

## MODELING FOR LASER-MATERIAL INTERACTION TO PREDICT AND CONTROL THE CROSS SECTIONAL AREA OF COAXIAL LASER CLADDING WITH POWDER

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**Abstract** Laser cladding has been widely used in direct laser fabrication and laser refabrication for metal parts. It is a high precision and complicated process due to multiple process parameters involved. These parameters are strongly tied to each other and their effects are still far from being completely understood. In order to make the optimal choice, a feasible mathematical model is established to describe the interaction between laser and powder particles and to predict and control the cross sectional area. Additionally, analysis concentrating on the effect of the various parameters on the cross sectional area is made. Results show that laser power, powder feed rate, scan speed and radius of focused powder stream are the main factors. Correlations between main process parameters and cross sectional area of an individual clad track have been found. The model also provides predictions of range of process parameters for melting powder to form specific cross sectional area, which will guide the experiment and greatly reduce the cost of the experimental investigations.

**Keywords:** laser cladding, direct laser fabrication, cross sectional area, laser-material interaction

### 1. INTRODUCTION

Over the last three decades, laser cladding has been widely used to produce high quality surface layers on top of new parts, to produce entire parts and to refurbish and improve used parts.

During the cladding process, the supply of the additive material is one of the key factors controlling the process. The most advantageous method is powder injection. This can be done by the use of a powder nozzle which can have several configurations. Two basic layouts are shown in Figure 1. The lateral supply of powder (also called off-axial powder injection, Figure 1 right) allows the treatment of all kinds of shapes by applying dedicated powder nozzles. The coaxial supply of powder (Figure 1 left) can be integrated with the optical system. An advantage of the coaxial powder supply is the independence of the powder supply of the direction in which the work piece moves. Other advantages of the coaxial powder supply are the controllable heating of the powder before it enters the melt pool and the high powder feed efficiency.

Laser cladding is a high precision and complicated process due to multiple process parameters involved, especially for coaxial laser cladding with powder. In order to achieve much better results, such as geometric accuracy and surface roughness, a great number of experiments must be performed to select process parameters appropriately. However, these parameters are strongly coupled with each other and their effects are still far from

being completely understood. So a feasible model is required.

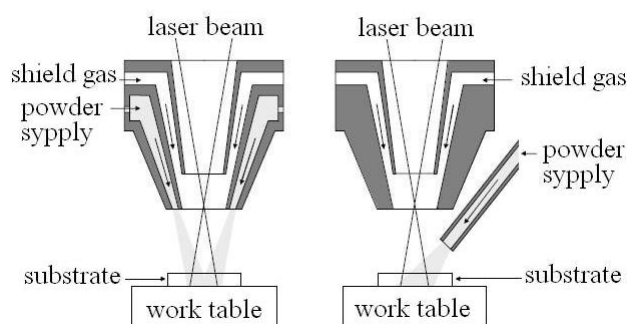


Figure 1: Two basic lay-outs of powder supply

Interaction between the laser and the powder particles leads to attenuation of the laser and makes the powder particles' temperature rise, even melt. There are several models for simulating and predicting the formation of various microstructures. To the author's knowledge, little information is available in literature about models for predicting and controlling the cross sectional area of coaxial laser cladding with powder. Qingmao Zhang studied the relationship between the cross sectional area and the multiple process parameters. However, his study focused on the lateral supply of powder (off-axial powder injection). The profile of the cross section is shown in Figure 2.

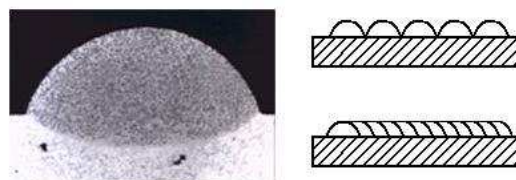


Figure 2: The profile of the cross section

In this paper, a mathematical model is presented to describe the interaction between laser and power particles and to study the cross sectional area of coaxial laser cladding with powder injection. Additionally, analysis concentrating on the effect of the various parameters on the cross sectional area was made. According to this model, the cross sectional area and the energy absorbed by powder particles and substrate can be determined computationally with given laser, material and other

process parameters. For an appropriate theoretical analysis of the main process parameters involved, a method based on gradual change of a single process parameter was examined. Correlations between main process parameters and cross sectional area of an individual clad track have been found.

