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Multiphysics simulation of laser cladding process to study the effect of process parameters on clad geometry

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Abstract

The present work reports two-dimensional simulation of laser cladding process to understand the influence of process parameters on clad geometry formation for better process optimization. The application deals with pure copper powder cladding of SS316L substrate for process feasibility for thicker coating layers by CO_2 laser. For this purpose, first mathematical model is developed and dealt numerically using multi-physics software. Conservation equation of energy, momentum and mass of this process are coupled through the temperature variable and solved to adapt the laser cladding process. The boundary conditions due to the laser melting process of dissimilar materials have to be deal with complex assumptions are applied in mathematical modelling to simplify problem due to the different materials properties. The deformation of free surface is calculated using moving mesh by the way of ALE (Arbitrary Lagrangian and Eulerian) method. In addition, thermo-capillary forces and their effect on fluid flow inside the melt pool are also considered in modelling to complete the process optimization. Thermal and stress distributions due to the process are also evaluated in the developed process simulation. The results provide approximate information about the effect of each selected parameters on clad geometry formation. The influence of process parameters have shown the best choice of optimization.

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*Keywords:*Laser cladding; Process parameters; Heat transfer; ALE method

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1. Introduction

Laser cladding process is one of the potential techniques to deposit thick layers development on similar and dissimilar coatings of high thickness. The development of pure copper coating on stainless steel substrates is having demand in advanced fusion reactor in vessel components applications [1]. The development of laser based systems for deposition of powders on substrates has attracted several industrial applications for the thick cladding or coatings, repairs. The process optimization has several critical challenges in achieving the desired properties of the final required cladding layer parameters like uniform thickness, good bond strength, dissolution and deformations [2, 3]. The experimental facility pose several limitations due to the involved technical challenges, the process parameters like laser power selection, laser beam spot size, laser travel speed, shield gas flow, powder feed rate and surface preparations etc. show influence on the final manufactured product[4,5]. Hence a thorough understanding of the process parameters for the control on final produced cladding joints is desired. Several authors have studied the detail process parameters effects by experimental mock-ups by thoroughly to explore best production of thick cladding or coatings [6, 7]. In addition, simulation studies are extensively carried to explore the process parameters selection and their influence on final product parameters by different techniques [8, 9]. The process simulation for understanding has been carried by developing 2D and 3D models by incorporating the critical boundary conditions by using finite element methods and COMSOL multi-physics models extensively [10,11]. Thermal and residual stress conditions at the interface layer also play critical role in the final clad samples distortion and performance of the final properties of the cladding [12-14]. The present study is aimed to develop simulation model for laser cladding process to understand effect of process parameters (like power, laser speed, spot size, etc.) on final properties of cladding joints like dissolution, thermal history, stress conditions and deformations. This study is helpful for final laser cladding process development for selection of appropriate parameters and their optimization before going for actual manufacturing / large scale production. For this purpose all mathematical model equations are coupled through common variable temperature and solved using COMSOL multi-physics software.

Nomenclature

Q_v	power generation per unit volume of the substrate [W/m³];
λ	thermal conductivity [W/m K];
c_p	specific heat capacity [J/kg K];
c_p^*	modified heat capacity [J/kg K];
T	temperature [k]
T_m	melting temperature [K];
T_O	ambient temperature [K];
ρ	density [kg/m^3];
g	gravity field [m/s^2];
μ	viscosity [kg/s m];
τ	numerical constant (0.001);
T_m	angle between surface normal and laser beam incidence;
p	pressure [N/m^2];
$p_\propto$	ambient pressure [N/m^2];
$\vec{n}$	normal vector of the free surface;
$\vec{t}$	tangential vector to the free surface
I	laser energy distribution on the work piece [W/m^2];
$\propto_0$	absorption factor;
hc	heat convection coefficient [W/m^2 K];
ε_t	emissivity;
σ	Stefan- Boltzmann constant [5.67 × 10 W/m^2·K^4];
γ	surface tension [N/m];
u	fluid velocity in x&y directions respectively [m/s];
r_l	beam radius [m];

r_p	radius of powder particles [m];
P_l	laser average power [W];
β	thermal expansion co-efficient [1/K];
d	powder diameter [m];
I_0	intensity scale factor [W/m^2];
ΔH_m	latent heat of fusion [J/kg];
f_L	liquid fraction;
κ	curvature (1/m)
Δt	elapsed time [s];

2. Mathematical model

The laser beam heating and mass addition such complex phenomenon, is challenging task to model due to the processes associated with laser cladding such as melting, solidification cycles which is similar to weld process phenomenon. The boundary conditions have to be distributed carefully by keeping the material properties with the process parameters in thermal process. Mathematical treatment has been carried by the obtained set of equations of model are coupled through the temperature variable and is solved using the COMSOL multi-physics software. The phenomenon of the laser cladding process representation with laser beam interaction parameters is shown in Fig.1 for reference. Deformed geometry caused due to continuously heating and mass addition incorporated in modelling via Arbitrary Lagrangian and Eulerian (ALE) equations.

