EMPIRICAL MODELING AND VISION BASED CONTROL FOR LASER AIDED METAL DEPOSITION PROCESS

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Abstract

This paper gives a brief description of the laser aided manufacturing process. Empirical models describing the process dynamics of the laser aided metal deposition process is developed based on some of the models found in the literature. These models provide the basis for process planning and real time control. An embedded vision system, a two color temperature sensor, and a laser displacement sensor are incorporated for real time monitoring and control of the deposition process. The temperature profile of the surface and geometric characteristics of the melt pool are studied to ensure consistent operation of the process.

Introduction

Lasers have a tremendous impact in manufacturing industries. With laser innovations, the world in now experiencing the use of optical energy in a wide range of applications, from materials processing to Rapid Prototyping (RP). The use of lasers, in conjunction with metal powder, is one of the latest extensions to rapid prototyping, which had earlier involved plastic parts exclusively. Rapid prototyping using lasers has enabled the fabrication of complex, near–net shape functional metal parts directly from a CAD model at a low cost and offers faster turn around. Currently this technology is implemented under a variety of names such as Direct Light Fabrication (DLF), Laser Metal Forming (LMF), Laser Engineered Net Shaping (LENS), Direct Metal Deposition (DMD), Selective Laser Cladding (SLC), etc. Though the system description and specifications of each of these vary, they all rely on the same principle of part fabrication, i.e. layer by layer deposition. A general description of the method of fabricating a part involves utilizing a laser to melt metal powder injected by a nozzle and laying down clad tracks via a positioning system having a controlled motion. In some cases the lasers may be directed along a defined path and tracks are laid down on a stationary table. To control the deposition process it is necessary to understand the process system mechanics for which relations among various parameters need to be studied. The optimization of the process requires the measurements and control of parameters such as the powder feed rate, process speed, melt pool temperature and melt pool quality. During the last few years many sensors have been tried; the high cost of such equipment, the lack of real time or on-line control have led developers to seek other solutions. The use of laser displacement sensor, temperature sensor and CCD matrix camera with embedded image processing tools are sufficient to monitor all relevant process parameters. These sensors with a standard data acquisition card and personal computer enable the operators to interact with the process and processing parameters.

Empirical Modeling of Laser Aided Metal Deposition Processes (LAMD)

The process mechanics describing processes such as Laser Cladding, Laser Forming, Laser Ablation, Laser Welding, Laser Surface Treatment, Laser Metal Deposition etc., are the same, except for certain variations in the control parameters describing these processes. Some of these may include powder deposition, with or without material removal, or the enhancement of metal properties by heat treatment. These processes require certain factors such as dilution, heat-affected zone, porosity, clad dimensions, powder catchment efficiency, etc. to be monitored. Identifying the control parameters and establishing relations to describe these factors forms the basis for empirical modeling. The first step involved is identification of parameters and categorizing them into dependent and independent variables based on certain assumptions. The need for these assumptions arises from the system's flexibility to control certain parameters. Studies have to be conducted by varying these parameters and determining their effect on the part quality and system performance. Figure 1 shows the classification and interaction of different system parameters (dependent and independent) describing the metal deposition process

