Research and Development of A Hybrid Rapid Manufacturing Process

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Abstract

This paper presents the research and development of a hybrid rapid manufacturing process being developed at the University of Missouri-Rolla. This process includes a laser deposition and a 5-axis CNC milling system. By combining laser deposition and machining processes, the resulting hybrid process can provide greater build capability and better accuracy and surface finish. The hybrid process can build some features that are difficult to build in using a purely deposition processes. The issues and related approaches in the research and development of the hybrid deposition-machining process, including laser deposition process, system design and integration, process planning, and sensor selection and control, are discussed.

Introduction

This paper summarizes an interdisciplinary approach to design and develop a hybrid rapid manufacturing process to build functional metal parts. This process uses laser deposition for material deposition and CNC milling for material removal as shown in Figure 1. This five-axis laser deposition/CNC machining process has been developed at the Laser Aided Manufacturing Processes (LAMP) Laboratory in the University of Missouri at Rolla (UMR). It includes two major systems: a laser deposition system (Rofin–Sinar 025) and a CNC milling machine system (Fadal VMC-3016L). The laser deposition system and CNC milling machine work in shifts in a five-axis motion mode. The laser deposition system consists of a laser and a powder feeder.

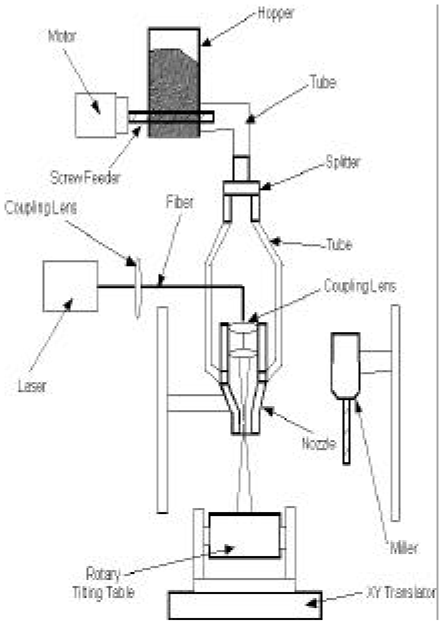


Figure 1. Schematic diagram of the hybrid system at UMR

In conventional 2.5-D laser deposition process to create three-dimensional parts, overhang and top surfaces of hollow parts need be supported. Often support materials for functional metal parts are not feasible. Moreover, deposition of the support material for metals leads to poor surface quality at the regions in contact with the support structure. Moreover, it increases the build time of the part and necessitates a time-consuming post-processing. Additionally use of support increases the build time of the part and necessitates a time-consuming post-processing. With a five-axis deposition process integrated with five-axis machining, these obstacles can be removed. This paper summarizes the issues and related approaches in the research and development of the hybrid deposition-machining process, including laser deposition, sensor selection, system control, and process planning.

Laser Deposition

For successful deposition, the Direct Laser Deposition, or DMD, process should be well designed and controlled. The scientific challenge is how to accurately control the physical dimension and material properties of the part. Close control of dimension will result in substantial savings in post process machining cost. Substantial cost reduction is possible, if desired properties can be achieved through process control thus minimizing post-process heat treatment. Control of the melt pool size and solidification time can offer both desired dimension by limiting the melt pool volume and desired properties through microstructure manipulation by controlling the cooling rate. This will require quantitative understanding of the relationship between independent process parameters (laser power speed, powder deposition rate etc.), and dependent process parameters (dimension, microstructure and properties, etc.). Issues related with these parameters and possible approaches are discussed below:

A. Independent process parameters

The major independent process parameters for the laser aided DMD process include the following: (1) incident laser beam diameter, (2) process speed, (3) laser beam power, (4) powder feed rate, and (5) laser beam path width (path overlap) as shown in Figure 2. Other parameters such as nozzle to surface distance (standoff distance), nozzle gas flow rate, absorptivity, and depth of focus with respect to the substrate also play important roles.

