5

Control of Laser Cladding Process

In spite of the many advantages of laser cladding, its industrial applications are still limited. This is not only because of the relatively high cost of laser systems, but also the high sensitivity of this process to disturbances. A small change in absorbed laser power, for example, can cause a large change in the melt pool size. Also, changes in the mass flow of the powder can produce significant variations in the overall geometry and microstructure of the clad. To make the process more stable and less susceptible to disturbances, it is important to understand the effects of involved parameters in the process, and clad quality and dimensions.

In Figure 2.7, the important parameters that determine the clad quality are listed under inputs and process columns. These parameters can be categorized into two groups:

- Intrinsic
- Extrinsic

Intrinsic parameters are those related to the substrate and powder properties. Some of these parameters include absorptivity, thermal conductivity, heat capacity, thermal diffusivity, and workpiece geometry. Extrinsic parameters are those related to the hardware used in the process such as laser, powder feeder, and positioning system. Some of these parameters include laser average energy, laser focal point, powder feeder mass flow, nozzle position and orientation, and relative position and velocity of the laser and substrate.

In general, there is no direct control on intrinsic parameters; however, the effects of changes in intrinsic parameters can be compensated by controlling the extrinsic parameters. For example, change in the absorptivity can be adjusted by controlling the laser average power.

The control of extrinsic parameters, on the other hand, is relatively easy for most of the parameters mentioned above. Commercial lasers, powder feeders, and positioning systems are equipped with built-in controllers that allow the user to set the desired values. This is in fact the approach that is used in many applications. After much trial and error, the parameters that result in a good quality clad or coating for a specific application are obtained. These parameters such as laser average power, focal point, speed, and powder feed rate are then used in an open-loop process control.

In Figure 5.1, the block diagram of the laser cladding process in both open and closed-loop is shown. The box indicating the open-loop process shows that the controllable parameters are set to predefined values and there is no feedback from the process output (clad) to adjust the parameters. In this method, any disturbance and error in the equipment outputs such as laser power, focal point, and velocity will affect the process output. Similarly, there is no mechanism to adjust the machines to compensate for the changes in the clad quality.

In a closed-loop control of the process, it is important to evaluate the actual clad in real time in order to compare it with the desired clad. In Figure 5.1, the measurable parameters that directly or indirectly can be used to determine the clad quality are shown. Direct parameters include the clad dimensions and roughness that can be measured using a camera. Indirect parameters include melt pool temperature and size that indirectly indicate the clad quality. The clad microstructure and rate of solidification are other indirect parameters that can be used to determine the state of the clad.

Having a measure of the clad condition and comparing this condition with the desired one, a controller can be used to change the controllable parameters on the fly to compensate for any disturbance or change in the process. It is important to note that all the controllable parameters are not independent and only some of them are needed to achieve a closed-loop control. For example, laser power and velocity are correlated, and only one of them is needed to change the effective power injected to a volume of substrate.

In general, open-loop control of laser cladding is useful when the application is fixed and is repeated over and over. Finding the right parameters is very time consuming; however, as long as there is no change in the application this method of control is effective and efficient. The advantages of this method are:

Cost Effectiveness: In this method, there is no need for additional costs for feedback sensors and a central controller to adjust the parameters on the fly to improve the clad quality.

Ease of Implementation: Since the devices used in the process have their own controllers, the parameters can be directly set on the machines.

The disadvantages of the open-loop control are:

Sensitivity: As mentioned earlier, laser cladding is very susceptible to changes in parameters. As a result, any variation in both intrinsic or extrinsic parameters results in a large deviation in the final product.

Tooling Time: For any new application and material, a significant amount of time is needed to arrive at a suitable set of parameters. This may not be feasible in many situations such as prototyping and low rate part fabrication.

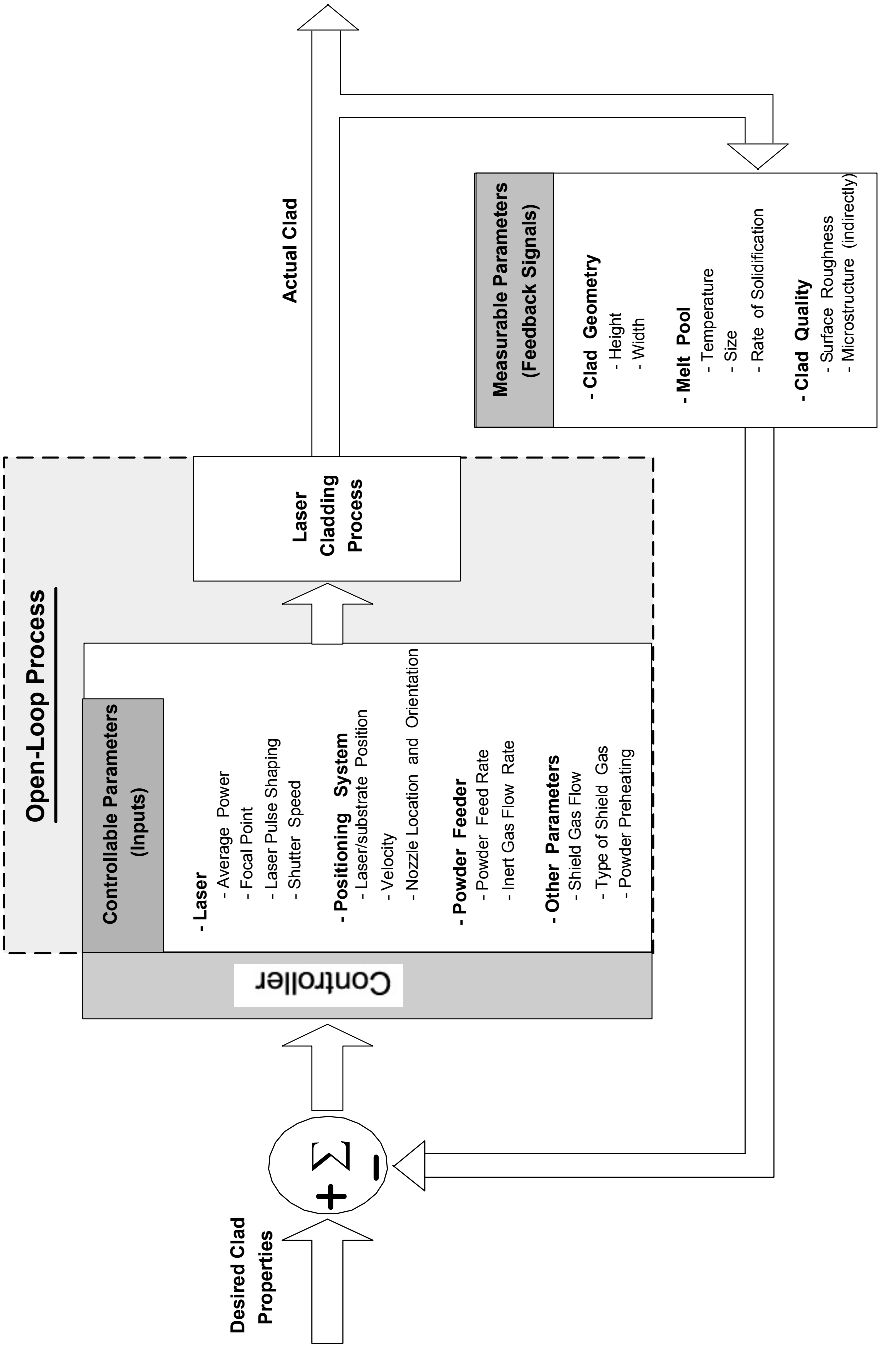

FIGURE 5.1

Open and closed-loop control of laser cladding.

To overcome the shortcomings of the open-loop systems, many studies have been directed at developing closed-loop control systems. In the following sections, different sensors for measuring the above-mentioned parameters are first studied. Current research in closed-loop control of laser cladding is then reviewed. In the end, a successful closed-loop control of laser cladding is discussed in detail.

5.1 Sensors

The parameters that can be used as feedback signals in a closed-loop control of the laser cladding process are shown in Figure 5.1 as the measurable parameters. The measurement of these parameters can directly or indirectly indicate the clad quality. When the correlation of these parameters with the input parameters are found, a controller can be designed to close the control loop as shown in Figure 5.1.

In general, measurable parameters related to the melt pool are temperature, size, rate of solidification. Measurable parameters associated with the actual clad size are height and width. The roughness of clad surface and associated microstructure can be indirectly estimated through the measurement of the clad geometry and rate of solidification. The sensors that are used for these measurements can be categorized into temperature and dimension sensors as follows.

