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Hybrid Manufacturing System Design and Development

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1. Introduction

Reliable and economical fabrication of metallic parts with complicated geometries is of considerable interest for the aerospace, medical, automotive, tooling, and consumer products industries. In an effort to shorten the time-to-market, decrease the manufacturing process chain, and cut production costs of products produced by these industries, research has focused on the integration of multiple unit manufacturing processes into one machine. The end goal is to reduce production space, time, and manpower requirements. Integrated systems are increasingly being recognized as a means to meet these goals. Many factors are accelerating the push toward integrated systems. These include the need for reduced equipment and process cost, shorter processing times, reduced inspection time, and reduced handling. On the other hand, integrated systems require a higher level of synthesis than does a single process. Therefore, development of integrated processes will generally be more complex than that of individual unit manufacturing processes, but it could provide simplified, lower-cost manufacturing.

Integrated systems in this research area have the ability to produce parts directly from a CAD representation, fabricate complex internal geometries, and form novel material combinations not otherwise possible with traditional subtractive processes. Laser metal deposition (LMD) is an important class of additive manufacturing processes as it provides the necessary functionality and flexibility to produce a wide range of metallic parts (Hopkinson et al., 2006; Liou & Kinsella 2009; Venuvinod & Ma, 2004). Current commercial systems that rely on LMD to produce tooling inserts, prototype parts, and end products are limited by a standard range of material options, building space, and a required post-processing phase to obtain the desired surface finish and tolerance. To address the needs of industry and expand the applications of a metal deposition process, a hybrid manufacturing system that combines LMD with the subtractive process of machining was developed achieving a fully integrated manufacturing system.

Our research into hybrid manufacturing system design and development has lead to the integration of additive and subtractive processes within a single machine footprint such that both processes are leveraged during fabrication. The laser aided manufacturing process (LAMP) system provides a rapid prototyping and rapid manufacturing infrastructure for research and education. The LAMP system creates fully dense, metallic parts and provides all the advantages of the commercial LMD systems. Capabilities beyond complex geometries and good surface finish include: (1) functional gradient material metallic parts where different materials are added from one layer to the next or even from one section to another, (2) seamlessly embedded sensors, (3) part repair to reduce scrap and extend product service life, and (4) thin-walled parts due to the extremely low processing forces (Hopkinson et al., 2006; Liou et al., 2007; Ren et al., 2008). This hybrid system is a very competitive and economical approach to fabricating metallic structures. Hybrid manufacturing systems facilitate a sustainable and intelligent production model and offer flexibility of infrastructure to adapt with emergent technology, customization, and changing market needs (Westkämper, 2007). Consequently, the design strategies, system architecture, and knowledge required to construct hybrid manufacturing systems are vaguely described or are not mentioned at all in literature.

The goal of this chapter is to summarize the key research findings related to the design, development, and integration of a hybrid manufacturing process that utilizes LMD to produce fully dense, finished metallic parts. Automation, integration, and control strategies along with the associated issues and solutions are presented as design guidelines to provide future designers with the insight needed to successfully construct a hybrid system. Following an engineering design perspective, the functional and process knowledge of the hybrid system design is explored before physical components are involved. Key results are the system architecture, qualitative modeling, and quantitative modeling and simulation of a hybrid manufacturing process.

In summary, this chapter provides an interdisciplinary approach to the design and development of a hybrid manufacturing system to produce metal parts that are not only functional, but also processed to the final desired surface-finished and tolerance. The approach and strategies utilized in this research coalesce to facilitate the design of a sustainable and intelligent production system that offers infrastructure flexibility adaptable with emergent technologies and customizable to changing market needs. Furthermore, the approach to hybrid system design and development can assist in general with integrated manufacturing systems. Applying the strategies to design a new system or retrofit older equipment can lead to increased productivity and system capability.

2. Related work

Any process that results in a solid physical part produced directly from a 3D CAD model can be labeled a rapid prototyping process (Kalpakjian & Schmid, 2003; Venuvinod & Ma, 2004). Equally, a process that converts raw materials, layer-by-layer into a product is a rapid prototyping process, but is typically referred to as additive manufacturing or layered manufacturing. Subtractive manufacturing is the process of incrementally removing raw material until the desired dimensions are met. Where additive processes start from the ground up, subtractive processes start from the top down. The combination of manufacturing processes from different processing categories establishes a hybrid manufacturing system. Herein, a hybrid manufacturing system refers to a manufacturing system that is comprised of an additive and subtractive manufacturing process.

Both additive and subtractive manufacturing cover a wide range of fabrication processes. For example, additive manufacturing can involve powder-based (e.g., selective laser sintering), liquid-based (e.g., stereolithography) or solid-based (e.g., fused deposition modeling) processes, each using a wide range of materials (Gebhardt, 2003; Kai & Fai, 1997; Venuvinod & Ma, 2004). While traditional subtractive manufacturing is typically reserved for metals, advanced or non-conventional subtractive processes have emerged to handle a greater variety of materials which include electric discharge machining, water jet cutting, electrochemical machining and laser cutting (Kalpakjian & Schmid, 2003). The physical integration of additive and subtractive manufacturing processes, such as laser metal deposition and machining, is the key to leveraging the advantages of each process. The vast domains of additive and subtractive manufacturing have provoked many to test boundaries and try a new concept, in an attempt to discover the next best system that will play a key role in advancing manufacturing technologies. Academic and industry researchers alike have been developing novel, hybrid manufacturing systems, however, the design and integration strategies were not published. On the other hand, a few approaches taken to develop reliable hybrid systems that deliver consistent results, with the majority based on consolidation processes, have published a modest guide to their system design. In following paragraphs, a number of hybrid manufacturing systems are reviewed to give an idea of what has been successful.

Beam-directed technologies, such as laser cladding, are very easy to integrate with other processes. Most have been integrated with computer numerically controlled (CNC) milling machines by simply mounting the cladding head to the z-axis of the milling machine. Kerschbaumer and Ernst retrofitted a Röders RFM 600 DS 5-axis milling machine with an Nd:YAG laser cladding head and powder feeding unit, which are all controlled by extended CNC-control (Kerschbaumer & Ernst, 2004). Similarly, a Direct Laser Deposition (DLD) process utilizing an Nd:YAG laser, coaxial powder nozzle and digitizing system as described by (Nowotny et al., 2003) was integrated into a 3-axis Fadal milling machine. Laser-Based Additive Manufacturing (LBAM) as researched at Southern Methodist University, is a technique that combines an Nd:YAG laser and powder feeder with a custom built motion system that is outfitted with an infrared imaging system (Hu et al., 2002). This process yields high precision metallic parts with consistent process quality. These four systems perform all deposition steps first, and then machine the part to the desired finish, consistent with conventional additive fabrication.

Two powder-based manufacturing processes that exhibit excellent material usage and in most cases produced components do not require finishing are Direct Metal Laser Sintering (DMLS) and Laser Consolidation (LC). Using layered manufacturing technology, a DMLS system such as the EOS EOSINT M270 Xtended system, can achieve an acceptable component finish using a fine 20 micron thick metal powder material evenly spread over the build area in 20 micron thick layers (3axis, 2010). Laser Consolidation developed by NRC Canada is a net-shape process that may not require tooling or secondary processing (except interfaces) (Xue, 2006, 2008). Parts produced using these processes exhibit net-shape dimensional accuracy and surface finish as well as excellent part strength and material properties.

Non-conventional additive processes demonstrate advanced features, alternate additive and subtractive steps, filling shell casts, etc. A hybrid RP process proposed by (Hur et al., 2002) combines a 6-axis machining center with any type of additive process that is machinable, a sheet reverse module, and an advanced process planning software package. What differentiates this process is how the software decomposes the CAD model into machining and deposition feature segments, which maximize the CNC milling machine advantages, and significantly reduces build time while increasing shape accuracy. Laser welding, another hybrid approach, involves a wire feeder, CO_2 laser, 5-axis milling center, and a custom PC-NC based control unit that has been used to produce molds for injection molding (Choi et al., 2001). Hybrid-Layered Manufacturing (HLM) as researched by (Akula & Karunakaran, 2006) integrates a TransPulse Synergic MIG/MAG welding process with a conventional milling machine to produce near-net shape tools and dies. This is direct rapid tooling. Welding and face milling operations are alternated to achieve desired layer height and to produce very accurate, dense metal parts. A comparable process was developed at Fraunhofer IPT named Controlled Metal Build-up (CMB), in which, after each deposited layer the surface is milled smooth (Kloche, 2002). However, CMB utilizes a laser integrated into a conventional milling machine.

