2

Background and Basic Overview

In this chapter, a basic overview on laser cladding is presented. The laser cladding classification, laser cladding process parameters, and comparison of laser cladding process with the competitive techniques are some of the topics addressed in this chapter.

2.1 Laser Material Techniques

A laser beam provides unique characteristics for material processing. The electromagnetic radiation of a laser beam is absorbed by the surface of opaque materials (e.g., metals). The interaction time between the laser and material leads to different processes as shown in Figure 2.1. The relative velocity of the laser beam with respect to the substrate causes the thermal cycle in the surface layer. The figure also shows a schematic representation of the physical phenomena that occur during various laser material processes. These processes are due to different combinations of absorption, heat conduction, melting, powder addition, and rapid solidification. However, the common physical phenomenon of all laser material processing techniques is rapid solidification, which causes a superior and fine metallurgical structure.

Laser cladding is one of the important types of laser material processing, in which a laser beam irradiates powder particles and the surface of the substrate moved by a positioning device. As a result of additive powder particles, a thin layer called a “clad” is produced on the substrate.

2.2 Differences Between Laser Cladding, Alloying and Glazing

Adding powder to the melt pool may create three different products depending on the type and the amount of material added. Figure 2.2 depicts schematic cross sections of the coating-substrate couple for these three processes. These

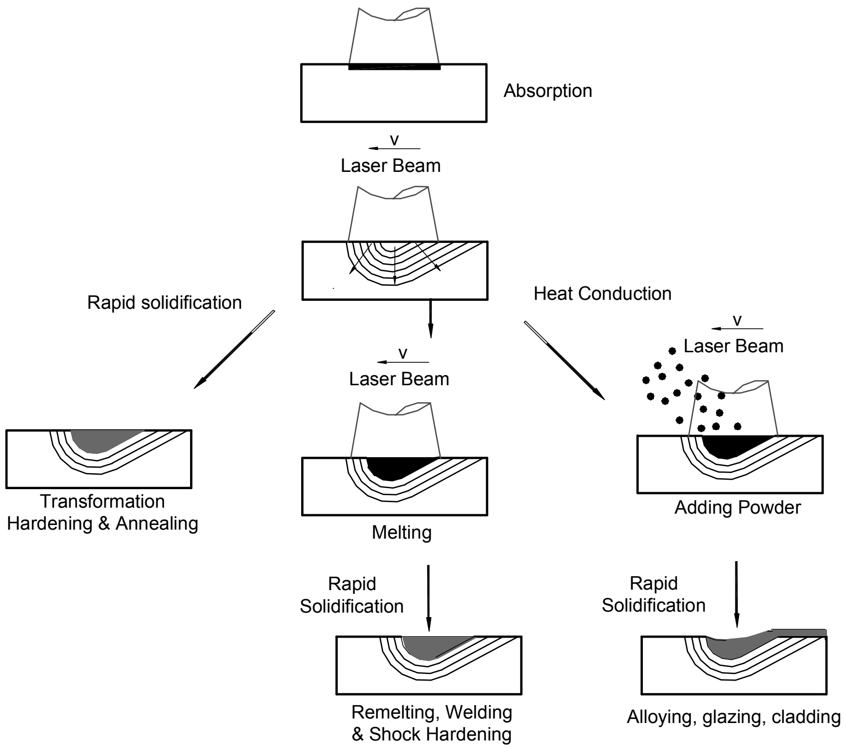

FIGURE 2.1
Schematic of physical phenomena during different laser material processing techniques.

are classified as laser cladding, glazing, and alloying. Included on the right is a schematic of the compositional profile across the coating-substrate couple.

In laser alloying, a small amount of powder is fed into the melt pool. As such, homogeneous mixing throughout the melt region may be obtained [96]. Laser cladding resembles laser alloying except that dilution by the substrate is kept to a minimum and more addition of material to the surface is required [35]. In laser glazing, a metallic glass coating is deposited in order to provide an environmentally effective surface in terms of wear and corrosion [97]. The principle advantage of laser glazing is that it alters microstructures without changing the composition [97, 98].

Using laser cladding, the following advantages can be obtained compared to other surface material processing [99, 100, 101]:

1. Reduced dilution, which is the mixing percentage of the substrate to the clad region (compared to laser alloying)

2. Improved wear resistance of a part
3. Reduced thermal distortion
4. Reduced porosity, particularly in laser cladding by powder injection
5. Improved controllability of the process
6. Reduced post-cladding machining time and cost

