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Applications of a Hybrid Manufacturing Process for Fabrication and Repair of Metallic Structures

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Abstract

Since its appearance, rapid prototyping technology has been of interest to various industries that are looking for a process to produce/build a part directly from a CAD model in a short time. Among them, the direct metal deposition process is the only process which directly manufactures a fully dense metal part without intermediate steps. However, challenges of the direct metal deposition process include building overhang structures, producing precision surfaces, and making parts with complex structures. Coupled between the additive and the subtractive processes into a single workstation, the integrated process, or hybrid process, can produce a metal part with machining accuracy and surface finish. Therefore, the hybrid process is potentially a very competitive process to fabricate and repair metallic structures. This paper summarizes the current development of the hybrid process to process high temperature metallic materials, including tool steel and Ti64. Research in simulation and modeling, process development, and actual part building and repair are discussed.

Introduction

For more than a decade, layered manufacturing technology, also known as Rapid Prototyping (RP) has given industry an approach to achieve the goal of providing products in a shorter time and at a lower cost. Most of the current RP systems are built on a 2.5-D platform. Among them, the laser-based deposition process is a potential technique that can produce fully functional parts directly from a CAD system and eliminate the need for intermediate steps. However, such a process is currently limited by the need for supporting structures – a technology commonly used in all the current RP systems. Support structures are not desirable for high strength and high temperature materials such as metals and ceramics since these support structures are very difficult to remove. Multi-axis systems can offer much more flexibility in building complex objects. Laser aided RP is advancing the state-of-the-art in fabrication of complex, near–net shape functional metal parts by extending the laser cladding concept to RP. The Laser Aided Manufacturing Process being developed in the Laser Aided Manufacturing Processes (LAMP) Laboratory at the University of Missouri-Rolla (UMR) combines laser deposition and machining processes to develop a hybrid rapid manufacturing process to build functional metal parts. This paper summarizes the research and applications of such a hybrid process for fabrication and repair of metallic structures.

A Hybrid Manufacturing System

In order to expand the applications of metal deposition processes, multi-axis capability is greatly needed. A multi-axis rapid manufacturing system can be hardware-wise configured by adding extra degrees of mobility to a deposition system or by mounting a laser deposition device on a multi-axis robot. The configuration could also be a hybrid system in which a metal deposition system is mounted on a multi-axis CNC machine. With the addition of extra rotations, the support structures may not be necessary for the deposition process in order to build a complicated shape. Figure 1 illustrates the process to build an overhang structure on a 2.5D and multi-axis deposition system. Due to the nature of the deposition process, it is driven by a so-called "slicing" procedure, which uses a set of parallel planes to cut the object to obtain a series of slicing layers. So far, the slicing software on the market is only able to handle 2.5D slicing in which the building/slicing direction is kept unchanged (usually Z+ direction) and it lacks the capability of changing directions to fully explore the capability of multiple degrees of freedom.

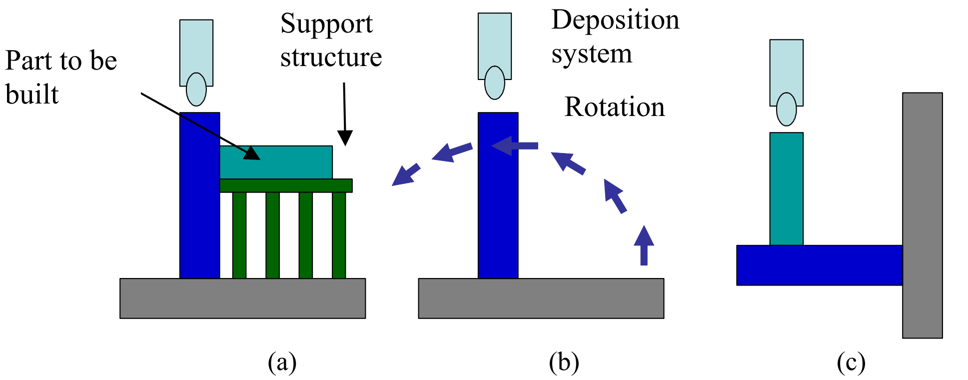


Fig 1. (a) build part with support structure; (b) with multi-axis capability, after building the column, the table can be rotated; (c) After rotation, continue to build the component from another direction.

