelling of Added Layers by Coaxial Laser Cladding

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Abstract

The laser cladding process is based on the generation of a melt-pool in a substrate where a filler material is injected, generating high quality layers with a minimum heat affected zone. This process is industrially used to generate 3D parts, being a sustainable alternative to traditional machining. One of the most important aspects for its industrial application is to know the clad geometry in order to calculate the deposited layer thickness. This work presents a model in which, starting from the concentration of injected material, real energy distribution and the melt-pool geometry, clad height is estimated. All input variables are obtained by three previous validated models.

Keywords: Laser Cladding; Modelling; Clad Geometry

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1. Introduction

In the recent years the industrial sectors dedicated to manufacture of high added value components are studying and developing new processes in order to reduce the costs of their production chains. In this sense, laser cladding process is becoming of high interest for these industries. This process is based on the localized melting of a substrate where a filler material is injected. Laser cladding generates clads with high mechanical properties and a strong union with the base material, avoiding a high heat affected zone. The injected material, in form of wire or powder, can be of same nature of substrate or provide properties that it does not possess. Thus, overlapping clads it is possible to generate layers of material which can fill

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damaged parts or create hard coatings on wear subjected zones. Moreover, these layers allow to manufacture 3D complex geometries in order to generate near shape parts that only require a finish machining. This fact supposes a great advantage for sectors such as mould and die industries, where integration of this process could reduce the high amount of waste material in form of chip that involves traditional machining. Other sector in which this process is becoming of interest is the aeronautical, where it is a feasible alternative to conventional welding processes such as TIG or plasma welding.

Generally, laser cladding process starts by a CAD design of the part, subsequently a CNC program with the trajectories is generated, and finally, the geometry of the part is obtained by a finishing machining [1]. In any case, it is necessary a tuning process in order to know clad quality and geometry before industrial application of laser cladding [2]. This previous experimental work increases costs of the process, and supposes a high obstacle for introducing laser cladding into industries. By using process models it is possible minimize the time invested in the previous tuning, avoiding unproductive time on the machine. Generally, laser cladding modelling involves a high complexity. In this sense, the strategy used to deal with cladding models consist on subdivide them into three steps: material flow study, thermal problem on the substrate an clad generation. Regarding clad geometry generation, it is possible to control the layer thickness if clad height is previously known. In turn, this makes it possible to optimize the z axis offset between layers in order to maintain constant beam spot size in the cladding zone [3].

This work is focused on clad geometry generation step during laser cladding process. There are all types of models for estimating clad geometry; from totally empirical models to fundamentally analytical ones, even semi-empirical models which use experimental parameters to adjust them. The empirical models [4], even though they are valid for process behaviour studying, do not reduce the experimental costs what is one of the aim of process modelling. The analytical models development [5] does not require any experimental test but it results of high complexity in its resolution. Therefore, it is necessary to do some assumptions that simplify the model but reduce his validity for a narrow range of input parameters. Finally, the semi-empirical models [6], despite of need a series of adjustment tests, allow to generalise the results for wide ranges of the process parameters without complex developments. Generally, these models assume, on one hand, that all material which reaches the melt pool is used to generate clad, and on the other hand, that the height is directly proportional to powder concentration that is injected on this zone. In this sense, it is necessary to know previously the melt pool shape where the powder will be added and the amount of powder reaching this melt pool. This fact requires that all the models of the process interact between them in order to obtain a global model which provides the clad geometry before application of the process. So, this global model must take into account the melt pool shape provided by thermal model, and the powder that reaches melt pool estimated by the concentration model, making possible to calculate the generated clads.

The presented model is a numerical model which, based on the data provided by a CFD model [7] and by a thermal model [8], allows to estimate the geometry of clads generated by laser cladding process. The models have been previously developed and validated providing with high accuracy powder concentration, energy distribution on the part surface and melt pool shape. The obtained results demonstrate the validity of the model to estimate the generated clad geometry, becoming a tool to make easier the industrial application of the process.