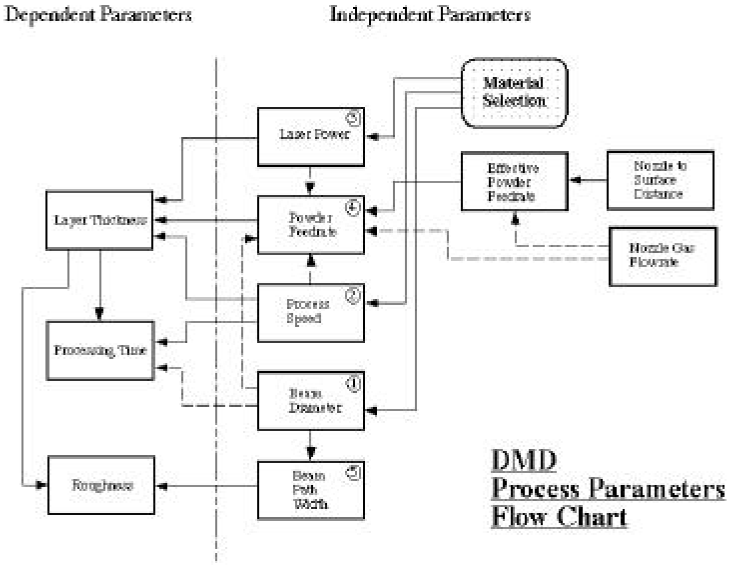


Figure 2. DMD Process Parameters Flow Chart

(1) Laser beam diameter

This parameter is one of the most important variables because it determines the power density. However it is very difficult to measure for high power laser beams. This is partly due to the nature of the beam diameter and partly due to the definition of what is to be measured. Many techniques have been employed to measure the beam diameter, but most are unsatisfactory in some respect or another. Single isotherm contouring techniques such as charring paper and drilling acrylic or metal plates suffer from the fact that the particular isotherm they plot is both power and exposure time dependent. Multiple isotherm contouring techniques overcome these difficulties but are tedious to interpret.

(2) Process speed

In general, decreasing process speed increases the layer thickness. However there is a threshold to reduce process speed since too much specific energy may cause previous layers tempered or secondary hardened (Mazumder, 1997). Process speed for DMD process should be well chosen since it has strong influence on microstructure.

(3) Laser beam power

The layer thickness during laser cladding process is directly related to the power density of the laser beam and is a function of incident beam power and beam diameter. Generally, for a constant beam diameter, the layer thickness increases with increasing beam power provided corresponding powder feed rate. It was also observed that the cladding rate (deposition rate) increased with increasing laser power (Weerasinghe, 1983).

(4) Powder mass feed rate

Powder mass feed rate is another important process parameter to decide the layer thickness. However effective powder feed rate, which includes powder efficiency during the DMD process, was turned out to be more important (Lin, 1998; Mazumder, 1999). Also the factor that most significantly affected the percent powder utilization was laser power. The powder nozzle is set up to give a concentric supply of powder to the cladding melt pool, and due to the nature of the set-up, the powder flow is hour glass-shaped. As shown in Figure 3, the powder flow initially is unfocused as it passes through the powder delivery nozzle, but the nozzle guides the powder concentrically towards its center, and essentially "focuses" the beam of powder.

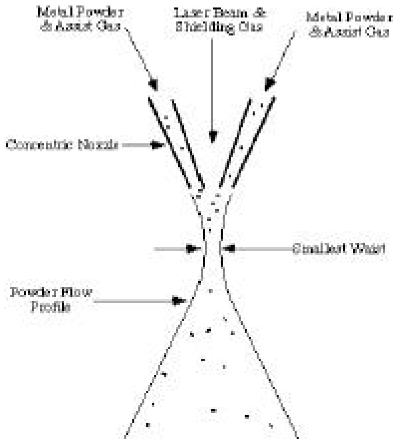
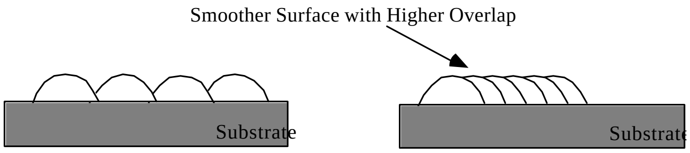


