Precision LCVD System Design with Real Time Process Control

Daniel L. Jean, Chad E. Duty, Brian T. Fuhrman, and W. Jack Lackey
Rapid Prototyping and Manufacturing Institute
Woodruff School of Mechanical Engineering
Georgia Institute of Technology
Atlanta, GA 30332

Abstract

A Laser Chemical Vapor Deposition (LCVD) system was designed using a fixed 100 Watt CO_2 laser focused on a moveable substrate. Temperature and height measurement devices monitor the reaction at the point of deposition to provide feedback for controlling the process. The LCVD system will use rapid prototyping technology to directly fabricate fully three-dimensional ceramic, metallic, and composite parts of arbitrary shape. Potential applications include high temperature structures, electronic/photonic devices, and orthopaedic implants.

Introduction

The Laser Chemical Vapor Deposition[1,2] (LCVD) process consists of using a laser as the heat source for a CVD reaction to selectively deposit one or many materials. The basic mechanism of pyrolytic LCVD is as follows: 1) a chamber is filled with reactive gases, 2) a laser enters the chamber and heats a small spot on a substrate inside the chamber, 3) the gases react at the spot and deposit the desired material, and 4) either the laser or the substrate is moved to "draw" a line of deposition. Many lines can be drawn to create a three-dimensional part. Different materials can be deposited by simply using different reactive gases in the chamber.

Various materials have been deposited using LCVD, including C, B, Si, SiC, Si_3N_4, Al_2O_3, TiN, TiC, Ni, Ag, and various other metals and ceramics.[3,4] LCVD was originally developed to draw conductive lines on microelectronic circuits, and it has been used to grow fibers, coatings, and objects and structures.[5,6,7] The structures created include scaffolds and micro-springs.[8,9]

The LCVD system will be combined with rapid prototyping technology to enable fabrication of precise metal and ceramic parts of arbitrary shape, thus advancing the current state of RP technology. Currently, RP systems are limited by material choice and part accuracy. The ceramic RP systems use a nozzle to deliver a powder or slurry, so the resolution of the system is limited by the nozzle diameter. Both ceramic RP parts and selective laser sintering (SLS) parts require post-processing steps such as high temperature curing to reduce porosity, which also reduces part accuracy. The resulting parts often still contain significant porosity, leading to poor mechanical properties.

The resolution of the LCVD system is limited by the laser spot size, which can be 1 μm or smaller for finely detailed parts. LCVD is an atom by atom deposition process, so the final parts approach 100% dense without the need for a sintering step. Since the reactants can be easily changed to deposit different materials, the LCVD system is capable of multi-material deposition within the same part.

Physical Description of System

The LCVD system[10] is designed to produce fast and accurate patterns of deposition. A 100 watt CO_2 laser is focussed onto a graphite substrate to provide the energy for the pyrolytic LCVD reaction. The substrate's position is controlled by three precision stages oriented in the Z, X, and θ directions (figure 1). This X-θ stage orientation enables high speed complete coverage of the substrate (using a spiral pattern) without the high reversal forces associated with an X-Y positioning system (figure 2). The two linear stages have a resolution of 0.1 μm, while the rotational stage has an encoder with 4000 lines per revolution corresponding to a resolution of 0.09 degrees. The limits of the stage travel allow for a cylindrical build envelope 3 cm in diameter by 3 cm high. The stages are housed in a chamber directly below the reaction chamber. The two chambers are separated by a flexible bellows that allows substrate movement without exposing the stages to the corrosive CVD gases (figures 3).

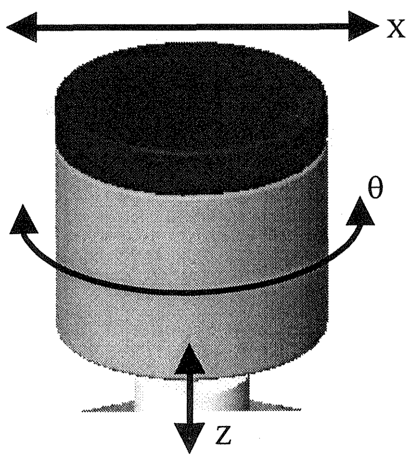


Figure 1. Rotating-translating stage.