Nomenclature

Thermal Model

a	Thermal diffusivity [m^2/s]
θ	Temperature [K]
A	Global looses parameter [-]
q_v	Heat Source
ρ	Density of substrate material [Kg/m^3]
C_p	Specific Heat [J/Kg·K]
λ	Thermal Conductivity [J/s·K·m]
t	Time [s]

Geometric Model

m_i^i	Powder mass injected on *i* point [Kg]
m_p^i	Mass of parallelepiped added on *i* point [Kg]
$\emptyset_i$	Powder flux on *i* point [Kg/m^2·s]
W	Width of added parallelepiped [m]
t	Injection time in each point [s]
Δs	Discretization step of the trajectory [m]
V_f	Nozzle feed rate [m/s]
ρ	Density of filler material [Kg/m^3]
H_i	Height of added clad in *i* point [m]

2. Model Development

The model development is supported on following assumptions:

1. The clad height for each point depends on the powder concentration of this point and on time in which it is injecting material over it.
2. All powder that reaches the melt pool is used to generate the clad.
3. The clad only grows on the melt pool area. The powder injected outside this area rebounds and is considered as lost material.
4. Powder concentration over the melt pool is obtained from a CFD model developed using FLUENT©. This model has been also previously developed and validated [7].
5. Melt pool shape is estimated by a thermal model previously developed and validated [8].
6. Real energy reaching the part surface is calculated by a previous attenuation model [9].

Fig. 1 shows the algorithm used to estimate the clad geometry. Firstly, CFD model obtains the powder flow in nozzle outlet. Then, attenuation model calculates the real energy reaching the substrate. This energy generates the melt pool on part surface, and its shape will be calculated by thermal model. Finally, geometric model uses all data provided by other models and estimates the clad geometry for each time step and for each point of the programmed trajectory.

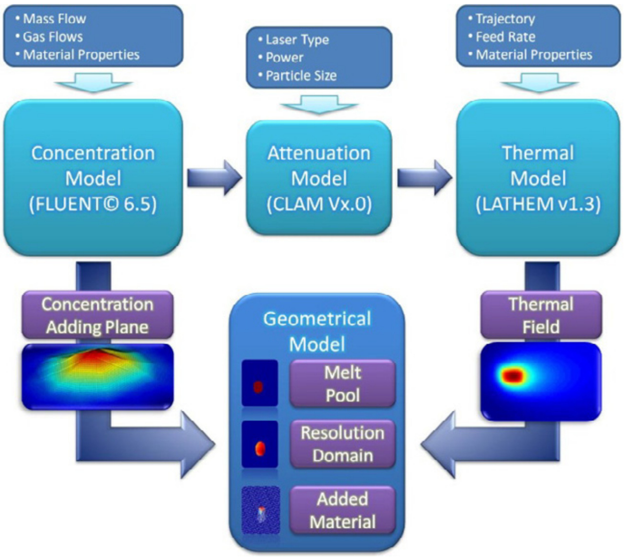


Fig. 1. Scheme of global model including all developed models

2.1. Powder Flux Model

The powder flux model has been implemented on Fluent© 6.5 and solves the Navier-Stokes equations for a turbulent flow using a standard κ-ε approximation. The discrete phase is treated by a Euler-Lagrange model where the continuous phase is treated as a continuous homogeneous medium and Navier-Stokes equations are solved for each time step. The discrete phase is calculated tracing a certain amount of particles in the previously calculated fluid field, and it can exchange mass, momentum and energy with the fluid phase. The main assumptions used for the model solving are:

1. Constant velocity and perpendicular flow to surface are considered in the nozzle inlets.
2. The model will study the steady-state problem and no transient-state is considered. Thus, the powder concentration distribution is no time dependent.
3. The discrete phase model is based on a force balance for each particle. In this balance only drag, inertial and gravity forces are considered. Interactions between the particles are not considered, only the collisions with the nozzle walls influence on the particle trajectories.
4. Great changes are not expected in the density; therefore, a segregated model with constant density was selected.
5. Particle flow influence on the continuous phase is ignored due to the low mass and concentration of the particles.