5.1.0.2 Temperature Measurement

For temperature measurement of the melt pool, a non-contact sensor is needed. Most non-contact temperature sensors measure the thermal radiant power of the infrared or optical radiation of the object and are categorized as the following:

- **Radiation Thermometers (Pyrometers)***:* These sets of sensors are based on Planck's law of the thermal emission of electromagnetic radiation [208]. This group of non-contact temperature sensors includes pyrometers, infrared thermal imaging cameras (with temperature measurement capability), line-measuring thermometers (so-called line scanners), and infrared radiation thermometers. These sensors estimate the temperature from the amount of thermal electromagnetic radiation received from the object. This group of sensors includes both spot or point measuring devices in addition to line measuring radiation thermometers, which produce 1-D and, with known relative motion, can produce 2-D temperature distributions. In thermal imaging, measurement is done over an area from which the resulting image can be displayed as a 2-D temperature map of the scanned area.

In laser material processing, Smurov et al. [209] use a radiation pyrometer to measure the melt pool temperature. Several other authors apply a thermal camera to measure the temperature distribution of the process interaction zone [210, 211, 171]. The data from a thermal camera can be evaluated in terms of maximum temperature and its location, and temperature gradient calculations. The camera can also be used to determine the melt pool shape and area. Since there is a correlation between the melt pool area and the melt pool depth, the thickness of the resulting layer may be calculated indirectly.

- **Optical Pyrometers***:* These sensors are also based on Planck's law of radiation. The main part of the sensor is a lamp filament, which is operated at a constant current. Brightness variation is caused by a variable density filter that changes the apparent filament brightness in the operator's view when compared to the unchanging brightness of the object being measured [212]. Several authors [101, 213] applied optical pyrometers to measure laser power during the process.

- **Acoustic and Ultrasonic Pyrometers***:* The concept of measuring temperature of the melt pool by measuring the speed of sound in the process zone has been exploited by several groups [214, 101]. In this technique, the sound's flight time, which is a function of temperature, is measured in the process zone. The sound's flight time results in the temperature of the process zone. Acoustic pyrometers suffer from setbacks such as low sensitivity and noise rejection.

- **Thermocouples:** Thermocouples are used extensively in measuring temperatures in different industrial applications. Tungsten-rhenium and platinum-rhodium thermocouples are utilized for measuring temperature distributions during the laser cladding process [215]. The upper limits for the temperature measurement of tungsten-rhenium and platinum-rhodium thermocouples are 2400 and 1480 ^{o}C, respectively. Since thermocouples are contact-based sensors, they are not very suitable for the process because of the disturbances they develop in the melt pool.

5.1.0.3 Dimension Measurement

For the clad geometry measurement, cameras and phototransistors are the most common devices. The challenges encountered using these devices in the laser cladding process are contamination of the images with plasma, powder particles, etc., and also processing time of the images in real time to extract the clad geometry.

Meriaudeau et al. [210] used a CCD camera to measure the height of a clad and optimize the process by averaging the height of the clad. However, their work does not indicate the accuracy and the rate of measurements and also its application to a closed-loop control.

Kinsman et al. [216] and Duley et al. [217] showed how a vision system can be used to monitor the process zone for laser material processing. In their technique, the size of the melt pool is determined by measuring the number of bright pixels in the images.

Mazumder et al. [14, 218, 219] and Koch et al. [93] disclosed the usage of a phototransistor for process monitoring of the laser cladding process. The phototransistor is used to signal clad height deviation for a desired threshold.

Another attempt at monitoring the process has been done by Stegemann et al. [220]. They combined microfocus-radioscopy with a high-speed video camera in order to observe the mass flow within the melt pool.

In general, there is a little work in direct measurement of the clad dimensions and the quality in real time, although it has a great potential in automated laser cladding. In Section 5.3, a successful vision-based technique for measuring both clad geometry and the clad quality are introduced.

5.2 Closed-Loop Control of Laser Cladding

As seen in Figure 5.1, there are several parameters that can be used in controlling the laser cladding. The choice of a parameter for controlling the process largely depends on the type of equipment used. For example, a Nd:YAG laser compared to CO_2 laser provides more flexibility in terms of controlling the input power, or a positioning system has a better bandwidth compared to a laser for controlling the average power delivered to a substrate. Developing a closed-loop control of the laser cladding involves the selection of a control input, the measurement of clad properties for the feedback signal, and finally a controller that relates the error between the desired and measured clad property to the control input.

In practice, the parameters most commonly used as the control input and the feedback signal are the laser average power and melt pool temperature, respectively. In Nd:YAG lasers, the average power can be changed relatively quickly (usually on the order of some 1/10 of a second); however, in CO_2 lasers, due to their large time constants the average power is changed by opening and closing a shutter. The shutter can be operated at a maximum of 10-20 Hz. Another approach in controlling the power is to change the laser focal point with respect to the substrate in which the input power density to the melt pool is changed. This technique, however, may result in a variable clad width, especially in cladding.

According to Figure 5.1, a multi-input multi-output (MIMO) closed-loop control system may seem more appropriate for the laser cladding process. Due

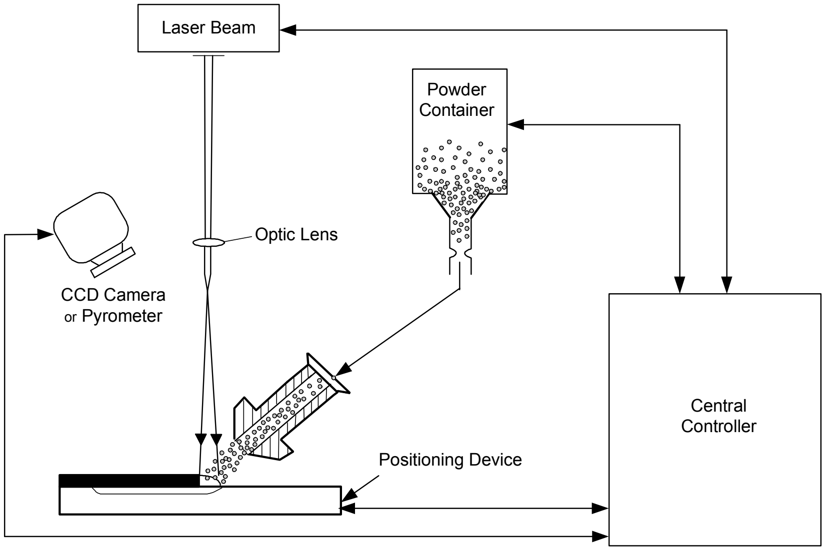

FIGURE 5.2
Closed-loop control of laser cladding.

to the complexity of the process and also the fact that the input parameters are not independent (similarly the feedback signals), there is no report for a MIMO control strategy for the laser cladding process. For other laser material processing, few authors attempted the MIMO approach. For example, Bataille et al. [178] used both the laser power and process speed during laser surface hardening.

Figure 5.2 shows the overall structure of a closed-loop control system of the laser cladding process. In a single input-single output (SISO) control system, the powder feeder and positioning system are not in the main process control loop and they set independently to predefined powder rate and specified path motion. Instead, the laser power is adjusted using direct control of the laser average power (in Nd:YAG lasers) or pulse modulation of the laser beam via a shutter (in CO_2 lasers) through the feedback from the melt pool temperature or geometry using a pyrometer or a camera.

Using the laser focal point technique, Morgan et al. [221] controlled the temperature of the melt pool via positioning the laser spot point relative to the workpiece. They performed experiments to demonstrate the effectiveness of closed–loop over open–loop control.

Li et al. [222, 140] developed a real-time laser cladding control system to determine the optimal operating conditions for a given requirement and for online fault diagnosis and correction.

Development of closed-loop control systems for laser material processing has been performed by several researchers. Kinsman et al. [216] and Duley et al. [217] disclosed a fuzzy logic controller for manipulating the laser processing variables such as laser power, laser intensity and laser beam velocity to control the penetration depth of welding.

Mazumder et al. [14, 218, 219] and Koch et al. [93] disclosed a feedback controller for adjusting the laser power based on the presence or absence of the laser beam from the process zone. This controller trims the control analog voltage, which is sent to the laser based on the TTL signal received from phototransistor. The modified analog signal sent to the laser causes the laser beam to be on and off for specific durations.

5.3 Closed-Loop Control of Laser Cladding, An Example

In the following, the details of a successful closed-loop control of the laser cladding process is discussed. Also, experimental results are presented to compare the open-loop with the closed-loop control approach in laser cladding.

