

CONTROL OF LASER CLADDING FOR RAPID PROTOTYPING – A REVIEW

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Abstract

Lasers have wide-ranging applications in the manufacturing field (e.g., cladding, welding, cutting, machining, drilling). Extensive work is being conducted to apply laser cladding as a Rapid Prototyping (RP) process. In this paper the authors illustrate various principles of laser cladding in rapid prototyping. Important process parameters for the control of the laser cladding process are discussed as well as the experimental methods adopted, and results obtained by, various authors.

Introduction

The past decade has witnessed the emergence of new manufacturing technologies, where manufacturing time for parts of virtually any complexity is measured in hours, instead of days, weeks or months. This is when Rapid Prototyping (RP) was conceived. Many RP technologies are available in the marketplace; however, these technologies utilize plastic (or similar) material to create parts and, thus, many parts are non-functional. Sterolithography Apparatus was the first commercially available RP system that successfully produced physical prototypes. It enabled the visualization of components produced directly from a CAD model by polymer curing with lasers. Laser-based RP systems have been introduced as a means of creating functional, metal prototypes with near-net shape geometries and development efforts are being conducted in research centers throughout the world (Laeng *et al.*, 2000). The drawbacks to these systems are their low productivity and inability to consistently regulate part quality in terms of mechanical properties and geometry. To overcome these drawbacks, process control strategies have been utilized. This paper provides an overview of this body of research.

Lasers have provided industry with a new form of energy. Their wide application is due to their ability to act as a medium for communication, photography, and medical applications, as well as their ability to evaporate materials at the atomic level. Laser applications in manufacturing industries include welding, cutting, surface treatment, and ablation, and have recently extended their potential to RP. Laser-aided RP is a significant advance in traditional RP techniques due to the direct fabrication of a near-net shape part compared to the two step process involving an intermediate step of mould preparation in conventional RP techniques. Laser aided RP is advancing the state-of-the-art in product design by extending the laser cladding concept to RP. Some of the earlier attempts to build complex parts by layer addition were based on laser cladding principles. Studies have been carried out to determine the effect of process parameters on the quality of the clad layer (Weerasinghe and Steen, 1983). The quality of the clad layer is of importance as it forms the building block of the prototype. The next issue of concern is the bonding (fusion) of layers to build the prototype. Combining these issues together with the

ability of the system to orient the part in the required direction during deposition makes it possible to build parts with complex contours. Experiments were also carried out successfully to develop prototypes based on these principles (Kreutz *et al.*, 1995). Laser Engineering Net Shaping (LENS) has demonstrated the feasibility to fabricate geometrically complex shapes with functional materials directly from a CAD model (Keicher *et al.*, 1998). Integration of layered manufacturing and material removal processes is the latest trend in rapid prototyping. This enables the manufacture of complex geometries with increased accuracy and surface finish. The deposition of each layer is followed by machining of the excess material, which is often referred to as “exterior sculpting” (Kulkarni *et al.*, 2000).

This paper reviews the successful application of Laser Cladding for RP and the control issues for this application. Laser cladding process dynamics and process parameters are studied to determine their importance in real-time control of the laser deposition process.