Song and Park have developed a hybrid deposition process, named 3D welding and milling because a wire-based gas metal arc welding (GMAW) apparatus has been integrated with a CNC machining center (Song & Park, 2006). This process uses gas metal arc welding to deposit faster and more economically. Uniquely, 3D welding and milling can deposit two materials simultaneously with two welding guns or fill deposited shells quickly by pouring molten metal into them. The mold Shape Deposition Manufacturing (SDM) system at Stanford also uses multiple materials to deposit a finished part, however, for a different purpose (Cooper, 1999). A substrate is placed in the CNC mill and sturdy material such as UV-curable resin or wax is deposited to form the walls of a mold, which then is filled with an easily dissolvable material. The top of the mold is deposited over the dissolvable material to finish the mold; once the mold has cooled down the dissolvable material is removed, and replaced with the desired part material. Finally, the sturdy mold is removed to reveal the final part, which can be machined if necessary. Contrary to the typical design sequence (Jeng & Lin, 2001) constructed their own motion and control system for a Selective Laser Cladding (SLC) system and integrated the milling head, which evens out the deposition surface after every two layers. Clearly, each system has its advantages and contributes differently to the RM industry.

Although using a CNC milling machine for a motion system is the most common approach to constructing a hybrid system, a robot arm can easily be substituted. This is the case with SDM created at Stanford University (Fessler et al., 1999). The robot arm was fitted with an Nd:YAG laser cladding head which can be positioned accurately, allowing for selective depositing of the material and greatly reducing machining time. Integration of a handling robot can reduce positioning errors and time between operations if the additive and subtractive processes are not physically integrated.

Most of the aforementioned systems have been built with versatility in mind and could be set-up to utilize multiple materials or adapted to perform another operation. However, an innovative hybrid system that has very specific operations and capabilities is the variable lamination manufacturing (VLM-ST) and multi-functional hotwire cutting (MHC) system (Yang et al., 2005). The VLM-ST system specializes in large sized objects, up to 3 ft. x 5 ft., by converting polystyrene foam blocks into 3D objects utilizing the turntable of the 4-axis MHC system during cutting; if the object is bigger still, multiple pieces are cut and put together.

The design strategy behind several of the reviewed hybrid systems was not emphasized and documented. Thus, key pieces of information for the design and development of hybrid systems are missing which prevents researchers and designers from easily designing and constructing a hybrid system of their own. The information contained within this chapter aims to provide a comprehensive overview of the design, development, and integration of a hybrid manufacturing system such that others can use as a guideline for creating a hybrid system that meets their unique needs.

3. Research approach

As previously mentioned, the design strategies, system architecture, and knowledge required to construct a hybrid manufacturing system is vaguely described if mentioned at all in the literature. Consequently, our research approach is mainly empirical. Although our approach relies heavily on observation and experimental data, it has allowed us to identify opportunities for applying theory through modeling and simulation.

A major challenge to hybrid manufacturing system design is accurately controlling the physical dimension and material properties of the fabricated part. Therefore, understanding the interaction of all process parameters is key. Layout of the preliminary system architecture provides a basis for qualitative modeling. Independent and dependent process parameters are identified through qualitative modeling, which defines the parameters that require a quantitative understanding for accurate control of the process output. Qualitative models of the hybrid manufacturing process are developed and analyzed to understand both process and functional integration within the hybrid system. This allowed lost, competing or redundant system functionality to be identified and used to inform design decisions. Modeling how the material and information flows through the hybrid system facilitates the development of the automation, integration, and control strategies.

Quantitative modeling and simulation of our hybrid manufacturing system concentrates on process control and process planning. Process control modeling is used to predict the layer thickness via an empirical model based on the direct 3D layer deposition, the particle concentration of the powder flow, the nozzle geometry, the carrier gas settings, and the powder-laser interaction effects on the melt pool. Process planning models are used to automate part orientation, building direction, and the tool path. These models assist with resolving the challenges of the laser deposition process including building overhang structures, producing precision surfaces, and making parts with complex structures.

Revisiting the preliminary system architecture design with the knowledge gained from qualitative and quantitative modeling has resulted in a system architecture that enables accurate and efficient fabrication of 3D structures. Decomposition of the system architecture allows for direct mapping of customer needs and requirements to the overall system architecture.

4. Hybrid manufacturing system

The laser aided manufacturing process (LAMP) lab at Missouri University of Science and Technology (formerly University of Missouri-Rolla) houses a 5-axis hybrid manufacturing system, which was established by Dr. Liou and other faculty in the late 1990s. This system entails additive-subtractive integration, as shown in Fig. 1, to build a rapid prototyping/ manufacturing infrastructure for research and education at Missouri S&T. Integration of this kind was planned specifically to gain sturdy thin wall structures, good surface finish, and complex internal features, which are not possible by a LMD or machining system alone. Overall, the system design provides greater build capability, better accuracy, and better surface finish of structures with minimal post-processing while supporting automated control. Applications of the system include repairing damaged parts (Liou et al., 2007), creating functionally gradient materials, fabrication of overhang parts without support structures, and embedding sensors, and cooling channels into specialty parts.

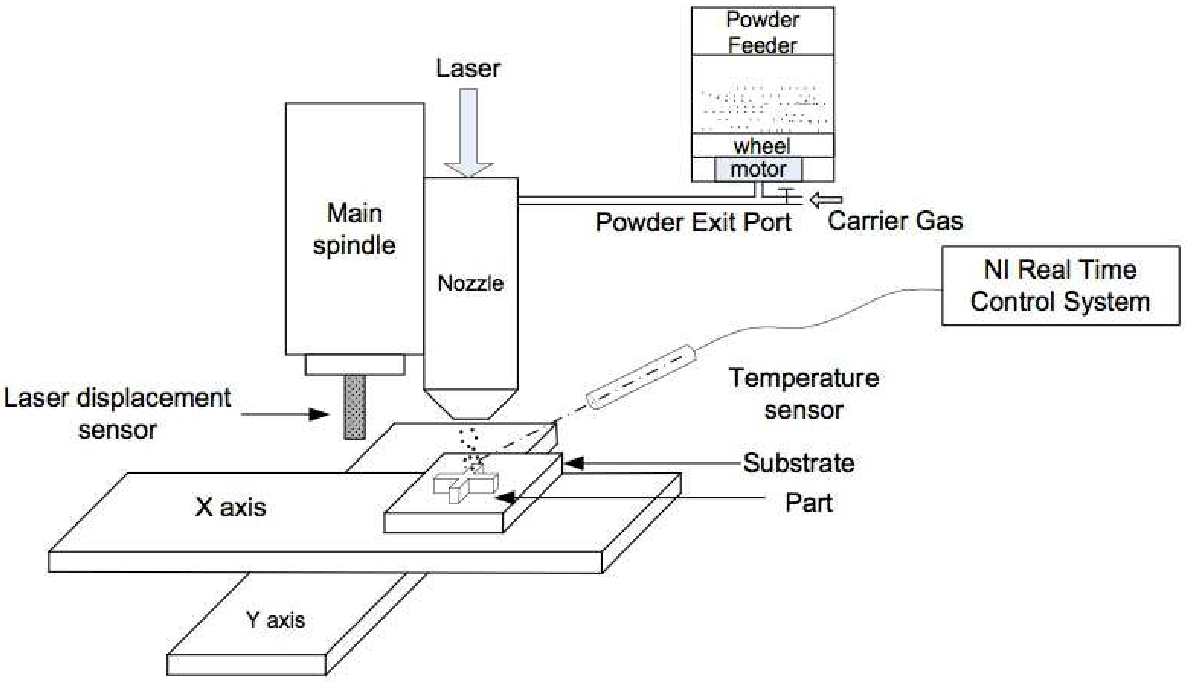


Fig. 1. Five-axis Hybrid Manufacturing Process (Adapted from Tang et al., 2007)

The LAMP hybrid system is comprised of five subsystems or integration elements: process planning, control system, motion system, manufacturing process, and a finishing system. Equipment associated with subsystem is described in the following paragraphs and summarized in Table 1.