This process uses laser deposition for material deposition and CNC milling for material removal. 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. In conventional 2.5-D laser deposition process to create three-dimensional parts, overhang and top surfaces of hollow parts need to 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 applications of the hybrid deposition-machining process, including laser deposition, sensing and control, and process planning.

Laser Deposition Research

Laser deposition is a solid freeform fabrication process that has the capability of direct fabrication of metal parts. The process uses a focused laser beam as a heat source to create a molten pool on an underlying substrate. Powder material is then injected into the molten pool through nozzles. The incoming powder is metallurgically bonded with the substrate upon solidification. The part is fabricated in a layer by layer manner in a shape that is dictated by the CAD solid model, which is sliced into thin layers orthogonal to the z-axis. After the slice data is then translated into laser scanning paths, an outline of each feature of the layer is generated and then the cross section is filled using a rastering technique to fabricate a single layer. After the deposition of a single layer, the subsequent layers are deposited by incrementing the nozzles and the focusing lens of the laser in the z-direction, until the three-dimensional part is completed. To successfully deposit powder material, in the laser deposition process, the powder beam and laser beam need to be carefully understood and controlled. Simulations of the phenomenon which occur during the laser deposition process are completed to increase knowledge of the process and measurements through sensors are conducted to validate those simulations. Research and modeling of the powder delivery system and laser-powder interaction process have been conducted.

The quality and efficiency of laser aided direct metal deposition largely depends on the powder stream structure below the nozzle. Numerical modeling of the powder concentration distribution is complex due to the complex phenomena involved in the two-phase turbulence flow. In this research, the gravity-driven powder flow is studied along with powder properties, nozzle geometries, and shielding gas settings [Pan05]. A 2-D non-spherical model includes β and R, as shown in Figure 2 and was used for powder simulation. In that model, the parameter β indicates how much the contact point C deviates from the foot of a vertical reference line through the particle gravity center and R shows the actual distance between the contact point and the gravity center. A random value of β can be used to model irregular bouncing. Realistic simulation normally requires the extension of 2-D models to 3-D.

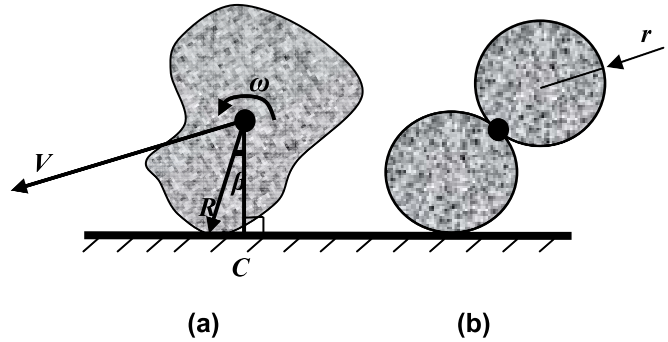


Fig 2. A 2-D non-spherical model was used to model powder flow.

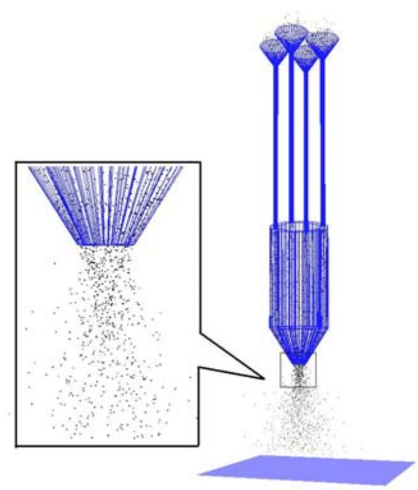


Fig 3. A 3-D simulation model to quantitatively predict the powder stream concentration variation for nozzle design and optimization.

