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ORIGINAL ARTICLE

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Melt pool temperature control using LabVIEW in Nd:YAG laser blown powder cladding process

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Abstract In laser cladding, the substrate temperature increases as the process progresses, which can lead to excessive dilution, the formation of a heat-affected zone (HAZ), thermal distortion and cracking due to the build-up of residual stresses. The feasibility of controlling heat build-up and dilution through on-line temperature control during Nd:YAG laser cladding is investigated using a LabVIEW graphical program with a real-time proportional, integral and derivative (PID) controller to control the temperature of the melt pool. Cladding trials were performed with and without temperature control. The effects of laser cladding conditions such as the substrate scan rate and powder feed rate on clad dilution and HAZ were determined by quantitative metallography. Results indicate that while the LabVIEW system can control the melt pool temperature, this does not necessarily result in a quality clad layer and highlights the need for multi-parameter process control.

Keywords Cladding · Hastelloy C powder · LabVIEW · monitoring · Nd:YAG laser

1 Introduction

In laser cladding, coating can be achieved using several methods, such as blowing powder into the molten pool created by a laser beam, by wire feed, pre-placed chips and pre-placed powder. Steen [1], one of the earliest researchers in the field, emphasized the advantages of the blown powder laser cladding technique because of its one step operation, which forms a fusion bond with low dilution, and is adaptable to automatic processing. Laser cladding using powder injection is suitable for the surface treatment of selected areas of components, and produces surfaces with superior wear and corrosion properties [2]. The process is now being exploited commercially for a number of applications, such as depositing super alloys on turbine blades, valve seats and mining components [3–5]. A feature of laser cladding, however, is the number of parameters, such as the laser power, process speed, powder mass flow rate and its distribution, that need to be monitored and controlled in order to maintain the quality of the clad layer [6]. These parameters influence clad layer dilution with the substrate, and its integrity in terms of porosity and cracks. They become critical when attempting to clad small and delicate components where the heat build-up may damage or distort the part. In order to control the heat input into the clad layer and substrate, a closed-loop control system is necessary.

In laser cladding, the temperature of the molten pool is high enough to generate visible radiation, and consequently radiation pyrometry using the Plank's radiation law is the most convenient method for measuring its surface temperature [7]. Due to the temperature range (most materials used for laser cladding have melting points greater than 800 °C), the region of interest lies between 0.7 and 15 μm, the part of the electromagnetic spectrum in which most radiometric surface temperature measurements are made [8, 9]. The sensor's output is based on the melt pool radiation, and consequently dependant upon the melt pool temperature, its shape, size, and the distance to the sensor, as well as the sensor's viewing angle [10]. Reports on monitoring systems using opto-electric sensing [9], pyrometers [1, 3, 11, 12, 14] and vision systems [15] indicate their feasibility in observing changes in laser cladding and their application to real-time process control; they also highlight the complexity of the laser cladding process itself.

As part of a study investigating the monitoring and control of Nd:YAG laser cladding, a system is being developed based on a pyrometer and photodiode to measure the surface temperature and size of the melt pool, and a LabVIEW platform running on a Pentium personal computer to control the laser power and workpiece speed. Reported in this study are experiments investigating the performance of the LabVIEW system in its ability to monitor and control the melt pool temperature, and consequently the quality of clad layer.

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2 Experimental setup

The experimental setup is illustrated in Fig. 1. A 2.5 kW cw Nd:YAG laser was used. The beam from the laser was delivered to the workpiece via a 10-m-long, 0.6-mm-diameter, step-index glass optical fiber. The output of the fiber was connected to a 50-mm-diameter collimating lens with a 200 mm focal length. The collimating lens was connected to a bending cube which contained a 45° bending mirror, and a focusing lens with a focal length of 200 mm. The focal spot was positioned 20 mm from the workpiece, which resulted in a defocused laser spot size of 4 mm at the substrate surface.