The LAMP process planning system is a in-house layered manufacturing or slicing software that imports STL models from a commercial CAD package to generate a description that specifies melt pool length (mm), melt pool peak temperature, clad height (mm) and sequences of operations. The objective of the process planning software is to integrate the five-axis motion and deposition-machining hybrid processes. The results consist of the subpart information and the build/machining sequence (Ren et al., 2010; Ruan et al., 2005). To generate an accurate machine tool path a part skeleton, which calculates distance and offset edges or boundaries, is created of the CAD model. Distance, gradient, and tracing functions were modified to allow more complicated and unconnected known environments for successful implementation with the LAMP hybrid manufacturing system. 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.

Hybrid Manufacturing Subsystems	LAMP Hybrid System Equipment
Process Planning	Commercial and in-house CAD software
Motion	Fadal 3016L 5-axis VMC
Manufacturing Process	Nuvonyx 1kW diode laser, Bay State Surface Technologies 1200 powder feeder
Control	NI RT PXI chassis & LabVIEW, Mikron temperature sensor, Omron laser displacement sensor, Fastcom machine vision system
Finishing	Fadal 3016L 5-axis VMC

Table 1. LAMP Hybrid System Equipment

True 3D additive manufacturing processes can be achieved with a 5-axis machining center without additional support structures (Ruan et al., 2005), as opposed to 2.5D that is afforded by a 3-axis machine. Therefore the motion subsystem for the LAMP hybrid manufacturing system is a 5-axis Fadal 3016L VMC, which also constitutes the finishing subsystem. Servo motors control the motion along the axes as compared with crank wheels and shafts in conventional machine tools. The Fadal VMC is controlled via G and M codes either entered at the control panel or remotely fed through an RS-232 connection.

The main manufacturing process of the hybrid system is laser metal deposition, the additive manufacturing process. Metal powder is melted using a 1kW diode laser while the motion system traverses in response to the tool path generated by the process planning software, thereby creating molten tracks in a layer-by-layer fashion on a metal substrate. Layers are deposited with a minimum thickness of 10μm. The melt pool temperature is between 1000°C and 1800°C, depending on the material (e.g. H13 tool steel, Titanium alloy), but is less than 2000°C. A commercial powder delivery system, designed for plasma-spraying processes carries the steel or titanium powder to the substrate via argon. The cladding head is mounted to the z-axis of the Fadal VMC to fully utilize the motion system and provide the opportunity to machine the fabricated part at any point in the deposition process by applying a translation algorithm. The beam focusing optics, beam splitter for out-coupling the process radiation from the laser beam path, water cooling connections, powder feeder connections, and various sensors (optional) are located within the cladding head. Built in to the cladding head are pathways for metal powder to travel through to the laser beam path in a concentric form, therefore, releasing metal powder in a uniform volume and rate. Quartz glass is used to focus the laser beam and water carried from the chiller to the cladding head by small plastic hoses reduces the wear on the focusing optics. Overall, the LMD subsystem includes equipment for lasing, cooling, and powder material delivery.

Control of the hybrid manufacturing subsystems require a versatile industrial controller and a range of sensors to acquire feedback. The National Instruments Real Time Control System (NI RT System) provides analog and digital I/O ports and channels, DAC, RS-232, and ADC for controlling all the subsystems of the hybrid system. The control system contains a PXI-

8170 Processor, 8211 Ethernet card, 8422 RS-232 card, 6527 Digital I/O card, 6711 Analog Output card, 6602 Timing I/O card, 6040E Multi-function card, and an SCXI Controller with 1304 card. PCI eXtensions for Instrumentation (PXI) is a PC-based platform for measurement and automation systems. PXI combines PCI electrical-bus features with the modular, Eurocard packaging of Compact PCI, and then adds specialized synchronization buses and key software features. Signal Conditioning Extension for Instrumentation (SCXI) is a front-end signal conditioning and switching system for various measurement devices, including plug-in data acquisition devices. Our control system offers modularity, expandability, and high bandwidth in a single, unified platform.

System feedback is acquired through temperature and laser displacement sensors. An Omron Z4M-W100 laser displacement sensor is used to digitally determine the cladding head height above the substrate. There are danger zones and safe zones that the nozzle can be with respect to the substrate. Output of the displacement sensor is -4 to +4 VDC which is converted into a minimum and maximum distance value, respectively. The temperature sensor is a Mikron MI-GA5-LO non- contact, fiber-optic, infrared temperature sensor. It was installed onto the Z-axis of the VMC with a custom, adjustable fixture. The set-up for data acquisition of the melt pool temperature, while deposition takes place is at an angle of 42°, 180 mm from the melt pool and sampling every 2 ms. There is also a machine vision system, a Fastcom iMVS-155 CMOS image sensor, to watch the melt pool in real-time. It has also been used to monitor melt pool geometry and assist with our empirical approach to fine tune process parameters.

5. Hybrid manufacturing system design and development

The critical success factors of an integrated system are quality, adaptability, productivity and flexibility (Garelle & Stark, 1988). Inclusion of additive fabrication technology in a traditional subtractive manufacturing system inherently addresses these four factors. Nevertheless, considering the four success factors during the initial design phase will ensure that the resultant manufacturing system will meet short and long term expectations, be reliable, and mitigate system obsolescence. In order for hybrid manufacturing systems to become a widespread option they must also be an economical solution. Dorf and Kusiakpoint out that the three flows within a manufacturing system i.e. material, information, and cost, which “should work effectively in close cooperation for efficient and economical manufacturing” (Dorf & Kusiak, 1994). This section reviews the qualitative and quantitative modeling efforts of material and information as well as the system architecture design that incorporates the knowledge gained through modeling. Cost modeling for the hybrid system has only been temporal, however, a cost benefit analysis as proposed in (Nagel & Liou, 2010) could be performed to quantify the savings.

5.1 System architecture

Initially, the LAMP system design was integrated only through the physical combination of the laser metal deposition process (additive manufacturing) and the machining center (subtractive manufacturing). Also, each subsystem housed a separate controller, including the LMD and VMC, which required manual control of the hybrid system. Reconfiguring the LAMP hybrid system to utilize a central control system, increased communication between the subsystems and eliminated the need for multiple people. Moreover, the process can be controlled and monitored from a remote location, increasing the safety of the manufacturing process. The hybrid manufacturing system architecture follows the modular, integration element structure as defined in (Nagel & Liou, 2010). Figure 2 shows the direct mapping of customer needs and requirements to the overall system architecture as well as the dependency relationships. Build geometry, surface finish, and material properties are the needs relating directly to the finished product. Efficient operation and flexibility are the system requirements to be competitive and relate directly to the system itself.

