Trussed Structures: FreeForm Fabrication without the Layers

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Abstract: *Recent progress in 3D-LCVD have demonstrated the advantages of rod micro-fabrication, both from the point of view of the range of volumetric deposition rates —from 10^2 to 10^9 cubic micron per second— and from the point of view of processable materials.*

A method for fabricating trussed structures by LCVD of ethylene was tested, based upon scanning of the laser focus perpendicular to the laser axis during rod growth. Control of the process is achieved though feedback of the laser power. A closed loop system was designed, which maintains a constant volumetric deposition rate during growth.

Such capability, combined with previous results by the authors and other researchers in the field, open a new approach to free form fabrication without layers. Indeed, current results constitute a proof of concept for the fabrication of truss structures akin to a finite element mesh.

Keywords: *3-D LCVD, SALD, Process Control, Rod growth, tessellation.*

1 INTRODUCTION

A novel approach to freeform fabrication is explored in this paper. Rather than scanning the layers of a part, whereby the entire volume must be swept, we propose that a tessellated structure, akin to a finite element mesh can be fabricated by 3-D LCVD.

The premises for this novel approach lie in prior works by Maxwell, Pegna et al. [1-4], and the works of Stuke et al. [5,6]. Preliminary investigations of layered manufacturing using 3-D LCVD revealed that the order of volumetric deposition rates ranges from 10^2 $\mu m^3/s$ for direct write, up to about 10^9 $\mu m^3/s$ for rod growth. For wall deposition of carbon from ethylene edgewise on a 2-D substrate for example, Pegna et al. [7] recorded a volumetric deposition rate of the order of 0.5 $10^6 \mu m^3/s$. By this measure, it would take nearly two months to build a 3 cm^3 layered structure —about the size of a small watch! This is clearly not rapid prototyping.

Yet, LCVD remains attractive to many researchers for its wide range of processable materials, including functionally graded materials, as was demonstrated by Maxwell et al. [4] for Ni-Fe alloys. In order to magnify the volumetric deposition rates, researchers have used LCVD to fill interstitial voids in between powder particulates. This is essentially the basis for SALD-VI [8]. Alternatively, Stuke et al. [5] have demonstrated the fabrication of triangulated free-form surfaces by direct write onto a preform that was then dissolved. That work essentially demonstrated the