The temperature of the melt pool was measured using a Maurer KTR 1075 two-color pyrometer capable of measuring temperatures in the range of 800–2500 °C. The pyrometer looked directly into the melt pool through the bending cube housing a partially transparent mirror, which in turn bends the Nd:YAG laser beam and reflects it onto the workpiece. The transmitted intensity of this transparent mirror at 1.06 μm is only 0.18%, and in the spectral region from 1.4 to 2.0 μm is 90%. The pyrometer sampled an area of about 2 mm in diameter on the melt pool surface. The output signals from the pyrometer were recorded by a National Instruments PCI-MIO-16E-4 data acquisition card. The LabVIEW graphical program, which included a PID controller, controlled the temperature in real-time and saved the collected data for off-line data analysis (Fig. 2). The input signals were acquired at a sampling rate of 1 kHz.

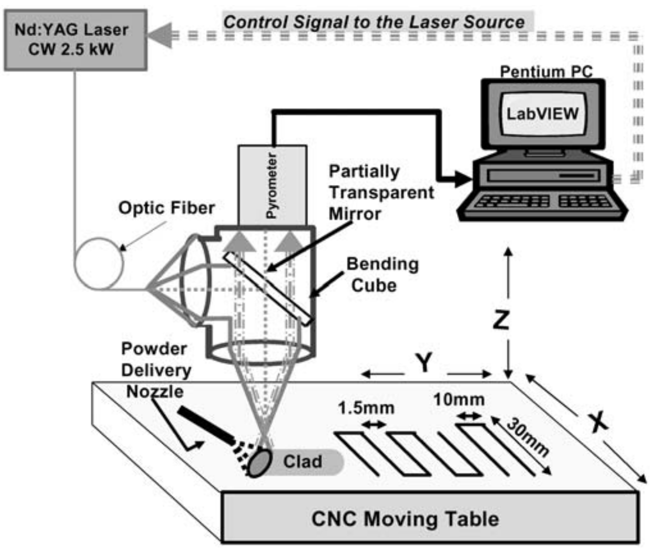

Fig. 1. Schematic of experimental setup

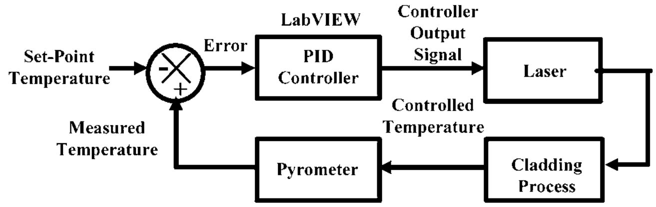

Fig. 2. Temperature feedback loop and its components

Table 2. The range of operating conditions

Laser power (W)	Processing feed rate (mm/min)	Powder mass flow rate (g/min)	Argon gas flow rate (l/min)
900 to 2400	400 to 2000	4.65 to 38.45	3

The experiments were performed with Hastelloy C powder (Table 1), delivered into the molten pool with a side injecting powder nozzle positioned at an angle of 60° to the substrate.

The diameter of the nozzle was 2 mm and was positioned 12 mm from the interaction zone. It produced a powder jet with a diameter of approximately 5 mm at the interaction zone. Sandblasted mild steel plates with thicknesses of 10 mm were used as substrates. The range of operating conditions used in the experiments is given in Table 2.

A series of experiments was conducted by depositing single and multiple track-clad layers in the direction perpendicular to the axis of beam delivery and powder nozzle. In the case of single tracks, a length of 30 mm was produced in one direction and 30 mm in reverse direction, with a 10 mm separation between the two. For the multiple tracks, a raster scan pattern was adopted with each track being 30 mm in length and overlapped normally by 50% (with an increment of 1.5 mm). Following cladding trials, the transverse sections of the clad layers were prepared and polished with 1 μm paste for microstructural studies. Nital (2%) was used to etch the cross-section of the coating and reveal the heat-affected zone and to measure dilution.