5.3.1 Equipment and Configuration

Figure 5.3 shows the schematic of the integrated system. As seen in the figure, the system comprises:

1. Pulsed Nd:YAG laser,
2. Powder feeder machine,
3. Positioning device,
4. Central process controller consisting of frame grabber, image processing and pattern recognition software, CAD/CAM software, and interfaces,
5. Optical CCD-based detector,
6. Nozzles for powder injection,
7. Processing head, including optic system and shield gas delivery system,
8. Frame grabber,
9. Powder delivery tube,
10. Fiber optic,
11. Halogen light,
12. Substrate.

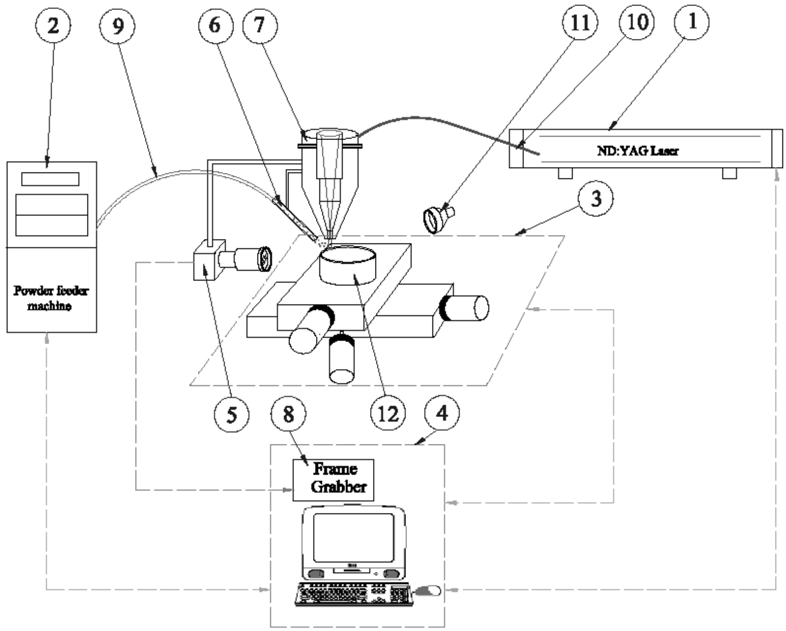

FIGURE 5.3
Schematic of the developed system.

Referring to Figure 5.3, the system includes a laser power source ① , which is connected to a fiber optic cable with 1.6 mm diameter ⑩ for transferring the beam to a processing head ⑦. The laser has an RS232 serial port for sending/receiving the information to/from the main controller ④.

The processing head ⑦ and/or the substrate ⑫ move by a positioning device ③. The processing head ⑦ is connected to a shield gas such as argon and is integrated with the laser optical system and protective ceramic head.

The spray nozzle ⑥ delivers a continuous powder stream through a flexible tube with 3 mm internal diameter ⑨. The powder stream with the desired powder feed rate and shield gas rate is provided by the powder feeder machine ②. The powder spray from the nozzle is conducted toward the intersection of the laser beam and the substrate ⑫, and, as a result, the powder particles and a thin layer of substrate are melted. Due to the metallurgical fusion between the deposited layer and the substrate a strong and uniform layer is built up on the substrate.

The relative position and orientation of the processing head and workpiece are commanded through the main process controller ④ via an RS232 serial port to control the clad location and also the laser focal point. The motion controller is able to adjust the relative velocity between the process spot and workpiece. Also, it traces the desired clad layer based on the CAD model of the workpiece available in the main controller ④. The CAD solid model of the desired object is sliced into many layers by the adaptive slicing technology, and the location, height and width of each layer are used by the main process controller to place and orient the workpiece and process head.

The optical CCD-based detectors ⑤ monitor the processing zone illuminated by a halogen light ⑪. The number of optical detectors can be two or three based on the desired object and the layer pattern.

Figures 5.4 and 5.5 show the two pictures of the system.

FIGURE 5.4
Integrated system.

5.3.2 Optical CCD-based Detector

Referring to Figure 5.6, a charge coupled device (CCD) camera ⑭ is used to provide images from the process zone. The images are then grabbed by a frame grabber ⑧ as shown in Figure 5.3. In the process zone, the high temperature of the melt pool emits light with different intensities and wavelengths. In addition, plasma and vaporized metal illuminate the melt pool. In order to filter undesired wavelengths, an interference filter with bandwidth of 500–700 nm ⑮ plus a neutral filter ⑯ are used. Magnification lenses ⑰ are used to magnify the process zone.

Referring to Figure 5.3, the frame grabber ⑧ receives the images from the

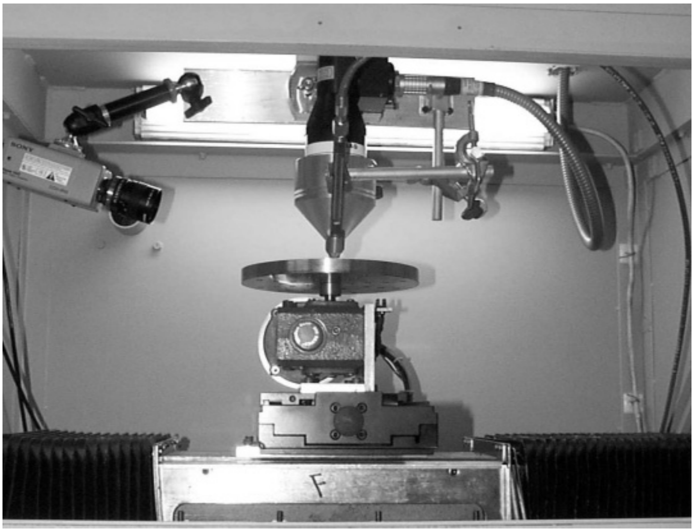

FIGURE 5.5
A close-up of the positioning device, processing head, nozzle, machine bed and optical CCD-based detector.

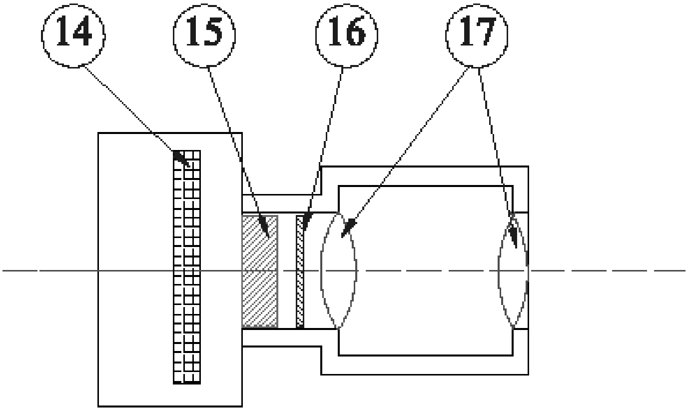

FIGURE 5.6
Optical CCD-based detector.

optical CCD-based detector ⑤. The size of original images is 640×480 pixels. To lessen the computational time, a preprocessing procedure is performed inside the frame grabber. The preprocessing reduces the images and limits them to the location of the center line of the laser beam in the right hand side of images and to the surface of the substrate in the lower part of images. Also, in the preprocessing procedure the images' brightness and contrast are decreased and increased by 10%, respectively. Figure 5.7a shows a typical image after preprocessing.

The preprocessed images are then fed into an algorithm developed for image processing and pattern recognition in the main controller. The software processes the images and finds the dimensions, roughness and the rate of solidification in real-time. The developed algorithm comprises:

1. Change an RGB image to a gray level

2. Create a threshold binary image using a threshold level which is computed by a global image threshold using Otsu's method applied on every tenth frame [223]

3. Extract the dimensions and the angle of the solid/liquid interface by finding the border of the white object in the image matrix as shown in Figure 5.7b. The clad's height can be calculated based on the number of bright pixels in the desired column of the matrix Also, the angle is obtained from the angle between the border of the bright area and a reference line.

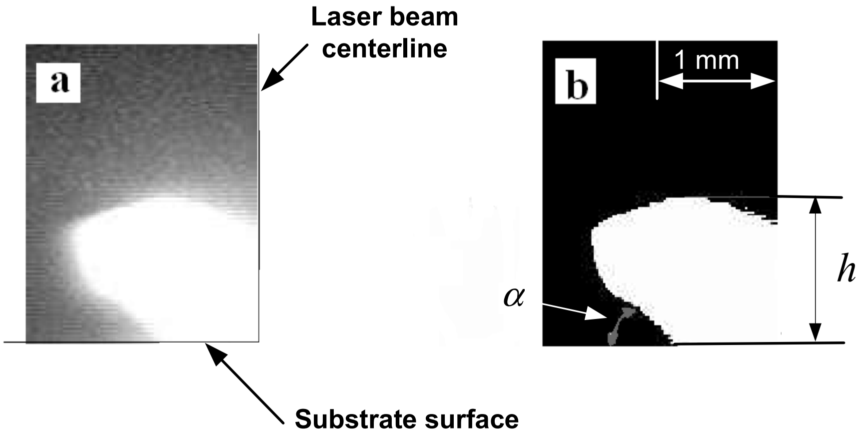

FIGURE 5.7
a) Typical image from a normal view to process zone, b) processed image.