This paper is directed to laser cladding with alloy powder Ni60 and a CO<sub>2</sub> laser as heat source.

### Nomenclature

$A$	absorptivity of laser beam on metal surface
$C$	specific heat capacity (J/(kg·°C))
$C_z$	concentration of traveling powder cloud (kg/m <sup>3</sup> )
$G$	acceleration of gravity (m/s <sup>2</sup> )
$h$	height of nozzle (m)
$I_0$	initial laser power intensity (W/m <sup>2</sup> )
$I_a$	absorbed power intensity (W/m <sup>2</sup> )
$I_t$	transmitted power intensity (W/m <sup>2</sup> )
$I_r$	reflected power intensity (W/m <sup>2</sup> )
$l$	effective laser path length (m)
$m$	mass of melted powder particles (kg)
$P$	laser power (W)
$Q_1$	energy powder particles absorbed (J)
$Q_2$	laser energy absorbed by powder particles (J)
$r_p$	mean radius of powder particles (m)
$R_1$	radius of laser beam (m)
$R_p$	radius of focused powder stream (m)
$S$	cross sectional area (m <sup>2</sup> )
$t$	interaction time of laser beam and metal powders (s)
$T_0$	preheat temperature (°C)
$T_f$	final temperature (°C)
$T_m$	melting point of the powder particles (°C)
$V_0$	powder flow speed (m/s)
$V_f$	powder feed rate (kg/s)
$V_s$	scan speed (m/s)
$\Delta T$	temperature difference (°C)
$\Delta H$	latent heat of fusion (J/kg)

### Greek symbols

$\varepsilon$	absorption coefficient
$\eta$	efficiency of laser-material interaction (%)
$\theta$	angle of incidence (rad)
$\rho$	density (kg/m <sup>3</sup> )

## 2. LASER-MATERIAL INTERACTION AND CROSS SECTIONAL AREA OF COAXIAL LASER CLADDING WITH POWDER

In this section, the mathematical model to describe the interaction between laser and powder particles and to predict and control the cross sectional area is established. A schematic presentation of coaxial powder injection is shown in Figure 3.

The model is based on the following assumptions:

(i) The powder particles are spherical with properties not depend on temperature and the interaction between them is neglected.

(ii) The powder particles are transported by the gravitation to the substrate.

(iii) The energy intensity across the laser beam in which the powder particles travel is uniform. The laser

beam can be seen as a cylinder because of the high focal length compared with the radius of the laser beam.

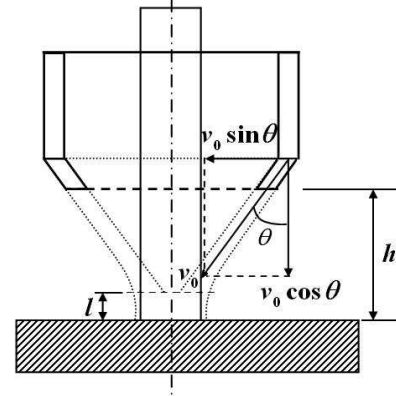


Figure 3: Coaxial powder injection

### 2.1 Cross sectional area of coaxial single-pass laser cladding with powder

The cross sectional area of coaxial laser cladding is analyzed by assuming for simplicity that all the powder particles have the same heating process  $T_0 \rightarrow T_m \rightarrow T_f$ .

After the heating process, the temperature of the powder particles reached at  $T_f$ . This process needs energy given by the following expression:

$$\begin{aligned} Q_1 &= m \cdot C \cdot (T_f - T_0) + m \cdot \Delta H \\ &= m \cdot (C \cdot \Delta T + \Delta H) \end{aligned} \quad (1)$$