3 System approximation for optimum controller tuning

In order to optimize the functionality of the controller, a mathematical model of the process was developed. A natural way to evaluate a physical system is the block diagram, because elements of the system can be partitioned into separate blocks. This leads to the transfer function or frequency domain model. The procedure for determining the relevant parameters for calculating the required transfer function (TF) of the laser involved record-

Table 1. Hastelloy C powder elemental compositions (wt%) and size

Powder	C	Cr	Si	W	Fe	Co	Ni	Mn	Mo	V	Size (μm)
Hastelloy C	0.03	15.92	0.62	4.48	6.02	0.15	Bal.	0.62	17.1	0.29	45–125

ing the output response of the system driven by a step input based on the parameters given in Table 3.

Fundamental characteristics of the system necessary for its dynamic behavior prediction are the natural frequency ω_n and damping factor ξ. The natural frequency and damping factor were calculated using Eqs. 1 and 2, extracted from [16]:

$$T_p = \frac{\pi}{\omega_n \sqrt{1-\xi^2}} \tag{1}$$

$$M_{P_t} = 1 + e^{-\xi\pi/\sqrt{1-\xi^2}} \tag{2}$$

The peak time T_P and the peak response M_{P_t} in this method of approximation were obtained from the step response of the actual system. The recorded data were used in MATLAB, and the controller transfer function of laser was calculated. With damping factor ξ and natural frequency ω_n known, the given system was approximated using the following second order transfer function:

$$\frac{C(s)}{R(s)} = T(s) = \frac{\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2} \tag{3}$$

A step input of 8.5 V to the laser system (corresponding to slightly more than 2000 W of laser power) leads to a rise in temperature from 800 °C at 14.67 seconds (arbitrary time reflecting the start of the cladding process after the start of the monitoring system) to a peak temperature of 1924.73 °C at 14.71 seconds respectively, along with a settling time of 0.06 seconds. The calculated transfer function in MATLAB was based on an arbitrary steady-state value of 1840 °C and a set-point of 1800 °C. Implemented in a closed-loop system with feedback, the transfer function was used to obtain optimum PID gains, which in turn were applied to optimize the step response output of the controller. Illustrated in Fig. 3 is the closed-loop block diagram utilized in this study, and shown in Fig. 4 is the step response of the laser system along with the tuned closed-loop response of the controller for a calculated natural frequency of $w_n = 12.74$ and a damping factor of $\xi = 0.55$.

It is of interest to mention that despite the fact that each step input voltage from 4 V to 10 V resulted in the calculation of different transfer functions, since there was only a slight change in the tuned PID values, the gains used for the current step input voltage of 8.5 V (2000 W) were applicable to maintain a good control response throughout the whole range of conducted experiments.

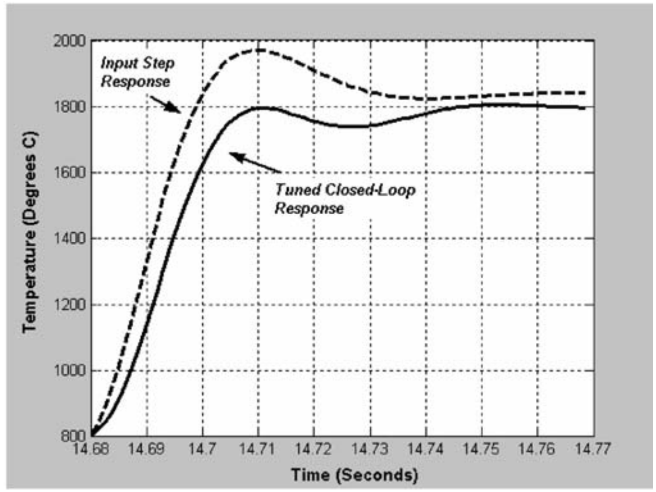

Fig. 4. The step response for $w_n = 12.74$ with $\xi = 0.55$ and the tuned closed-loop response of the controller

4 Results and discussion

4.1 Temperature control in single-track laser cladding process

To examine the practicality of the developed monitoring and control system and applied tuning of the controller parameters, a series of detailed cladding experiments was conducted by depositing both single and multiple tracks. Shown in Table 4 are the selected process parameters and the relevant details of the controller reaction towards changes in three selected temperature set-points – 1400 °C, 1600 °C and 1800 °C.