The above-mentioned preprocessing and pattern recognition algorithm are also shown in Figure 5.8 using block diagrams. Experiments show that the height of the melt pool somewhat away from the laser centerline gives the most precise height.

Extracting the height and the angle using the algorithm provides valuable information and insight into the process. The clad's roughness and surface quality can be obtained by analyzing the fluctuation of the clad's height obtained in Step 3. Large fluctuations in the clad's height indicate a rough surface clad while lower fluctuation is an indication of a high quality clad with smooth surface finish.

As reported by Gilgien et al. [204] and Pie et al. [37], the measured angle can be used to determine the rate of solidification. Using the rate of solidification, the microstructure of the clad can be estimated. The metallurgical properties can then be extracted from the microstructure of the clad. Referring to Figure 5.9, if the process speed U and the angle α are known, the local rate of solidification, U_s, can be obtained from

$$U_s = U \cos\left(\frac{\pi}{2} - \alpha\right) \tag{5.1}$$

The microstructure of the solidified clad is directly dependent on the rate of solidification and the temperature gradient in liquid and can be experimentally obtained for any material. In general, a higher rate of solidification results in finer microstructure, which improves the mechanical properties of the clad [80].

5.3.2.1 Performance of the Optical CCD-based Detector

The performance of a device that provides the feedback signal (sensor) in a closed-loop control system is usually defined based on range, accuracy, sensitivity, stability, and response time. The range of a sensor defines the limits of the parameters that can be detected by the sensor. The accuracy is defined based on the error between the actual and measured values. The sensitivity is the minimum possible tolerance that may exist between two successive values. The response time is defined as the time that the sensor requires to produce the output signal.

The performance of the sensor was examined experimentally and listed in Table 5.1 for the dimension measurement.

The response time of the detector directly depends on the speed of the computer and the software platform used to implement the image processing algorithm. Using a Pentium II-450 MHz computer and MATLAB/SIMULINK platform, a maximum rate of 16 Hz was obtained. This rate can be improved by converting the image processing algorithm into an efficient high level computer language and use of a real time operating system.

In order to examine the accuracy of the real-time measurement, an offline measurement was utilized by the image processing technique. Pictures of the

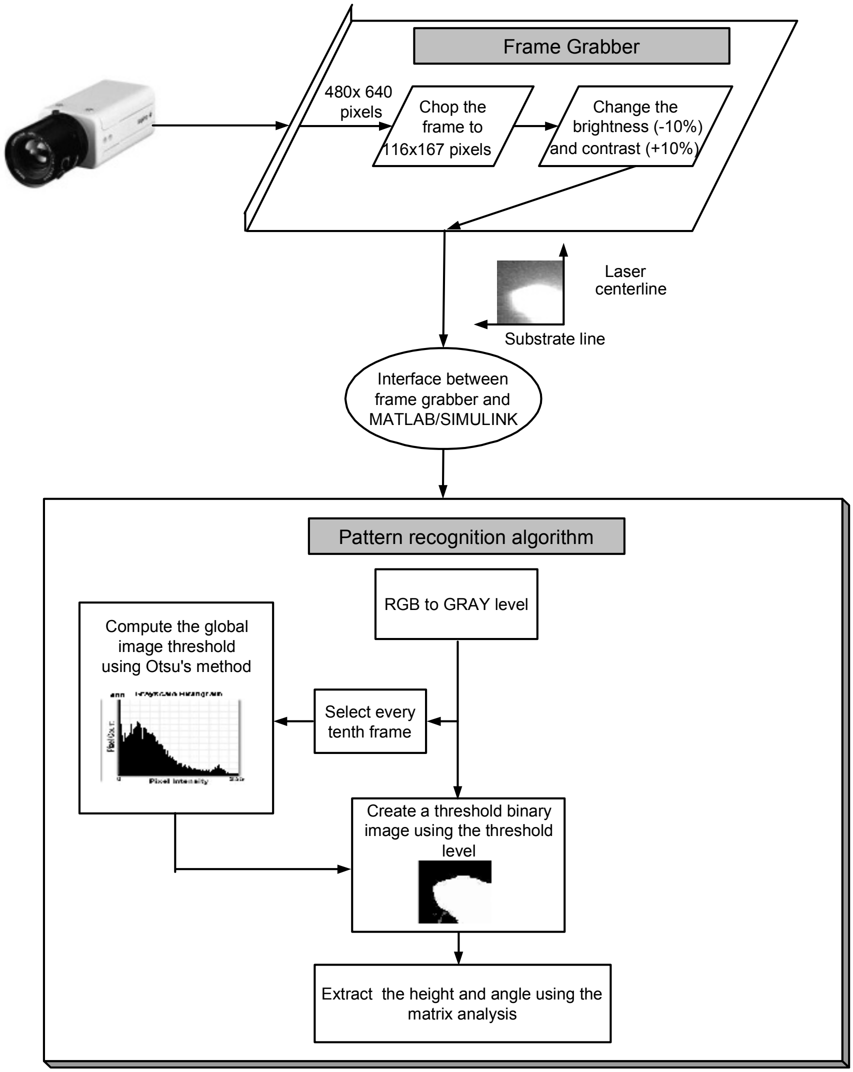

FIGURE 5.8
Optical CCD-based detector, frame grabber and pattern recognition algorithm.

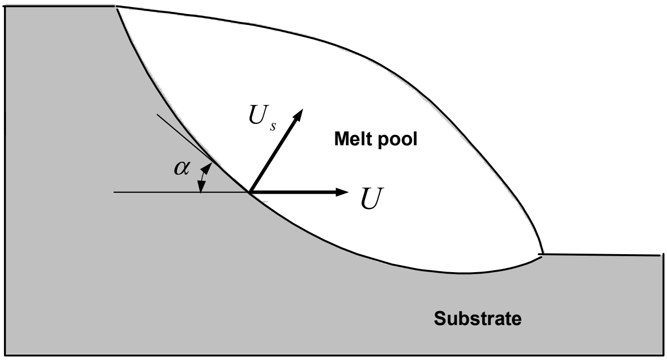

FIGURE 5.9
Solid/liquid interface and corresponding angle.

TABLE 5.1
Optical CCD-based detector performance

Specification	Geometry Measurement
Range	0.25 to 2.2 mm of clad dimension for laser power of 80 W to 600 W and process speed of 0.5 to 3 mm/s
Accuracy	0.1 mm
Sensitivity	0.02 mm

clads were taken by a digital camera and using an edge detection approach, the height of the clads were obtained with a resolution better than $\pm 50\ \mu$m. The results were then compared with real-time measurements.

Figure 5.10 shows the comparison. The results were obtained when the laser pulse frequency was changed from 70 to 100 Hz, and the laser energy = 5 J, powder mass rate = 1 g/min, laser pulse width = 3 ms, substrate speed = 1.5 mm/s.

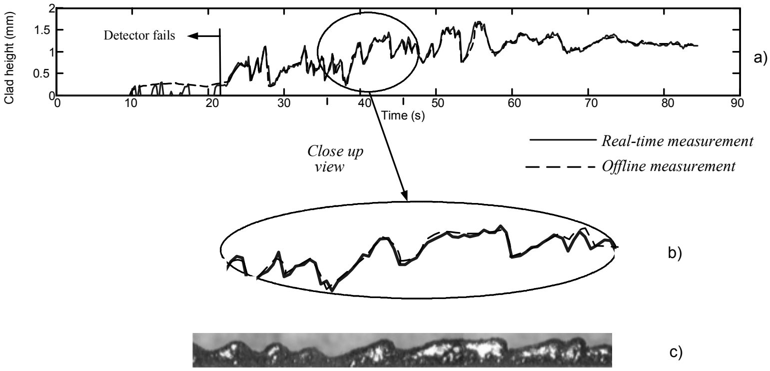

FIGURE 5.10

Comparison between the real-time and offline measurements of clad height, a) real time and offline measurements, b) comparison, c) actual clad.

5.3.3 Control Strategy

In this section, several classical and fuzzy logic controllers implemented to the laser cladding process are discussed. These controllers are able to adjust the laser pulse energy and the process speed.