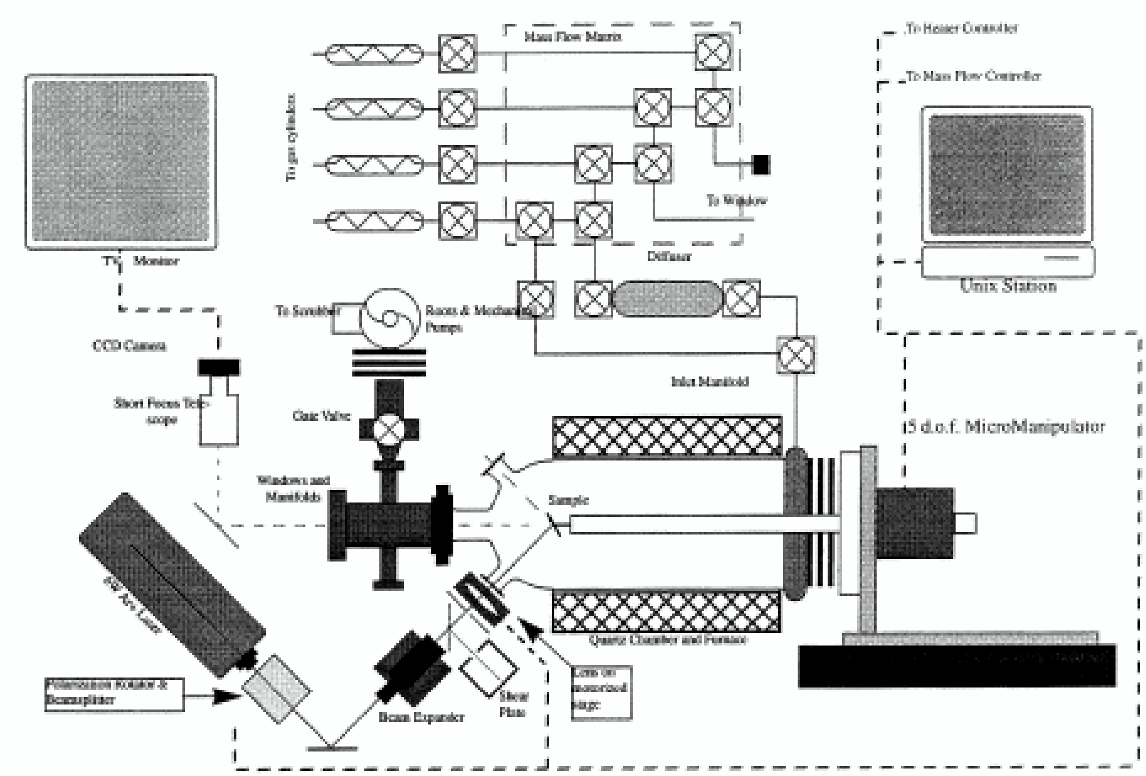

FIGURE 1. Schematic diagram of the 3-D LCVD reactor.

possibility of producing 3-D shapes about a millimeter in size using a process inherently slow (less than $10^4 \mu m^3/s$.) Most recently, Stuke et al. also demonstrated the feasibility of fabricating highly complex periodic rod microstructures by scanning a twin laser focus though a deposit transparent to the wavelength [6]. This experiment demonstrated for the first time the feasibility of using 3D-LCVD toward the fabrication of micromechanical photonic band gap devices not achievable by any other means. What makes this approach feasible for manufacturing purposes is that it capitalizes on the many folds increase in the order of magnitude of volumetric deposition rate in rod growth mode as opposed to direct write. Indeed assuming a conservative volumetric rate of $3.\ 10^5 \mu m^3/s$ —typical of high pressure LCVD of graphite [9]— and 0.6% volumetric fill —typical of a pyramidal tessellation 1 mm on the side with a $\phi 20 \mu m$ fiber— then the fabrication time of our sample $3 cm^3$ volume falls to 16 hours, or the equivalent of growing a 60 m fiber!

The above example shows that to be viable as a free form fabrication tool at the centimeter scale, 3-D LCVD must be exploited in rod growth mode to generate densely packed meshes. In order to achieve this result, the major obstacles to overcome are:

1. The ability to grow rods that are slanted with respect to the substrate and each other. This issue is addressed in Section 3.1, where two approaches will be pursued: One using a stationary laser tilted with respect to the substrate, and another by scanning the laser focus during rod growth. The latter revealed most promising and a series of experiments were carried out to determine the relationship between the angle and the scan rate for a number of different pressures.
2. The ability to join independently grown rods. This issue is covered in Section 3.2.
3. The ability to build trusses atop each other. This represents the current status of our work and

is covered in Section 3.3.
In addition, a preliminary result on braiding carbon fibers grown by 3-D LCVD is presented Section 3.4.

2 EXPERIMENTAL

2.1 Equipment

A schematic diagram of the Rensselaer 3D-LCVD system is shown in Figure 1 The 3D-LCVD reactor consists of a custom quartz tube with ports for viewing and laser input. The chamber is connected to a pumping station via a gate valve. The vacuum chamber and gas-delivery systems are enclosed within a ventilated hood for safety purposes. For the growth of pyrolytic graphite, 133 - 665 mbar (100-500 Torr) ranges of ethylene pressures were employed.