Figure 3. Powder Delivery Flow Profile

The smallest diameter focus of the powder "beam" is dependent upon the design of nozzle. If the laser beam diameter becomes too small as compared to the beam diameter, e.g., 100µm, much of the supplied powder may never reach the cladding melt pool. Thus, there will be unacceptably low powder utilization.

(5) Beam path width (Beam width overlap)

Beam width overlap has strong influence in top surface roughness. The reason for this decrease in surface roughness is depicted in Figure 4. As the cladding pass overlap increases, the valley between passes is raised due to the overlap therefore reducing the surface roughness. In order to obtain the best surface quality, the percent pass overlap should be increased as much as possible. On the other hand, in order to decrease the wall surface roughness, the cladding layers should be kept as thin as possible.



Cladding with Low Pass Overlap

Cladding With High Pass Overlap

Figure 4. Surface Profile Change from Increase in Percent Overlap

B. Dependent process parameters

The major dependent process parameters are considered to be (1) layer thickness, (2) surface roughness, and (3) process time. Other dependent parameters such as hardness, microstructure, and mechanical properties, etc should be also considered, but in this paper we will focus only on the parameters related with physical dimension.

(1) Layer thickness

There is a large range of layer thickness as well as deposition rates that can be achieved using laser deposition. However, part quality consideration put a limit on optimal deposition speeds. Both the layer thickness and the volume deposition rates are affected predominately by the specific energy and powder mass flow rate. Here, specific energy (SE) is defined as: SE = p/(D*v*), where p is the laser beam power, D is the laser beam diameter and *v* is the process speed. Also it has been well known that actual laser power absorbed in the melt pool is not same as nominal laser power measured from laser power monitor due to reflectivity and other plasma related factors depending on the materials (Duley, 1983). The use of adjusted specific energy is thus preferable. Considering the factors, it was reported that there is a positive linear relationship between the layer thickness and adjusted specific energy for each powder mass flow rate (Mazumder, 1999).

(2) Surface roughness

Surface roughness was found highly dependent on the direction of measurements with respect to the cladding (Mazumder, 1999). In checking the surface roughness, at least four directions should be tested from each sample; the length and width direction on the top surface, and the horizontal and vertical directions on the walls. Since the largest roughness on each sample is of primary interest, measurements should be only taken perpendicular the clad direction on the top surface and in the vertical direction on the walls, based on our preliminary experiments.

(3) Process time

The overall deposition processing time is mainly dependent upon the layer thickness per slice, process speed and laser beam diameter. As an example, if the layer thickness is 250 μm/slice, and process speed is 12.7 mm/s, and laser beam diameter is 1 mm, the process volume deposition rate is about 0.2 cm^3/min. However, the processing conditions need to be optimized prior to optimize the processing time, since the processing time is directly influenced by the conditions. If the laser beam diameter is increased, the specific energy and power density will be decreased under the same process condition, that means, less deposition rate unless the laser power and powder mass flow rate are correspondingly increased. Similarly when the process speed is increased, all other process parameters including laser power and powder mass feed rate, etc should be optimized.

Sensor Selection

The temperature of the melt pool, the thickness of the deposited layer and the physical dimensions and characteristics of the melt pool should be determined for feedback control. Since molten metal is deposited in very thin layers on a steel substrate, the temperature range of the melt pool is between 1000°C and 1500°C but less than 2000°C. The layers are deposited with a minimum thickness of 10μm. The diameter of the laser beam would typically be a little less than 1 mm.