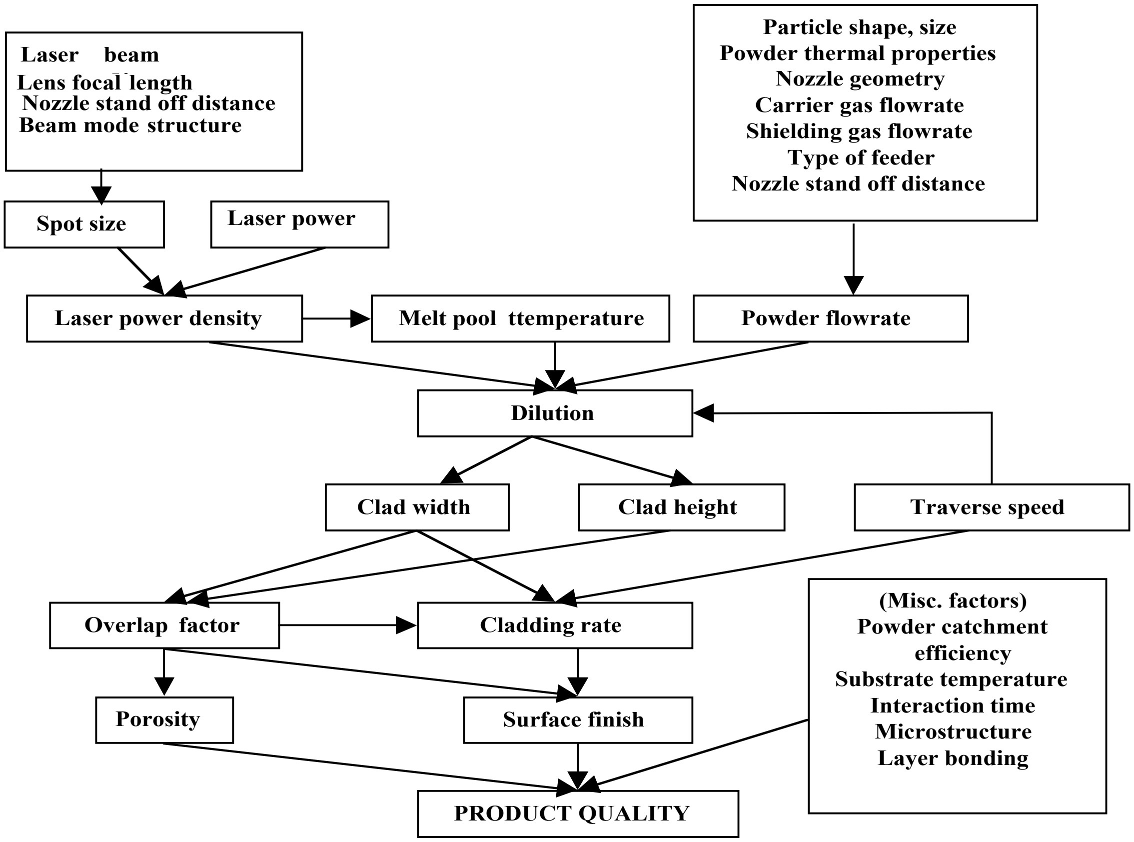

Figure 1. General description of interacting parameters and their effect on quality of part

The second step involves developing analytical/empirical relations of the parameters describing the process. The final step involves fitting these relationships into models, performing specific experiments to evaluate the model constants, and specifying the conditions for which these relations hold.

A. Process Parameters

Powder Feeder: Screw fed powder–feeding systems with a carrier gas is the general powder feeding system used in many deposition processes. The powder fills the screw either by weight or by the pressure of a carrier gas in the hopper. The amount of powder (in weight) being driven by a twin–fluted screw per revolution can be expressed as

$$m = 2\rho A_d r \tag{1}$$

where m is the powder mass per revolution (gm/rev), r is the feed screw helix lead (mm), ρ is the powder density (gm/mm^3), and A_d is the cross sectional area (mm^2) of one flute measured at a right angle to the screw axis. In practice, density depends on the hopper elevation, acceleration (if it is a mobile one), void factor (ratio of the space of air to that of solid), particle size, powder viscosity, and powder level in the hopper. If V_m is the motor speed (rev/sec) then the powder mass flow rate M (gm/sec) can be expressed as (Li *et al*., 1993)

$$M = mV_m \tag{2}$$

By controlling the amount of powder flowing into the melt pool, the energy input to the substrate can be controlled, thereby governing the amount of dilution that will occur (Blake *et al*., 1985).

Energy Delivery System: The amount of heat input to a process depends on the system parameters. The heat delivered should be sufficient enough to melt the layers for proper bonding. Overheating results in more dilution and the part may melt back. The laser beam diameter at the laser material interaction is defined as spot size (D) and can be obtained from the relation

$$D = D_b Z / F \tag{3}$$

where D is the laser spot size (mm), D_b is the laser beam diameter (mm), Z is the laser nozzle stand off (mm), and F is the focal length of the focusing lens (mm). Specific energy is defined as

$$E = P / Dv \tag{4}$$

where E is the specific energy (J/mm^2), v is the traverse speed or feed rate (mm/sec), and P is the laser power (W).

Powder Utilization Efficiency (η_p): The powder utilization efficiency is expressed as the ratio of the powder delivered, to the powder deposited on the substrate within the duration of the laser irradiation on the substrate. Powder utilization efficiency also depends on material characteristics such as type, particle size, and shape of powder particles. It can be expressed mathematically as (Hu *et al.,* 1998)

$$\eta_p = W_c / W \tag{5}$$

where η_p is the powder utilization efficiency, W_c is the net clad weight (gm), and W is the total weight of the powder delivered (gm). The total weight of the powder delivered is given by

$$W = \int_0^t M(t)dt \tag{6}$$

where t is the time (sec).