Figure 5 shows the response of the melt pool temperature at the selected set-points together with the surface profile of the tracks. It can be observed that for the relatively large set-point temperature range, the controller maintained the target set-points with the degree of control decreasing with set-point. The temperature overshoot upon turning on the laser (the powder stream is allowed to stabilize for 15 seconds before turning on the laser) was approximately 125 °C for the 1800 °C set-point, 453 °C for

Table 3. Process parameters involved in system's dynamic behavior identification

Step input (V)	Laser output (W)	Process speed (mm/min)	Powder mass flow rate (g/min)	Recorded temperature (°C)
4 to 10	635 to 2450	600, 1000, 1400	14	1350 to 2150

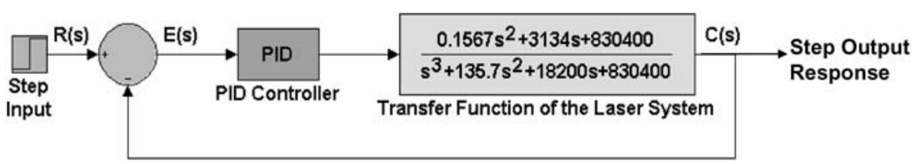

Fig. 3. Block diagram representing the applied closed-loop control system based on the calculated transfer function for an 8.5 V step input voltage

Table 4. Selected process parameters and the relevant details of the controller reaction towards changes in assigned temperature set-points

Track no.	Translation speed (mm/min)	Powder mass flow rate (g/min)	Set-point (°C)	Controller output (V)	Laser power (W)
1	600	14	1800	∼ 7.4– ∼ 8.7	∼ 1780– ∼ 2120
2	"	"	1600	∼ 6.5– ∼ 6.9	∼ 1520– ∼ 1650
3	"	"	1400	∼ 3.1– ∼ 4.3	∼ 250– ∼ 800

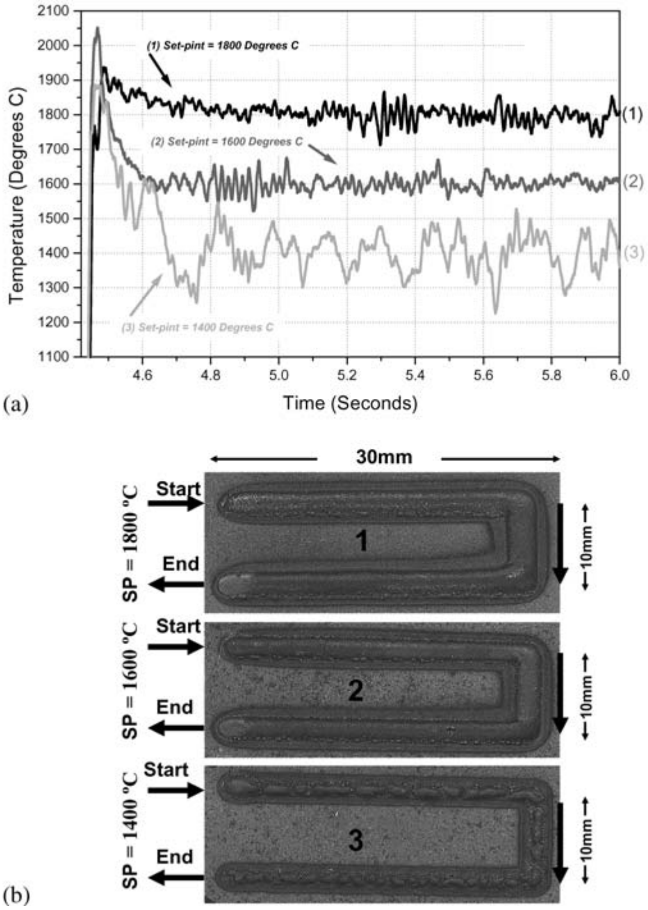

Fig. 5a,b. Temperature control responses **a** for the first 15 mm, and surface profiles **b** of complete single-tracks