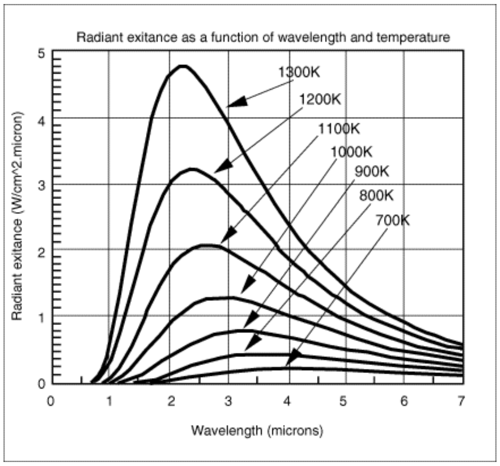


Figure 5. Radiant exitance as a function of wavelength and temperature

A. Temperature Sensors

Due to the nature of DMD process, the temperature sensor should be a non-contact sensor and must work with the Nd:YAG laser. *Infrared*

Thermometry is best suited for non-contact application.

Every object emits radiant energy and the intensity of this radiation is a function of its temperature. Radiance in the visible range is quite low. The radiance at every wavelength increases with increasing temperature as shown in Figure 5 and the determination of the radiance at any wavelength serves to establish the emitters' temperature. Because of this fact, temperature-measuring devices that are based on a single wavelength do not give the absolute temperature. Hence, *two-color infrared thermometry* is preferred.

The *two-color infrared thermometry* utilizes the two-color principle, in which the temperature measurement is made by *ratioing* the radiation intensities of two adjacent wavelengths rather than from absolute intensity as with single band (or single color) instruments as shown in Figure 6. Thus, these sensors are: independent of emissivity, unaffected by dust and other contaminants in the field of view, independent of target size, and can take accurate readings with only 10% of the target area within the field of view.

Most of the sensors work with wavelengths around 1µm. Since the Nd:YAG laser operates at 1.06µm wavelength, it might interfere with the temperature sensor being used. One possible solution is to shut off the laser for a relatively small period of time, about 20 to 50ms (typical response time of the temperature sensor) every 2s, to facilitate sensing. The disadvantage of opting for this method was that the feed-rate could not exceed 0.01 m/s for a proper deposition layer without discontinuities. Hence, temperature sensors working with wavelengths around that of the primary laser could not be used. A *Williamson Corporation* temperature sensor working with wavelengths around 1.5 µm was chosen for this particular application.

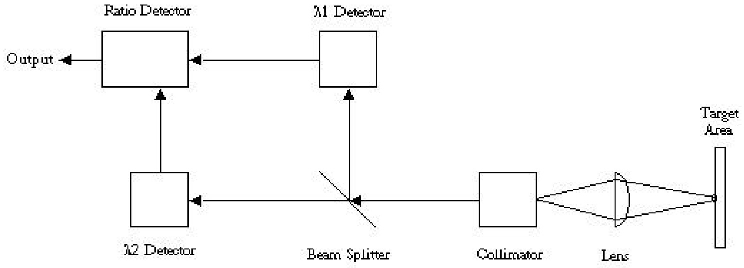


Figure 6. Block diagram of two-color infrared temperature sensor

B. Displacement Sensor

The main criteria for choosing a displacement sensor is the measuring range, resolution and spot size, which is unique to each laser-based direct metal deposition system. Since the displacement sensor has to be a non-contact sensor and cannot be mounted vertically on top of the spot to be measured, a laser displacement sensor (LDS) has to be used which can be mounted at an inclination. The laser displacement sensor is not focused on the melt pool, but rather with a little offset, to measure the thickness of the deposited layer. The laser displacement sensor emits a beam of laser and detects the deflection in the reflected beam. The thickness of the deposited layer is proportional to the deflection of the beam. The deflection of the beam is detected by a laser detector, which outputs a voltage that is proportional to the thickness of the deposited layer. An *Omron Laser Displacement Sensor* was chosen for this particular system.