The laser energy absorbed by the powder particles during the interaction time  $t$  is

$$Q_2 = \eta \cdot P \cdot t \quad (2)$$

where  $\eta$  is the efficiency of laser-material interaction which represents the percentage of energy absorbed by powder particles with respect to energy exported by laser beam. According to the law of conservation of energy,  $Q_1$  equals  $Q_2$ , which yield the following relationship between  $m$  and  $P$ :

$$\eta \cdot P \cdot t = m \cdot (C \cdot \Delta T + \Delta H). \quad (3)$$

It can be solved to obtain

$$m = \frac{\eta \cdot P}{C \cdot \Delta T + \Delta H}. \quad (4)$$

Since the length of scan line in unit time is equal to scan speed  $V_s$ , the cross sectional area  $S$  can be given by the following expression:

$$S = \frac{m}{\rho \cdot V_s} = \frac{\eta \cdot P}{\rho \cdot V_s \cdot (C \cdot \Delta T + \Delta H)}. \quad (5)$$

### 2.2 Efficiency of laser-material interaction

The initial laser powder intensity  $I_0$  can be divided into three parts:  $I_a$ ,  $I_t$  and  $I_r$ , that is

$$I_0 = I_a + I_t + I_r. \quad (6)$$

According to the Beer-Lambert Law, the transmittance is given by

$$\frac{I_t}{I_0} = e^{-\varepsilon \cdot l \cdot C_z}. \quad (7)$$

Here  $\varepsilon$  is absorption coefficient, which depends on the wave length of the laser beam and physical property of the metal powders.

Time during which powder particles moves from the nozzle to the surface of the substrate is:

$$t_1 = \frac{2h}{\sqrt{v_0^2 \cdot \cos^2 \theta + 2gh + v_0 \cdot \cos \theta}}. \quad (8)$$

Similarly, time cost from the nozzle to the position where powder particles focus can be given by the following expression:

$$t_2 = \frac{2(h-l)}{\sqrt{v_0^2 \cdot \cos^2 \theta + 2g \cdot (h-l) + v_0 \cdot \cos \theta}}. \quad (9)$$

Thus, interaction time  $t$  can be calculated by

$$t = t_1 - t_2. \quad (10)$$

Since  $l$  is small, the focused powder stream is columnar. Therefore, concentration of the traveling powder cloud  $C_z$  is expressed as

$$C_z = \frac{V_f \cdot (t_1 - t_2)}{\pi \cdot R_p^2 \cdot l}. \quad (11)$$

Substituting  $C_z$  from equation (11) into equation (7), the transmittance can be shown to be

$$\frac{I_t}{I_0} = e^{-\frac{\varepsilon \cdot V_f \cdot t}{\pi \cdot R_p^2}}. \quad (12)$$

At certain wavelength of the laser beam, for CO<sub>2</sub> laser, which is 10.6 $\mu$ m, absorption coefficient  $\varepsilon$  can be estimated using the following experience-formula:

$$\varepsilon = \frac{3(1-A)}{2r_p \cdot \rho}, \quad (13)$$

where  $r_p$  presents the mean radius of powder particles. Near the melting point of the metal particles,  $A \approx 0.9$ . So  $\eta$  can be given by

$$\eta = \left(1 - \frac{I_t}{I_0}\right) \cdot A = \left(1 - e^{-\frac{3V_f \cdot t \cdot (1-A)}{2\pi \cdot \rho \cdot r_p \cdot R_p^2}}\right) \cdot A. \quad (14)$$

Substituting  $\eta$  from equation (14) into equation (5), the cross sectional area  $S$  is rewritten by the following expression:

$$S = \frac{P \cdot \left(1 - e^{-\frac{3V_f \cdot t \cdot (1-A)}{2\pi \cdot \rho \cdot r_p \cdot R_p^2}}\right) \cdot A}{\rho \cdot V_s \cdot (C \cdot \Delta T + \Delta H)} \quad (15)$$

### 3. RESULT

Physical parameters of alloy powder Ni60 used in the study are listed in Table 1.

**Table 1: Physical properties of Ni60 used in this study**

$C$ (J/(kg·°C))	$\Delta H$ (J/kg)	$\rho$ (kg/m <sup>3</sup> )	$r_p$ (m)	$A$
$0.464 \times 10^3$	$0.248 \times 10^6$	$8.522 \times 10^3$	$0.074 \times 10^{-3}$	0.9

For an appropriate theoretical analysis of the effect of the variation of main process parameters on the cross sectional area, a method based on gradual change of a single parameter was examined. Table 2 shows the process parameters and their ranges used for computations in the study.