2.1. Assumptions

- The powder particles are considered to be like sphere of radius r_p.
- The geometry of the melt pool is considered to be of elliptical cross section and the width of the melt pool is considered equal to the diameter of the laser beam.
- The loss of material due to evaporation is not considered during the model development.
- Energy absorbed by the powder particles and the base material is constant during the entire process.
- There is no heat loss in convection and radiation by the powder particles because of the short time of interaction with the laser.
- The amount of energy absorbed by the powder particles is less than 2% of the amount of energy absorbed by the base material.
- Huge difference of viscosity and density between liquid metal and air allows us to reduce domain computation without considering the air.
- The liquid metal is assumed to be an incompressible Newtonian fluid. Flow in the molten pool is considered to be laminar.

2.2. Governing equation of Domains

In order to formulate the problem at initial step, it is considered that laser beam interaction surface of steel plate region is covered by laser beam heat flux (Gaussian). The heat conduction process as dominant phenomena is take place in domain1 (as shown in Fig.1). There is some region of melt pool of stainless steel and remaining portion of copper powder melted by laser is represented in domain 2. Energy conservation phenomenon now converted into the mass conservation and momentum conservation.

2.2.1. Conservation of Energy

$$\rho C_p^* \left[\frac{\partial (T)}{\partial t} + \nabla (u\,T) \right] - \nabla (\lambda \nabla T) = Q_v \quad (1)$$

In above equation the velocity field u calculated using momentum and mass conservation equation.

2.2.2. Conservation of momentum

In the laser cladding process, the conservation of momentum is one of the important governing laws. The momentum equation is represented as

$$\rho_0 \left[\frac{\partial u}{\partial t} + u(\nabla u) \right] = \nabla \left[-pI + \mu(\nabla u + (\nabla u)^T \right] + F_b + F_G \quad (2)$$

Where, ρ_0 is density at $T = T_m$, F_b is Buoyancy Force, F_G is Darcy Force. [12].

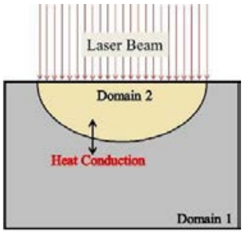


Fig. 1. Physics phenomenon of process

2.2.3. Conservation of mass

The continuity equation is represented by

$$\nabla u = 0 \tag{3}$$

The effect of latent heat of fusion on the temperature distribution can be approximated by increasing the specific heat capacity as

$$C_p^* = C_p + \Delta H_m \frac{\partial f_L}{\partial T} \tag{4}$$

Buoyancy force in the momentum equation taken in account using the following equation

$$F_b = \rho_0 \left[1 - \beta (T - To)\right] \cdot g \tag{5}$$

Darcy’s governing equation in the momentum equation can be given by

$$F_G = \frac{-180\mu}{d^2} \frac{(1 - f_L)^2}{(f_L{}^3 + \tau)} u \tag{6}$$

f_L is liquid fraction, which can be express as:

$$f_L = \begin{cases} 0 & T_S \leq T \\ \dfrac{T - T_S}{T_L - T_S} & T_S < T < T_L \\ 1 & T > T_L \end{cases} \tag{7}$$

2.3. Boundary Conditions

For the laser cladding process, a set of complicated boundary conditions should be satisfied. However, a set of important boundary conditions are as follows: [13]

- The effect of the laser beam and the powder flux can be modelled as a surface heat source and heat flux, defined by the boundary condition as

  $$q_{in} = \propto_0 \cos(\theta) I_0 - h_c (T - To) - \varepsilon_t \sigma \left(T^4 - To^4\right) \text{ (For Domain 1)} \tag{8}$$

  $$q_{in} = - h_c (T - To) - \varepsilon_t \sigma \left(T^4 - To^4\right) \text{(For domain 2)} \tag{9}$$

- A continues laser beam with homogenous intensity is considered for energy distribution. The laser beam intensity calculated using following formula

  $$I_0 = Laser\ intensity = \begin{cases} \dfrac{\propto_0 \cos\theta P_l}{\pi r_l^2} & r \leq r_l \\ 0 & r > r_l \end{cases} \tag{10}$$