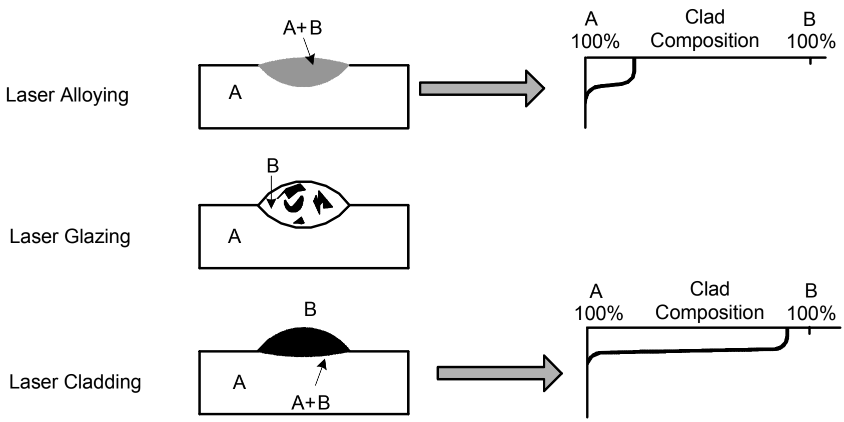

FIGURE 2.2
Different microstructures of laser alloying, glazing, and cladding.

2.3 Different Methods of Laser Cladding

Basically, there are two different techniques for laser cladding as follows:

1. Two-step process (pre-placed laser cladding)
2. One-step process

In the two-step process, the first stage consists of a layer of coating material being placed before laser irradiating. It is then melted with the substrate material by the laser beam in the second stage (see Figure 2.3a) [102].

In the one-step process, an additive material is fed into the melt pool. The additive material may be supplied in the following different forms:

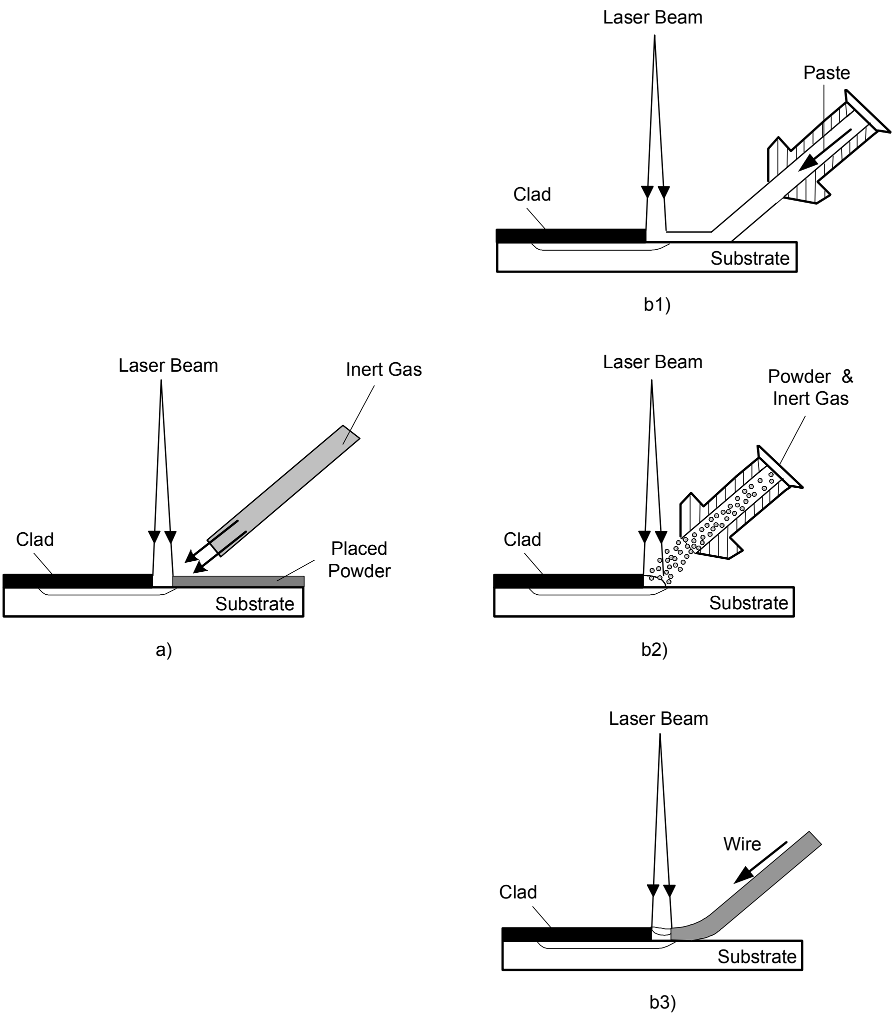

FIGURE 2.3

Different methods of laser cladding: a) two-step laser cladding, b) one-step laser cladding, including b1: paste laser cladding, b2: powder injection laser cladding, b3: wire feeding laser cladding.

- Powder injection
- Wire feeding
- Paste

Figure 2.3b depicts one-step laser cladding techniques where an inert gas shrouds the laser material interaction zone to prevent oxidation of the surface at the high processing temperature.

Powder injection cladding is a more robust method than wire and paste cladding, because there is no direct contact with the melt pool, and the laser beam can pass through the stream of powder particles instead of being obstructed by the wire or paste. In the following, we briefly address several issues involved in two-step laser cladding; then we concentrate on laser cladding by powder injection for the rest of this chapter and the book.