C. Imaging Sensor

An imaging sensor is mounted on top of the nozzle with a beam bender so that it can "look" at the melt-pool from nadir. The melt-pool images can be processed to monitor bean width and melt-pool quality. Since real-time processing was a concern a camera with embedded DSP processor was favored. The conventional camera technology is based on CCD sensors, however CCD sensors have low dynamic range so that the bloom of the laser processing saturates the sensor. One possibility was to shut the laser for a few milliseconds while the image is captured, however it the thought to interfere with the deposition processes. Thus a camera based on new CMOS technology is opted. Due to self-adaptive gain feature, these sensors can achieve very high dynamic range so that it is possible to "see through" the bloom. Moreover this camera affords random access to any region of interest.

Control

The implementation of process control for deposition processes is scarce. Parameters such as melt pool profile, melt pool temperature, and overlap factor must be regulated while each layer is being placed to indirectly control the part microstructure and layer bonding. The bead width and height should also be regulated such that removal processes are not unduly required to even the surface, as this will decrease productivity dramatically. Powder catchment efficiency is always an important parameter to maximize, too, as it directly affects the system cost.

Since the deposition process is relatively new, it is not surprising that advanced control theory has not been utilized. The state–of–the–art still utilizes classical control theory where the gains are not chosen systematically and the different phenomena (e.g., melt pool temperature) are regulated separately. Also the models are typically static. The empirical relationships do not account for inherent process variability, and the process and servomechanism dynamic effects have not been taken into account. In the LAMP Lab, we are developing system theoretic, dynamic models of the laser metal deposition process for simulation and controller development. A schematic of the control architecture is shown in the Figure 7. The three major components that affect the laser metal deposition process are the powder feeder, laser, and CNC traverse velocity. The dynamics are inherent in these components as well as in the deposition process. Note that the communication with the CNC via an RS232 port induces delays. There are also physical transport delays in the powder feeder system. The process control system will utilize a Smith Predictor–Corrector algorithm to account for these delays, multivariable control techniques is used to account for multiple control inputs and outputs, and parameters estimation is employed to account for process variability.

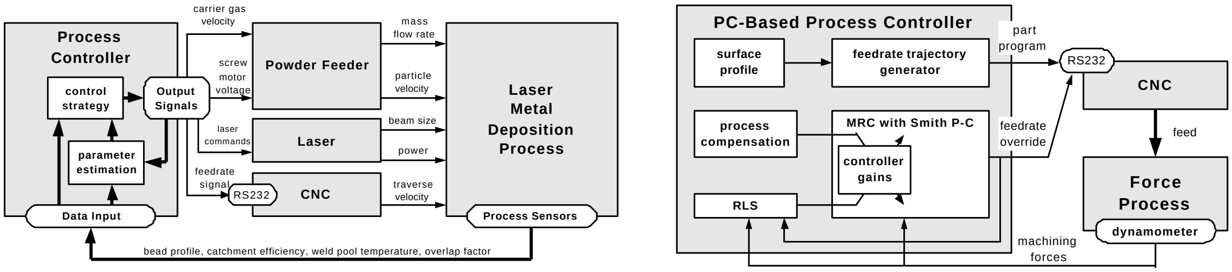


Figure 7. Deposition (left) and Structural Deflection (right) Process Control Architectures

As opposed to the literature in deposition process control, the literature in removal process control is immense and will not be reviewed in this paper. In the hybrid process, the main concern of the machining process is to remove excess material as quickly as possible while meeting the part geometry constraints. If the part is damaged during the removal process and must be scraped, the cost will be tremendous, as machining is the finishing process. The parts built by the hybrid process typically have thin sections and complex geometries, and the material to be removed will typically have an uneven distribution over the surface from which it will be removed. The removal process is required before the part is reoriented, or when access to a surface to be machined may be blocked by further deposition. For the removal process, the issues are to ensure that the structural deflections are not excessive, that regenerative chatter, excessive tool wear, and tooth chippage do not occur, and that the machine's geometric and thermal errors are compensated.

