CLOSED LOOP CONTROL OF 3D LASER CLADDING BASED ON INFRARED SENSING

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Abstract

In this paper, a heat input closed-loop control system based on infrared image sensing for 3D laser cladding is introduced. A high frame-rate (up to 800 frames/s) camera is installed coaxially on the top of the laser-nozzle setup. Complete of the infrared images of the molten pool can be acquired with a short nozzle-substrate distance in different scanning directions, eliminating the noise from the metal powder. The characteristics of the images show a clear relationship with the parameter variations of the cladding process. A closed-loop control system is built based on the feedback of the infrared image sensing. The control results show a great improvement in the geometrical accuracy of the part being built.

Keywords: SFF, Laser Cladding, Infrared Image Sensing, Control.

1. Introduction

Solid Freeform Fabrication (SFF) is a novel manufacturing technology that could be used for the rapid creation of models, prototypes and patterns and for limited-run production. Nowadays, several SFF methods have been developed, such as 3D welding [1,2], micro-casting [3], selected laser sintering [4], Laser Engineered Net Shaping (LENS) [5], Shape Deposit Manufacturing (SDM) [6], Directed Light Fabrication (DLF) [7], 3D laser cladding [8] and some hybrid methods [9-11]. Among these SFF methods, 3D laser cladding has been considered to be very suitable for building metallic parts. A laser beam could be easily delivered and controlled and could be focused on a very small area, so that the interaction zone of a laser process can be accurately positioned and the bead track could have a small width (< 1 mm). This means that higher geometrical accuracy and surface quality of the final part can be achieved. Moreover, because of the powder delivery feature in 3D laser cladding, no inert-gas protection chamber is required. So, a larger part can be produced, and a more complicated cladding path can be traced, including four-dimensional and five-dimensional paths. By controlling the mass flow rate of the metal powders from different powder feeders, a composite material or alloy with a functionally gradient distribution can also be produced.

When laser cladding is used for SFF, it builds parts by adding powder material (e.g. layer by layer) and in a way that it resolves a complicated manufacturing process into a series of simple and repetitive layer procedures. A stable and repeatable layer procedure is therefore crucial for the quality of the part produced. However, the laser cladding process is governed by a large number of parameters [11]. Some of the parameters are sensitive to the environment variations and some of them affect the other laser cladding parameters. In order to perform successful 3D laser cladding operations, an on-line closed-loop control of the process is necessary.

Several previous research works [12-18] have been done to control the laser cladding process. Some of them are focused on controlling the powder delivery in order to achieve more stable powder delivery [12,13], or study the powder stream distribution and laser-powder interaction [14,15]. Others deal with the optimization of the laser cladding process by a closed-loop control, using a CCD camera [16-18] or a phototransistor [19] as the sensing device. However, the CCD camera or the phototransistor is installed usually from one side of the nozzle. This installation is not practical for SFF 3D cladding. The distance between the nozzle and the substrate is very small (~5mm), so the viewing area of the cladding is limited. The images are deformed due to the angle between the optical central line of the camera and the laser-nozzle setup. Also, the images acquired from an asymmetrically installed camera will vary according to the scanning direction, which is always changing in SFF processes.

This paper discusses the control of the heat input in 3D laser cladding for SFF. A closed-loop control system based on infrared image sensing is developed. A high frame-rate (up to 800 frame/s) camera is installed coaxially on the top of the laser-nozzle setup. Complete infrared image of the molten pool and surrounding area can be easily acquired with a short nozzle-substrate distance and different scanning directions, eliminating the noise from the metal powder. The characteristics of the images vary with the cladding process parameters and have a clear relationship with variations of those parameters. A series of laser cladding experiments were conducted with and without the closed-loop control. The experimental results show a great improvement in the geometrical accuracy of the part being built.

2. Development of closed-loop control system

The 3D laser cladding system is comprised of four subsystems: a 1 kW Nd:YAG laser source, a powder delivery system, a 3-axis positioning system and an infrared image acquisition system. The complete system is shown in Figure 1. The 3D metal part is produced layer by layer by synchronizing the X-Y motion, the Nd:YAG laser and the injection of metal powder. The infrared image acquisition system takes the images of the molten pool in real time and calculates the dimensions of the molten pool. It compares the recorded information to the preset value and creates a feedback control value to modify the output of the laser source. In this way, a stable molten pool with desired dimensions is obtained, and thus it will be possible to produce stable and repetitive layers if stable powder delivery is ensured.