2.3.1 Two-Step Laser Cladding (Pre-placed Laser Cladding)

Pre-placed laser cladding is a simple method used for coating and prototyping. Several issues are involved in this process. The pre-placed powder particles on the substrate must have not only enough bonding to the substrate, but also enough cohesion to each other. It is necessary to prevent the powder particles on the substrate from removing due to the gas flow during the melting in the second step of the process. To overcome this problem, the powder is usually mixed with a chemical binder to ensure its cohesion with the substrate during the process. The side effect of a chemical binder is porosity in the clad due to its evaporation during the process.

In the second step of the process the following phenomena occur:

1. Creation of a melt pool in the top surface of the pre-placed powder due to the radiation of laser beam
2. Expansion of melt pool to the interface with the substrate due to the heat conduction
3. Penetration of heat to the substrate causing a fusion bond

The control of heat is a very important issue in this method to prevent the high dilution. Dilution is considered to be the mixing percentage of the substrate to the clad region. This problem is one of the important shortcomings of two-step laser cladding that usually limits the process only to single track cladding.

Powell et al. [102] developed a theoretical model and analysis technique for pre-placed laser cladding. Their theoretical calculation resulted in a plot, which shows the effect of interaction time on the position of the melt pool front. This result is shown in Figure 2.4. The results indicate that the dilution increases with increasing interaction time (decreasing the process speed).

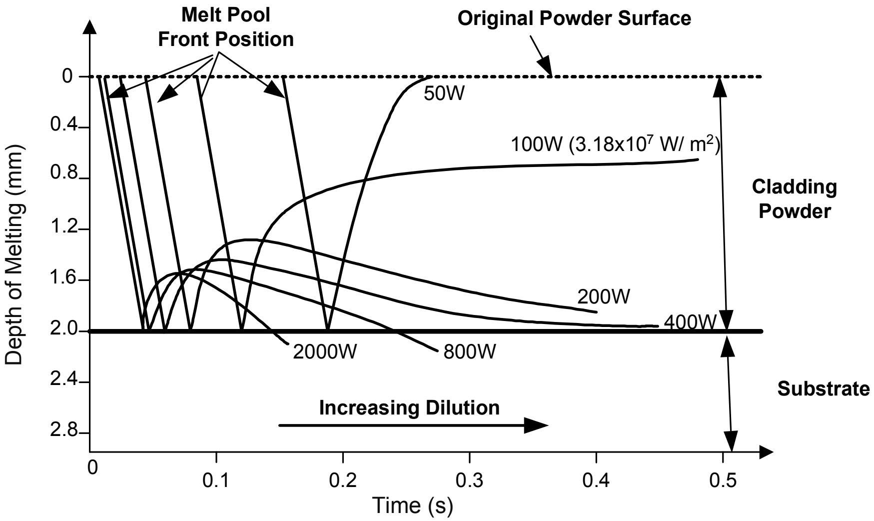

FIGURE 2.4
Displacement of melted front with respect to interaction time at various average laser powers, when the beam radius is 1 mm [102].

2.3.2 One-Step Laser Cladding

As they are shown in Figures 2.3b1 to 2.3b3, one-step laser cladding can be categorized into three methods: powder injection, wire feeding, and paste laser cladding. The common feature of all three methods is the feeding of deposited material in the presence of the laser.

2.3.2.1 Laser Cladding by Powder Injection

In laser cladding by powder injection, powder particles are fed into the heat zone to produce a layer of clad as shown in Figure 2.3b2. We will address this process in depth throughout this book.

2.3.2.2 Laser Cladding by Wire Feeding

In laser cladding by wire feeding, the main idea is to use wire instead of powder as shown in Figure 2.3b3. The wire is usually fed through a ceramic drum containing the desired material wire. Due to the nature of feeding mechanisms, it is essential to use a wire that has been straightened and stored without plastic deformation to ensure stable transport without vibration [103, 104]. Compared to laser cladding by powder injection, it has been claimed that laser cladding by wire feeding has some special advantages [105]. One of its most important advantages is its adaptation to the cladding position. Metal wires are cheaper than metal powders, and also wire feeding wastes less material than powder feeding. In contrast, low surface quality, low bonding strength, porosity, cracks and drop transfer are some problems of wire cladding. The melted liquid at the end of the wire does not flow smoothly and continuously onto the workpiece, which is called drop transfer phenomena. Kim et al. [104] conducted research to find the best process parameters that prevent the drop transfer phenomena. They showed that by selecting correct wire feeding direction and position, the splashing of molten drop for laser cladding with wire feeding can be solved. In this case, wire can be plunged into the melt pool and be melted by the heat of the molten metal. However, a successful process strongly depends on the process parameters, and in the presence of disturbances the quality of clad drops dramatically.