**Table 2: Default values and their ranges of main process parameters**

Parameter	Value	Range
$T_0$ (°C)	2 5	25 ~ 385
$P$ (W)	1 500	750 ~ 2250
$V_s$ ( $\times 10^{-3}$ m/s)	5	1 ~ 9
$V_f$ ( $\times 10^{-3}$ kg/s)	0 .25	0.1 ~ 0.7
$h$ ( $\times 10^{-3}$ m)	1 0	11 ~ 29
$l$ ( $\times 10^{-3}$ m)	5	3 ~ 9
$R_p$ ( $\times 10^{-3}$ m)	1 .5	1.15 ~ 3.85

The effects of the various process parameters are examined separately. Using equations (14) and (15), the efficiency of laser-material interaction and the cross sectional area can be calculated considering  $V_0 = 0.3$  m/s,  $\theta = 45^\circ$ . They are plotted in Figs.4-10 (The left column is  $\eta$  and right column  $S$ ).

Investigation of Figs.4-10 leads to the following conclusions:

(i) The efficiency of laser-material interaction keeps steady when preheat temperature, laser power or scan

speed changes. It increases when powder feed rate or effective laser path length increases, and decreases when height of nozzle or radius of focused powder stream increases.

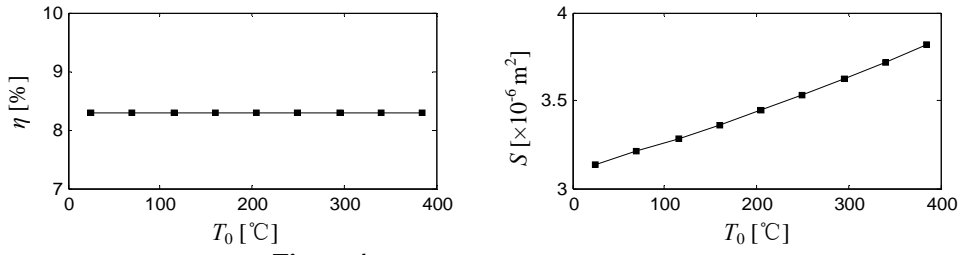


Figure 4: Effect of preheat temperature

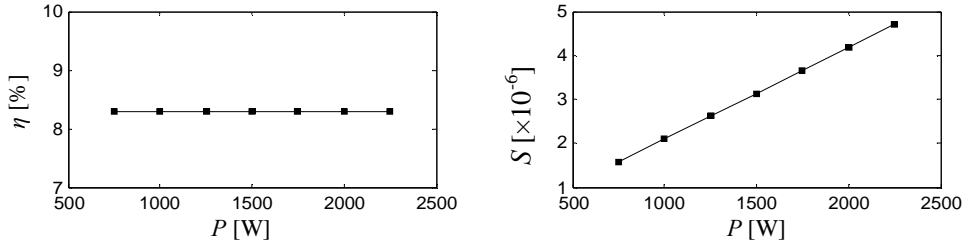


Figure 5: Effect of laser power

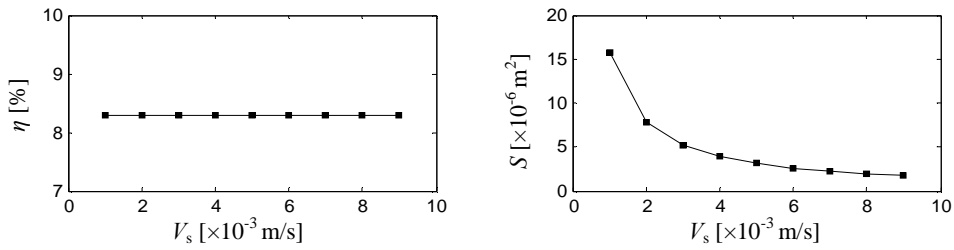


Figure 6: Effect of scan speed

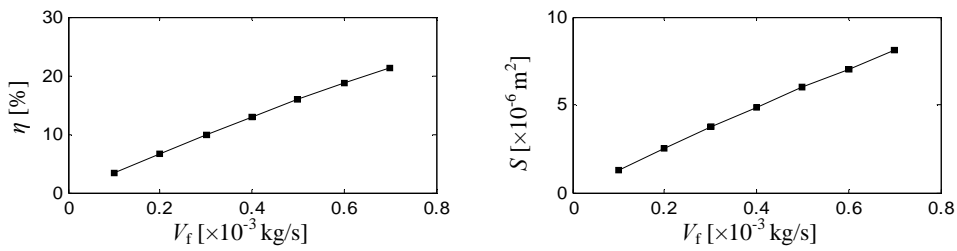


Figure 7: Effect of powder feed rate

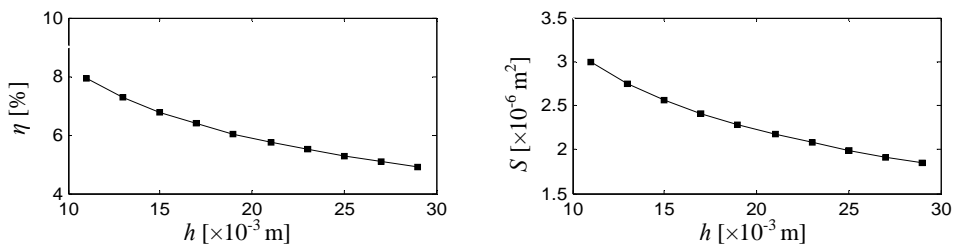


Figure 8: Effect of nozzle height

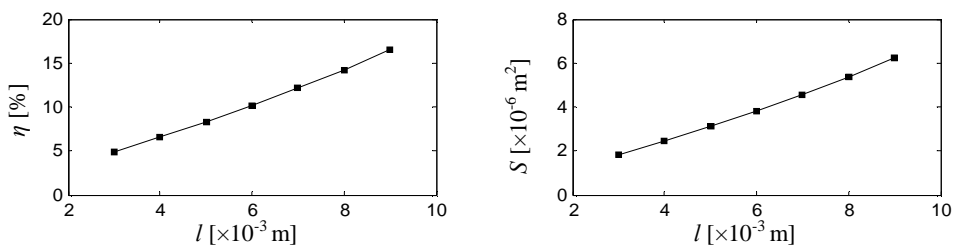