The difficulties of image sensing in 3D laser cladding arise from several problems. The distance between the cladding nozzle and the substrate is short (~5 mm). This distance blocks the sight if the observation is from the sides of the nozzle. In order to observe the molten pool of cladding from one side, the camera is usually installed at a large angle with respect to the central line of the nozzle setup. The image acquired will be distorted due to that angle as well as to the direction of the motion. This problem will be exaggerated when the scanning path is multi-dimensional where the part could come in collision with the camera or could obstruct the direction of observation. Other problems of image sensing come from the intense light produced by laser cladding. The metal powder adds to the difficulty of image processing as well.

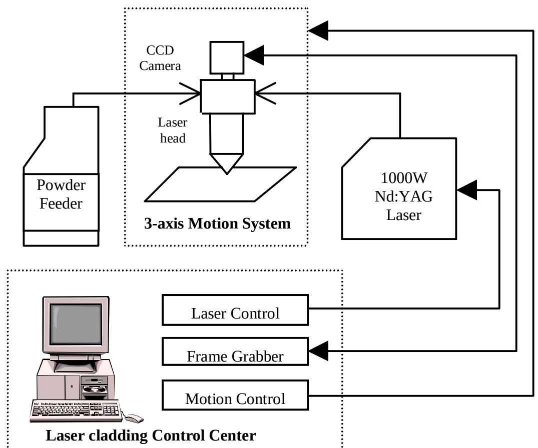
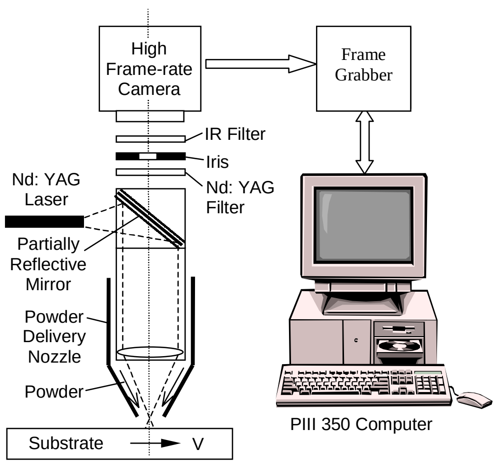


Figure 1 System Integration of 3D laser cladding.

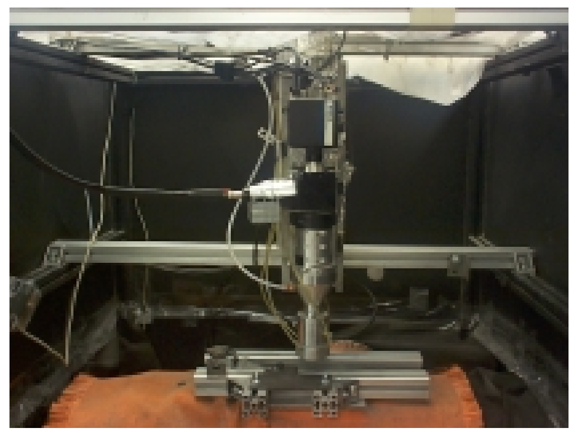
A coaxially installed image sensing setup with respect to the laser beam is developed to solve the problems mentioned above. The optical part of the laser head (Figure 2(a)) provides another optical path for the observation of the laser processing. A high frame-rate (up to 800 frames/s) camera is installed on top of the laser head, taking gray-scale images with a size of 128×128 pixels. The radiation from the molten pool produced by the laser cladding passes through the partially reflective mirror and an infrared filter, forming an image on the CCD chip of the camera. A Nd: YAG laser blocking filter (~1.06 μm) is utilized to protect the camera from laser damage. An iris is used to adjust the intensity of the radiation received by the camera to prevent over-exposure. In order to get the infrared image of the molten pool, which reduces the high intensity light from the molten pool and eliminates the image noise from the metal powder, an infrared filter is selected (>700 nm) and installed between the iris and camera. During the laser cladding process, the camera acquires images of the cladding process in a frame rate of 200 frames/s. Images are transferred to the frame grabber installed on a PC computer that carries out the sensing and control process. The real system setup is shown in Figure 2(b).