2.4. Fluid flow boundary condition

On the free surface of melt pool capillary and thermos capillary forces, both are acts on the normal direction and on the tangential direction. The corresponding equations of forces are given below: [12]

$$\sigma_n = -p_\propto \vec{n}\ \Upsilon(T) \cdot \kappa \vec{n} \text{ (For domain 1)} \tag{11}$$

$$\sigma_t = \frac{\partial \Upsilon}{\partial T} \nabla T \cdot \vec{t} \text{ (For domain 1)} \tag{12}$$

$u = 0$ (For domain 2) (13)

2.5. Moving mesh

The computational domain includes two moving interfaces: a liquid/solid interface and a liquid/gas interface. Only the liquid/gas interface is explicitly tracked using an ALE method. In this method, the displacement of boundary nodes is controlled by the fluid mechanics phenomena and is insured by a Lagrangian description whereas domain nodes follow an almost Eulerian description. Internal nodes are nevertheless moved to avoid numerical instabilities when computing. COMSOL multi-physics propose two smoothing algorithms to control the displacement of the nodes: Winslow and Laplace [12].The calculations presented in this paper are performed using Winslow method. Coupling of ALE method with momentum conservation equations is made through expression.

$V_{mesh}\vec{n} = V_{mat}\vec{n}$ (For domain 1) (14)

$V\vec{n} = 0$ (For domain 2) (15)

V_{mesh} is the mesh velocity (m/s) and V_{mat} is the material velocity (m/s) computed from momentum conservation equations.

3. Numerical model

The developed computational model is based on the positions of laser power that enters and exits from the molten pool, considering the process to be pseudo-stationary to study the effect of each input parameters on outputs. A series of FEM simulations are performed in COMSOL multi-physics by incorporating all mathematical equations in 2D model. First step in this technique is to provide global definition for process, as many options available like input process parameters, variables, functions and geometry subsequence which are desired in the problem formulation. For the laser cladding simulation procedure, three different physics: heat transfer, structural mechanics and mathematics included in model. In model creation, first rectangle is generated with length and thickness of substrate. For the clad geometry the ellipse are generated separately and through the Boolean operations geometry complete. The size of ellipse is coupled to laser beam diameters, so varying the beam size we can automatically vary the clad dimension. For 2D modelling of laser cladding process triangular element is used in meshing. Winslow method used in COMSOL multi-physics for deformed mesh generation due to moving heat sources. The coupled thermo-mechanical analysis of cladding process is based on the fact that the temperature field obtained from the thermal analysis serves as the basis for prediction of clad geometry, clad dilution. Further, for mechanical analysis as no external loading is considered apart from the application of thermal load as moving heat flux for residual stress analysis. Time dependent study is used to find temperature distribution and to find stresses stationary problem is consider in modelling. Temperature dependent material properties (stainless steel and copper) are considered for modelling. Input process parameters in simulation model are on the basis of experimental process conditions to investigate their effects on final geometry. Outputs of simulation for the same parameters as experimental parameters are given in below Table 1.

Table 1. Input and output parameters of simulation

Input Parameters				Output Parameters			
Power (W)	Laser scanning speed (mm/s)	Mass flow rate (gm/min)	Laser beam diameter (mm)	Clad height (mm)	Dilution (mm)	Temperature (K)	Stress (MPa)
2500	8	10	3	0.27	0.1	2747	264
2750	8	10	3	0.28	0.1	2996	299
2750	8	12	3	0.48	0.21	2926	283
2750	8	14	3	1.8	0.9	2827	275
3000	8	14	3	1.3	0.75	2850	272
3000	8	12	3	1.25	0.63	2901	280
3000	8	10	3	1.21	0.52	2917	284