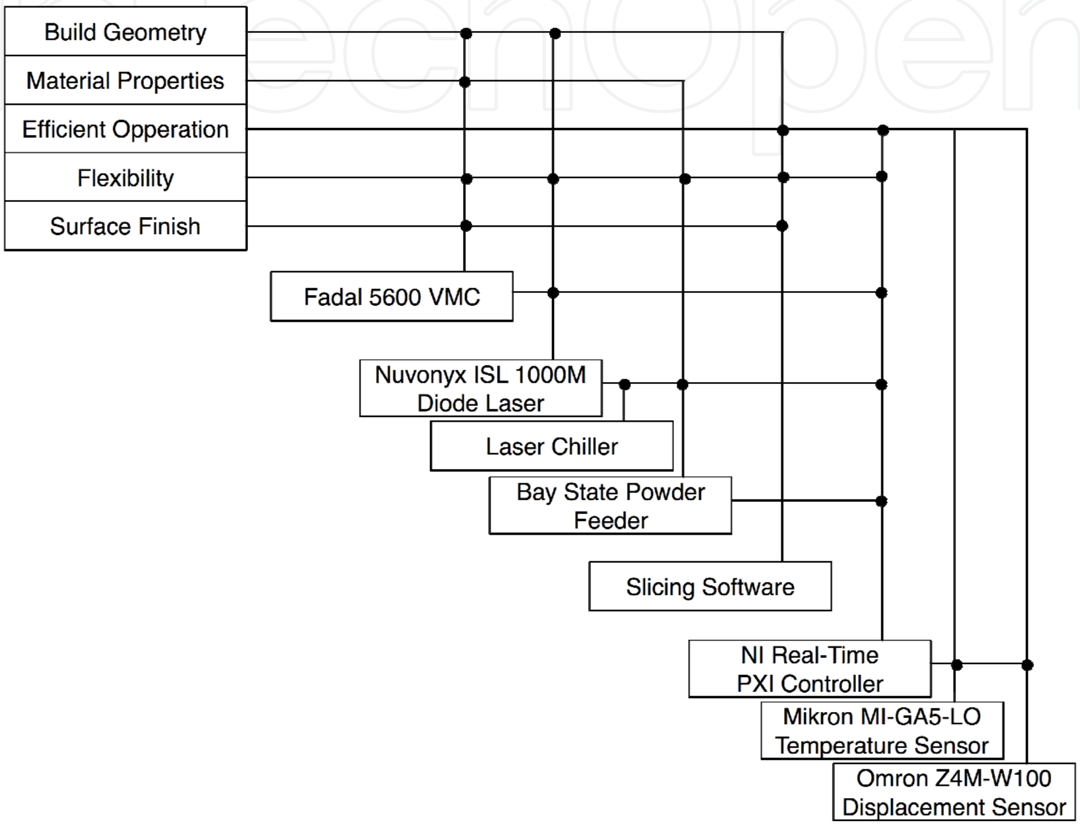


Fig. 2. LAMP Hybrid System Architecture

5.2 Qualitative modeling

Qualitative modeling efforts are focused on understanding process parameters and the flow of the process. Modeling the process parameter interactions uncovers the independent and dependent process parameters where as modeling the manufacturing process identifies opportunities for optimization. The following subsections summarize how qualitative modeling has been used to gain knowledge of the relationships among process parameters and resources utilized in each step of the hybrid manufacturing process.

5.2.1 Independent process parameters

The major independent process parameters for the hybrid manufacturing system include the following: laser beam power, process speed, powder feed rate, incident laser beam diameter, and laser beam path width (path overlap) as shown in Fig. 3 (Liou et al., 2001). Other parameters such as cladding head to surface distance (standoff distance), carrier gas flow rate, absorptivity, and depth of focus with respect to the substrate also play important roles.

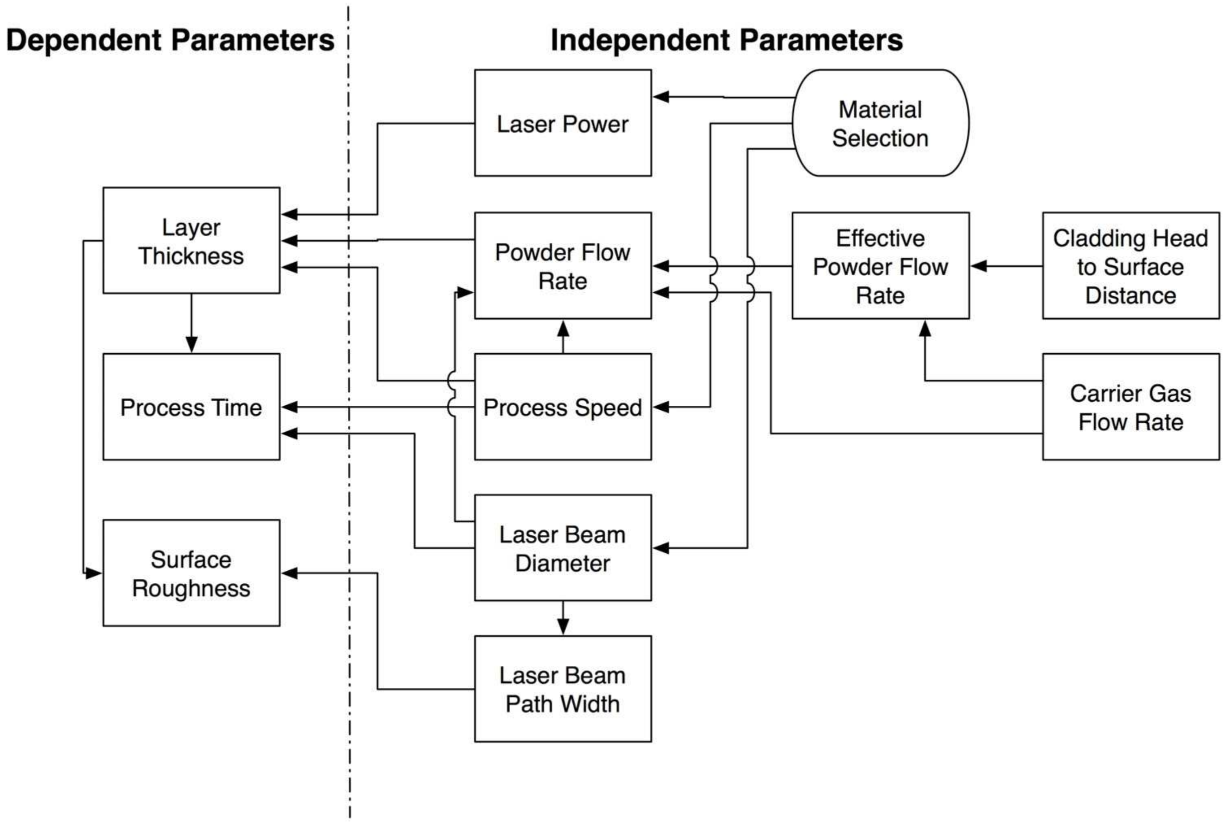


Fig. 3. LAMP Hybrid System Process Parameters (Adapted from Liou et al., 2001)

The layer thickness process parameter 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 deposition rate increased with increasing laser power (Weerasinghe & Steen, 1983).

Powder mass flow rate is another important process parameter which directly affects layer thickness. However, effective powder flow rate, which includes powder efficiency during the LMD process, turned out to be a more important parameter (Lin & Steen, 1998; Mazumder et al., 1999). Also the factor that most significantly affected the percent powder utilization was laser power. The cladding head nozzle is set up to give a concentric supply of powder to the melt pool, and due to the nature of the set-up, the powder flow is hour glass-shaped. The powder flow initially is unfocused as it passes through the cladding head, but the nozzle guides the powder concentrically towards its center, and essentially "focuses" the beam of powder. The smallest diameter focus of the powder "beam" is dependent upon the design of the cladding head nozzle. Also, if the laser beam diameter becomes too small as compared to the powder beam diameter, e.g., 100μm, much of the supplied powder will not reach the melt pool. Thus, there will be unacceptably low powder utilization.

Process speed has a big impact on the process output. In general, decreasing process speed increases the layer thickness. There is a threshold to reduce process speed, however, as too much specific energy (as defined in Section 5.2.2) will cause tempering or secondary hardening of previous layers (Mazumder et al., 1997). Process speed should be well chosen since it has strong influence on microstructure.

The laser beam diameter parameter is one of the most important variables because it determines the power density. It can be difficult to accurately measure high power laser beams. This is partly due to the shape of the effective beam diameter (e.g., Gaussian, Top hat) and partly due to the definition of what is to be measured. Single isotherm contouring techniques such as charring paper and drilling acrylic or metal plates are well known but 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.

Beam path width or beam width overlap has a strong influence on surface roughness. As the deposition pass overlap increases, the valley between passes is raised due to the overlap therefore reducing the surface roughness. Powder that has adhered to the surface, but has not melted will be processed in successive passes. In order to obtain the best surface quality, the percent pass overlap should be increased as much as possible. Conversely, to decrease the surface roughness, the deposition layers should be kept as thin as possible.

5.2.2 Dependent process parameters

The major dependent process parameters of the hybrid manufacturing system are: layer thickness, surface roughness, and process time (Fig. 3). Other dependent parameters such as hardness, microstructure, and mechanical properties should also be considered, but in this chapter we will focus only on the parameters related with physical dimension.

There is a large range of layer thicknesses as well as deposition rates that can be achieved using LMD. However, part quality consideration puts 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: $SE = p/(Dv)$, 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 the same as the nominal laser power measured from a 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, there is a positive linear relationship between the layer thickness and adjusted specific energy for a range of powder mass flow rates (Liou et al., 2001).

Surface roughness was found to be highly dependent on the direction of measurements with respect to the deposited metal (Liou et al., 2001; Mazumder et al., 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 thin walls. Since the largest roughness on each sample is of primary interest, measurements should be only taken perpendicular to the deposition direction on the top surface and in the vertical direction on the walls, based on our experiments.