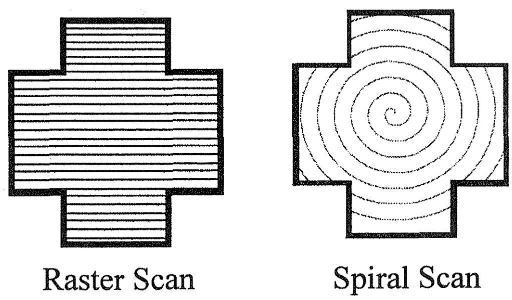


Figure 2. Raster scan and spiral scan for laser paths during deposition.

To increase the reaction rate, the reactive gasses are introduced directly into the reaction zone via a nozzle. The nozzle replenishes the reactants at the reactive zone much faster than conventional diffusion. This increase in available reactants will greatly increase the deposition rates over diffusion alone. Morishige and Kishida reported an increase in deposition rate of over an order of magnitude by using a nozzle to deposit lines of gold[11].

To further increase deposition rates, the substrate is heated from two sources. A Kanthal wire resistive heating element globally heats the substrate to a temperature just below the deposition temperature. Additionally, the laser is used to locally heat a small spot on the substrate to the reaction temperature. The global heating will reduce the thermal stress in the deposit due to a smaller temperature gradient at the laser spot. It will also speed up the process since the laser has to raise the substrate's temperature by only a small portion of the total heating required.

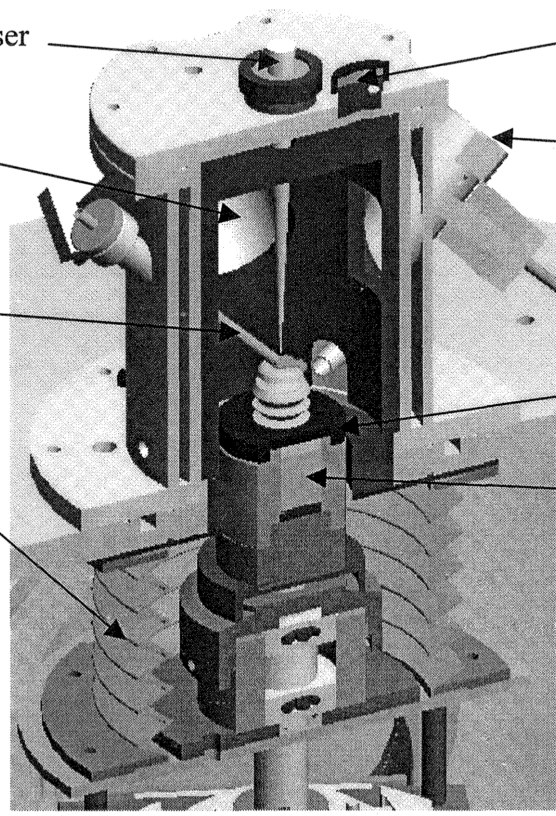


Figure 3. LCVD upper reaction chamber.

Need for Process Control

To create precise parts, the individual lines of deposition must have the same height and width. Process parameters such as temperature and deposition height will be monitored to accomplish the required uniform deposition.

Since deposition rates are highly dependent on temperature, there is a narrow temperature region required for a uniform deposition rate. The deposition temperature varies during processing due to several factors. One possible variation in deposition rate occurs when the deposit is more thermally conductive than the substrate. As a line of deposition is drawn, the new deposit will conduct more heat from the laser spot than the substrate alone, so the laser spot temperature will decrease. The deposition will be smaller with the decrease in temperature, and less heat will be conducted away from the laser spot, resulting in a higher temperature. A delayed feedback loop occurs that results in a periodic deposition, observed by Y. C. Du *et al.* while depositing lines of polycrystalline silicon[12] (figure 4).