A 3-D numerical model was used to quantitatively predict the powder stream concentration variation in order to facilitate coaxial nozzle design optimizations as shown in Figure 3. A commercial computational fluid dynamic (CFD) code, FLUENT, was used to solve the momentum and turbulence equations to obtain the flow field and predict particle phase motions. Effects of outer shielding gas directions, inner/outer shielding gas flow rate, powder passage directions and opening width on the structure of the powder stream have been systematically studied. A series of experimental studies is designed to determine the effects of the outer gas injection angle and outer gas flow rate on the particle concentration mode as well as to validate the simulation. Measurements are carried out at 30°

and 60° outer gas settings respectively. In each setting, the outer gas flow rate is varied for 8.5, 13.7 and 22.1 litres/min, while keeping the inner gas flow rate constant at 2.43 litres/min. These experimental conditions can be summarized in Table 1:

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
Nozzle angle	30°/60°	30°	30°	30°	60°	60°	60°
Inner gas (L/min)	0	2.43	2.43	2.43	2.43	2.43	2.43
Outer gas (L/min)	0	8.5	13.7	22.1	8.5	13.7	22.1

Table 1. Gas flow rates and directions used in experiments.

The numerical simulation results are compared to the experimental data using prototyped coaxial nozzles as shown in Figure 4. The results are found to match and then validate the simulation. This study shows that the particle concentration mode is influenced significantly by nozzle geometries and gas settings.

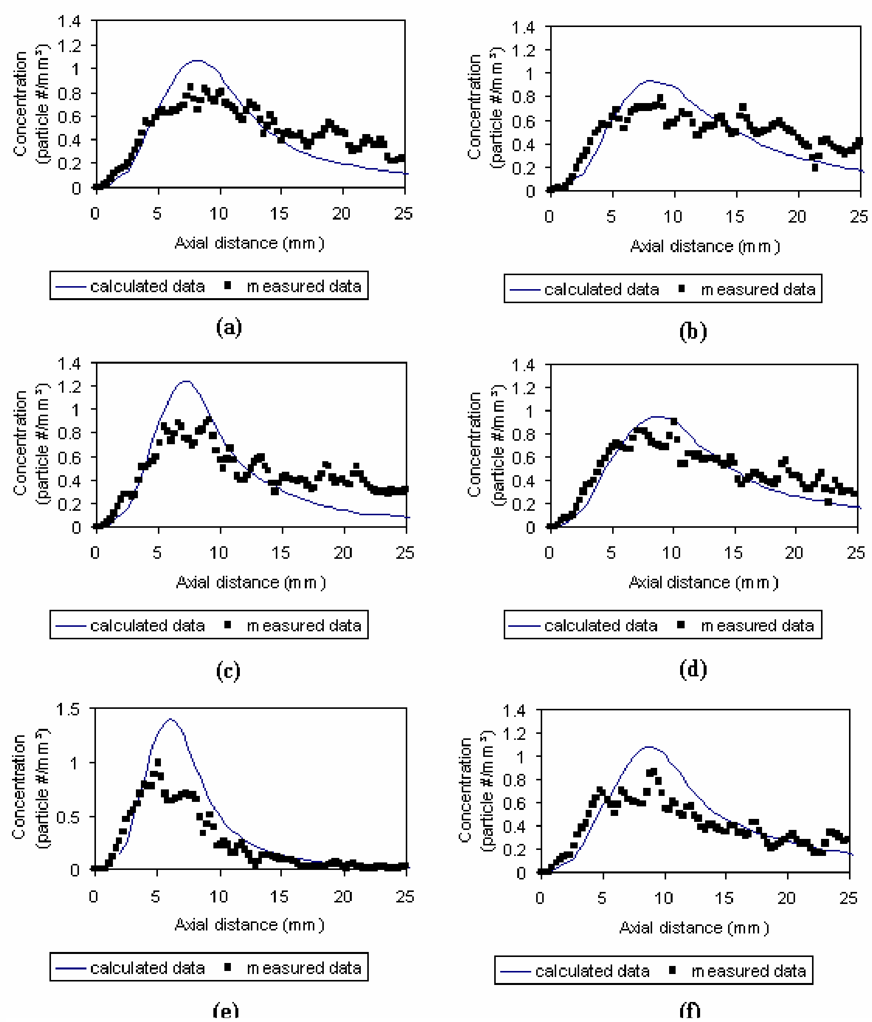


Fig. 4. Measured and calculated particle concentration variation along central axis. (a) case 2; (b) case 5; (c) case 3; (d) case 6; (e) case 4; and (f) case 7.