As mentioned earlier in Section 4.8.1, the clad height becomes a linear function of the laser pulse energy around the operating point. As a result, simple models can be developed around different operating points to predict the clad height as a function of the laser pulse energy. One of the models discussed in Section 4.8.1 is used in designing the controller in this section.

For the control, a PID controller [224] is considered with the identified model and a threshold limiting the upper and lower ranges of the laser pulse energy as shown in Figure 5.11. In this figure, h_d is the desired and h_r is the actual generated clad height. The main reason for using the lower and upper thresholds is to address the clad bead quality and the laser system limitations, respectively.

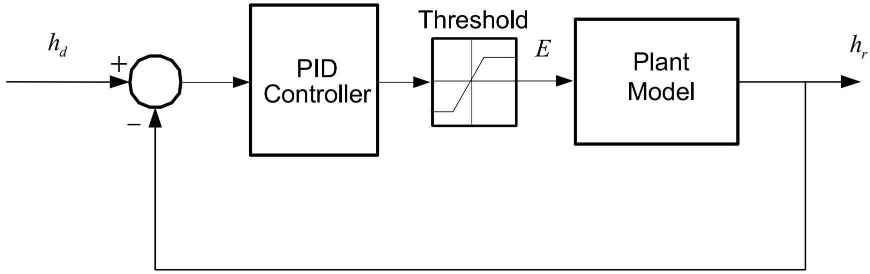

FIGURE 5.11
PID controller integrated with a threshold and the identified plant model.

For optimizing the PID gains, an optimization algorithm is used based on the minimization of the quadratic Hessian function [225]. The algorithm optimizes the PID gains based on the desired overshoot, settling time, and rising time. For the laser cladding process, the desired situation is one for which the overshoot, settling time and the oscillations around the set point become minimum, so that a clad with the desired height can be produced rapidly and precisely. The optimization results in the proportional, integral and derivative gains as $K_p = 5.5$, $K_i = 0.8$ and $K_d = 0$, respectively, for an operating point in which $U = 1.5$ mm/s, $\dot{m} = 1$ g/min, $F = 96$ Hz, $W = 3$ ms, and desired clad height is 0.8 mm. The other process parameters were similar to those used in Section 4.8.1.3.1. Since $K_d = 0$, it can be concluded that a PI controller gives a better process performance.

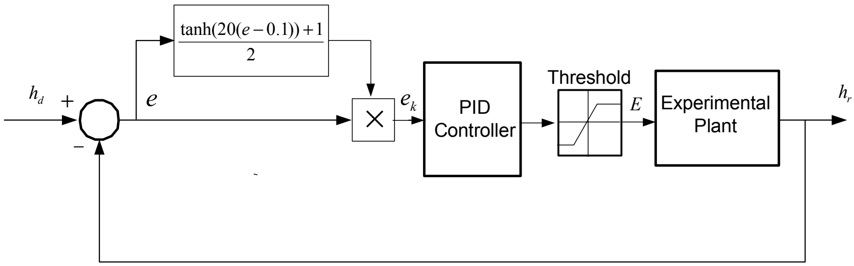

FIGURE 5.12
Application of a PID controller to the laser cladding process.

To evaluate the controller, experiments were conducted using the system shown in Figure 5.3. Initial results showed that the model in Figure 5.11 was not effective because of the instability of the laser due to large deviations in the input signal to the laser.

To overcome this setback, a filter in the form of

$$e_k = e\frac{\tanh(20(e-0.1))+1}{2} \tag{5.2}$$

was added to the controller. In this filter e is the error and e_k is the filtered error in the control loop as shown in Figure 5.12. This function smooths the error and eliminates large fluctuations form the input signal to the laser. Implementation of this filter in the apparatus significantly improves the controller and in turn the clad quality. Figure 5.13 compares the experimental and simulation results.

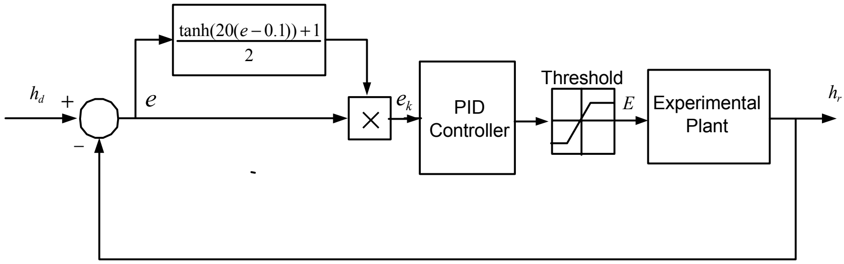

FIGURE 5.13
Comparison between the simulation and experimental results where K_p= 5.5, K_i= 0.8 and K_d= 0.

5.3.4 Closed-Loop vs. Open-Loop

In a layer-by-layer laser part manufacturing process, it is important to fabricate the desired slice with high precision. Initiation of a layer using an open-loop laser cladding system with a constant energy causes a gradual growth in the clad height in the initial stage of the first layer. Also, the same energy used in the first layer is more than sufficient for the other layers, which in turn damages the underlying layers through remelting. A closed-loop control system can overcome these issues by applying higher energy in the start up of the clad and reducing the energy afterward.

In order to investigate and compare a closed-loop versus an open-loop controller during process startup, an experiment with U = 2.25 mm/s, $\dot{m}$ = 2 g/min, F = 96 Hz, and W = 3 ms is conducted. The gains of the controller are set to $K_p = 10$, $K_i = 0.4$ and $K_d = 0$.

Figure 5.14 compares the results. For this highly repeatable experiment, the average error of the generated clad heights in 5 seconds with respect to the

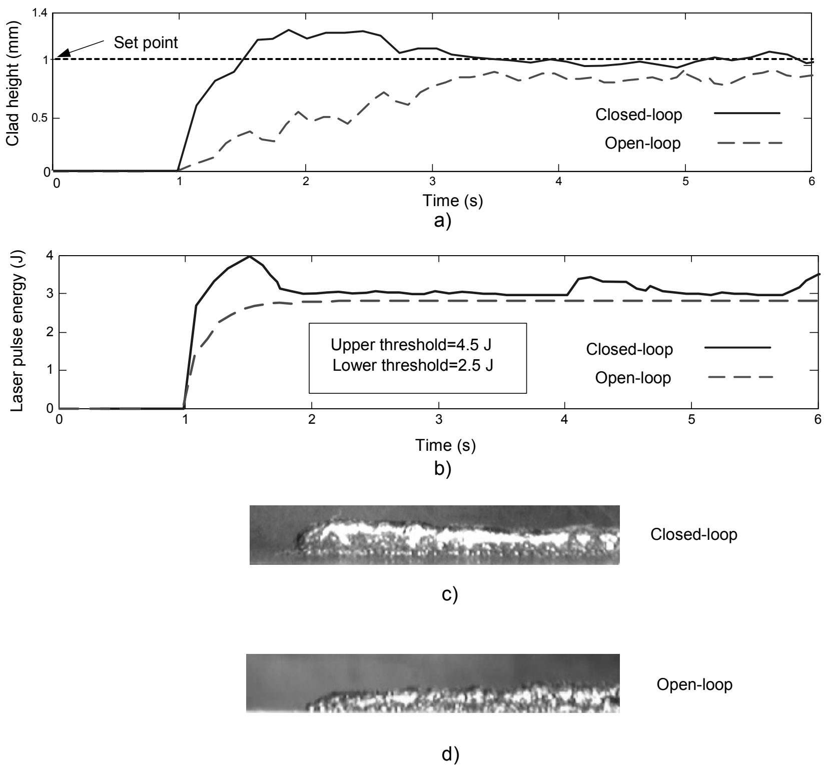

FIGURE 5.14

Performance of the closed-loop PID control and the open-loop systems during clad startup: a) clad height, b) corresponding laser pulse energy, c) a side view of the generated clad by the closed-loop PID control system, d) side view of generated clad by open-loop PID control system.

desired value (1 mm) was 31% for the open-loop and 7% for the closed-loop control systems.

Another fluctuation in the process that a closed-loop control method can attenuate is the absorptivity factor, β. Absorptivity factor is a function of surface condition and temperature [101]. Changes in the absorptivity creates disturbances during laser cladding, which causes the total energy absorbed by the substrate to change. Consequently, these changes affect the quality of the clad in terms of geometrical, mechanical and metallurgical qualities.