6. Powder size distribution has been calculated from experimental data and adjusted using a Rosin-Rammler particle size distribution.
7. Laser radiation and other heat sources are not considered because the particle flow is not influenced by these sources.

2.2. Attenuation Model

Attenuation model is based on a typical shadow model, which incorporates some general aspects allowing its use in industrial laser cladding operations. It is therefore a semi-empirical model that requires a previous characterization of the interaction between the laser and the material, for subsequently being generalized to a range of parameter combination of the process. The proposed model is based on the following assumptions:

1. The attenuation is proportional to the shadow generated by the particles of powder. The shadow between particles is also neglected since it can be considered that the powder concentration is much lower than the gas volume.
2. Attenuation does not depend on the laser power. This assumption is only valid for low powers because if the power increases, particles could be partially evaporated varying their diameter.
3. Particles are considered spherical and their projection on the plane are approximated to a circle. Rosin-Rammler particle size adjustment made for the CFD model is also used in the model.
4. Previously developed and validated CFD model provides powder concentration on different planes normal to nozzle axis.
5. Material properties are considered to be independent of temperature maintaining constant density and particle size.
6. It is considered that the attenuation is produced after a plane in which the distribution profile of concentration is consolidated and takes a Gaussian form.

2.3. Thermal Model

Thermal model solves heat transfer equation using a finite differences algorithm implemented in Matlab© 7.8. The model uses the following assumptions in order to solve the problem:

1. It has been added a losses parameter which involves the energy losses due to beam reflections in the part surface as well as the losses that can decrease the energy absorbed by the part. This parameter has a value of 0,2 in laser cladding processes on steel milled parts. So, the equation solved by the model takes the form (Eq. 1):

$$a\nabla^2\theta \pm (1-A)\frac{q_v}{\rho c_p} = \frac{\partial\theta}{\partial t} \tag{1}$$

2. The initial temperature is introduced globally in each element of the part as an initial condition for the first time step.
3. The heat flux for elements located in the part faces is locally considered as boundary flux condition using a Newmann condition in each time step. This condition is null on surfaces where the laser is not irradiating.
4. Since all energy radiated by the laser is focused on quite small area, high thermal gradients are reached because of material heat conductivity. So, conductive heat flux is not considered and its effects are took into account in the losses parameter.
5. Nonlinearities in material properties are considered. These properties, such as material conductivity or density, are temperature dependant and are calculated for each time step.
6. Solid state phase transformations during heating and cooling steps are considered as energy consumptions. The numerical approach treats phase transformations with an additive principle, i.e. the percent phase transformed in each simulation step (f_i) is an accumulation of the phase transformed in the previous step (f_{i+1}). The kinetic equation of Johnson-Melh-Avrami is used to model diffusive transformation during heating, allowing to calculate the fraction of transformed material over time in isothermal conditions. To model non isothermal conditions the fraction of transformed material balance is done in differential time steps.

2.4. Geometric Model

The model starts from data provided by the other models and calculates in each point and in each instant the height of generated clad. In order to accomplish this, parallelepipeds of W^2 section and H height are used to discretise clad geometry (Fig. 2).