The overall deposition processing time is mainly dependent upon the layer thickness per slice, process speed, and laser beam diameter. The processing conditions need to be optimized prior to optimizing the processing time, since the processing time is directly influenced by the processing conditions. If the laser beam diameter is increased, the specific energy and power density will be decreased under the same process condition, that means, a lower deposition rate unless the laser power and powder mass flow rate are increased correspondingly. Similarly, when the process speed is increased the independent process parameters should be optimized accordingly.

5.2.3 Process modeling

Process modeling used to model the hybrid manufacturing system aims to optimize the sequence with which the material flows through the system (Shunk, 1992; Wang, 1997). Following the process modeling approach by (Nagel et al., 2009), process events and tasks within each event were identified. Part A of Fig. 4 shows the manually controlled hybrid manufacturing process. Decomposition of the system process aided with identification of integration points to reduce the number of steps and events within the process resulting in significant time savings. Part B of Fig. 4 shows the optimized process.

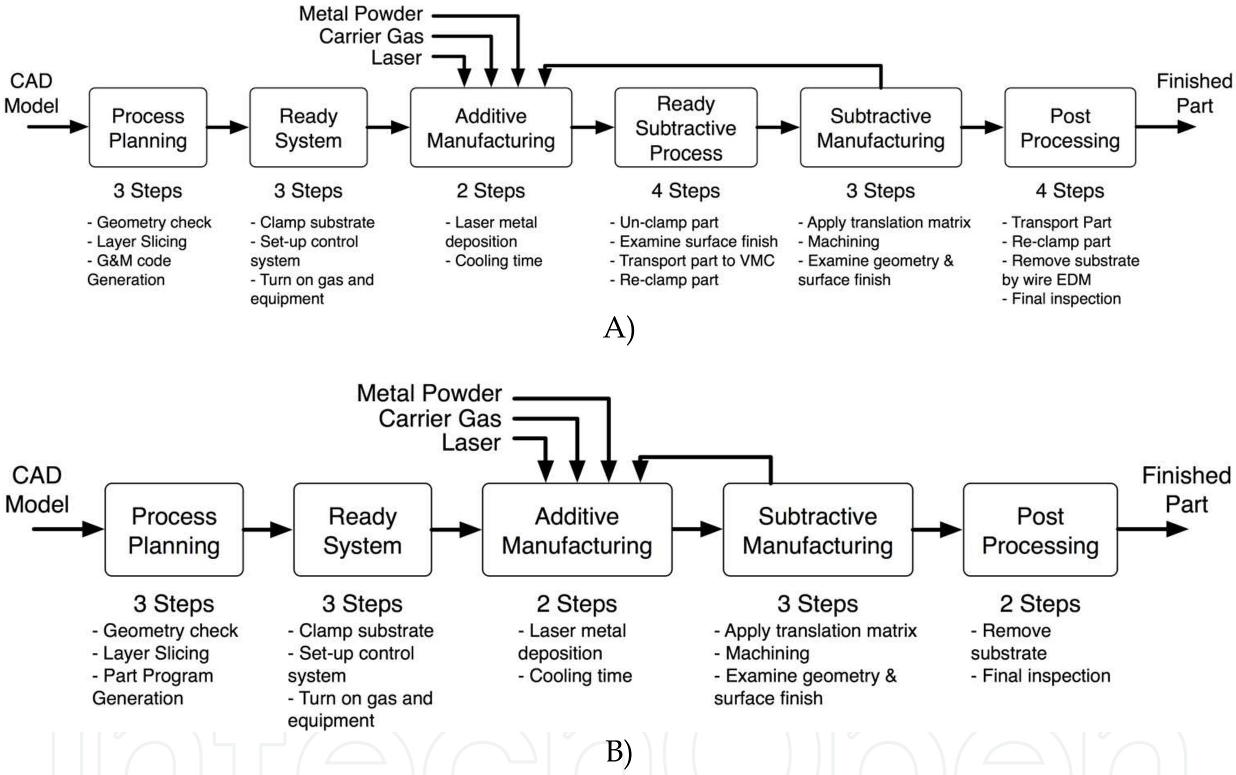


Fig. 4. LAMP Hybrid System Process Models, A) Before integration and optimization, B) After integration and optimization

Once the process is clearly laid out, the motion system and control system can be accurately defined. Reconfiguring the LAMP hybrid system elements to utilize a central control system increased communication between the subsystems and eliminated the need for multiple people. Moreover, the process can be controlled and monitored from a remote location, increasing the safety of the manufacturing process. Supplementary improvements were made to the process planning software, laser metal deposition subsystems, and the VMC. In efforts to eliminate the separate VMC computer, required only to upload machine code via direct numerical control, the RS-232 communication protocol utilized by Fadal was reverse engineered and implemented via LABVIEW. The laser, cooling, and powder material delivery subsystems of the laser metal deposition process are equipped with external control ports, but were not utilized in previous system configurations. Subsequently, all subsystems and modules were directly connected to the control system hardware so external control could be utilized. Initializing communications among the LAMP subsystems became the foundation for the control system software. Off-line, the in-house layered manufacturing software only converted CAD models into layer-by-layer slices of machine code to create the tool path. With the central control system now in place, the in-house layered manufacturing software was changed to generate machine code, laser power, and powder flow commands, which together comprise a part program and are distributed via the control system software. Overall, manufacturing process integration has resulted in modularity, easy maintenance, and process improvement. Thus, increasing system productivity and capability.

5.3 Quantitative modeling and simulation

Quantitative modeling and simulation provides a theoretical foundation for explaining the phenomena observed through empirical research. Additionally, detailed modeling assists with developing a quantitative understanding of the relationship between independent process parameters and dependent process parameters. Understanding the relationships among parameters affords accurate control of physical dimension and material properties of the part. While separate modeling efforts were undertaken, outputs of one model feed into another. The following subsections summarize how quantitative modeling has been used to develop a theoretical understanding of the LAMP hybrid manufacturing process.

5.3.1 Melt pool modeling and simulation

Melt pool geometry and thermal behavior control are essential in obtaining consistent building performances, such as geometrical accuracy, microstructure, and residual stress. A 3D model was developed to predict the thermal behavior and geometry of the melt pool in the laser material interaction process (Han et al., 2005). The evolution of the melt pool and effects of the process parameters were investigated through modeling and simulations with stationary and moving laser beam cases.

When the intense laser beam irradiates on the substrate surface, the melt pool will appear beneath the laser beam and it moves along with the motion of the laser beam. In order to interpret the interaction mechanisms between laser beam and substrate the model considers the melt pool and adjacent region. The governing equations for the conservation of mass, momentum and energy can be expressed in following form:

$$\frac{\partial}{\partial t}(\rho) + \nabla \cdot (\rho \mathbf{V}) = 0 \tag{1}$$

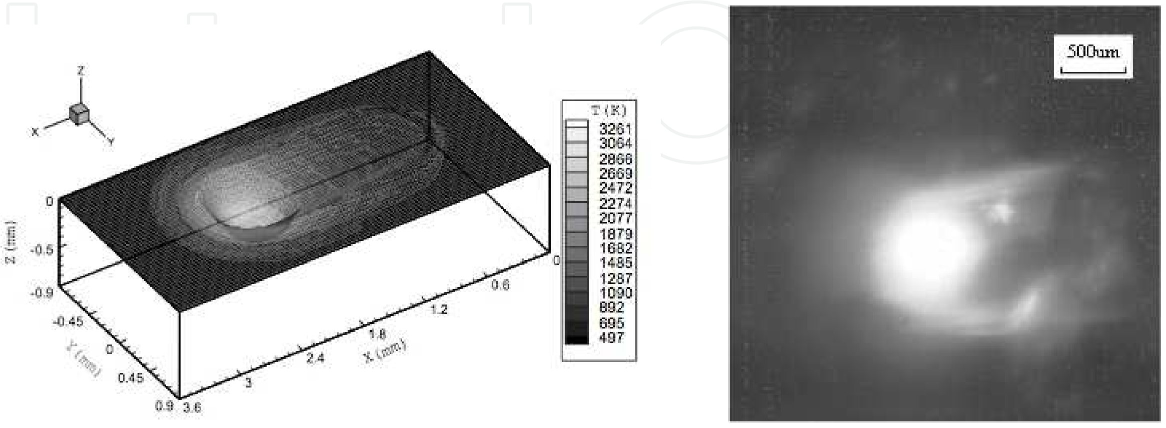
$$\frac{\partial}{\partial t}(\rho \mathbf{V}) + \nabla \cdot (\rho \mathbf{V}\mathbf{V}) = \nabla \cdot (\mu_l \frac{\rho}{\rho_l} \nabla \mathbf{V}) - \nabla p - \frac{\mu_l}{K}\frac{\rho}{\rho_l}(\mathbf{V} - \mathbf{V}_s) + \rho g \tag{2}$$