A melt pool formed during laser deposition is a critical factor and melt pool geometry is a crucial factor in determining clad quality. To obtain a high quality resulting part, a deep understanding of the underlying mechanisms is required. In this research, a mathematical model, as shown in Figures 5 and 6, was developed to simulate the coaxial laser cladding process with powder injection, which includes laser-substrate, laser-powder and powder-substrate interactions [Han04]. The model considers most of the associated phenomena, such as melting, solidification, evaporation, evolution of the free surface and powder injection. The fluid flow in the melt pool, which is mainly driven by the Marangoni shear stress as well as particle impinging, together with the energy balances at the liquid-vapor and the solid-liquid interfaces are investigated. Powder heating and laser power attenuation due to the powder cloud are incorporated into the model in the calculation of the temperature distribution. The influences of the powder injection on the melt pool shape, penetration, and flow pattern are predicted through the comparison for the cases with powder injection and without powder injection. Dynamic behavior of the melt pool and the formation of the clad are simulated. The effects of the process parameters on the melt pool dimension and peak temperature are further investigated based on the validated model.

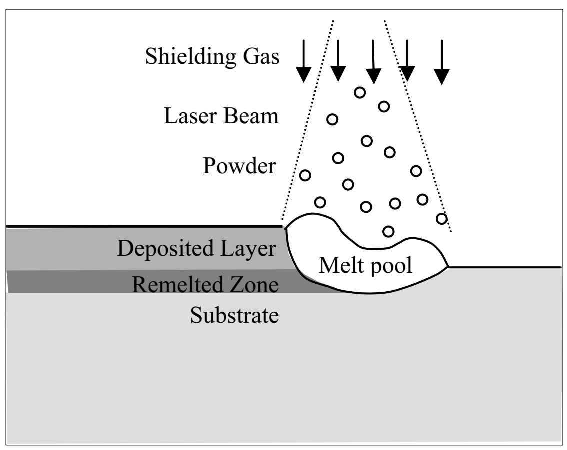


Fig. 5. Schematic diagram of the calculation domain for laser cladding process.

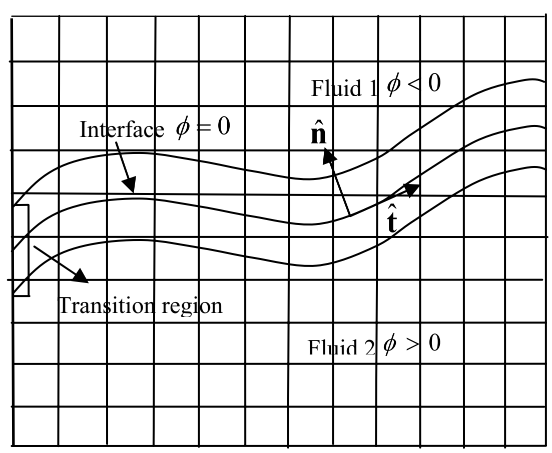


Fig. 6. Interface transition region.

In order to give the quantitative comparison, the clad height is calibrated accurately for a length of 5.5 mm starting from the deposition point, and the resulting comparison is presented in Figure 7. As seen in the plot, the simulation result agrees well with the experiment and the error of the average height is around 8.7 %. Four typical laser power levels, which are 300 W, 500 W, 750 W and 1000 W, were tested and the results are presented in Figures 8 and 9. It can be seen from the plot that although there is about 90 K over-prediction on average in peak temperature, the general trend between the simulation and experiment is consistent.

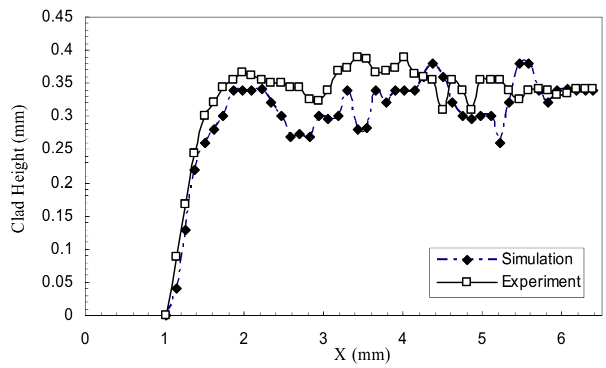


Fig. 7. Comparison of the clad height between simulation and experiment.