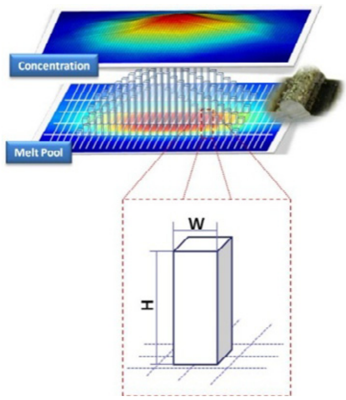


Fig. 2. Model approach and clad discretization starting from powder concentration and melt pool shape

The model is based on a mass balance between injected material in each point and mass of the parallelepiped generated in that point (Eq. 2).

$$m_i^i = m_p^i \quad (2)$$

The injected mass can be calculated multiplying the material flow in that point by the time during which powder is being injected on it (Eq. 3).

$$m_i^i = \phi_i\left[\frac{Kg}{m^2 \cdot s}\right]\cdot W^2\left[m^2\right]\cdot t\left[s\right] \quad (3)$$

Where injection time can be calculated as length of discretization step divided by the cladding nozzle velocity (Eq.4).

$$t = \frac{\Delta s\left[m\right]}{V_f\left[m/s\right]} \quad (4)$$

Finally, the mass of generated parallelepiped is obtained multiplipying its volume by the material density (Eq. 5).

$$m_p^i = \rho\cdot\left[\frac{Kg}{m^3}\right]\cdot W^2\left[m^2\right]\cdot H_i\left[m\right] \quad (5)$$

These expressions allows to develop the mass balance presented in Eq. 2.

$$\phi_i \cdot W^2 \cdot \frac{\Delta s}{V_f} = \rho\cdot W^2 \cdot H_i \quad (6)$$

Simplifying the Ec.6 allows to obtain the geometric model formulation that allows to calculate the clad height for each point of the domain (Eq.7).

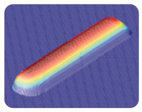
$$H_i = \frac{\phi_i \cdot \Delta s}{\rho\cdot V_f}\left[m\right] \quad (7)$$

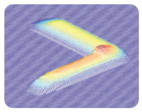
3. Results and Discussion

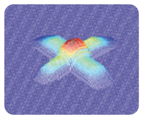
Once the different models have been presented the global model calculates step by step the variables used to estimate the clad geometry. Firstly, material flux model calculates the powder distribution on planes normal to nozzle axis covering the distance between cladding zone and nozzle outlet. This information is used, on one hand, by the attenuation model to calculate the real energy reaching the substrate, and on the other hand, by the geometric model in Equation 6 in order to estimate clad growth. So, the attenuation model takes the powder distribution on planes where the flux is consolidated and calculates step by step the attenuation suffered by the beam until reaching the substrate. Then, thermal model uses this attenuated distribution to estimate the temperature field on the substrate for each time step. Finally, geometric model using both the powder distribution and the temperature field on the substrate surface, calculates the added clad geometry for each step of the trajectory. The algorithm localizes the points on the surface with temperature higher than melting point, these points allow to limit the melt pool area where the Equation 6 will be applied in order to calculate the clad growth in each point. As shown Table 1, geometric model is not only capable of calculate the geometry of the added clads but it also can estimate local effects such as changes in the trajectory direction or clad overlapping. Moreover, model has been experimentally validated for a nickel based superalloy commonly used in aeronautical industry, The average errors observed in validation tests for both estimated height and width are below 8% of measured values (Table 1). These errors show the validity of the model as tool in the adjustment step of the laser cladding process and its industrial implementation.

Table 1. Validation tests results

Feed Rate (g/min)	Power (W)	Height (mm)		Error (%)	Width (mm)		Error (%)
		Measured	Modelled		Measured	Modelled	
	900 W	0,095	0,095	0	2,903	2,4	17,3
4.1	1000 W	0,098	0,098	0	2,727	2,5	8,3
	1100 W	0,098	0,102	4,0	2,82	2,7	4,3
	900 W	0,121	0,114	5,4	2,743	2,5	8,9
5.2	1000 W	0,123	0,12	2,4	2,763	2,5	9,5
	1100 W	0,134	0,124	7,5	2,697	2,7	0,1
	900 W	0,157	0,132	15,7	2,787	2,5	10,3
6,3	1000 W	0,149	0,137	8,3	2,653	2,5	5,8
	1100 W	0,163	0,142	13,1	2,66	2,7	1,5







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