Figure 3 provides an infrared image acquired by the coaxially-installed camera under practical laser cladding condition. Because the observation is directly from the top of the molten pool, a full view image of cladding can be acquired without any blocking. With the correct combination of the Nd: YAG filter and the IR filter as well as the right iris aperture, a clear image of the molten pool can be obtained without the noise from the metal powder. The radiation wavelength received by the camera is between 0.7 and 1.06 μm.

Meriaudeau and Truchetet [16] calibrated the CCD camera with an IR filter, and concluded that the gray level of the pixels has a linear relationship with the temperature. So, the infrared images acquired reflected the temperature distribution around the molten pool. Due to the temperature range in laser cladding, the wavelength region of 0.7-1.06 μm occupies the part of the electromagnetic spectrum in which most radiometric surface temperature measurements are made. Figure 3(b) shows the gray level isotherms of the unprocessed infrared image shown in Figure 3(a). In a closed loop control of 3D laser cladding process, an absolute temperature measurement is not necessary, as only the relative difference is necessary for generating the feedback.



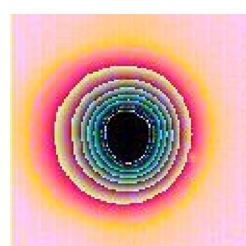
(a) Schematic presentation



(b) Close-up

Figure 2 Infrared image acquisition system

(a) unprocessed



(b) processed

Figure 3 Acquired infrared image

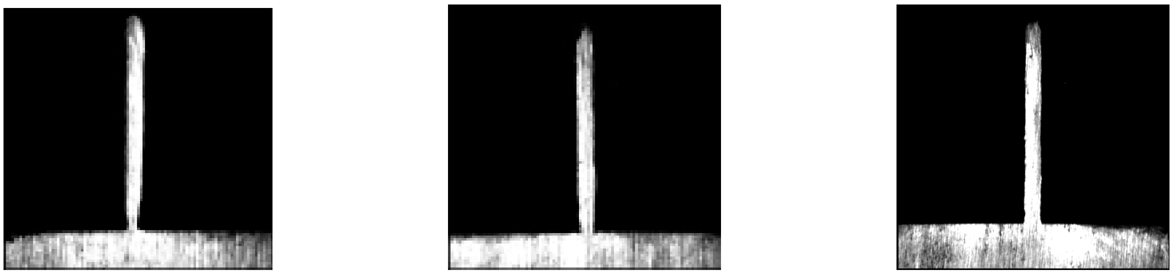
3. Laser cladding experiments

A set of laser cladding experiments have been performed to test the control effect of the developed closed-loop control system based on infrared image sensing. The substrate material utilized in the experiments is mild steel, and the metal powder is an H13 tool steel powder with a -100/+325 mesh size. The powder delivery rate is kept constant at 5.2 g/min. The experiments are carried out at a constant scanning speed of 8 mm/s, but at different laser powers.

To compare the processing results, single-bead walls are built under the following three varied processing conditions. The first type of samples are built with no pre-heating of the substrate and no closed-loop control for the heat input. The second type of samples are built with pre-heating but no control, and the third type of walls are built utilizing the closed-loop control function. The walls are produced in a repetitive manner. The nozzle moves along the positive direction of the X axis first to build one layer, moves up a small increment along the Z axis after the layer is built up, and then moves back along the negative X direction for the next layer's deposition. During the wall building process, the area of the thermal field with a threshold of 50 is recorded continuously with an image-processing rate of 10 frames/second.