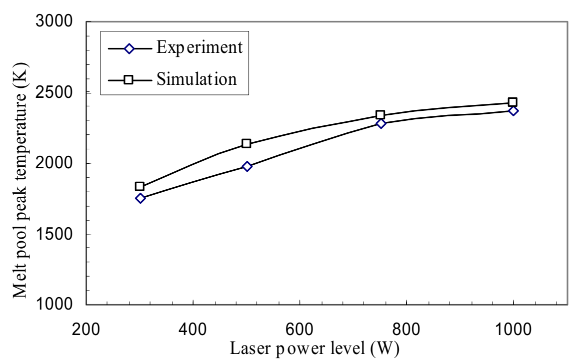


Fig. 8. Melt pool peak temperature comparison between simulation and experiment at different laser power level.

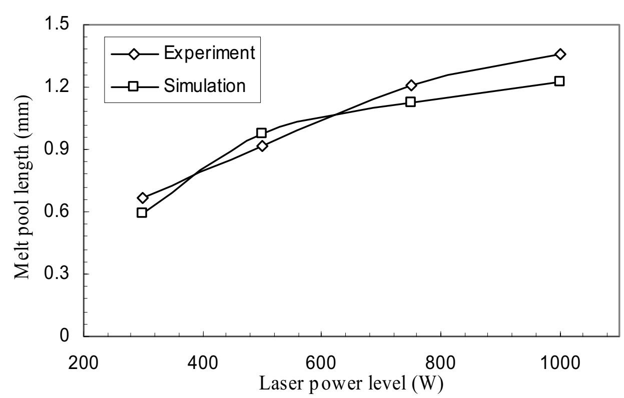


Fig. 9. Comparison of melt pool geometry (length) between simulation and experiment for different power levels.

Automated Process Planning System

Process planning, simulation, and tool path generation for the LAMP allow the designer to visualize and perform the part fabrication from a 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 [Ruan05]. 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 a 3-D polyhedron is needed. The algorithm is based on a classification scheme for points on the skeleton computation 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 is 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.

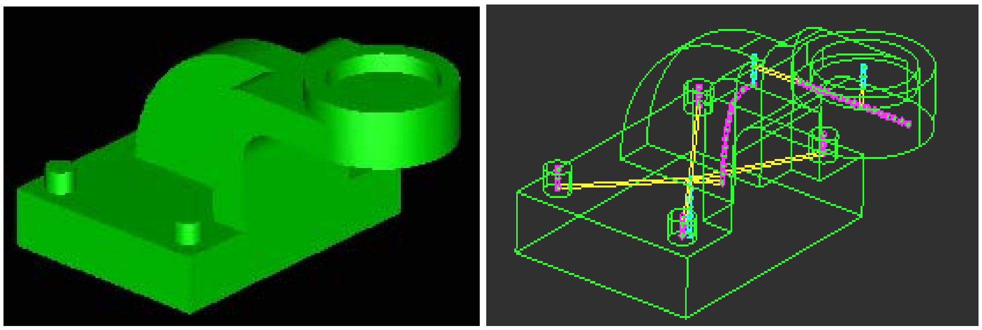
4) Building Sequence

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.

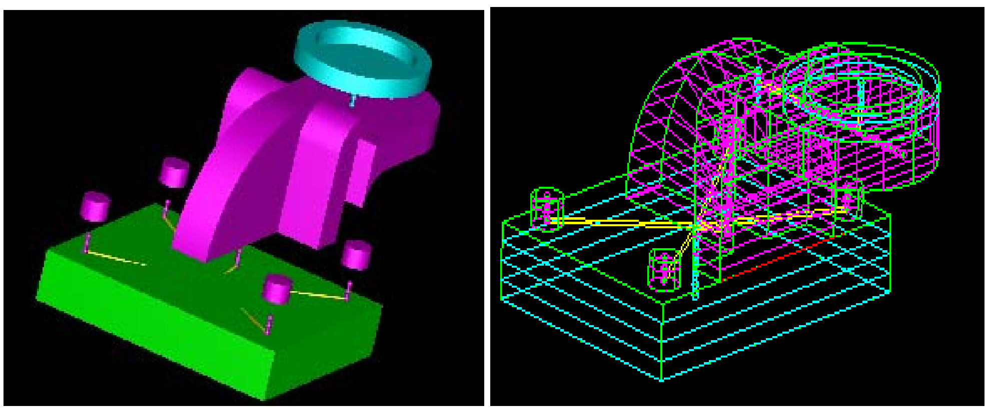
5) Machinability Check

The main purpose of a 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 the set, the buildability check and machining time computation is performed to find an optimal building sequence.