2.3.2.3 Laser Cladding by Paste

In laser cladding by paste, a stream of paste-bound material is deposited on a point of the substrate that is usually a little bit ahead of the laser beam [106], as shown in Figure 2.3b1. The paste consists of the hardfacing powder with a suitable binder. However, the binder must be dried in a short period of time while the hardfacing material in a compact form is still kept; otherwise powder particles are blown away by the shielding gas.

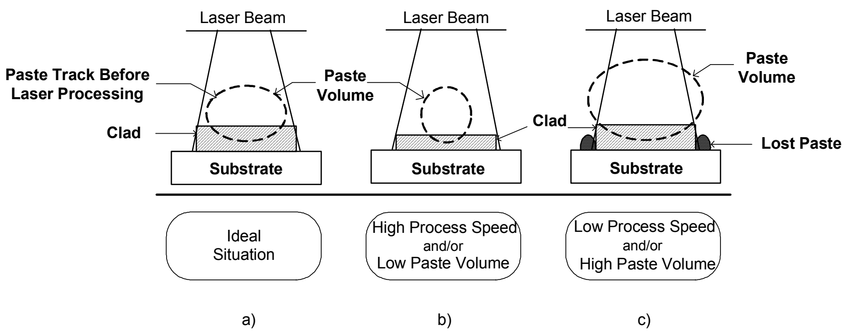

FIGURE 2.5
Effect of process speed and paste feed rate on the quality of clad [106].

For this process, a special paste feeding system should be designed. Lugscheider et al. [106] designed and implemented a paste feeding system along with a cooling system to protect the paste from thermal emissions from the process zone. The shape of paste on the substrate is controlled by paste feed rate and substrate speed. To have a good clad quality, it is essential to optimize these parameters. A poor paste supply or too high process speed causes high dilution and low track height if the laser energy is kept constant. An oversupply of paste on the substrate increases pores formation since evaporation of the binder is inhibited, and it increases the loss of hardfacing material. Figure 2.5 shows the effect of substrate traverse speed and paste feed rate on the quality of the final clad layer.

High porosity, extreme sensitivity of the process to disturbances, and difficulties in paste feeding mechanism are troublesome conditions of paste laser cladding.

2.4 Clad Dimensional Characteristics

Several parameters are associated with the clad geometry, which are shown in Figure 2.6. In this figure, h is the clad height, w is the clad width, θ is the angle of wetting, and b is the clad depth representing the thickness of substrate melted during the cladding and added to the clad region.

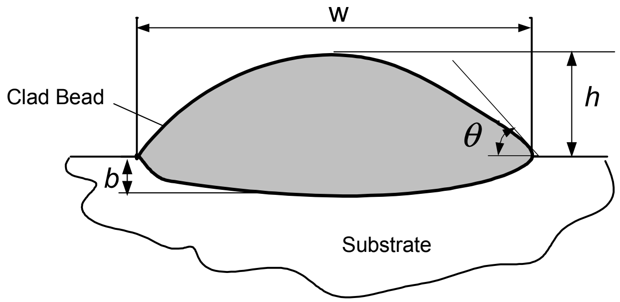

FIGURE 2.6
A typical cross section of a clad bead.

2.5 Important Parameters in Laser Cladding by Powder Injection

A large variety of operating parameters and physical phenomena determine the quality of laser cladding. Figure 2.7 summarizes these parameters grouped as inputs, processes, and outputs. Generally, the inputs or operating parameters are the laser, motion device, powder feeder set points, and also the material and ambient properties. The outputs of the process which represent the clad quality are the geometry, microstructure, cracks, porosity, surface roughness, residual stresses and dilution [107, 35, 108, 109, 110]. In the following, some of the major associated parameters with the process are explained.

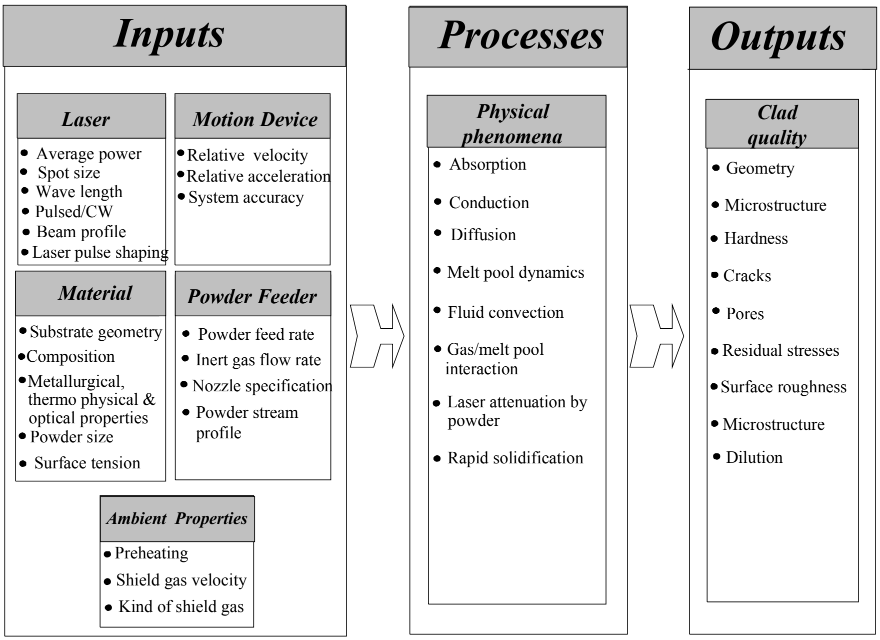

FIGURE 2.7
Inputs, outputs and process parameters of laser cladding by powder injection.