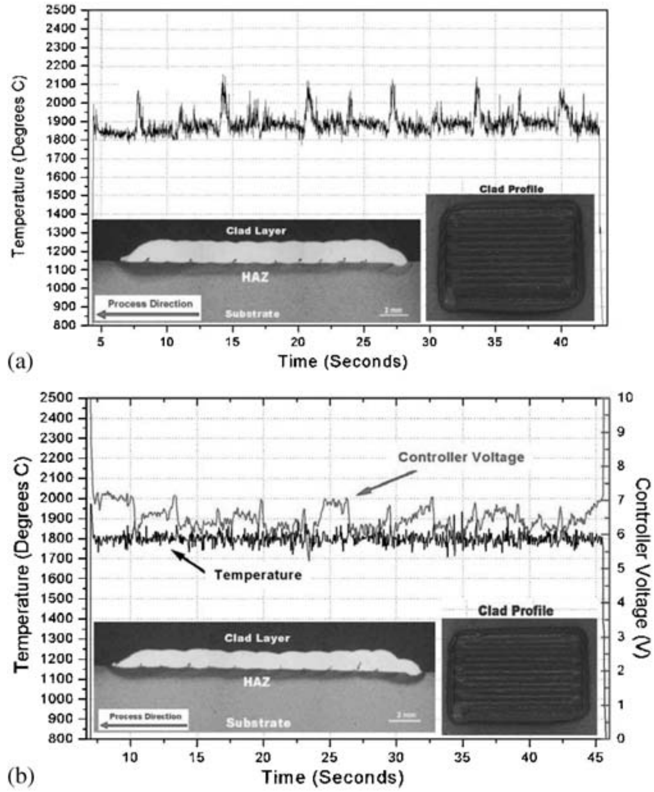

Fig. 6a,b. Uncontrolled **a** and controlled **b** responses at powder mass flow rate of 14 g/min and a translation speed of 600 mm/min together with images of clad layer surface profile and cross-section

the 1600 °C set-point, and 485 °C for the 1400 °C set-point. It is observed that for the 1400 °C set-point, large temperature oscillations occurred about the set temperature. The reasons for the observed results lie in the fact that as the set-point level is reduced, the level of applied laser power is reduced, which results in insufficient power to fully melt the delivered powder and fuse it to the substrate.

The visual inspection of the surface profile of the clad layers shown in Fig. 5b clearly demonstrated the effect of the change in temperature set-points. At the set-point of 1800 °C, which required laser power in the range of 1670–2000 W, a wider clad bead was formed and a good quality clad layer was produced. Also, an acceptable clad quality was produced at the set-point of 1600 °C (with a laser power range of ∼ 1470 to 1650 W). The deficiency caused as a result of lower laser power of 240–650 W at the temperature set-point of 1400 °C, occurred in the form of a very poor quality and incomplete cladding process. The combination of laser power, process speed and powder mass flow rate resulted in the formation of a narrower and more intermittent clad bead.