A typical group of single-bead-wall samples built by laser cladding at the same laser power (290 W) is shown in Figure 4. It can be observed that, when no heat input control is utilized, the root of the wall is obviously narrower than the upper part of the wall, as shown in Figure 4(a) or (b). Moreover, this trend is even more pronounced within the wall built without preheating (Figure 4(a)). The geometrical change of the uncontrolled 3D laser cladding process results from the variation in heat loss. At the beginning of the wall building, due to the large heat conduction of the substrate, the created beads are narrower. As the wall grows up, there is less heat conduction along the built wall, and the bead becomes wider until it reaches a new equilibrium value. For the wall with preheating, the initial heat loss conducted into the substrate is reduced because of the high temperature of the substrate, and thus more energy is used to create the molten pool, which results in a wider wall than that without preheating. The role of the closed-loop control system in laser cladding is just to overcome the effect of heat variation. At the initial stage of wall building, because a lot of heat is conducted into the substrate, a small molten pool is created. The control system reacts by increasing the laser power in order to produce a molten pool with the preset dimensions. As the wall grows, heat conduction loss is reduced and the laser power output returns to a normal level. With this feedback control function, the size of the molten pool could be kept nearly constant, resulting in the constant wall width along the entire height of the wall.

This process can be more clearly explained with the use of the recorded infrared images recorded during laser cladding. As was mentioned before, the pixel number of the infrared image reflects the temperature distribution of the laser cladding as well as the size of molten pool. It can be observed from Figure 5(a) that, when neither preheating or heat input control is applied, the pixel number of the thermal field area starts with about 1,000 for the first layer, and it gradually increases up to 5,000 and stays there for the rest of the buildups. However, when a preheating procedure is applied, the pixel number of the infrared images at the beginning is relatively high compared to the case without preheating, as shown in Figure 5(b). This fact corresponds to the geometrical comparison of the walls built under these two conditions. Figure 5(c) shows the pixel numbers of the images acquired from the laser cladding of a single-bead wall with heat input control. Apparently, a very stable pixel number is obtained which corresponds to a uniform width of the wall. Contrary to the stability of the pixel number, the laser power fluctuates greatly (Figure 5(d)), showing the obvious control function of the closed loop control system.

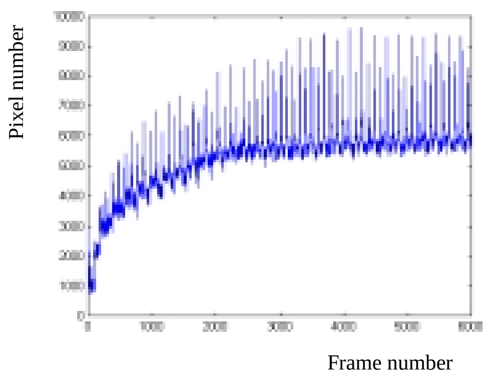


(a) Without preheating and without heat input control

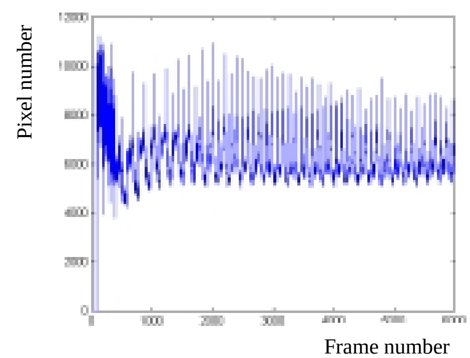
(b) With preheating and without heat input control

(c) With heat input control

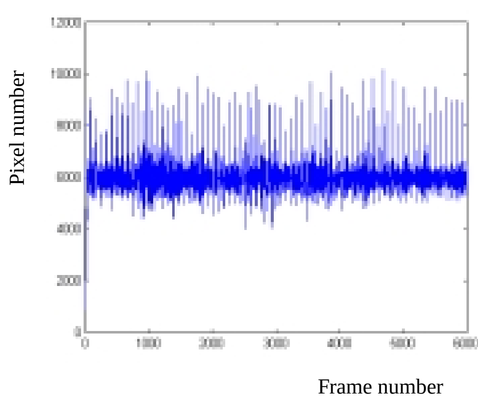
Figure 4 Single-bead walls built by 3D laser cladding process.