Previous Work in Laser Cladding for Rapid Prototyping

Laser Cladding is a material processing technique in which a laser is used as a heating source to melt the alloy powder to be cladded onto a substrate. The application of this technique is being extended to obtain layers of deposition of desired height and width with superior properties in terms of pureness, homogeneity and surface finish. Thus, a metal prototype can be generated by selective cladding point-by-point and layer-by-layer. Some efforts have been made to produce metal prototypes by a layer additive approach (Kosh *et al.*, 1993). They have examined building parts in one and two dimensions, taking into consideration the time and cost involved in the process as compared with traditional methods. Direct Light Fabrication (DLF), which is being developed at Los Alamos National laboratory, has proven capable of producing metal parts with reasonably good accuracy and improved metallurgical properties (Lewis *et al.*, 1994; Milewski *et al.*, 1998). It is based on the same principle of adding layers until a near net-shape part is obtained. One such application was carried out using a CO₂ laser with inert gas propulsion of material powder into the molten pool generated by laser radiation on the substrate. A specially designed nozzle was used for this specific application. The movement of the substrate in X and Y directions in combination with the movement of the optics in Z direction and a simultaneous change of nozzle angle allowed the generation of arbitrary three-dimensional structures (Kreute *et al.*, 1995). The geometry of the clad was also investigated by metallographic techniques in combination with optical microscopy. Laser Direct Cladding (LDC) and Selective Laser Cladding (SLC) are based on the same principle as laser cladding, where a gas jet containing fine metal powder is directed via a coaxial nozzle through the path of the laser beam, which is focused slightly above the workpiece. The powder heats up to form molten particles and this laser/melt stream is traversed across the workpiece. A small melt-pool is formed on the surface of the workpiece where the molten particles land to form a layer upon cooling, about 0.5 mm thick, after the laser beam has moved on. It is also possible to lay down very narrow tracks in this way (0.8 mm) and multiple layers can be deposited on top of each other, allowing the formation of complex parts in a relatively short time (Morgan *et al.*, 1997; Jeng *et al.*, 2000). Laser Engineering Net Shaping (LENS) is one developing rapid metal forming process that has demonstrated the feasibility of laser metal forming to produce near-net shape metal parts. It utilizes STL file rendition of a CAD solid model to build an object one layer at a time. The file is sliced electronically into a series of layers that are subsequently used to generate

the motion to deposit each layer of the material. These layers are then deposited in a subsequent fashion to build the entire part (Keicher *et al.*, 1998). Direct Metal Deposition (DMD) is being used to fabricate molds and dies and for part repair. Its wide application in aerospace and medical fields is due to its large savings in cost. Mazumder *et al.* (1999) demonstrated the application of laser aided DMD to generate components with dimensional accuracy of 0.01 inch with the required control of process parameters to obtain the desired microstructure.

Relevant Parameters and Factors Effecting Laser Cladding

The characteristics of a built up part using the above-mentioned techniques mainly depends on the clad properties. Therefore, the parameters governing the cladding process have to be studied carefully. These parameters play an important role in determining the clad profile, dilution of the cladding metal, fusion between layers, homogeneity of the layers, surface finish, defects such as porosity, cracking due to thermal stresses, plasma formation, etc. Dilution is an important factor and a desired range should be set to determine various other factors and parameters governing the laser cladding process. It determines the thickness of the liquid layer on the substrate to ensure the bonding of the current layer with the previous layer. It is not possible to predict the influence of an individual parameter on the cladding process. In general, several parameters have to be varied simultaneously to obtain the desired characteristics of the deposited layer. There are also several limitations that restrict the variations of process parameters. Vetter *et al.* (1994) performed experiments to determine the state of powder when it arrives on the substrate surface. This forms an important limitation as the particles of the powder should be hot enough to adhere to the surface and form a layer, but not too hot such that the particles vaporize, followed by ionization and plasma formation. Thus, the energy available per unit length of clad pass per unit mass of powder and interaction time form the key factors in controlling the state of the powder, provided the other parameters such as powder mass flow rate, CNC table traverse speed, etc. are kept constant. The Heat Affected Zone (HAZ) induces surface distortion and residual stress and may be critical when producing small parts. In overlapping of tracks, the HAZ structure of prior tracks may be tempered by subsequent passes. The width and depth of the HAZ have to be used as indices for determining process performance in some cases. Once the conditions are set to control the above factors, the process parameters can be varied in a defined range to obtain the required clad height and thickness, which in turn are determined by bead geometry and overlap factor. These parameters depend on the powder feed rate, power density and CNC table feed rate. Some common surface defects such as the staircase effect (occurs due to part slicing of part), chordal effect (induced when a STL file is generated from the CAD model), support structure burrs and errors due to starting and ending of deposition are to be minimized to eliminate dimensional inaccuracies and improve surface finish. Different control techniques have to be applied to optimize these system parameters to accomplish the required quality and precision in fabricating a part. By exercising on-line control of these parameters, complex metal parts may be built by adding layers. Care should be taken to avoid porosity, which occurs due to cavities between tracks that form from overlapped tracks or the evolution of entrapped gasses in the clad tracks. This can be avoided by proper choice of overlap factor, which also determines the surface finish of the part. Figure 1 shows the process parameters and their interaction in determining the quality of the part.