2.5.1 Dilution

One of the properties of the clad layer is called dilution. Dilution has two definitions: geometrical and metallurgical [107]. The geometrical definition of dilution is illustrated in Figure 2.6. According to the specified parameters in the figure, the dilution is

$$dilution = \frac{b}{h+b} \tag{2.1}$$

where b is the thickness of substrate that was melted during the cladding process [mm], and h is the height of the clad bead [mm].

Alternatively, dilution may be defined as the percentage of the total volume of the surface layer contributed by melting of the substrate [107]. According to the composition, dilution is defined as

$$dilution = \frac{\rho_c(X_{c+s} - X_c)}{\rho_s(X_s - X_{c+s}) + \rho_c(X_{c+s} - X_c)} \tag{2.2}$$

where ρ_c is the density of melted powder alloy [kg/m^3], ρ_s is density of substrate material [kg/m^3], X_{c+s} is weight percent of element X in the total surface of the clad region [%], X_c is the weight percent of element X in the powder alloy [%], and X_s is the weight percent of element X in the substrate [%].

Of interest is the fact that dilution increases with increasing laser power but decreases with increasing travel speed.

2.5.2 Wetting Angle and Interfacial Free Energies

In laser cladding, either pre-placed or powder injection, wetting angle and interfacial free energies are important parameters that indicate the quality of the clad. In general, three types of clad cross section may be produced by laser cladding as shown in Figure 2.8. These cross sections represent the amount of dilution, corresponding wetting angle θ, and interfacial free energies γ [J/m^2]. Three interfacial energies for laser cladding can be considered as solid-liquid interfacial free energy γ_{SL}, solid-vapor interfacial energy γ_{SV}, and liquid-vapor interfacial energy γ_{LV}.

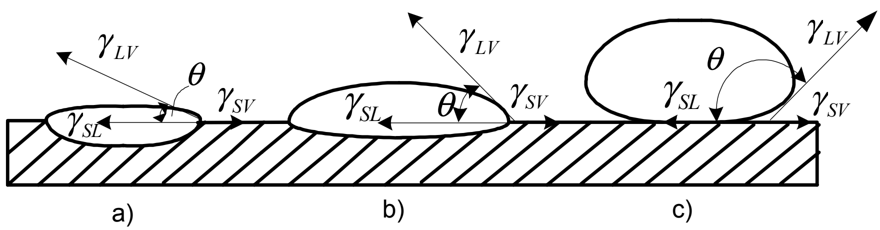

FIGURE 2.8

Laser cladding cross sections, associated wetting angle and interfacial free energies: a) high dilution, well wetting, b) ideal clad, c) no dilution, non-wetting.

A balance between the mentioned energies governs the shape of the clad bead. This balance is expressed by

$$\gamma_{SV} - \gamma_{SL} = \gamma_{LV}\cos(\theta) \tag{2.3}$$

The liquid will wet the substrate as $\cos(\theta) \rightarrow 1$ or equivalently, if $\gamma_{SV} - \gamma_{SL} >$

γ_{LV}, which corresponds to Figure 2.8b. A large positive spreading factor $S = \gamma_{SV} - \gamma_{SL} - \gamma_{LV}$ causes spreading, whereas a lower number causes a non-wetting system as shown in Figure 2.8c. When the laser energy is high, dilution increases and wetting angle decreases as shown in Figure 2.8a.

In laser cladding, oxidation is a serious problem at higher processing temperatures, which are required for melting the metals. The oxidation causes a low quality clad as shown in Figure 2.8c. This is due to the poor wetting of an oxide substrate by a liquid metal and also much lower surface energies of metal oxides.