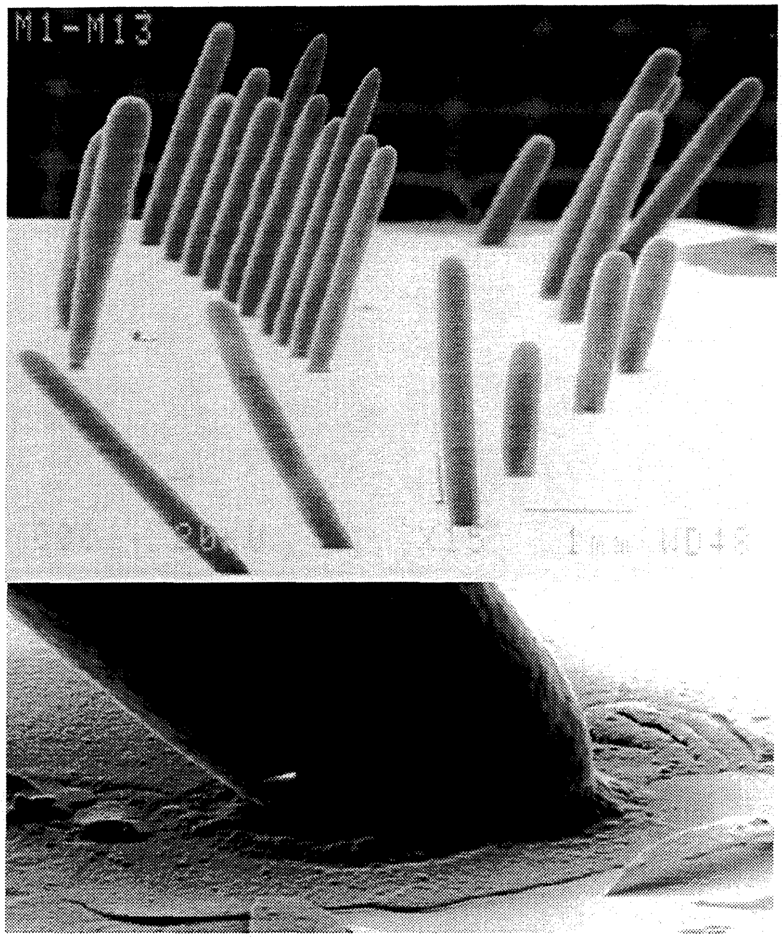

FIGURE 2. Top: Sample population of angled rod grown with a stationary laser at an angle to the substrate. Bottom: Sample rod base.

The beam source was a Coherent. model CR-18 argon ion laser with a maximum output of 12Watts (multi-mode) at the 488/514 nm primary lines. To vary the laser beam power, a liquid-crystal retarder and polarizing beam splitter were placed in series, allowing peak-to-peak power swings in under 200 ms. Incident powers reported herein represent total beam power at the deposit. Observation of the sample during growth and laser alignment is made with a custom-built short-focus telescope and CCD camera.

A photodetector, covered with narrow band filters, was mounted to one of the chamber windows, at a distance of roughly 200 mm from the sample. Using a two-decade pre-amplifier, the sensor could measure emissions as small as 0.25 mW at the substrate (at 656nm). The amplified signal was recorded by an Omega Nubus data acquisition system, with a typical sample period of 0.05-0.10 seconds, and was later time averaged as needed for real-time control.

At the core of the system is a precision five-degrees-of-freedom manipulator. This micromanipulator was designed to allow beam scanning not only in the plane of the substrate, but at any angle and orientation to the sample. This is effected through a computer-driven 5-axis micromanipulator. This tool allows sub-micron positioning with stepping motor control from outside the vacuum chamber. The translational and angular resolutions of this micro-manipulator are 1 μm and 0.005° at the full step control mode.

The manipulator arm holds the sample within the chamber. The manipulator attaches to the vacuum chamber via a flexible bellows to limit vibrations transmitted to the sample. Both the manipulator and the laser lie on a vibration-isolated table, their relative position is fixed.

2.2 Trussed structure Fabrication Process Control

To fabricate the desired trussed structure, the laser power and motion of the manipulator need to be controlled during the process. A Macintosh computer with Omega Nubus data acquisition system and a custom C language program handle the entire process. The process sequence is as follows. The desired discretized trajectory of a path is generated by input data. Using this trajectory and calculated motion speed, the pulse trains of each stepping motor are generated. This pulse train signal is sent to the each stepping motor during the process. The laser power is controlled using the feedback signal, which is emitted during the deposition process as the substrate moves independently. Proportional-Integral-Derivative (PID) gains were fine-tuned to follow the desired reaction rate signal using the system response.

3 RESULTS AND DISCUSSION

3.1 Angular Rod Growth

3.1.1 Stationary Laser at an Angle to the Substrate: The most immediate approach to growing a rod at an angle to the substrate is to incline the orientation of a stationary laser. Figure 2 shows such sample rods at varied inclinations constructed by this method. In this configuration, growth is more difficult to initiate since reflection of the laser at the surface is increased. Nevertheless, angles up to 45° to the substrate were achieved with this technique. Once rod growth is initiated though, it becomes similar in all regards to regular stationary growth, exhibiting similar growth rates and rod morphology. These results demonstrate the practicality of this method for building needles at an angle. As we shall see in Section 3.2, however, this method will prove unpractical for truss building.