$$\frac{\partial}{\partial t}(\rho h) + \nabla \cdot (\rho \mathbf{V} h) = \nabla \cdot (k \nabla T) - \nabla \cdot (\rho (h_l - h)(\mathbf{V} - \mathbf{V}_s)) \tag{3}$$

where ρ, **V**, *p*, μ, *T*, *k*, and *h* are density, velocity vector, pressure, molten fluid dynamic viscosity, temperature, conductivity, and enthalpy, respectively. *K* is the permeability of mushy zone, **V***s* is moving velocity of substrate with respect to laser beam and subscripts of *s* and *l* represent solid and liquid phases. Since the solid and liquid phases may coexist in the same calculation cell at the mushy zone, mixed types of thermal physical properties are applied in the numerical implementation. The liquid/vapor interface is the most difficult boundary for numerical implementation in this model since many physical phenomena and interfacial forces are involved there. To solve those interfacial forces the level set method is employed to acquire the solution of the melt pool free surface (Han et al., 2005). To avoid numerical instability arising from the physical property jump at the liquid/vapor interface, the Heaviside function $H(\varphi)$ is introduced to define a transition region where the physical properties are mollified.

The energy balance between the input laser energy and heat loss induced by evaporation, convection and radiation determines surface temperature. Laser power, beam spot radius, distance from calculation cell to the beam center, and the absorptivity coefficient are used to calculate the laser heat influx. Heat loss at the liquid/vapor interface is computed in terms of convective heat loss, radiation heat loss and evaporation heat loss. The roles of the convection and surface deformation on the heat dissipation and melt pool geometry are revealed by dimensionless analysis. It was found that interfacial forces including thermo-capillary force, surface tension and recoil vapor pressure considerably affect the melt pool shape and fluid flow. Quantitative comparison of interfacial forces indicates that recoil vapor pressure is dominant under the melt pool center while thermo-capillary force and surface tension are more important at the periphery of the melt pool.

For verification, the intelligent vision system was utilized to acquire melt pool images in real time at different laser power levels and process speeds, and the melt pool geometries were measured by cross-sectioning the samples obtained at various process conditions (Han et al., 2005). Simulation predictions were compared to experimental results for both the stationary laser case and moving laser case at various process conditions. Model prediction results strongly correlate to experimental data. An example of melt pool shape comparison between simulation and experiment for the moving laser beam case is shown in Fig. 5.

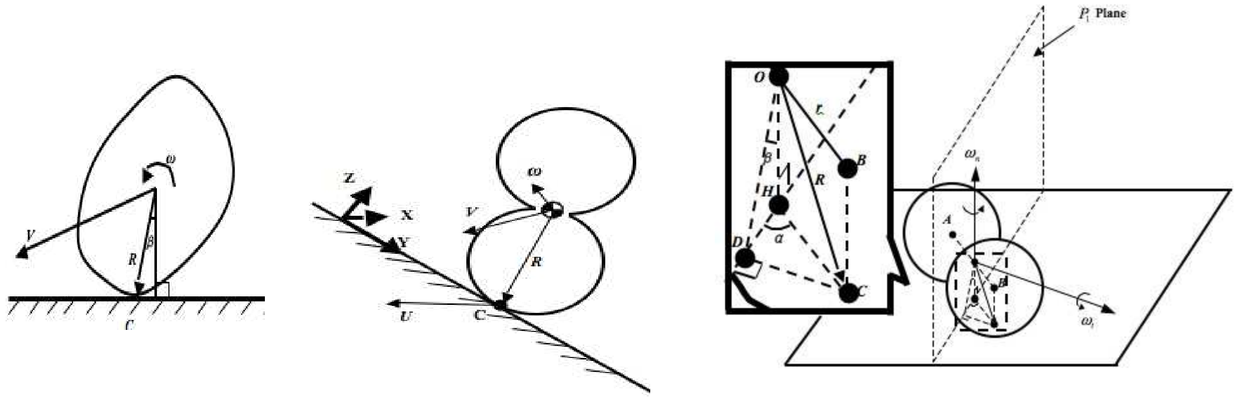


A) B)

Fig. 5. Melt pool shape comparison, A) Simulation result of melt pool shape and surface temperature, B) Experimental result of melt pool shape (Adapted from Han et al., 2005)

5.3.2 Powder flow dynamics modeling and simulation

Analysis of metallic powder flow in the feeding system is of particular significance to researchers in order to optimize the LMD fabrication technique. Powder flow simulation holds a critical role in understanding flow phenomena. A stochastic Lagrangian model for simulating the dispersion behavior of metallic powder, or powder flow induced by non-spherical particle-wall interactions, is described (Pan & Liou, 2005). The numerical model also takes into consideration particle shape effects. In wall-bounded, gas-solid flows, the wall collision process plays an important role and is strongly affected by particle shape. Non-spherical effects are considered as the deviation from pure spheres shows induced particle dispersion, which has a great impact on the focusibility of the powder stream at the laser cladding head nozzle exit. The parameters involved in non-spherical collision are analyzed for their influencing factors as well as their interrelations.



A) B) C)

Fig. 6. Particle Collision Diagrams, A) 2D non-spherical particle-wall collision model, B) Local coordinate for collision model, C) of 3-D non-spherical particle-wall collision model (Adapted from Pan & Liou, 2005)

The parameters involved in the 2-D non-spherical model include β and R, as shown in Fig. 6, Part A, where β indicates how much the contact point C deviates from the foot of a vertical from the gravity center of the particle and R shows the actual distance between the contact point and the gravity center. The collision coordinate system used to describe the 3D collision dynamics is defined in Fig. 6, Part B. The contact velocity is computed from:

$$U = V + \omega \times R \tag{4}$$

where V is the particle translational velocity vector, ω is the angular velocity vector, and R is the vector connecting particle mass center to contact point C. The change in the contact point velocity can be obtained by the following equation:

$$\Delta U = [\frac{1}{m} I - R^{\times} J^{-1} R^{\times}] \Delta P \tag{5}$$

where m is particle mass, I is the 3x3 identity matrix, and R^x is the canonical 3x3 skew-symmetric matrix corresponding to R, ΔP denotes the impulse delivered to the particle in the collision, and J^{-1} is the inverted inertia tensor in the local coordinate. As shown in Fig. 6, Part C, a cluster that consists of two identical spheres with equal radius *r* represents the non-spherical powder particle of the 3D model. This representation leads to generalized modeling of satelliting metallic powder particles.

Wall roughness also effects powder dispersion behavior, therefore in this model the roughness effect was included by using the model and parameters proposed by (Sommerfeld & Huber, 1999). The instantaneous impact angle is assumed to be composed of the particle trajectory angle with respect to the plane wall and a random component sampled from a Gaussian distribution function. It was also assumed that each collision has 30% possibility to be non-spherical, which implies the stochastic model was applied in 30% of the total collisions during the feeding process simulation. Simulations using the spherical model (0% non-sphericity) were also conducted.

The non-spherical model successfully predicts the actual powder concentration profile along the radial and axial directions, whereas the spherical particle model underestimates the dispersion and results in a narrow spread of the stream along the radial direction. When compared to the experimental results, the 3D simulated powder stream is in strong agreement, which demonstrates validation of the model. The model also predicts the peak powder concentration or focal point of the power stream for specific cladding head nozzle geometry. It is essential to establish a well-focused powder stream at the exit of the nozzle and to know the ideal stand-off distance in order to increase powder catchment in the melt pool, achieve high material integrity, and reduce material waste.