2.5.3 Laser Pulse Shaping

The laser beam can be in the form of continuous wave (CW) or pulsed wave. In the form of pulse wave, several parameters associated with shape of pulses are defined: laser pulse energy E, laser pulse width (laser pulse duration) W, laser pulse frequency (laser pulse repetition rate) F, average power P_l and duty cycle C. These parameters which are shown in Figure 2.9 can be expressed by

$$C = FW \tag{2.4}$$

$$P_l = EF \tag{2.5}$$

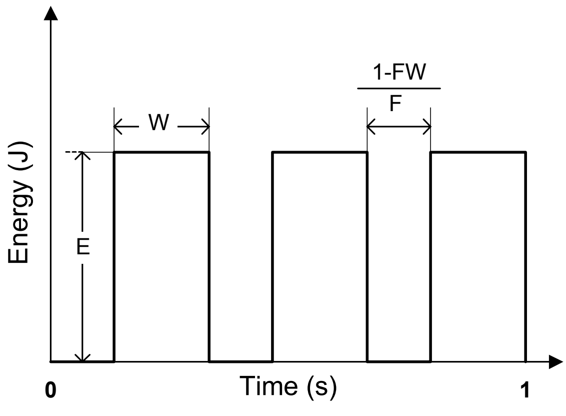

FIGURE 2.9
Laser pulse shaping, including pulse width W, pulse energy E and pulse frequency F.

2.6 Combined Parameters

Due to the numerous parameters involved in the process, it is essential to use the combined parameters to address the clad quality of the process by finding the correlation between the combined parameters and the clad quality. Different effective parameters have been reported, which are categorized for continuous and pulsed laser energy. In the following, these combined parameters are introduced.

2.6.1 Aspect Ratio

Aspect ratio AR is a ratio between width and height of the clad represented by

$$AR = \frac{w}{h}$$

2.6.2 Combined Energy and Powder Densities' Parameters

There are different approaches to show the correlation of the clad aspect ratio and the effective energy. However, they can be categorized into two types of laser beam waves: continuous wave (CW) and pulse wave.

2.6.2.1 Combined Parameters for Continuous Wave (CW) Laser Beam

Steen et al. [42] showed that the beginning of non-wetting (i.e., discontinuous clad track) is correlated with combined parameter $\frac{P_w}{2r_l U}$, and the melting through of the substrate is correlated with combined parameter $\frac{P_w}{U}$ where, P_w is the absorbed energy to the substrate laser power [W], U is process speed [mm/s], and r_l is the laser spot radius on the substrate surface [mm]. They also showed that combined parameter $\frac{2P_w U r_l}{\dot{m}}$ is correlated with the aspect ratio, where $\dot{m}$ is the powder feed rate [g/s] [111].

In addition, they showed that a term $\frac{P_w}{2r_l \dot{m}}$ has a maximum value before dilution occurs (e.g., 2500 J/(gmm) for Colmonoy Wallex PC6) and also combined parameter $\frac{P_w}{2r_l U}$ represents the minimum energy required for cladding before the track starts to be discontinuous (e.g., 22 J/mm^2 for Colmonoy alloy). They have arrived at a general plot which shows the correlation of these combined parameters and feasibility of cladding process as shown in Figure 2.10. The figure shows the hatched area that the cladding process is feasible.

For continuous wave, Wu et al. [112] introduced two combined parameters for laser cladding by powder injection, which can be fitted to the process to present the critical states. These two combined parameters result in a simpler interpretation of the cladding process. They are called specific energy

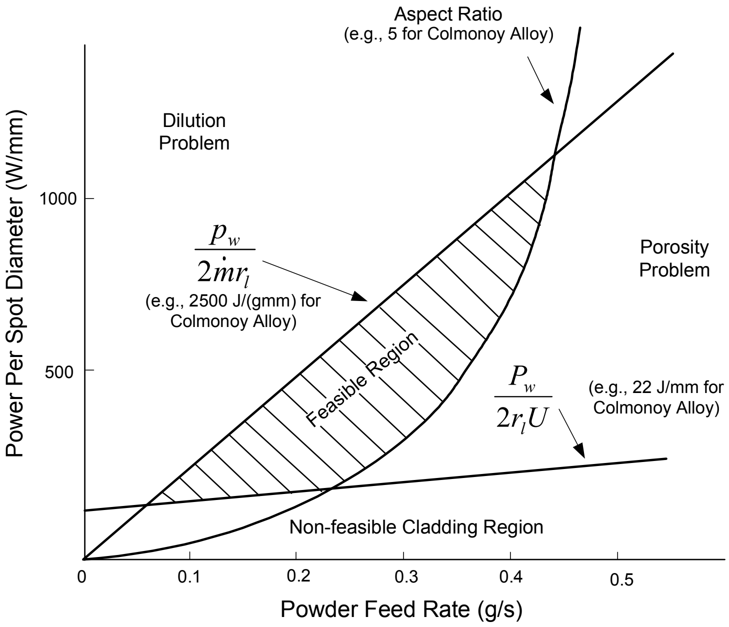

FIGURE 2.10
Correlation of aspect ratio, combined parameters, power per spot diameter, and powder feed rate with feasibility of laser cladding by powder injection [42].