Lin *et al.* (2000) performed experiments to determine the attenuation of optical energy through a focused powder stream and through a columnar powder stream for different nozzle stand off distances. This helps in determining powder utilization efficiency since this depends on the amount of energy being delivered to the substrate.

Dilution: Dilution can be defined mathematically as the ratio of the clad depth in the substrate to the sum of clad height (above the substrate surface) and clad depth. It determines the amount of the liquid layer that needs to be formed on the substrate to ensure proper layer bonding. There are several parameters that determine the amount of dilution. These parameters include the powder flow rate, laser power delivered to the substrate, and table traverse speed. However the dilution mainly depends on specific energy. If specific energy is below a certain value (K_{min}), bonding between the layers does not occur, i.e.

$$E < K_{\min} \quad or \quad P/Dv < K_{\min} \tag{7}$$

Also, if specific energy is more than a certain value (K_{max}), the previous tracks may melt back, i.e.

$$E > K_{\max} \quad or \quad P/Dv > K_{\max} \tag{8}$$

These values of specific energy can be used as indices in determining the range over which other parameters can be varied.

Heat Affected Zone (HAZ): The heat–affected zone is the region beneath the bead which has a different microstructure as compared to the unaffected zone. This may result in cracking and surface distortions due to the hardening mechanism, particularly in steel. The width and depth of the HAZ can also be used as indices in determining the range of variation of other parameters. Specific energy determines the depth of the heat–affected zone. For a given powder feedrate, a higher specific energy indicates more energy will be transferred to the substrate and the depth of the heat–affected zone will increase. Hu *et al.* (1998) performed experiments to show that penetration depth increases almost linearly with increase in the specific energy.

Porosity: Porosity occurs due to cavities between tracks that form from overlapped tracks or due to the evolution of entrapped gases in the clad tracks. Porosity can be avoided if the aspect ratio (ratio of the clad width to clad height) is more than five and the percentage overlap is less than 70% (Steen *et al.,* 1986).

B. Process Model

The quality and surface of finish of the part fabricated by the laser metal deposition process is determined by the clad geometry and its dimensional accuracy. Bead geometry can be defined by clad width and clad height, which depend on a number of other parameters. Empirical relations have to be developed to determine the effect of these parameters on clad geometry. Specific energy can be used to regulate the clad dimensions. For a given powder flow rate, the clad width can be regulated by varying the specific energy delivered to the substrate. Also, the specific energy depends on the laser spot size and traverse speed, which is evident from equation (4).

Williams and Deckard (1998) showed that the average part density at a particular specific energy is greater for a larger laser spot size. The range for which the traverse speed and laser spot size cause a variation in bead width needs to be determined experimentally. Also, the range of traverse speed and spot size is limited by the amount of dilution as seen in equations (7) and (8). Thus, the relationship between bead width and, traverse speed and laser spot size is (Steen *et al.*, 1986).

$$W = D(1 - av) \tag{9}$$

where W is the bead width (mm) and a is an empirical constant. Hu *et al.* (1998) showed that an increase in powder flow rate results in wider cladding tracks provided the other variables are kept constant and there is sufficient energy available to form a clad. The net clad weight can be determined from the relation

$$W_c = \int_0^t \eta_p(t) M(t) dt \tag{10}$$

where W_c is the net clad weight (gm). Assuming the cross section of the clad to be a parabolic arch, clad height can be theoretically defined as

$$H_t = 3A/2W \tag{11}$$

where H_t is the theoretical clad height (mm) and A is cross section area of the clad (mm^2). Hu *et al.* (1998) performed experiments to show that the clad height increases with increased powder flow rate or specific energy, or with a decrease in traverse speed. An empirical relation can be developed to determine height, taking these factors in consideration.

$$H_e = bM/v \tag{12}$$

where H_e is the experimental value of clad height (mm) and b is an empirical constant. The experimental values of clad height can be compared with the theoretical values of clad height using equations (12) and (13).

Aspect Ratio: Aspect ratio is defined as the ratio of clad width to clad height and is expressed as

$$A_r = W/H_e \tag{13}$$

From equations (10) and (13), the aspect ratio can be expressed as

$$A_r = D(1 - av)/(bM / v) \tag{14}$$

Cladding Rate: The cladding rate be expressed in terms of overlap factor (i), clad width (W), and traverse speed (v) as (Manjuluri, 2001)

$$C = (1 - i)Wv = (1 - i)(1 - av)Dv \tag{15}$$

where C is the cladding rate (mm^2/sec) and i is the overlap factor, which is defined as the ratio of the part of the bead overlapped to the overall bead width.