5.3.3 Tool path modeling and simulation

Process planning, simulation, and tool path generation allows the designer to visualize and simulate part fabrication prior to manufacturing to ensure a successful process. Adaptive multi-axis slicing, collision detection, and adaptive tool path pattern generation for LMD as well as tool path generation for surface machining are the key advantages to the integrated process planning software developed for the LAMP hybrid system (Ren et al., 2010).

Basic planning steps involve determining the base face and extracting the skeleton of an input CAD model (Fig. 7, top left). The skeleton is found using the centroidal axis extraction algorithm (Fig. 7, top right). Based on the centroidal axis, the part is decomposed into sub-components and for each sub-component a different slicing direction is defined according to build direction. In order to build some of the components, not only translation but also rotation will be needed to finish building the whole part because different sub-components have different building directions (Fig. 7, bottom middle), and the laser nozzle direction is always along the z-axis. After the decomposition (Fig. 7, bottom left) results are obtained, the relationship among all the components is determined, and a building relationship graph is created.

From the slicing results and build directions, collision detection is determined. Collision detection is implemented by Boolean operation, which is an intersection operation, on a simulation (Ren et al., 2010). If the intersection result of the updated CAD model and the cladding head nozzle is not empty, then collision will happen in the real deposition process. The deformation of the CAD model following the building relationship graph includes two categories: positional deformation and dimensional deformation. Positional change means translation or rotation of the CAD model. The dimensions will change after every slicing layer is finished. For every updated model, collision needs to be checked before the next slicing layer is added. Following the collision detection algorithm, if a potential collision is detected the sequence of the slicing layers is reorganized (Ren et al., 2010). The output of the collision detection algorithm will be the final list of slicing layers, which comprise the actual building sequence when manufacturing the part.

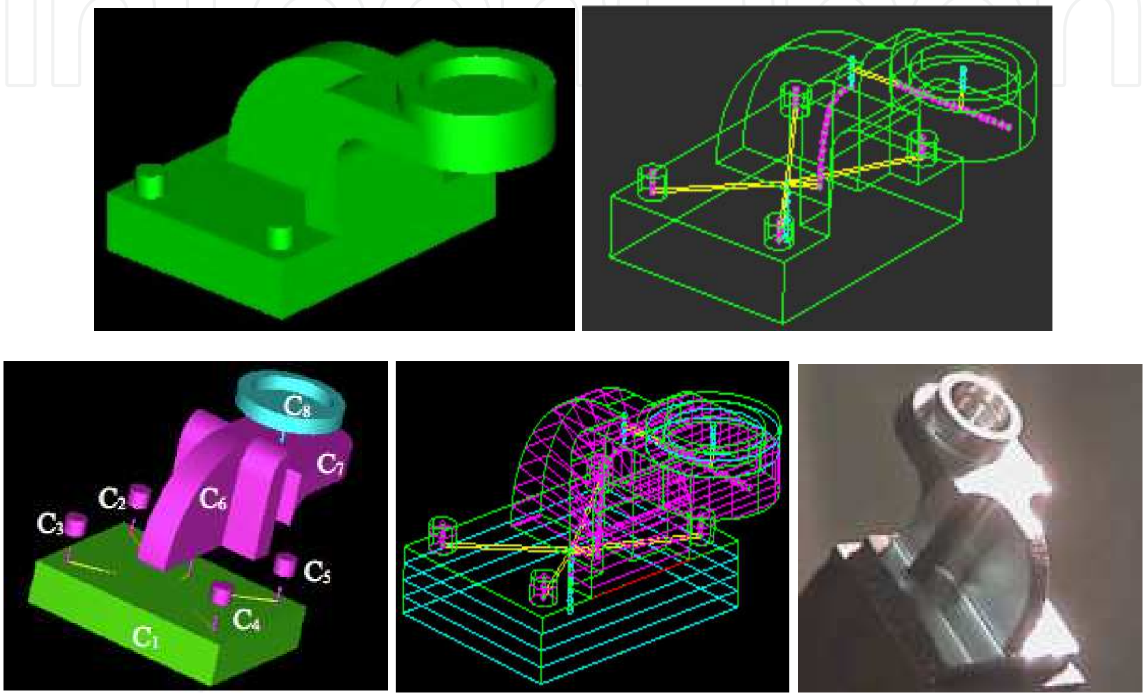


Fig. 7. Process Planning and Fabrication of 3D Part (Adapted from Liou et al., 2007; Ren et al. 2010)

The final piece of process planning is tool path generation. Common tool path patterns are the raster, contour-parallel offsetting, zig-zag, and interlaced. Each pattern has advantages and disadvantages. The adaptive deposition tool path algorithm considers each pattern when predicting the possibility of deposition voids. The goals of the algorithm are to adjust the tool path to remove deposition voids and increase time efficiency. Multiple tool path patterns may be used during fabrication and the algorithm may also prescribe alternating the appropriate tool path pattern when necessary.

Surface finish machining is a sequential step used after deposition to improve manufacturing quality after deposition is finished. The process planning software allows the designer to specify the machining parameters including the feed rate, spindle speed, and depth of cut before determining the number of machining cycles necessary. As with LMD, alignment will be also integrated for 3D geometries to achieve the accuracy without reloading the deposited part to be machined. Again, the tool path will be generated such that a collision-free machining tool path will be generated for the deposited part. A visibility map algorithm (Ruan & Liou, 2003) is applied to detect the collision between the tool and the deposited part.

The final process planning step is to generate the part program. This step is the bridge between the algorithmic results of process planning, quantitative modeling of process parameters, and the realistic operational procedures as well as parameters of the 5-axis manufacturing environment. It will build the map of the process planning results and the real operational parameters and then interpret the final planning tool path as the corresponding movements of the hybrid manufacturing system. The software will combine and refine those movements and translate them into machine executable code. Resulting in a text file composed of three columns of data to needed for the control system to command the laser, powder feeder, and motion system (Ren et al., 2010). The final set of operations is based on the building relationship graph, build directions that avoid collisions, tool path, and time required.

6. Hybrid manufacturing system integration

During the course of this research several integrated manufacturing system designs were analyzed to identify what characteristics comprise a successful hybrid system. Based on this background research, and the experiences of working with and refining the LAMP system, the key elements of a hybrid manufacturing system were identified. The five key elements represent an effective way to design a hybrid manufacturing system, as compared to a reconfigurable or mechatronic design, because the identified elements contain necessary subsystems, are easily modularized, and advocate the use of off-the-shelf hardware and software. Within an integrated system, each element acts as a separate subsystem affording a stable modular design (Gerelle & Stark, 1988).

A strategy for controlling the integrated LMD and machining processes, the 5-axis motion system, and the data corresponding streams provides the basis for fully automating the system. Considering scalability, our integration strategy emphasizes modularity of the integrated components but also modularity of the controlling software. Our control strategy allows data streams to be easily added or removed. Furthermore, our design allows an operator to optimize the control strategy for a particular geometry.

6.1 Physical Integration

Obstacles arise during the development of any manufacturing system; however, by identifying obstacles and solutions the industry as a whole can benefit. Outside of cost and yield, the obstacles of developing a hybrid manufacturing system discussed here cover a range of topics. Table 2 summarizes the obstacles associated with the physical integration of the LAMP hybrid system and provides documented solutions. The documented information in Table 2 does not address every possible integration obstacle, but is meant to be comprehensive from what is found in the literature and personal experience. Issues outside of integration, such as material properties can be found in (Nagel & Liou, 2010).

After central control, integration, and modularity were enforced in the LAMP hybrid system, manufacturing defects and time were significantly reduced, and safety was significantly increased. Material integrity was improved as the laser could be precisely commanded on/off or pulsed as needed during deposition. Furthermore, by integrating the laser power and powder flow commands into the process planning software and automating the distribution of commands, functionally graded parts were manufactured effortlessly.