4.2 Temperature control in multiple-track laser cladding process

Once the controller was operational with single tracks, the experiments with multiple tracks were conducted to demonstrate temperature control in continuous cladding and its effectiveness on clad quality. For the multiple tracks, a raster scan pattern was adopted with each track being 30 mm in length and overlapped by 50%. The constant cladding parameters were a processing speed of 600 mm/min and a powder mass flow rate of 14 g/min. Fig. 6 illustrates the temperature as a function of cladding time with and without temperature control, together with surface profile and cross-section of the clad layer. For temperature measurements without the control (Fig. 6a), the laser power was set at 1900 W (set voltage of 8V), which produced an initial temperature of 1830 °C, which rose to about 1900 °C at the end of the clad. The profile of the clad showed an acceptable surface quality but demonstrated some porosity in the interface between the clad layer and substrate. This so-called "inter-run porosity" [17] is caused by the excess powder delivered into the interaction zone, which forms a single track with a relatively low aspect ratio (width/height). An increase in the HAZ and dilution was also observed as the layer was formed. In addition, the rise in temperature from the start to the end of the clad layer of about 75 °C, represented the heat built-up in the clad layer and substrate. The observed increase in process temperature (∼ 220 °C) at each directional change of the CNC table corresponds to the accumulation of laser beam-induced heat input when the CNC table momentarily stopped. Using the developed PID controller the temperature of the melt pool at the same translation speed and powder mass flow rate is shown in Fig. 6b. The controller reacted properly, maintaining the assigned set-point temperature of 1800 °C, with a tolerance of ±50 °C. The controller not only eliminated the above increase in average temperature, but also facilitated a reduction in the amount of the "inter-run" porosity due to the reduction and control of the laser power. More uniform and lower HAZ, as well as lower dilution, was obtained compared to the above un-controlled clad layer (Table 5).

Repeating the above un-controlled multiple tracks at an increased translation speed of 1000 mm/min resulted in a temperature of 1800 °C, which was more uniform and showed minor oscillations when the scanning direction changed (Fig. 7).

The produced clad layer was thinner and pore-free, but had a higher dilution (Fig. 7a). The HAZ was similar to that at lower speed. The increase in dilution simply reflects the decrease in clad layer thickness (penetration into the substrate is similar) due to lower powder mass flow rate delivered per millimeter of track. The use of the controller again resulted in the formation of more uniform and narrower HAZ, and improved the quality of the produced clad layer (Fig. 7b). The extent of penetration into the substrate was also improved with a reduction in the dilution level compared to the previously produced un-controlled clad layer (Table 6). It is noted that, compared to the controlled cladding of 600 mm/min, the controller output voltage in the case of 1000 mm/min showed an increase from 5.5–7 V to 7–8.5 V in maintaining the selected set-point of 1800 °C.

Experiments were performed to test the controller under more extreme conditions of powder mass flow rate. It was observed that an increase in the powder mass flow rate had a significant effect on the achieved quality of the produced clad layer, in spite of the controller maintaining the assigned set-point temperature. Illustrated in Fig. 8 is the temperature as a function of cladding time for a mass flow rate of 28 g/min and translation speed of 1400 mm/min under controlled response of the system. It can be observed that although the set temperature of 1800 °C is maintained, as the clad layer progresses there is a gradual increase in the clad layer thickness. It can also be observed that this increase corresponds to an increase in the control voltage, and hence the delivered laser power from about 7.5 V at the start of the clad layer to 9 V at the end. The reason for this is believed to be due to the interaction of the molten pool and the powder stream. It is known from experiments that the diameter of powder stream at the interaction point is larger than that of the melt pool. It appears therefore that at the operating conditions used, the melt pool increases in size as the clad layer is formed. This increase in size allows it to capture more powder, which lowers the melt pool temperature. However, as the controller is required to keep this temperature at 1800 °C, it requests more power (higher control voltage) from the laser. Therefore, this be-