Sensors for LAMD Process

The quality of deposition process using laser aided metal deposition process is controlled by a large number of interrelated parameters. It is important to monitor and control these parameters to ensure consistent and efficient operation of the process. We show in this article, that the use of a two-color temperature sensor, displacement sensor and a standard CCD camera enables us to control and optimize the laser cladding process.

The CCD camera is used to find the geometrical parameters such as the height and width of the track in real time. The camera also provides the temperature profile of the melt pool. This provides the operator with information related to process parameters like dilution factor and melt pool quality. Dual color infrared temperature sensors measure the surface temperature of objects without contact. The sensors work is based on the principle that infrared energy emitted by an object is proportional to its temperature. The temperature output signals can be input into a computer, for process monitoring and control. Displacement sensor uses high precision laser to detect small vertical displacement with 30μm resolution. The advantage with this displacement sensor is that, it has a reasonable stand off distance (80mm) and works efficiently in high temperature environment. Table 1 shows important parameters provided by in-process sensors.

Table 1. Summary of process parameters measured by sensors

Sensors	Dilution	Quality	Geometry	Efficiency
IR Temperature	Absolute temperature	Dilution	-----	Melt pool temperature
Imaging	Thermal profile	Cold spots, thermal contour, melt pool profile, and porosity	Bead width	Melt pool quality
Displacement	-----	Surface finish	Clad height	Track dimensions

A. Shape Measurements

Preliminary experiments were conducted using CCD camera and imaging techniques to extract dimensions, thermal profile and quality of the molten pool in mild steel sample fabricated using the LAMD process. A total of 300 frames/run were recorded at a rate of 30 frames/sec with a CCD camera. The results shown are for mild steel material**,** at a laser power of 1500W and traverse speed of 10 mm s^{-1}**.** In order to monitor the bead geometry during the process, the CCD camera is installed right on top of the nozzle head. The image captured in this angle enables us to compute the temperature variation in the melt pool. The images are captured during the off time of the pulsed mode operated laser. Simple algorithm is used to calculate the bead length and width in real-time. The bead height is obtained from the laser displacement sensor. This enables us to check the track dimensions being deposited online. The system is able to detect fluctuations in the mass feed rate. As the mass feed rate increases, the height of the tracks also increases, up to a threshold, after which lack of power prevents the powder to correctly bond to the substrate. This threshold is a function of the laser power and the beam diameter. (Griffith *et al.,* 1998) Figure 2 shows the digital image of the molten pool and the adjacent material created during the processing. The field of view encompasses approximately 4 mm.

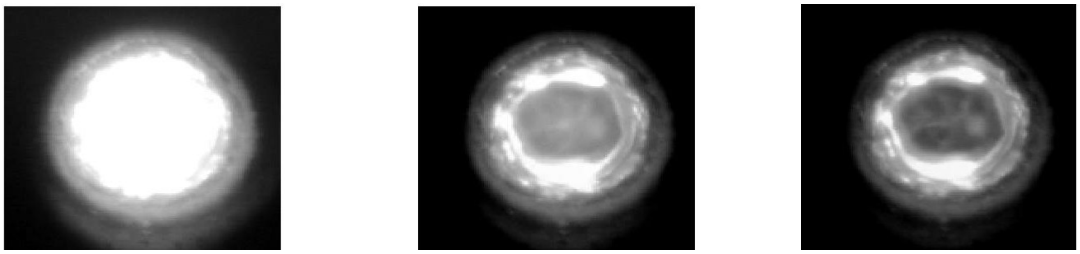

Figure 2. Sequence of images taken at a time interval of 1/60th of a second during laser off time

B. Temperature Measurements

The knowledge of the thermal behavior is critical to reliable and repeatable fabrication during LAMD processing. Our initial experiments show promise in both monitoring as well as understanding the thermal behavior. During the cladding process the camera scans the melt pool and provides information of the temperature distribution within the melt pool. Of the images acquired, we take an average in order to remove unrepresentative features of the distribution like the movements within melt pool and presence of bursting bubbles during the process, which lead to large fluctuations in temperature. (Meriaudeau *et al.,* 1997). By processing the images we obtain two gaussian distributions, the first one (low gray level) is related to the cold areas, the other gaussian centered on the average temperature contains information about temperature distribution within the melt pool. (Truchetet *et al.,* 1996) The study of temperature profile of the melt pool provides us important parameters like dilution and melt pool quality.