Figure 10 shows a bearing seat example. The part was first computed to find the skeleton diagram. Based on the skeleton diagram, it is then decomposed into sub-components for slicing.



(a) (b)

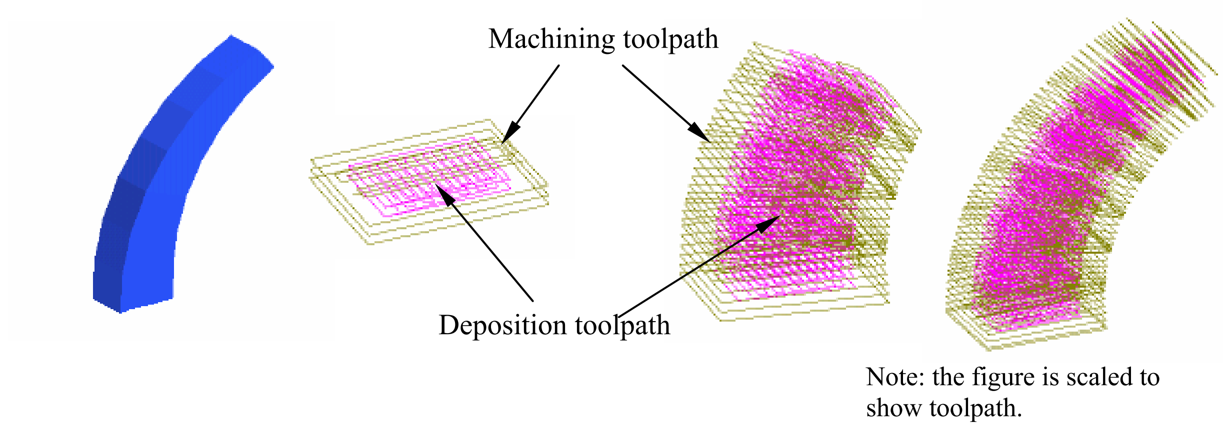


(c) (d)

Fig. 10. Example of a bearing seat.

Implementation and Applications

The part building process is demonstrated by several examples. Figure 11 illustrates a 3-D layer building process. In Figure 11 (b), a deposition result is shown. The STL model and process planning results are shown in Figure 11 (a). The side milling and top milling processes are demonstrated in Figure 11 (c) and (d) respectively. The final part with a total degree of 45 after conducting the final machining process is shown in Figure 11 (e). Compared to regular 2.5D rapid systems, the LAMP system saves about 80% of the support structures as shown in Figure 11.



(a) Process planning result

(c) Side milling (d) Top milling

(e) Final overhang part

Fig. 11. A part built with 3-D layers.

One unique application of such a hybrid deposition and machining system is for repair applications. In the LAMP process, the paths for deposition were generated in the software written in Visual C++ using the ACIS 3D toolkit. Layer height was set at 0.03 inches. The track width was set to be 0.1 inch with 50% overlap. The contour-parallel was used. The results are shown in Figure 12. The deposition paths were then sent to a postprocessor to generate the NC codes. Experiments were done for the third repair option as well. The result of the repaired part is shown in Figure 13 [Eiamsa-ard 05].