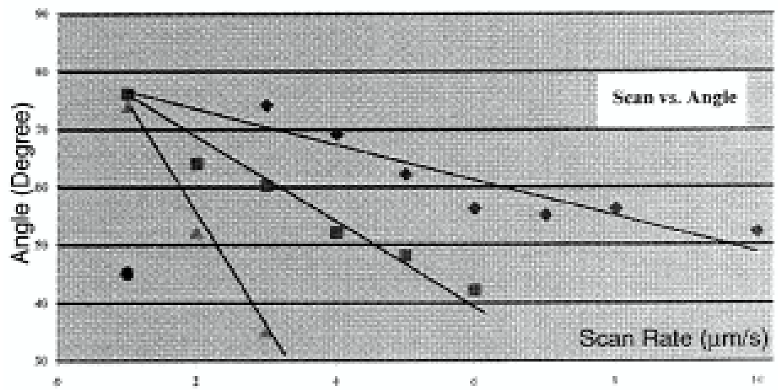

FIGURE 3. Rod angle with substrate as a function of scan rate for various precursor pressure. Laser power adjusted to maintain constant volumetric deposition rate. Deposit: carbon from ethylene. Substrate: quartz. Legend:

Index:	◆	■	▲
Pressure (Torr):	400	300	200
Em. Sign. (V)	0.1	0.1	0.1
Vol. Rate ($10^6 \mu m^3/s$)	2	1.5	0.8

3.1.2 Angular rod growth by laser scanning subject to constant volumetric deposition rate.
A series of angular rod growth experiments were conducted to determine the dependence of the angle on pressure and scan rate. Figure 3 shows the results for constant volumetric deposition rate. The pressure ranged from 200 to 400 Torrs. For constant pressure the slope decreases with the

scan rate in a nearly linear fashion. This is to be expected. Let α be the angle between rod and substrate, V_s be the scanning speed, and R_o be the axial growth rate. As the axial growth rate is related to the scan rate by:

$$\cos\alpha = \frac{V_s}{R_o}, \qquad \text{(EQ 1)}$$

near α=90°, this relation appears approximately linear.

The graph shows that, for constant scan rate, the slope with respect to the substrate increases with pressure, which is consistent with prior results showing the increase of axial rate with pressure [3]. Finally, Figure 3 also shows the limit of vertical development for a given volumetric deposition rate. For example; it was found that, at the lower pressures, i.e.; 100 torr, only a very slow scan rate (1 µm/sec) resulted in a rod of any inclination, any faster rate resulted in direct write of a line on the substrate. The steepest angle achieved was 40° under the conditions of 200 Torr at 3 µm /sec.

Sample slanted rod structures grown by laser scanning under constant volumetric deposition rate are shown in Figure 4, along with their emission signature (representative of volumetric rate), controller input, and laser power. To achieve this growth, the laser power was modulated using the liquid crystal retarder in order to keep the emission signal at a set value of 0.07 Volts. Note the consistency of the growth over the two samples. Also mark the reduced power need once rod growth is initiated.