Dilution: The powder flow rate and laser power govern the dilution of the melt pool. An uneven distribution of the temperature is the result of unmelted powder particles in the melt pool, due to lower laser power. This introduces porosity and poor mechanical properties. As the laser power increases, the surface temperature increases resulting in higher dilution. This causes the melting of previous tracks and residual stresses may be induced upon solidification (Steen *et al*., 1986).

Melt pool quality: Thresholding is performed on the averaged image of the melt pool cross section to obtain the geometric characteristics and subsequently the melt pool quality. A well-formed melt pool has a definite boundary with finely distributed powder. An uneven or jagged boundary is a result of uneven distribution of the powder or high laser power. This is one of the important aspects of quality control.

Control Architecture for LAMD Process

A closed loop control system is designed to monitor the bead width, bead height and melt pool temperature during the ongoing process and correspondingly the process parameters are adjusted in order to achieve desired performance. The control architecture to optimize the laser deposition process is shown in Figure 3. Adaptive optimal controller based on empirical process model is used to regulate laser power, feed rate, and powder flowrate to obtain an efficient cladding.

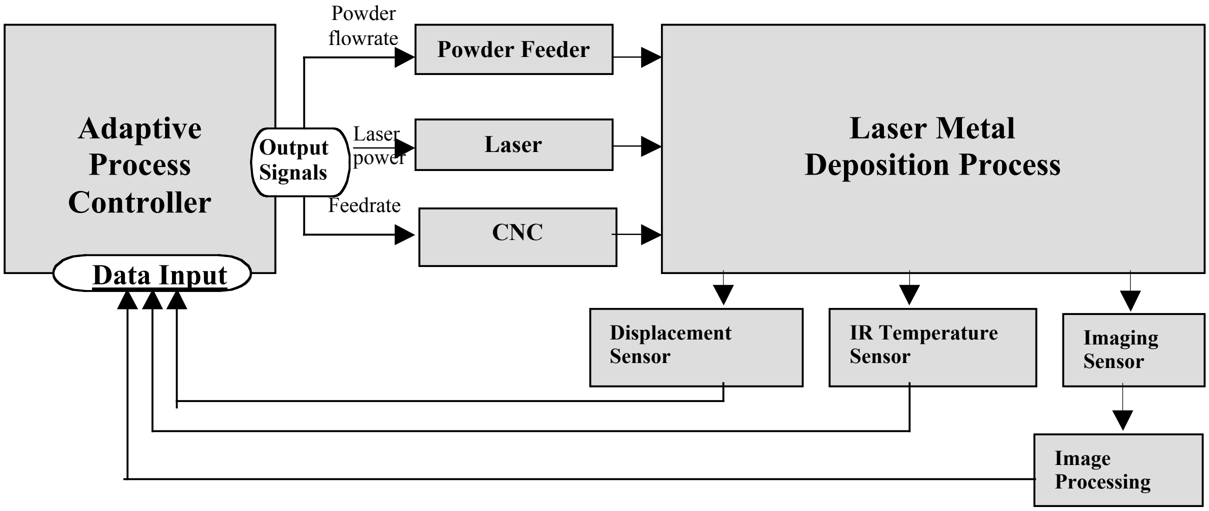

Figure 3. Sensor Control Architecture

The two-color temperature sensor, displacement sensor and a standard CCD sensor, monitor the process in real-time and provide the process parameters (as shown in Table 1) to the adaptive controller. Adaptive controller provides control output in the form of powder flow rate, laser power and feed rate. The imaging sensor obtains sequence of images, which are processed using image processing tools to provide a feedback to adaptive controller. Empirical models, which describe the process dynamics, were used to design the adaptive process controller to optimize the LAMD process.

Conclusion

An empirical model describing the process mechanics is presented for the LAMD process. A low cost system using laser displacement sensor, temperature sensor and CCD matrix camera has been presented which enables the operator to obtain information about laser cladding process. Some information is available in real-time and can be used in a closed loop control. The use of CCD technology enables determination of the clad width and temperature gradient of the melt pool. We showed that the data provided by our system enables us to improve the control of the cladding process through an adaptive process controller. Effects of some controller parameters on material processing are investigated. A statistically designed experimental matrix is used for this study.

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