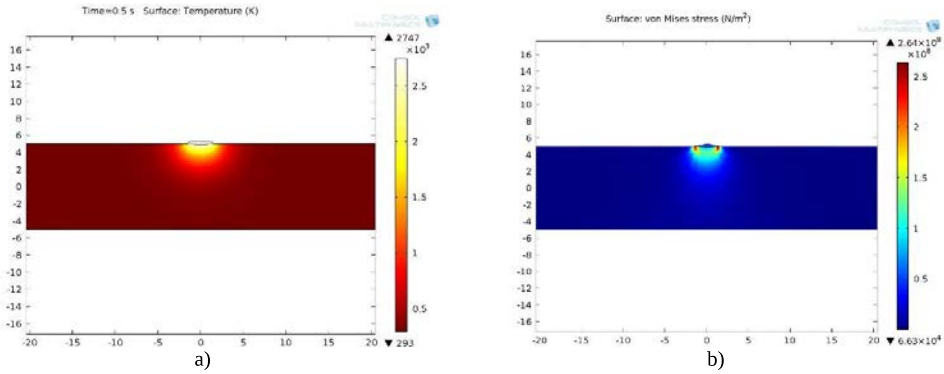


Fig. 2. (a) Temperature distribution; (b) Stress distribution

4. Results and discussion

To understand the effect of process parameters, simulation is performed by varying one parameter and at that time other three parameters keep constant. This will give clear idea of influence of process parameters effect on output of clad geometry. Selection of constant process (power, laser beam diameter, scanning speed and mass flow rate) parameters values and variation range of parameters were taken on the basis of data is taken from reference[15]. The input process parameters for conducting the simulations are given in Table 2, which are further referred for the results presented here.

Table 2. Input parameters for simulation

Input Parameters	Constant Value	Parameters Variation range
Power (W)	3000	~500 – 5000(Scale range: 100)
Laser beam diameter (mm)	3	1, 1.5, 2, 2.5, 3, 3.5, 4
Laser scanning speed (mm/s)	8	2, 4, 6, 8, 10
Mass flow rate (gm/min)	10	2, 4, 6 , 8, 10, 12, 14

4.1. Effect of power variation on clad geometry outputs

The effect of laser power is analyzed by simulation study by varying laser power from 500Wto 5000W in the incremental each step of 100W as input parameter and kept value of other parameters constant. The obtained results are shown in Fig. 2 for each output parameters (Clad thickness, dilution, Temperature and stresses), which exhibited increasing trend with increase in laser power. Further, substrate (SS plate) receives more heat due to high power input and more melt pool generated, which increase dilution. Dilution in software is measured by zooming in outputs of simulation model. During simulation process, stress analysis is done by considering input load as heat source (temperature) only. So as the power increase temperature increase and so stress also increase. Power input is one of the most affecting parameters on clad geometry as compared to other parameters.

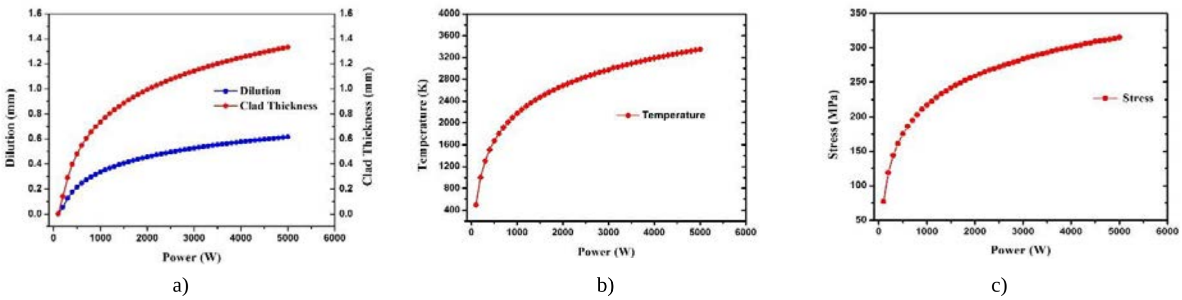
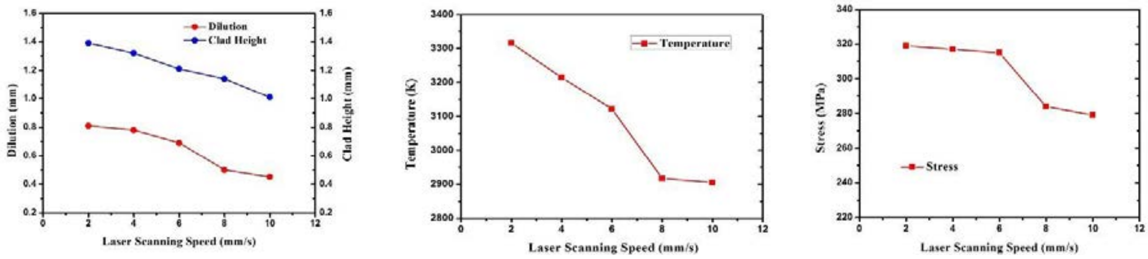


Fig. 3. (a) effect of power variations on dilution & clad height;(b) effect power variations on temperature;(c) effect power variations on stress

4.2. Effect of laser scanning speed on clad geometry outputs

Study of traveling speed variation on output of clad geometry indicate that as the traveling speed increase clad height, dilution, temperature and stress are decrease. The reason behind this is as the speed increase at constant power and mass flow rates, so addition of copper and heat input to surface decrease due to less interaction time. Because of this reason less heat input which minimize all outputs of clad geometry.