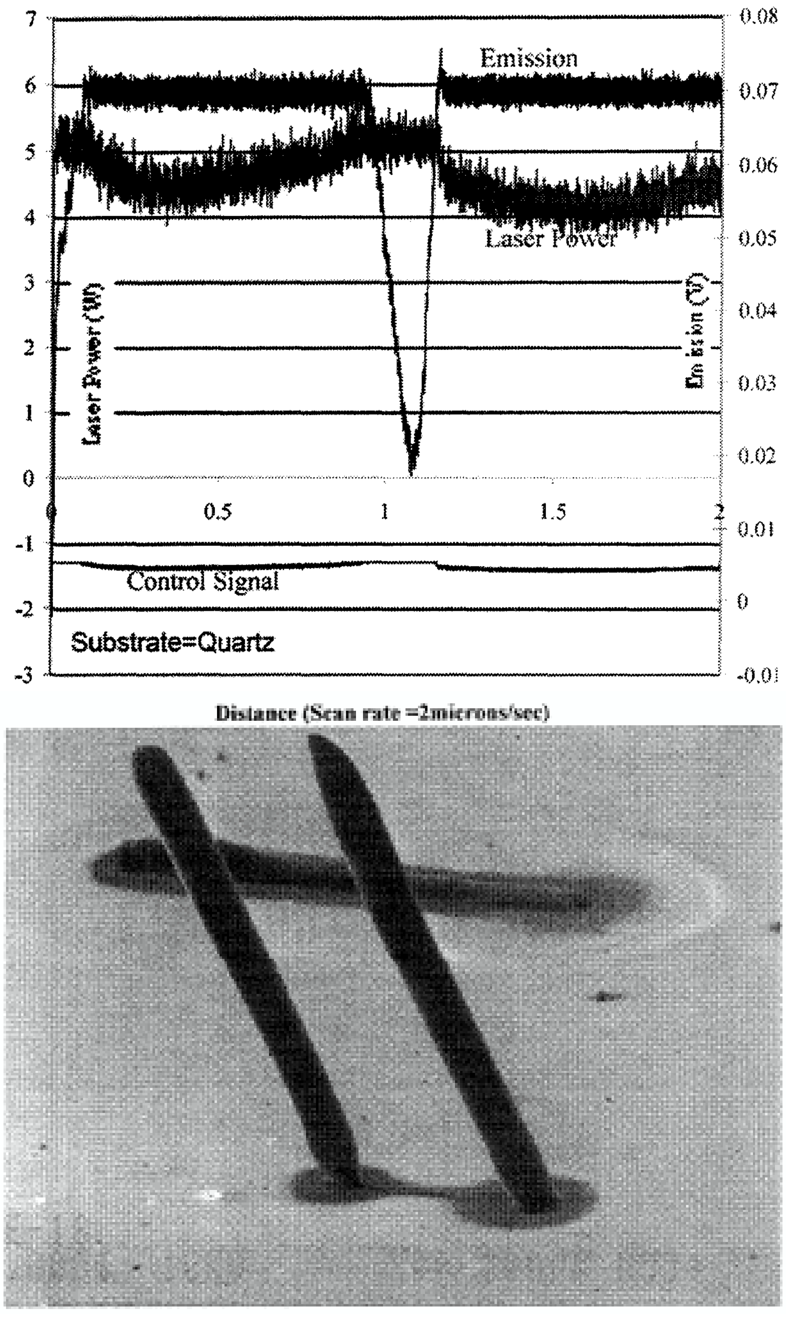

FIGURE 4. Sample constant volumetric rate rod growth for a constant scan rate of 2µm/s, Pressure: 250 Torr. Top: Emission signal and laser power. Bottom: Sample rod structures.

Slanted rods grown by scanning the laser focus over the substrate display a characteristic axial ridge on their posterior side (opposite the laser.) A close-up view of rods grown under such conditions is shown in Figure 5.

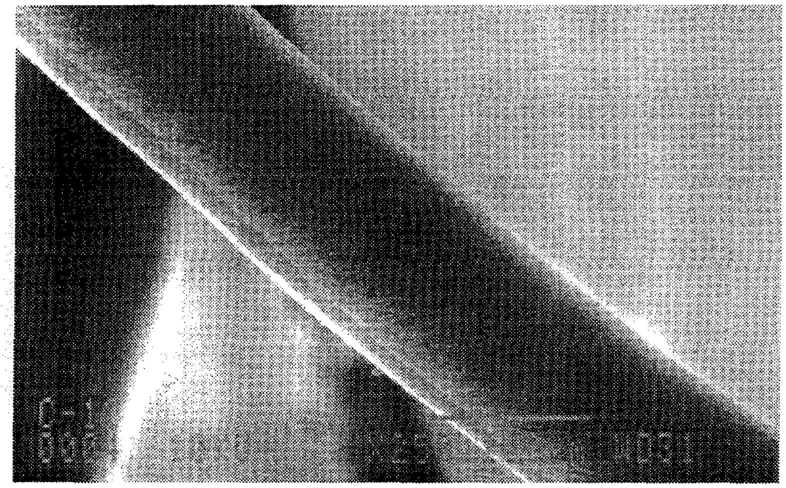

FIGURE 5. Close-up view of an angled rod showing the characteristic ridge on the posterior side.

Bending fracture of a typical angularly grown rod reveals an interesting morphology. The rod appears to be composed a two regions: An amorphous core and cylindrical graphitic skin. This is consistent with the results of Wallenberger and Nordine [9]. who showed that carbon fibers can be fabricated under high pressure LCVD of Methane.