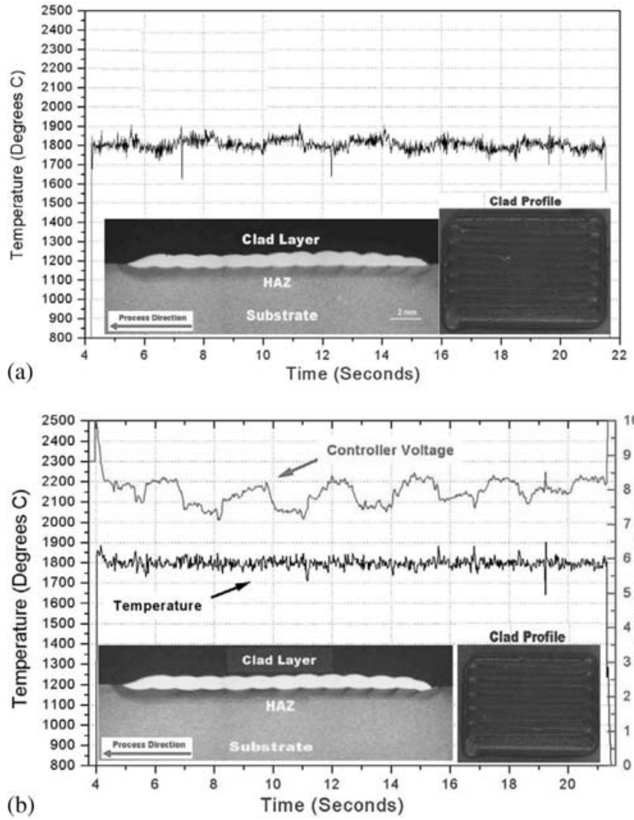

Fig. 7a,b. Uncontrolled **a** and controlled **b** responses at powder mass flow rate of 14 g/min and a translation speed of 1000 mm/min together with images of clad layer surface profile and cross-section

Table 5. Process parameters involved in controlled and uncontrolled cladding process at powder mass flow rate of 14 g/min and a translation speed of 600 mm/min

Clad	Control	Control voltage (V)	Laser power (W)	Clad thickness (mm)	Penetration (mm)	HAZ (mm)	Dilution (%)
a)	No	8	1905	1.46	0.14	0.61–0.81	9
b)	Yes	5.5–7	1187–1670	1.21	0.08	0.71–0.57	6

Table 6. Parameters involved in controlled and uncontrolled cladding process at powder mass flow rate of 14 g/min and a translation speed of 1000 mm/min

Clad	Control	Control voltage (V)	Laser power (W)	Clad thickness (mm)	Penetration (%)	HAZ (%)	Dilution (%)
a)	No	8	1905	0.67	0.13	0.68–0.80	16
b)	Yes	7–8.5	1670–2 045	0.70	0.11	0.57–0.84	13

Table 7. Parameters involved in controlled and uncontrolled cladding process at powder mass flow rate of 14 g/min and a translation speed of 1400 mm/min

Control voltage (V)	Laser power (W)	Clad thickness (mm)	Penetration (mm)	HAZ (mm)	Dilution (%)
7.5–8.7	1788–2 185	1.15–2	0.03–0.02	0.46–0.44	2–1

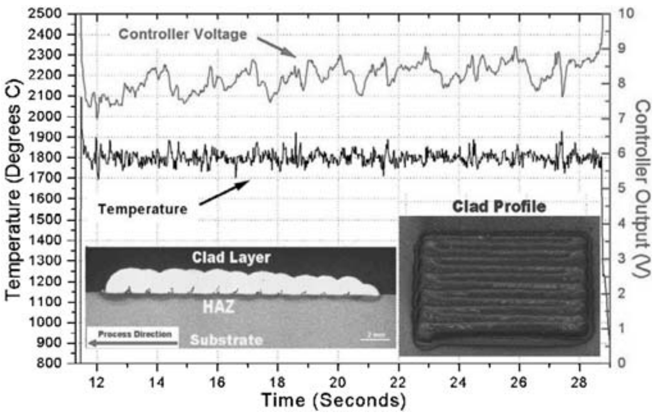

Fig. 8. Controlled response of the system at 1400 mm/min and 28 g/min together with images of clad layer surface profile and cross-section

comes a positive feedback loop leading to the observed results given in Table 7.

5 Conclusion

A LabVIEW-based PID controller has been developed and used to monitor and control melt pool temperature during laser cladding. It was observed that the use of a controller can produce better quality clad layers compared to un-controlled cladding. In a series of experiments to investigate the effect of temperature control in enhancing the quality of clad layer in terms of its dilution and the extent of HAZ, it is shown that control of temperature alone will not produce desired cladding results. It is believed that controlling the melt pool size with another operating parameter – such as translation speed – is also required to effectively control the process and quality of clad layer under a wide range of operating conditions. The control of powder mass flow rate is unlikely to produce the desired results because of the slow response of powder delivery systems in general.

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