Structural deflections will be the first issue addressed in the LAMP Lab. A schematic for a structural deflection control system is shown in the figure above. During the deposition process, the bead profile will be monitored; therefore, the profile of the excess material to remove off of each surface will be known. Using a mechanistic model of the machining process, an optimal feedrate trajectory can be calculated such that a constant machining force, and hence structural deflection, may be maintained. This feedrate profile will be embedded in the part program. However, due to model inaccuracies and unknown changes in the force process, a feedback loop will also be required to maintain a constant force while machining the surface. A Model Reference Controller (MRC) with a Smith Predictor–Corrector algorithm (to account for the communication delay with the RS232 port) will be implemented. Using the surface profile, process compensation will be used to adjust the controller gains to account for known process changes, while a Recursive Least Squares (RLS) algorithm will be utilized to estimate variations in model parameters due to unknown process changes. These compensation schemes will adjust the controller gains allowing for a robust control scheme.

Process Planning

Process planning, simulation, and tool path generation for the LAMP allow the designer to visualize and perform the part fabrication from the desktop. The Laser Aided Manufacturing Process Planning uses STL models as input and generates a description that specifies contents and sequences of operations. The objective of the process planning is to integrate the five-axis motion and deposition-machining hybrid processes. The results consist of the subpart information and the build/machining sequence. Basic planning steps involve determining the base face, extracting the skeleton, decomposing a part into subparts, determining build sequence and direction for subparts, checking the feasibility of the build sequence and direction for the machining process, and optimization of the deposition and machining.

(1) Skeleton Computation

An algorithm for computing the skeleton of 3-D polyhedron is needed. The algorithm is based on a classification scheme for points on the skeleton computation (Sherbrooke, 1995) in which the continuous representation of the medial axis is generated with associated radius functions. Because it is used as a geometric abstraction, the skeleton is trimmed from the facets that touch the boundary of the object along every boundary edge for which the interior wedge angle is less than π rad.

(2) Part Orientation

The determination of the base face from which the building process of the part starts is very important. The base face functions as the fixture in the machining process. Therefore, when in the machining process, it must provide enough resistance against the cutting force. The maximal resistance force depends on the area of the base face. The base faces have to satisfy the following conditions: 1) Located on the convex hull of the part, and 2) Certain amount of contact area.

(3) Part Decomposition and Building Direction

The objective of part decomposition is to divide the part into a set of subparts, which can be deposited and machined. The topology of the part can be obtained from the skeleton. Each branch of the skeleton corresponds to a subpart. One of the partitions that are preformed is along a non-planar surface. Therefore, close to the partition area, 3-D layers are needed to build the connection between two subparts. The build direction of a subpart may not be constant. It changes when the part is built layer by layer so that for two adjacent layers, the later layer can be deposited based on the early layer without any support structures. To achieve the non-support build, the build directions need to be along the skeleton.

(4) Building Sequence

The results of decomposition are recorded in an adjacency graph where nodes represent subparts, and edges represent the adjacency relationship between connected nodes. After considering part building order, a directed graph that represents the precedence relationship among subparts can be constructed. From the precedence graph, one can identify in what order the subparts can be built. With the precedence graph, a set of alternative building plans can be generated. Each plan represents a possible building sequence on the decomposed geometry and can be chosen optimally depending upon machine availability or other criteria such as minimum building time.

(5) Machinability Check

The main purpose of machinability check is to choose an optimal building sequence from the sequence set. Local and global collision checks are operated first to choose acceptable sequences since the building direction is different in each sequence. If any kind of collision happens or an under cut plane appears, the corresponding sequence will be discarded. For the rest of the building sequences in set, the buildability check and machining time computation is performed to find an optimal building sequence.

Conclusion

The research and development of a hybrid material deposition and removal system is summarized in this paper. It outlines some issues and approaches to establish this system.

Acknowledgments

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