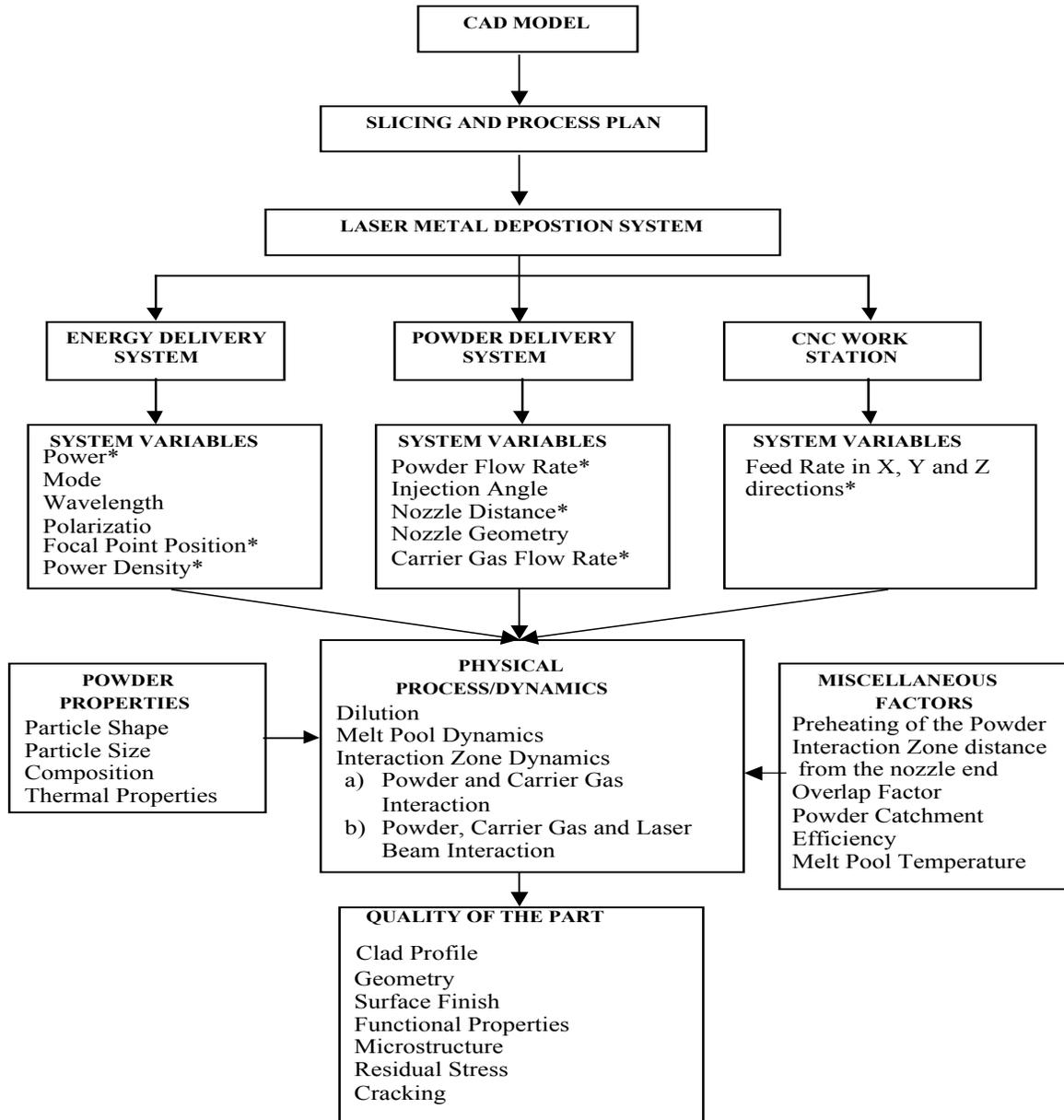


Figure 1: Laser Metal Deposition Process Parameters and Their Interactions. The starred (*) parameters may be varied on-line.