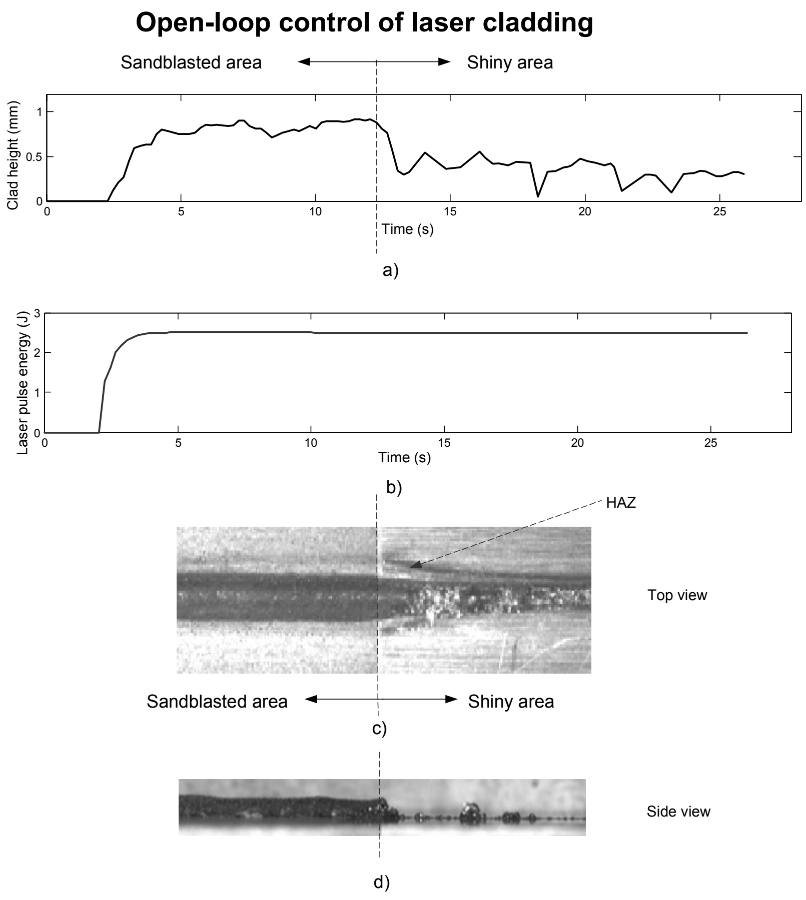

FIGURE 5.15
Open-loop laser cladding under the absorption variation: a) generated clad, b) laser pulse energy, c) top view of the generated clad, d) side view of generated clad.

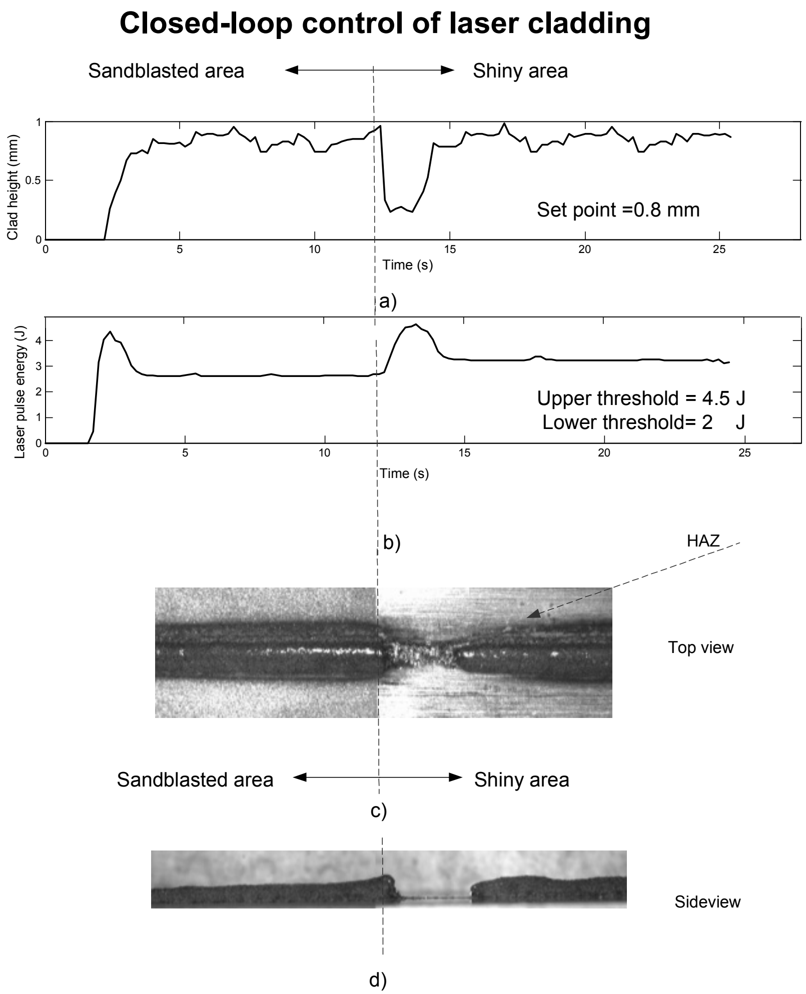

FIGURE 5.16

Closed-loop laser cladding under the absorption variation: a) generated clad, b) laser pulse energy, c) top view of the generated clad, d) side view of the generated clad.

In order to evaluate the performance of the controller, an experiment is conducted. Mild steel samples, half shiny and half sandblasted, are prepared. Numerous tests with different laser pulse energy and $U = 1.5$ mm/s, $\dot{m} = 1$ g/min, $F = 96$ Hz, and $W = 3$ ms are performed when the other process parameters are the same as those described in Section 4.8.1.3.1. The main reason for performing these experiments is to find the critical energy on the substrate in the presence of the absorption disturbance. It is concluded that $E = 2.6$ J is the critical energy for this circumstance resulted in a poor clad in the shiny area as shown in Figure 5.15. As seen, the generated clad in the shiny area has a lower height and poor quality (it could be easily removed after the process) due to the lack of energy as shown in Figures 5.15c and 5.15d. Of interest is the fact that the HAZ (heat-affected zone) line is visible in Figure 5.15c. It also provides evidence of the lack of sufficient energy absorbed by the substrate when the surface is shiny.

In contrast, the closed-loop system can sense and overcome the lack of energy in the system, when the same conditions of the open-loop experiment are applied to the apparatus. The result of the closed-loop control for the absorptivity disturbance is shown in Figure 5.16. As seen, the closed-loop control system compensates for the disturbance. Although due to the low control cycle rate (typically 5 to 7 Hz) and large response time of both the laser and the process, a portion of the clad had low quality.

A geometrical disturbance is one of the most likely disturbances in the laser cladding process. It may arise from the desired part geometry or even from the deformation of the underneath layer due to thermal distortion. The process speed is the most important parameter that can significantly compensate the geometrical disturbances. However, the laser energy can also be selected as the command signal to compensate the effects of small geometrical fluctuation around the desired set point.

In order to examine the performance of the controller under geometrical disturbances, a simple test is considered. A step is machined on some mild steel plates with a depth of 0.25 to 0.3 mm. The fabricated step on the flat plate not only changes the underneath layer positions but also changes the effective position of the laser spot point and the intersection of the laser and powder stream on the workpiece.

Several experiments are performed for both open- and close-loop conditions, where $U = 2.5$ mm/s, $\dot{m} = 2$ g/min, $F = 93.5$ Hz, $W = 2.92$ ms, and the other process parameters are set as those used in Section 4.8.1.3.1.

Figure 5.17 shows the result of an open-loop laser cladding process where the laser energy is set to 2.8 J. As seen in the figure, the clad height is significantly changed. Figure 5.17c also shows a side view of the step zone.

Figure 5.18 shows the performance of the closed-loop control system for a step down in the underneath layer. Figure 5.18c also shows a longitudinal view of the sample in the step zone. As seen, the controller compensates the effect of the geometrical disturbances very effectively.