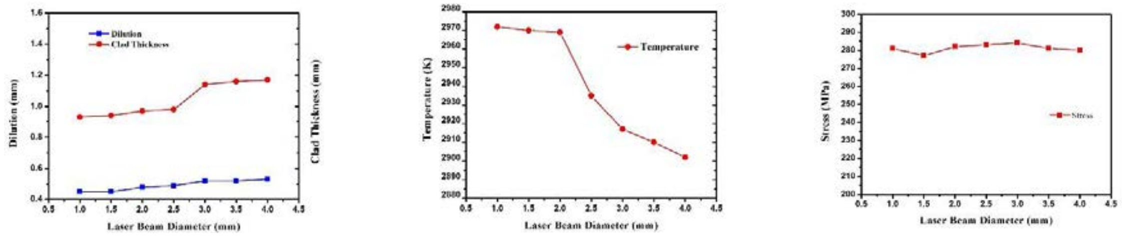


a) b) c)

Fig. 4. (a) scanning speed effect on dilution & clad height; (b) effect on temperature; (c) effect on stress

4.3. Effect of laser beam diameter on clad geometry outputs

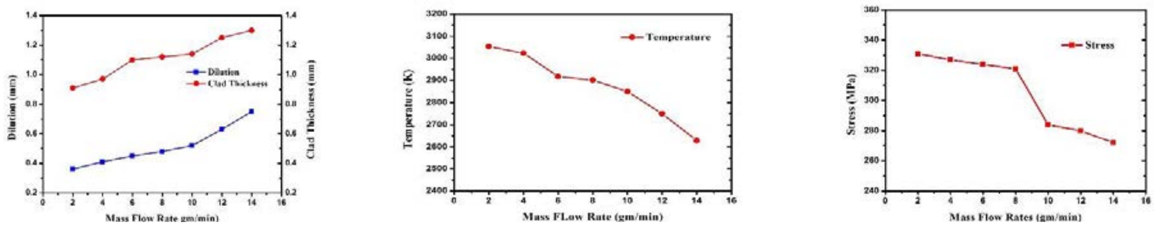
As the laser beam diameter increase temperature and stress profile decrease but dilution and clad height increase. The reason for this is as the laser beam diameter increase more surface area heated at constant power input 3000W which increase more mass addition and melt pool but less heat input because power distributed over surface. Because of this reason the temperature and stress decrease with increase in the laser beam diameter and dilution and clad layer thickness increase with increase in laser beam diameter.



a) b) c)

Fig. 5. (a) laser beam diameter effects on dilution & clad height; (b) effects on temperature;(c) effects on stress

4.4. Effect of mass flow rate on clad geometry outputs



a) b) c)

Fig. 6. (a) effect of mass flow rates variations on dilution & clad height (b) effects on temperature (c) effects on stress

As the mass flow rates increase clad height and dilution are increases and other parameters shown decreasing trend. This because as the mass flow rates increase more heat absorbed by the copper powder because more quantity of powder and less heat to the SS substrate. So more copper powder melt and that add on the surface of steel and higher clad layer thickness generated. Because of more heat distribution to powder at constant power and less heat is supplied to substrate which causes decrease trend in temperature and stress profile of clad geometry. The simulation process has shown the following trend of the influence on the process parameter conditions which have played a commendable role in choosing the process selection.

5. Conclusion

This study in dealing with the laser cladding process parameters effects through simulation model is very useful for optimization of final stage manufacturing process. Mathematical model has been developed incorporating by material properties(temperature dependent) of both Copper and SS316L have been incorporated with different conditions for simulating the output parameters like thermal conditions (Temperature behaviour), stress conditions, dilution and clad height. ALE method has been incorporated to study and evaluate the complex decoupled thermal-mechanical phenomenon of laser cladding process.

The main conclusion of the present study is as follows.

- On the basis of simulation study, it is observed that the laser power is the main affecting process parameter to clad geometry. As the power increase the clad height, dilution, temperature and stresses are increase with power.
- With increase of Laser spot diameter, clad height and dilution increase and temperature and stress decreases.
- As the laser scanning speed increase, all the output parameters clad height, dilution and temperature and stress are decreased.
- The increase of mass flow rate increase clad height and dilution and temperature, dilution and stresses decreases.

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