$E_{specific}$ [J/mm^2] and powder density G [g/dm^2], which are expressed by

$$E_{specific} = \frac{P_w}{2Ur_l} \tag{2.6}$$

$$G = \frac{\dot{m}}{2Ur_l} \tag{2.7}$$

where P_w is the laser power on the substrate [W], U is the process speed [mm/s], r_l is the radius of the laser beam on the substrate [mm], and $\dot{m}$ is the powder feed rate [g/min]. Figure 2.11 shows the correlation between $E_{specific}$ and G [g/m^2] and the critical situation in the laser cladding process of Cobalt-based alloy on an A_3 steel substrate [112].

2.6.2.2 Combined Parameters for Pulsed Wave Laser Beam

Two combined parameters, effective energy density E_{eff} [J/mm^2] and effective powder deposition density ψ_{eff} [g/mm^2], are defined for a pulsed wave laser beam [3, 4, 113] and are expressed by

$$E_{eff} = \frac{EF}{A_{eff}} \tag{2.8}$$

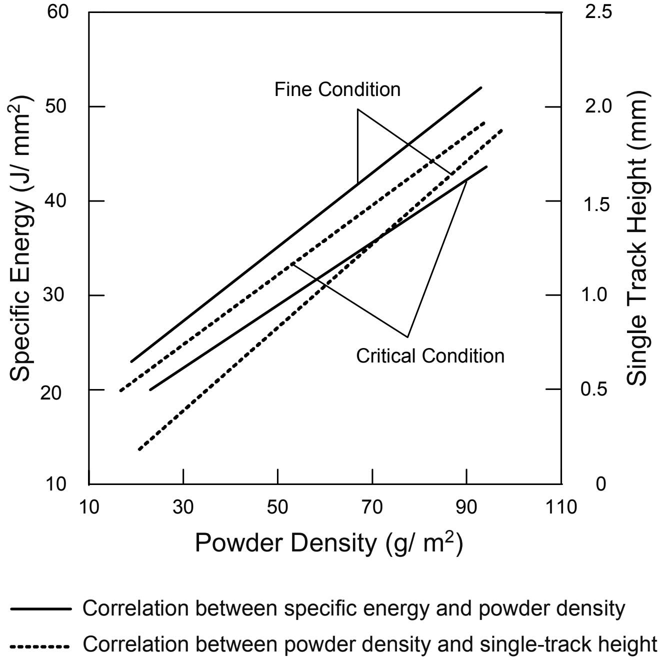

FIGURE 2.11
Correlation between specific energy $E_{specific}$ [J/mm^2] and powder density G [g/m^2] and their effect on single track height for Co-based alloy on an A_3 steel substrate [112].

$$\psi_{eff} = \frac{\dot{m}FW}{A_{eff}} \tag{2.9}$$

where A_{eff} is the effective area per second which is irradiated by the laser beam and powder stream [mm^2/s], E is the pulse laser energy [J], F is the laser pulse frequency [Hz], W is the laser pulse width [s] and $\dot{m}$ is the powder feed rate [g/s]. This is determined not only by the substrate velocity but also by the pulse characteristics of the laser beam. Referring to Figure 2.12 and performing the geometrical analysis, the following equation is obtained for the effective area per second as

$$A_{eff} = \begin{cases} \pi r_l^2 + 2Ur_l - 2F\left[\frac{1-FW}{F}Ur_l - \frac{1-FW}{2F}yU - r_l^2\left(\frac{\pi}{2} - \sin^{-1}\left(\frac{y}{r_l}\right)\right)\right] & \text{for } r_l > \frac{1-FW}{2F}U \\ \pi r_l^2 F + 2Ur_l WF & \text{for } r_l \leqq \frac{1-FW}{2F}U \end{cases} \tag{2.10}$$

where

$$y = \sqrt{r_l^2 - \left(\frac{1 - FW}{2F}U\right)^2} \tag{2.11}$$

U is the process speed [mm/s], and r_l is the laser spot radius on the substrate [mm]. Equations (2.10) and (2.11) are derived based on subtracting A_c, which is the half uncovered area of a rectangle created by two successive laser pulses (See Figure 2.12), from the total area covered by the pulses per second.

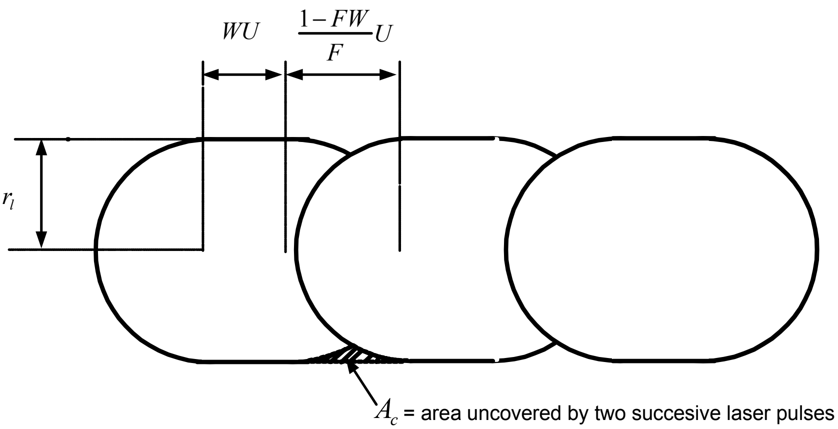

FIGURE 2.12
A schematic of the affective area of cladding created by succesive laser pulses.