The temperature will also vary due to history effects. A line deposited adjacent to a previous deposition may have a higher temperature due to the residual heat from the previous deposition. Changes in reagent product concentration and flow rates will also cause changes in deposition rates. The flow of reagent to the deposition spot will change depending on the surface features of the part being made. Certain regions on the part will have specific features, different from other areas on the part. The gas flow pattern will change depending on the surface features, and so different precursor supply rates will be present during deposition. To account for the changing process parameters, the system will use various sensing components outlined in the next section to determine the deposition temperature and deposition rates in order to control the LCVD process.

Control Techniques

An optical 2-color micro pyrometer is used to measure the temperature at the laser spot. The pyrometer compares the radiation at 2 wavelengths, so the reading is independent of variables that affect the radiation the same at both wavelengths (e.g. dust). The pyrometer can remotely measure temperature independent of the target's emissivity, assuming the target is a gray body (an accurate assumption for a graphite substrate). The pyrometer reading will be used to regulate the temperature at the laser spot by adjusting the laser power.

The global temperature of the substrate will be monitored by a thermocouple placed on the underside of the substrate. This temperature reading will be used to control power to the global resistance heater located below the substrate.

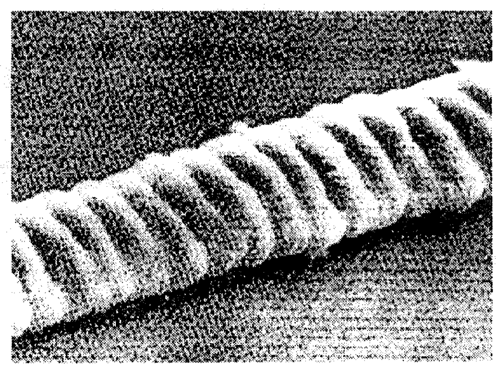


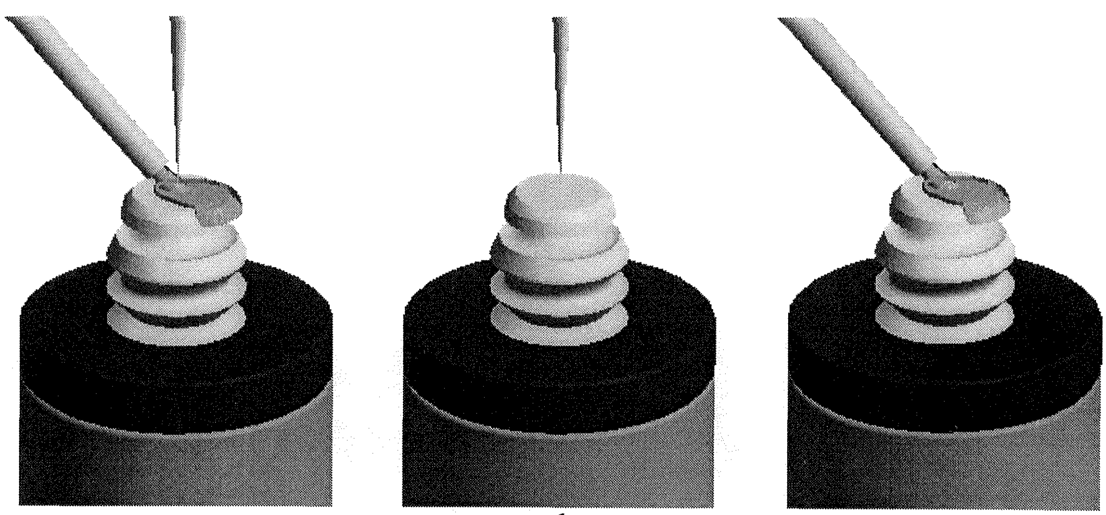
Figure 4. Periodic structure, Y.C. Du *et al.*[12]

To measure the deposition height, a laser triangulation sensor is used. The deposition height sensor would be extremely useful if it could accurately measure the deposition at the laser spot and thus allow for corrections in the deposition rate. The height sensor must be offset from the substrate by 7 inches due to the geometry of the reaction chamber. Unfortunately, the sensor's maximum resolution is 5 μm at the 7 inch offset, which is much greater than the layer thickness. Therefore the height sensor cannot be used to directly control the process during deposition. If it were able to give instant readings at the deposition spot, the stage speed could be adjusted to account for the varying deposition rates. Instead of controlling the process, the height sensor is used to measure several points on the deposited object after many layers have been deposited. The resulting point cloud will be compared to the original CAD model to determine if and where material needs to be deposited to correct for errors during the deposition process.