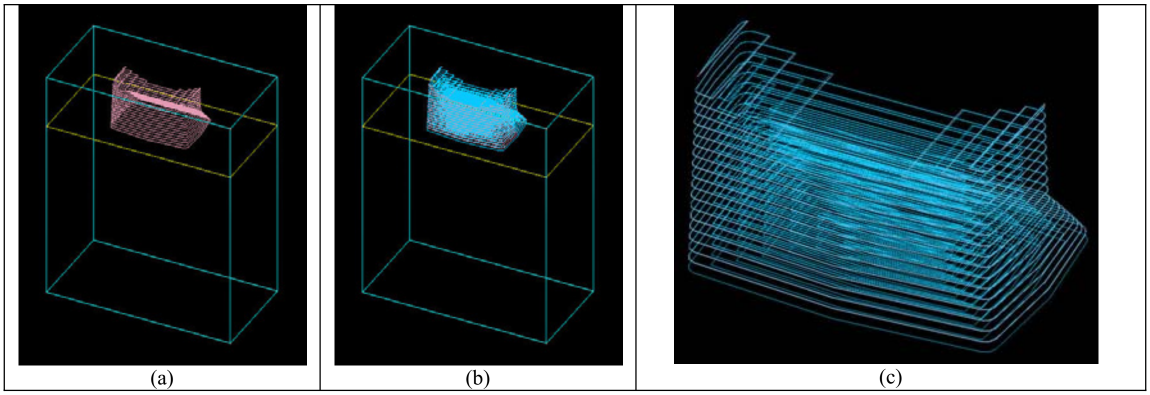


Fig. 12: (a) Slices (b) Deposition paths (c) Deposition paths (close up)

Fig. 13: Part after repairing.

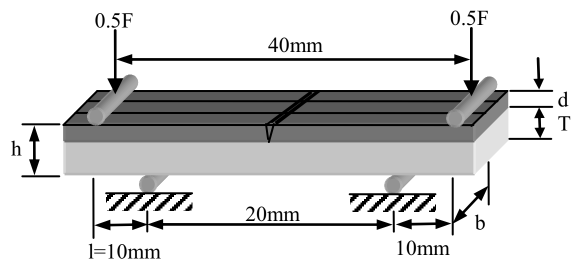


Fig. 14: Bending test set up.

The interfacial strength is determined from the four-point bend test (Figure 14). The four-point flexture test is based on the storage of elastic energy on bending. Interfacial cracks propagate when the strain energy release rate equals to the critical energy release rate (G_c) of the interfacial failure. The four-point bend test has been used to analyze the interface between the substrate and the cladding produced by laser processing. The 50x6x1 mm specimens are cut out from the deposition. A center pre-crack is made on the specimen in order to induce symmetrical cracks along the clad-substrate interface. The specimen is then loaded in a four-point flexture on an Instron TT-B Universal Testing machine until a new crack propagates through the entire cladding. The interfacial fracture energy of the laser cladding tool steel specimen is compared to the tool steel weld specimen of the exact same dimension. The results are shown in Table 2.

Properties	Notation	Laser cladding	Welding
Modulus of Elasticity of cladding (Pa)	E_f	2.10E+11	2.07E+11
Thickness of cladding (m)	d	2.00E-03	2.00E-03
Critical load of de-lamination (N)	F_c	11556	11428
Distance between inner and outer rollers (m)	l	1.00E-02	1.00E-02
Width of substrate (m)	b	6.00E-03	6.00E-03
Thickness of substrate (m)	T	8.00E-03	8.00E-03
Modulus of Elasticity of substrate (Pa)	E_s	2.10E+11	2.10E+11
Interfacial Fracture Energy (J/m^2)	G_c	15848.59	15278.02

Table 2: Interfacial fracture energy or bond strength comparison between laser cladding and welding processes.

Conclusion

The research and applications of a hybrid material deposition and removal system is summarized in this paper. The modeling and simulation of powder flow and powder-laser interaction help design and set the process parameters for laser deposition. The overall goal for process planning is not only to find a solution to build a part but also to look for an answer to produce it in the least amount of time; therefore, the least amount of switching between the machining process and deposition process, the better since each switch requires retreating and relocating the deposition nozzle as well as the machining tool, which may cost extra time. The process planning analyzes the slicing results and compares them to the original geometry in STL format to find an optimal process sequence. With integration of multi-axis deposition and machining processes on the same work station, a hybrid system is able to produce complicated geometry, especially the overhang structure with less or no support structures, which saves material cost. The switch between the machining and deposition process is optimized to save operation time/cost. Based on different geometry shapes, usually the LAMP system can save up to 50~60% of support structures. The surface quality of the final product is similar to the industrial milling capability.

Acknowledgments

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