State-of-the-Art in Laser Cladding Control

Rapid Prototyping via lasers requires synchronization of three basic components of the laser deposition system, Powder Feeder System, Energy Delivery System, and CNC workstation. To enhance the part quality, close monitoring and control of the variables of these systems are required. Feedback controllers have to be designed to regulate these variables mainly to control melt pool size, temperature distribution in the melt pool, cooling rate (for microstructure manipulation) and clad height and width. These variables may vary during the operation due to

fluctuations in system parameters such as powder flow rate, beam position and diameter, output power, and CNC feedrate, and pre-setting these operating parameters is not appropriate. They have to be monitored and optimized continuously to obtain the desired conditions. This forms the initial step for real-time process control.

The dimensional accuracy of the part depends on the uniformity and repeatability of the clad height and width being deposited. Mazumder *et al.* (1999) described the application of multiple sensors for closed-loop feedback control of the bead height. The height controller shuts off the laser until it passes the excess built up region, thus preventing the powder from melting. An alternative way to control the bead dimensions is by regulating the powder flowrate, provided the traverse speed of the CNC table is kept constant. Regulation of powder flow rate controls the dilution for a given powder density. Also the carrier and shielding gas flowrate can influence the amount of powder being deposited. By increasing the carrier and shielding gas flowrate, the excess powder can be blown out of the way of the laser beam (Mazumder *et al.*, 1999). Most of the powder feeder systems used for laser cladding were open loop without flow rate sensing. The basic disadvantage of these were their inability to control the flowrate which continuously changes due to variations in powder volume density, with time and level of powder in the hopper although the control settings are kept constant. A small deviation in mass flowrate results in large variations in the geometry and microstructure of the produced tracks. To account for these problems, Li and Steen (1993) designed a closed-loop control system employing Proportional plus Integral plus Derivative (PID) controller with a feed-forward strategy for on-line feedback control of powder flowrate. Carvalho *et al.* (1995) designed a closed loop control system using a (PID) controller for independent delivery of two different powders for variable composition laser cladding. A specially designed coaxial nozzle was used which increased the powder utilization efficiency from approximately 30–50% to values higher than 80% (Hu *et al.*, 1997; Lin and Steen, 1998).

Temperature is another critical factor that requires continuous monitoring and control. It determines the melt pool dimensions and, hence, the dilution. If the temperature is too low, the resulting melt pool catches little powder and if the temperature is too high, it may melt back the workpiece. Morgan *et al.* (1997) described an effective means of controlling the temperature by controlling the laser power via positioning the laser focus relative to the workpiece. It also required a constant adjustment as the height of the structure steadily increases. Experiments were performed to demonstrate the effectiveness of closed-loop over open-loop control of these parameters. Li *et al.* (1987) developed an in-process laser control loop, which is based on an algorithm involving tune currents. The system used a microprocessor based in-process beam control unit using beam sensing via a Laser Beam Analyzer (LBA). Derouet *et al.* (1997) estimated the melt pool depth from the surface width and maximum temperature of the melt pool. This melt pool depth was controlled by a feedback loop using a PID controller. Laser power and scanning velocity were used as the parameters to control the depth of melt pool. Li *et al.* (1987) developed a real-time expert system and a laser cladding control system to determine the optimal operating conditions for a given requirement and for online fault diagnosis and correction. Koomsap *et al.* (2001) presented a simulation-based design of a laser based, free-forming process controller. A simplified model called metamodel was introduced to express the relationship between process characteristics and three process parameters: laser power, traverse speed, and powder feedrate. A dynamic metamodel was obtained and a temperature feedback controller was used to regulate the process. A Proportional plus Integral (PI) controller