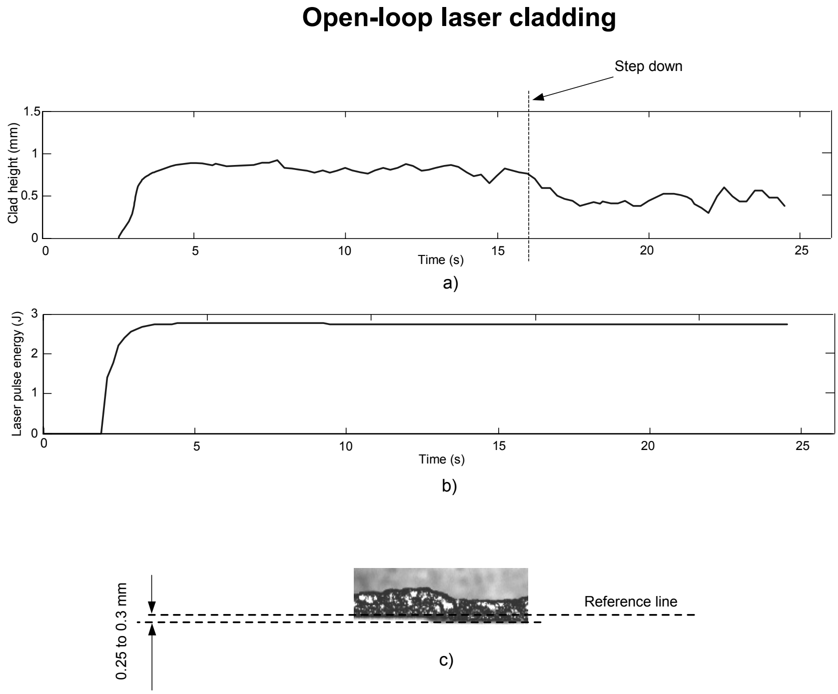

FIGURE 5.17
Open-loop control of laser cladding experiment for a geometrical disturbance: a) clad height, b) fixed laser pulse energy, c) side view of the generated clad in the step zone.

5.3.5 Application of the Developed Controller to Fabrication of Two Simple Components

To investigate the role of a closed-loop controller on a layer-by-layer part manufacturing, the controller is used in fabricating a thin wall and a thin curved shape. Several layers need to be deposited on each other to form the desired object.

For both shapes, an open-loop and closed-loop process is performed. In the experiments $U = 2.25$ mm/s, $\dot{m} = 2$ g/min, $F = 96$ Hz, and $W = 3$ ms whereas the laser pulse energy for the open-loop experiment is 3.5 J. Other process parameters are similar to those used in Section 4.8.1.3.1. When a layer is finished the laser is moved up by 0.38 mm before the next layer is deposited.

Figure 5.19 shows the results of the open-loop and closed-loop controller in the fabrication of the thin-wall prototypes. As seen, the closed-loop control system has enhanced the geometry of the prototypes significantly.

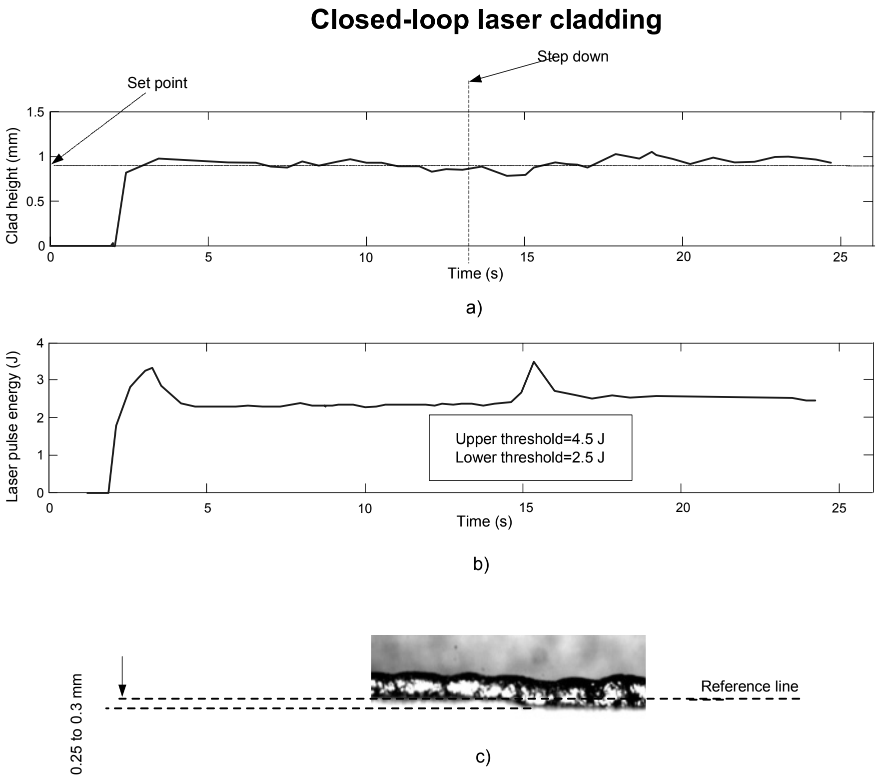

FIGURE 5.18

Closed-loop control of laser cladding experiment for a geometrical disturbance: a) clad height, b) laser pulse energy, c) side view of the generated clad in the step zone.

Figure 5.20 shows the power changes in layers. It can also be concluded that the main reason for a poor quality in the open-loop system is the high amount of delivered energy to the process causing remelting of the underneath layer.

Figure 5.21 illustrates the results of a closed- and open-loop prototyping of a thin curved shape. As seen in the figure, the controller has a significant effect in improving the process for prototyping.

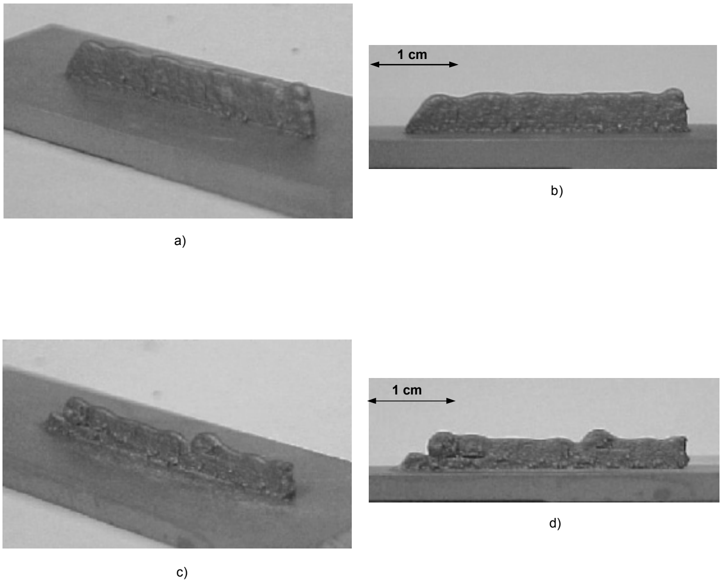

FIGURE 5.19
Comparison between a closed-loop and open-loop controlled productions of the thin wall: a) closed-loop, b) closed-loop side view, c) open-loop, d) open-loop side view.

5.4 Application of Knowledge-Based Control to Laser Cladding

As noticed and discussed so far, laser cladding is a complex and nonlinear process with many uncertainties. For such systems, application of classical controllers in which a good model or well-predicted behavior is needed may not be appropriate. Knowledge-based control techniques such as fuzzy logic or neural network, on the other hand, can handle these systems more conveniently. In the following, we investigate numerically the application of fuzzy logic to the control of laser cladding. For the laser cladding process, we use the Hammerstein-Wiener model developed in Section 4.8.1.2. This nonlinear model relates the clad height to the process speed. In the control development process, we apply the standard and modified version of a fuzzy logic controller and compare the results.

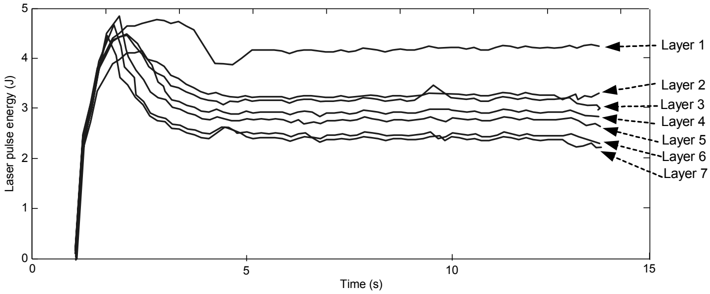

FIGURE 5.20
Comparison between the laser pulse energy for different layers in a closed loop control system.

5.4.1 Fuzzy Logic Controller

Fuzzy logic was invented by Zadeh [226] and developed in the past three decades. With fuzzy logic, it is possible to analyze complex systems without having their mathematical models [227].

In this fashion, the fuzzy logic controller was introduced [228]. The basic paradigm for fuzzy logic control is a linguistic or rule-based control strategy, which maps the observable inputs of the given physical system into its controllable outputs with applying a set of implication linguistic rules.

Figure 5.22 shows a fuzzy control strategy, where a fuzzy logic controller and fuzzy logic gain scheduler are incorporated in the controller decision making part.