A CCD camera is used to observe the morphology of the structure being deposited during operation. The lens on the camera is capable of 200 times magnification at a six-inch offset, so great detail can be seen during the deposition process. This allows for *in situ* visual observation of the LCVD deposition process.

Operation

The LCVD system is capable of three modes of operation, depending on the use of the nozzle and the laser (figure 5). In the first mode of operation, the nozzle supplies the reagent, and the laser spot defines the heated reaction zone. The second mode of operation uses the laser without the nozzle, and the entire chamber is filled with the reagent gasses similar to conventional LCVD techniques. These first two modes can be compared to determine the effectiveness of the nozzle. The third mode of operation uses the nozzle but no laser. The substrate is heated to the reaction temperature with the global heater, and the nozzle defines the deposition area by supplying the reactive gas to the desired location. This third mode is similar to CVD since no laser is used, but there is a nozzle to control the selective areas of deposition. In all three modes of operation, the deposition material can be changed by simply changing the reagent gasses giving the system multiple material deposition capability.



a b c

Figure 5. Three modes of operation: a) laser and nozzle, b) laser only, and c) nozzle only.

Potential Applications

The LCVD system is best suited for applications involving precise, 3-dimensional, multiple material parts. Applications include 3-D laminated structures and electro-mechanical devices. The laminated structure can be fabricated with varying orientations of the laminated layers to promote isotropic properties while increasing strength and fracture toughness. Accelerometers can be fabricated with the LCVD system, incorporating 3 axes in one small package without the need for assembly. The LCVD system provides the fully 3-dimensional capability not present in current micro-fabrication processing systems such as surface micro-machining and lithography.

Conclusion

The LCVD system (figure 6) has the versatility and process control to accurately fabricate arbitrarily shaped multi-material objects. The precision stages ensure accurate deposition. The temperature feedback helps to control the processing conditions, while the height measurement device allows for the correction of height differences during processing. The CCD camera allows for detailed visual inspection of the reaction zone during deposition. These feedback systems provide the control needed for accurate deposition.

Several features were incorporated into the design to ensure high deposition rates. A nozzle delivers the reactants to greatly increase their concentration over conventional diffusion. The dual heating of the substrate shortens the time to reach deposition temperature, and the stage design allows for fast, accurate, and complete coverage. These advances give the LCVD system the control needed to fabricate net-shape multiple material parts from the gas phase.

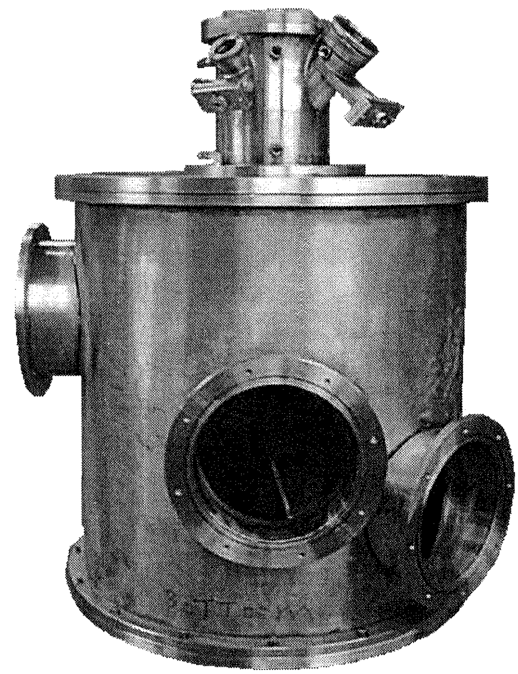


Figure 6. LCVD reaction chamber. The lower chamber is 22 inches in diameter and 22 inches high, and the upper chamber is 5 inches in diameter and 8 inches high.

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