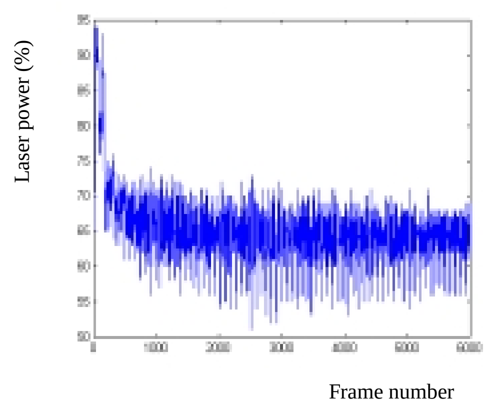
(a) Without preheating and heat input control



(b) With preheating and without heat input control



(c) With heat input control



(d) Power level corresponding to (c)

Figure 5 The area of thermal field in 3D laser cladding.

The geometrical parameters of cross-sections of the walls built under different processing conditions are given in Table 1. The average width of the wall w_a is calculated by averaging 10 width measurements taken at 10 evenly spaced heights from the substrate surface. w_{min} means the minimum width of the wall, which normally corresponds to the root of the wall. A geometrical accuracy η is introduced to express the width variation of each wall sample, which is calculated by the following formula:

$$\eta = \left| \frac{w_a - w_{\min}}{w_a} \right| \times 100\%$$

Table 1: Geometry of the walls built under different conditions

Power Level (W)	Without preheating and without control			With preheating and without control			With control **		
	Average width w_a (mm)	Minimum width w_{min} (mm)	Geometrical accuracy η (%)	Average width w_a (mm)	Minimum width w_{min} (mm)	Geometrical accuracy η (%)	Average width w_a (mm)	Minimum width w_{min} (mm)	Geometrical accuracy η (%)
290	0.95	0.45*	53%	0.95	0.62	35%	0.91	0.90	1%
370	1.33	0.58	56%	1.26	0.9	29%	1.02	1.01	1%
450	1.48	0.79	47%	1.5	0.94	37%	1.35	1.15	15%
540	1.61	0.945	41%	1.60	1.0	38%	1.58	1.29	19%
620	1.7	0.99	42%	1.75	1	43%	1.67	1.31	22%

*: The bonding of the wall with the substrate surface is not continuous.
**: The laser powers listed are transformed from the calibrated pixel numbers

The geometrical change of the walls with laser power is shown in Figure 6. When no heat input control is applied, a preheating procedure contributes to improve the geometrical accuracy of the wall, especially when the laser power is less than 500W. With the increase of laser power, the influence of preheating becomes of less importance. This is because a higher laser power could compensate for the difference in heat loss due to the different thermal conditions

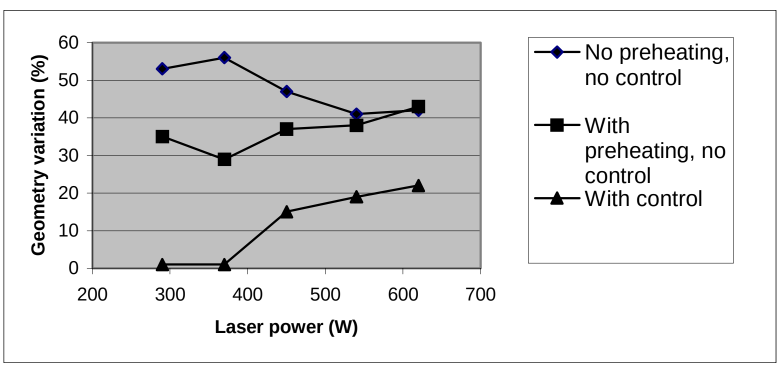


Figure 6 Geometrical accuracy Vs laser power

It can also be observed that, under all laser power levels, the geometrical variation of the cross sections of the walls built with heat input control is much lower than those without control. When the laser power is below 400W, there is almost no width variation along the wall height if a control function is applied. Even at higher laser power levels, the geometrical accuracy gradually goes down, but it is still far superior to that without any control function.

4. Conclusions

Infrared image sensing is an efficient sensing method for 3D laser cladding for SFF. Clear infrared images of the molten pool generated by the laser beam can be acquired easily by a coaxial camera even in the case of a short nozzle-substrate distance and in different scanning directions. The infrared image reflects the temperature information that is a significant parameter affecting the cladding result. The closed-loop-controlled 3D laser cladding based on the infrared image sensing can overcome the effects of thermal variation and thus achieve a consistent processing quality of 3D laser cladding.

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6. References

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