Figure 9: Effect of effective laser path length

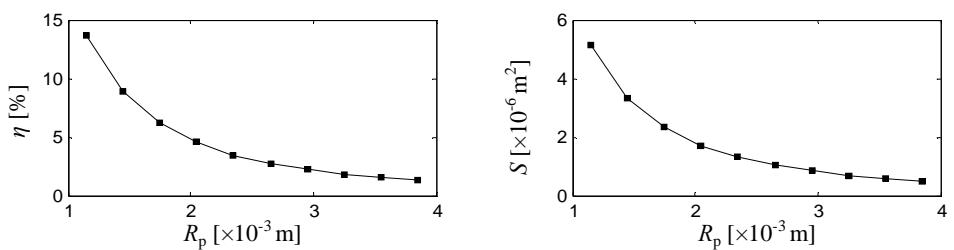


Figure 10: Effect of radius of focused powder stream

(ii) The cross sectional area increases with increasing preheat temperature, laser power, powder feed rate or effective laser path length, and decreases with increasing scan speed, height of nozzle or radius of focused powder stream.

#### 4. CONCLUSIONS

A mathematical model is developed to analyze laser-material interaction and the effects of process parameters on cross sectional area of coaxial laser cladding. According to this model, the cross sectional area can be determined computationally. Correlations between main process parameters and geometrical characteristics of an individual laser track have been found. The model should be useful in selecting process parameters, reducing the amount of experiments and their cost.

The result fits the experimental data well. It is seen that the cross sectional area is significantly affected by laser power, scan speed, powder feed rate and radius of focused powder stream. It should be pointed out that efficiency of laser-material interaction is quite low (always below 10%). Therefore, method to improve it must be developed. One method is to control the radius of focused powder stream by using a high accuracy powder feed nozzle.

In the future, we will investigate the effect of the various process parameters on the profile of single track.

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