Inherent in Equation (2.9) is the assumption that when the pulse is off, no powder is deposited on the substrate due to the absence of the energy provided by the laser pulses. This aspect of the process is introduced through the inclusion of the duty cycle $C = FW$ in Equation (2.9).

Using these two combined parameters, a general plot can be obtained for iron-aluminide coating on mild steel or H13 [3, 4, 113] that presents the corresponding clad quality based on effective energy density and effective powder deposition density as shown in Figure 2.13

FIGURE 2.13
Correlation between effective energy density E_{eff} and effective powder deposition density ψ_{eff} for iron-aluminide coating on mild steel.

2.7 Comparison Between Laser Cladding and Other Metallic Coating Techniques

The application of laser cladding should compete with several major coating techniques such as thermal spray, welding, chemical vapor deposition (CVD), and physical vapor deposition (PVD).

The thermal spray can be categorized into three methods, which are combustion torch (e.g., flame-spray, high-velocity oxy fuel, and detonation gun), electric (wire) arc, and plasma arc. In addition, PVD can be categorized into ion plating and ion implantation. CVD is also categorized into: sputtering, ion plating, plasma-enhanced CVD, low-pressure CVD, laser-enhanced CVD, active reactive evaporation, ion beam and laser evaporation [114].

Table 2.1 compares several major features of these coating techniques to provide the advantages and disadvantages of these processes for metallic and non-metallic coating applications. As it is listed in Table 2.1, laser cladding creates a very strong bond with low dilution, where a very low heat-affected zone (HAZ) is produced in the substrate. However, the investment cost and

TABLE 2.1
Comparison between laser cladding and other coating techniques.

Feature	Laser Cladding	Welding	Thermal spray	CVD	PVD
Bonding strength	High	High	Moderate	Low	Low
Dilution	High	High	Nil	Nil	Nil
Coating materials	Metals, ceramics	Metals	Metals, ceramics	Metals, ceramics	Metals, ceramics
Coating thickness	50 μm to 2 mm	1 to several mm	50 μm to several mm	0.05 μm to 20 μm	0.05 μm to 10 μm
Repeatability	Moderate to high	Moderate	Moderate	High	High
Heat-affected zone (HAZ)	Low	High	High	Very low	Very low
Controllability	Moderate to high	Low	Moderate	Moderate to high	Moderate to high
Cost	High	Moderate	Moderate	High	High

maintenance cost of the laser cladding machine are currently high, which are disadvantages of this process.

It is anticipated that because of the fast growing of the new generation of lasers such as high-power diode and fiber lasers, which offer higher efficiency and lower maintenance cost, laser cladding technology will play an important role in the metallic coating market in the near future.

2.8 Comparison Between Laser Cladding and Other Prototyping Techniques

There are about 20 methods of rapid prototyping. Some of the major rapid prototyping techniques are: stereolithography apparatus (SLA), fused deposition manufacturing (FDM), selective laser sintering (SLS), 3D printing, and laser cladding-based prototyping (i.e, DMD, LENS, ALPD, laser consolidation, etc.).

Table 2.2 compares the features of these techniques. In this table, one of the features is called "support structure", which refers to parts to place in the unsupported geometries during fabrication, such as the supporting part for fabrication of the top portions of a part with the shape of the letter "T". These supports are usually calculated and added to the part by the system's software and may be formed of the same material as the part, or from an entirely

TABLE 2.2
Comparison between laser cladding-based and other prototyping techniques.

Feature	**Laser cladding** (e.g., DMD, ALPD, etc.)	**SLA**	**FDM**	**SLS**	**3D Printing**
Dimensional accuracy	Moderate	Moderate	Moderate to high	Low	Low to Moderate
Prototype's material	Metals and ceramics	Polymers and photopolymers	Filament ABS plastic	Polymers, metals and ceramics	Hard plastic, runner
Prototype's quality	High	Low to moderate (e.g., fragile)	High	Low (e.g., Porosity and cracks)	Low (e.g., fragile)
Support structure	Not required	Required	Required	Not Required	Required
Cost of machine	High (still under R&D)	Relatively Moderate	Moderate	Moderate	Low

different material. Support structures are either mechanically removed or dissolved away in secondary operations before the part can be used.

As Table 2.2 indicates, prototyping techniques, which are performed based on laser cladding technology, have superior features for metallic rapid prototyping. However, the cost of this technology is still high due to the need of highly qualified personnel and the cost of laser systems.

The development of an autonomous system for performing the laser cladding process without any need to expert personnel is under research and development in several research groups and industry. It is anticipated that providing a fully intelligent laser cladding apparatus will overcome the shortcomings of this technology.