Issue	Solution	Result	Reference
Adding the laser cladding head to a VMC	A platen with precisely tapped holes for the cladding head mounted to the Z-axis of the VMC	Laser cladding head is securely mounted and future equipment or fixtures can be added	
Protection of Equipment	Retract laser head or position it far enough away from the machining head	Protect laser nozzle	Kerschbaumer & Ernst, 2004
	Mount a displacement sensor on the Z-axis	When cladding head gets too close to X-Y axes the process halts	
Unknown communication protocol	Use reverse engineering to figure out communication protocol	Subsystems can be controlled from a central control system	Stroble et al., 2006
Quality control	Implement control charts, pareto charts, etc.	Manual quality control	Starr, 2004
	Sensor feedback utilized by closed-loop controllers	Automated quality control	Boddu et al., 2003; Doumanidis & Kwak, 2001; Hu & Kovacevic, 2003; Tang, 2007
Transition between additive and subtractive processes	Apply a translation matrix that repositions the X-Y axis for the desired process	Accurate positioning for machining or LMD	
Placement of sensors to monitor melt pool due to high heat of the LMD process	Mount the sensitive vision system in-line with the laser using a dichromatic mirror attachment for the cladding head, and custom hardware mounted to the platen holds the temperature probe at an acceptable viewing angle	Sensors are safe, and the LMD process is accessible	Boddu et al., 2003; Tang & Landers, 2010

Table 2. Physical Integration Issues and Solutions

6.2 Software Integration

Utilization of a central control system directly resulted in automation of the LAMP hybrid system and allowed unconventional possibilities to be explored. To achieve the central controller, a framework consisting of a multi-phase plan and implementation methodology was developed. The automation framework involves controlling the laser, powder feeder, and motion system, and utilizing sensor feedback, all through the NI PXI control subsystem. Open and closed-loop controllers were designed, along with compatibility and proper module communication checking. Moreover, compensation for undesired system dynamics, delays and noise were considered to ensure a reliable and accurate automated manufacturing process. The result of the automation framework is an automated deposition program (developed in LabVIEW) with a customized graphical user interface and data recording capabilities.

Figure 8 is a visual description of the LAMP hybrid system communications layout, including process planning that occurs outside the control system. Once process planning completes the part program, with laser power and powder mass flow rate commands in the form of voltages, the control system parses through the information to automatically fabricate the desired part. While commands are being sent to the physical devices, sensors are monitoring the process and sending feedback to the control system simultaneously, allowing parameters to change in real-time.

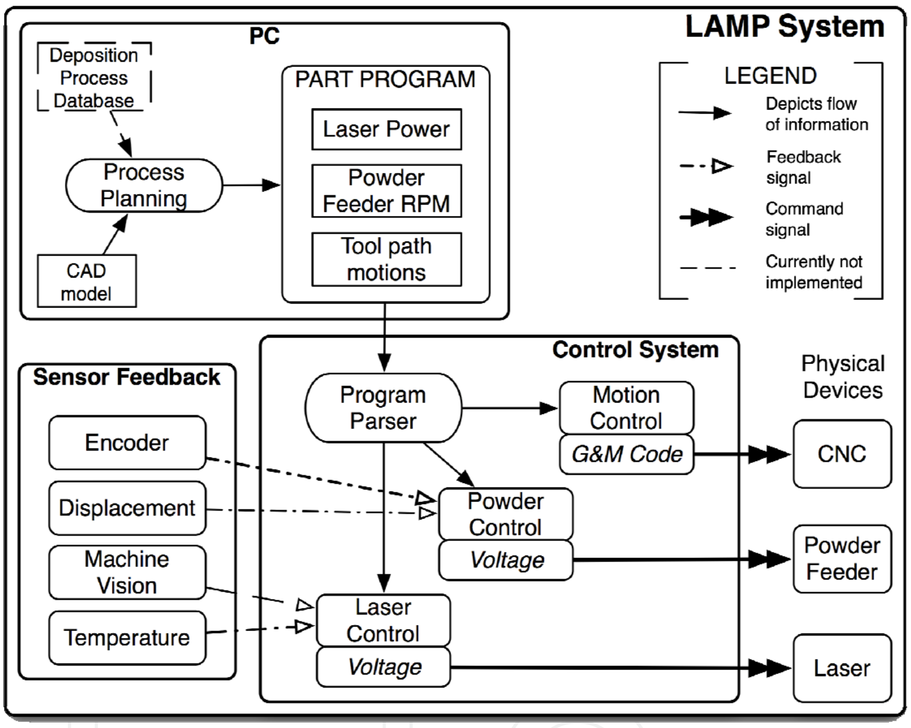


Fig. 8. LAMP Hybrid System Communication Schematic

Unique to the LAMP hybrid system is that the hardware and software are both modular. The automated deposition program that is executed by the control system has three different modes: dry-run, open-loop control, and closed-loop control. Fundamental code within the automated deposition program is shared amongst each of the modes, much like the control system is central to the LAMP hybrid system. Additional portions of code that control the laser, control the powder feeder, utilize feedback, or simply read in, display and record data from sensors are turned on or off by each mode. Code modularity prevents large amounts of the control system software from being rewritten when equipment is upgraded or subsystems are replaced.

During dry-run mode only machine code is distributed by the control system, allowing the user to monitor the VMC motions without wasting materials and energy. This mode is primarily utilized to check uncertain tool paths for instances when the laser should be shut off or when a tool path transition seems too risky. For instance, transitions from one geometry to another may rotate longer than desired at one point causing a mound to form and solidify, which destroys the overall part geometry and could collide with the laser cladding nozzle. Open-loop and closed-loop control modes are provided for fabricating parts and include system monitoring and data acquisition features. The modular software allows multiple closed-loop controllers optimized for a particular geometry to be added as research is completed, such as a feed forward controller (Tang et al., 2007) that regulates powder flow to the melt pool for circular, thin walled structures or thin walled structures with many arcs.

7. Conclusion

In an effort to shorten the time-to-market, decrease the manufacturing process chain and cut production costs, research has focused on the integration of multiple manufacturing processes into one machine; meaning less production space, time, and manpower needed. An integrated or hybrid system has all the same features and advantages of rapid prototyping systems, plus provides a new set of features and benefits. Moreover, hybrid manufacturing systems are increasingly being recognized as a means to produce parts in material combinations not otherwise possible and have the ability to fabricate complex internal geometries, which is beyond anything that can be accomplished with subtractive technologies alone. Internal geometries such as complex conformal cooling channels provide better product thermal performance, which additive fabrication processes create them with ease, giving the manufacturer a better product with little extra cost. As manufacturers and customers dream up more complex products, requiring more advanced equipment and software, hybrid systems will emerge. In short, integrating additive and subtractive technologies to create new manufacturing systems and processes is going to advance the manufacturing industry in today’s competitive market.

Modeling and simulation, both qualitative and quantitative, were shown to be an integral part of hybrid system design and development as well as motivate areas of research that a pure empirical approach does not reveal. Although this research is focused on integrating additive and subtractive processes, the general principles can also be applicable to integrating other unit manufacturing processes (NRC, 1995). Integrated processes can combine multiple processes that fall within the same family, such as different material removal processes, or they can combine processes that are in different unit process families, such as a mass-change process and a microstructure-change process. The results can lead to significant processing breakthroughs for low-cost, high-quality production.

Future work includes applying integrated process and product analysis to various hybrid processes that integrate different manufacturing processes and applying the hybrid system concept to other types of configurations, such as those that include robots. Model-based simulation reveals various new opportunities for simultaneous improvement of part quality, energy and material efficiencies, and environmental cleanness. Thereby, accelerating the hybrid integration process. Other work includes applying an open architecture for the hybrid controller, as such an architecture avoids the difficulties of using proprietary technology and offers an efficient environment for operation and programming, ease of integrating various system configurations, and provides the ability to communicate more effectively with CAD/CAM systems and factory-wide information management systems.

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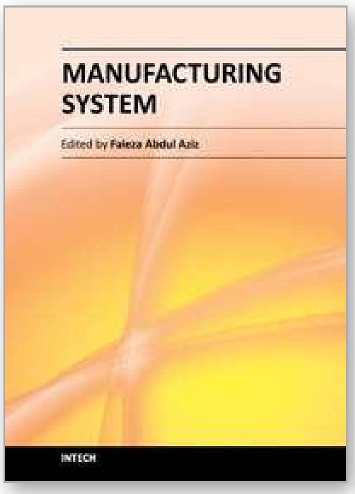

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This book attempts to bring together selected recent advances, tools, application and new ideas in manufacturing systems. Manufacturing system comprise of equipment, products, people, information, control and support functions for the competitive development to satisfy market needs. It provides a comprehensive collection of papers on the latest fundamental and applied industrial research. The book will be of great interest to those involved in manufacturing engineering, systems and management and those involved in manufacturing research.

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