This strategy maps the error, $e = y_d - y$, into the control action u. At the heart of this control scheme is a fuzzy logic control algorithm that maps the normalized error e_k and rate of change of error d_k to the change in the control output or δu_k. A typical rule in fuzzy logic controller is

$$\text{if } \; e_k \; \text{ is } \; LP \; \text{ or } \; SP \text{ and } \; d_k \; \text{ is } \; LN \text{ or } SN\text{, then } \; \delta u_k \; \text{ is } \; Z.$$

where LP, SP, LN, SN, and Z stand for large positive, small positive, large negative, small negative, and zero, respectively [228]. Figure 5.23 shows fuzzy membership functions over the normalized domains of definition of the relevant variables and the mathematical meanings of LP, SP, LN, SN, and Z in a normalized range.

For a system with a large settling time such as the laser cladding, the process command can also be amplified at the beginning of the process. As a result, a controller with a gain scheduler is developed to address this issue using a fuzzy approach. The basics of the developed fuzzy logic control paradigm is to choose the value of normalization factor in output of the standard fuzzy controller by another set of fuzzy rules, which is a so-called fuzzy logic

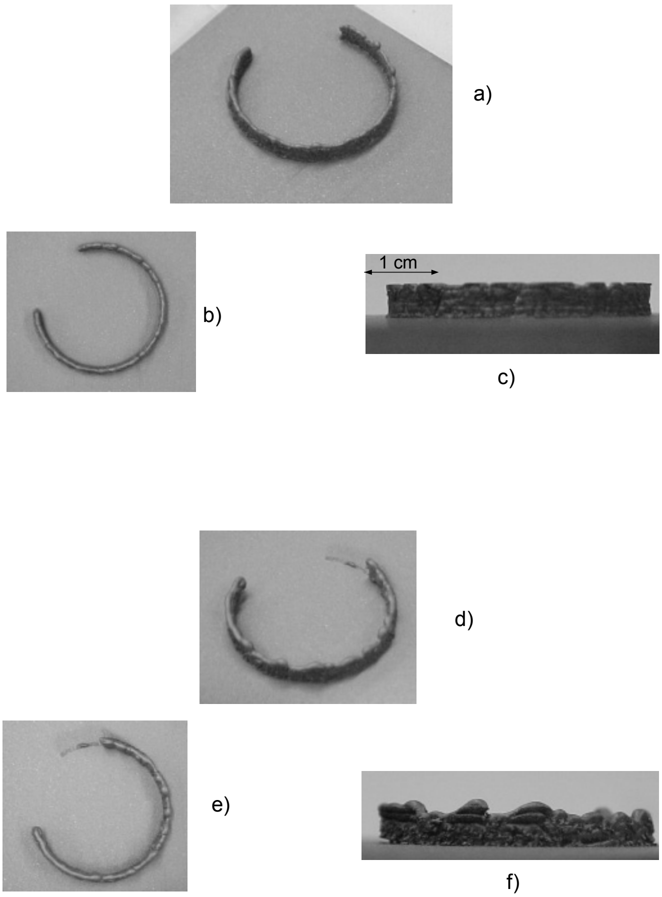

FIGURE 5.21
Comparison between a closed-loop and open-loop fabrication of a curved shape: a) closed-loop perspective view, b) closed-loop top view, c) closed-loop side view, d) open-loop perspective view, e) open-loop top view, f) open-loop side view.

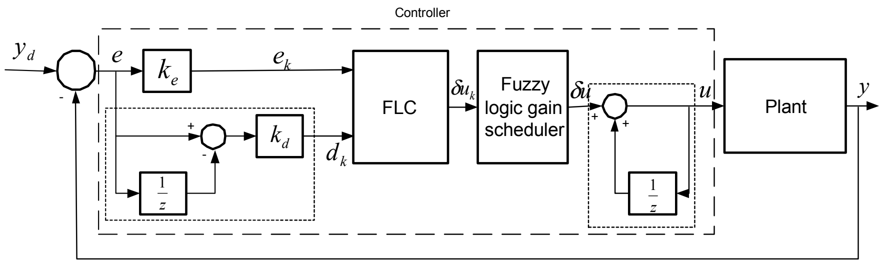

FIGURE 5.22
Proposed fuzzy logic controller.

gain scheduler.

To keep control over the response, it is proposed that the area below the steady-state line be divided into several appropriate subregions of L, N, H, as shown in Figure 5.23. During the startup, the value of gain is switched to a higher value to accelerate the system response. Conversely, it is decreased when the response approaches the steady-state response.

Implementation of the designed fuzzy logic controller to the laser cladding process is subjected to the compensation of the nonlinear terms identified in the Hammerstein-Wiener model. As a result, the inverse functions of f and g which were introduced in Section 4.8.1.2 are incorporated in the fuzzy controller as shown in Figure 5.24.

In order to investigate the effect of the fuzzy controller on the system response, a standard fuzzy controller is implemented into the model as well. The standard fuzzy controller has the same structure except the fuzzy gain scheduler is eliminated. The classic fuzzy controller results in a sluggish response as seen in Figure 5.25. Conversely, the fuzzy controller with a gain scheduler can considerably reduce response time of the system and improve the system response (generated clad height) significantly, as shown in the figure.

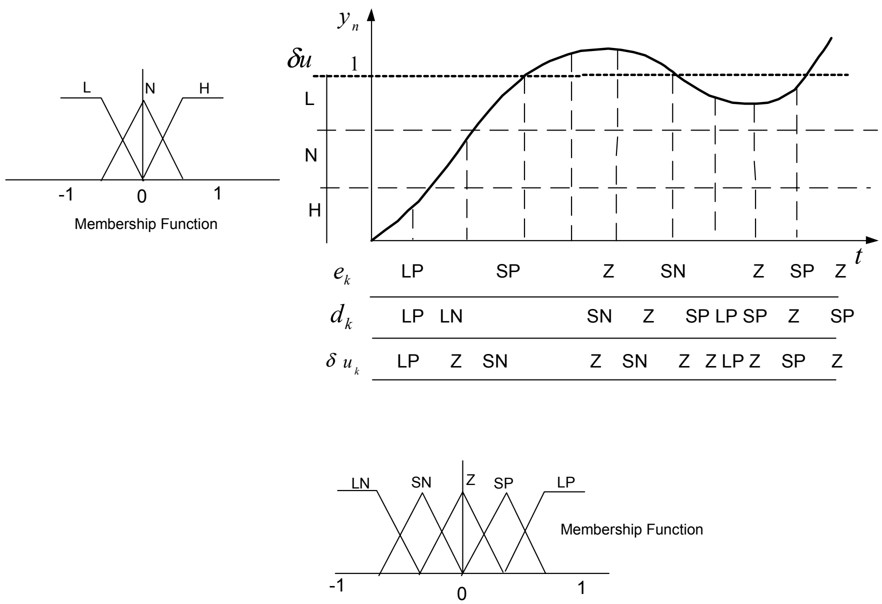

FIGURE 5.23
Control rules and membership function.

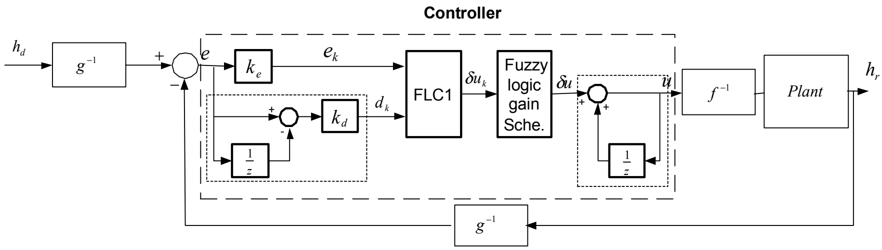

FIGURE 5.24
Proposed fuzzy logic controller integrated with knowledge-based functions for the laser cladding process.

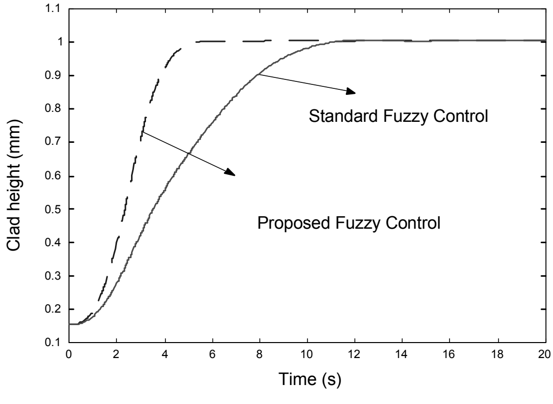

FIGURE 5.25
Comparison between the standard fuzzy logic (without gain scheduler) and proposed fuzzy logic (with gain scheduler).