was used to regulate the system. Bouhal *et al.* (1999) and Han and Jafari (1999) proposed a tracking controller for positioning and deposition accuracies in part fabrication for fused deposition processes. Fang and Jafari (1999) designed a statistical feedback control architecture integrating Statistical Process Control (SPC) and Automated Process Control (APC) to adjust parameters such as powder flowrate to minimize the possible defects in the next layer. They focused on on–line process parameter adjustment using a layer–to–layer controller. Doumanidis and Skoredli (2000) established a dynamic distributed parameter model with in-process parameter identification to generate a 3D surface geometry. Geometric predictions were made by a real-time model. A controller was designed to regulate the part geometry taking advantage of these predictions. Table 1 shows some of the process control techniques discussed in various papers.

References	Laser Power (kW)	Traverse Speed (mm/sec)	Powder Flow Rate (g/min)	Process Characteristics	Controlling Parameters	Control System	Principle
Morgan et al. (1997)	0.5	8.34		melt pool temperature, clad height	laser focus, melt pool temp	closed loop temperature., laser power	comparison of wavelength of light collected
Hu et al. (1997)	1.3-2.4	3-6	4.8-15	clad zone, interface zone, HAZ	powder flowrate	closed loop powder feeder	fluidized bed metering mechanism
Meriaudeau et al. (1997)			2-3	powder distribution, clad geometry	melt pool temp.		camera used as spectral thermometer
Fang et al. (1999)				overfills, underfills	powder flowrate, traverse speed	layer-by-layer controller for process control	SPC to monitor and APC to adjust variables
Koomsap et al. (2001)	7-14	5-50	6-60	dilution	laser power, traverse speed, powder flowrate	P.I. controller to regulate process parameters	dynamic metamodel was designed
Srivastava et al. (2000)	0.3-0.4	1-24	1-11	clad dimensions, microstructure	scanning rate, laser power	closed loop powder feeder	
Mazumder et al. (1999)	0.7	17	5.6	melt pool size, cooling rate, microstructure	laser power, powder , gas flowrate	closed loop for bead height regulation	
Keicher et al. (1998)	0.18	8.4		surface finish, clad dimensions	laser power, particle size		statistically designed experiment for process control
Derouet et al. (1997)	8-10	5-20		melt pool depth, microstructure, hardness	scanning speed, laser power	P.I.D. controller for melt depth control	
Koch et al. (1993)	0.4	8-12	11	powder utilization efficiency, clad dimensions	melt pool dimensions, laser beam diameter		

Table 1: Process Control Techniques Applied to Regulate Various Parameters.

Summary and Conclusions

Research conducted by various authors in the successful implementation of Laser Cladding for RP has been reviewed, and the impact of the critical parameters in this process has been discussed. Control techniques applied to processes such as dilution, laser power

distribution, powder flowrate, melt pool depth, etc., and on-line control of the parameters governing these processes were discussed.

The study of various works indicates that systematic implementation of process control requires a complete understanding of relation between various parameters and its effect on individual processes and the system as a whole. Most authors have put in efforts in designing closed loop control systems for real-time application of laser cladding for RP. In doing so, many assumptions such as the CNC feed rate and powder flowrate were assumed constant in determining the effect of laser power on processes such as dilution. In real-time application these may not be constant, as the powder flowrate keeps changing as the volume density of powder keeps varying depending on the level of powder in the hopper. Also there might be slight variations in the CNC feedrate, due to accelerations and decelerations while depositing at the edges of the prototype being built. These may lead to overfills and underfills. Hence these deviations need to be taken into consideration and feedback control systems have to be designed to account for these deviations and for process automation and control for optimal operating conditions. Commercial application of laser cladding for RP requires cost oriented design and operating conditions of the laser deposition system, mainly the powder feeder systems, which have to be analyzed to increase powder utilization efficiency which is as low as 30–50% in many of the experimental works.

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