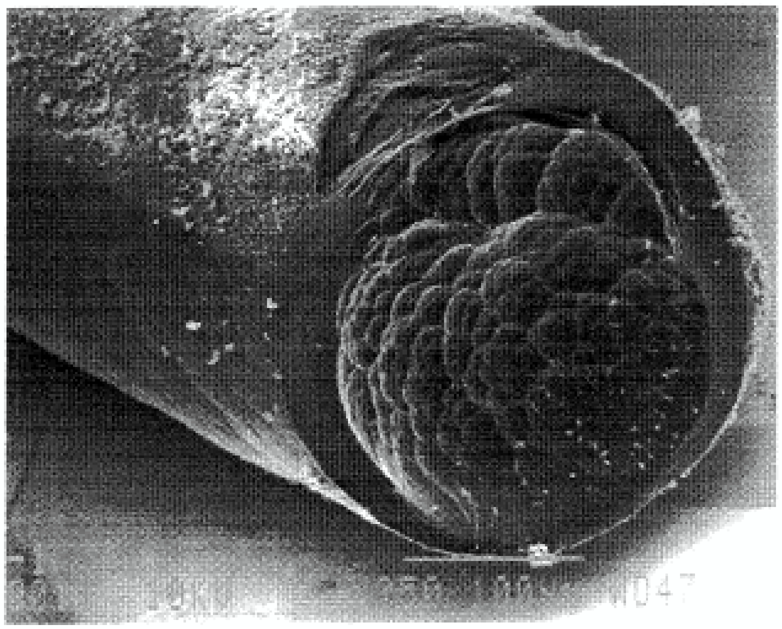

FIGURE 6. Close-up view of a fractured angled rod showing the uniform graphitic "skin", amorphous core, and axial ridge on the posterior side of the rod.

3.2 Weld Formation

The single critical step toward fabrication of micro-trusses for the purpose of rapid prototyping will be the ability to join fibers together at nodal points. This demonstration is critical to the proof of concept for the technique proposed herein. Experiments were thus designed with the aim of examining the feasibility of joining two needles together by each of the angular growth methods.

3.2.1 Stationary Laser: Experiments involving the growth of rods at an angle to the substrate and in such a manner that they would fuse at the tip proved inconclusive. In fact, they voided the concept. Let alone complications due to the accuracy requirements in positioning the laser with respect to the just completed rod, the method turned out to yield two main results:

1. The rod tip occluded the laser and the second rod grew out of the first, and
2. The rod tip was clear of the laser path and the two rod grew past each other.

These results are illustrated by Figure 7.

3.2.2 Scanning Laser: In addition to better trajectory control, rods obtained by the scanning laser approach avoid the occlusion problem discussed earlier in Section 3.2.1. Hence the next development attempted was to grow needles into each other directly so that they would meet at the tip. While success rate is still low in this case, about 30 percent of the samples did interlock. Figure 8 shows a such successful attempts at meeting the needles at the tip. In addition, it was found that all the welded rods display a stronger attachment to the substrate and are able to sustain stronger loads than single rods, indicating a complete juncture.

3.3 Truss Building

The realization that a butt weld is possible with angled rod structure now open another avenue to free-from fabrication. Rather than scanning layers, the question becomes: Can we build a mesh akin to finite elements, whereby one could build a carbon fiber preform out of rods?

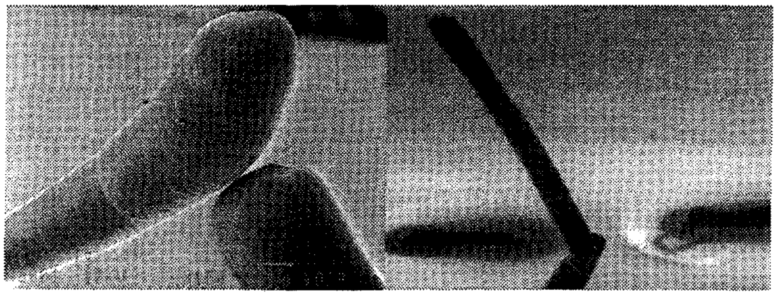

FIGURE 7. Typical joining problems with stationary laser growth. Left: First rod does not occult the laser and the rods grow past each other. Right: The first rod occults the laser and the second rod grows on top of the first one.

This section presents our preliminary answers to this question. Attempts at building micro-trusses were conducted, with mitigated results. Accurate location of the rod tip during fabrication remains a metrology challenge in this project, leading to a rather large amount of defects in the joining. Figure 9 shows sample micro-trusses structures obtained by the scanning laser method. It should be emphasized that there was no preform used in this construction and that the structure does not need to be optically transparent to the laser wavelength. These features differentiate this approach from the remarkable results obtained by Stuke et al. [6]. In addition, we demonstrated the possibility of constructing a multi-level truss with three-dimensional features.

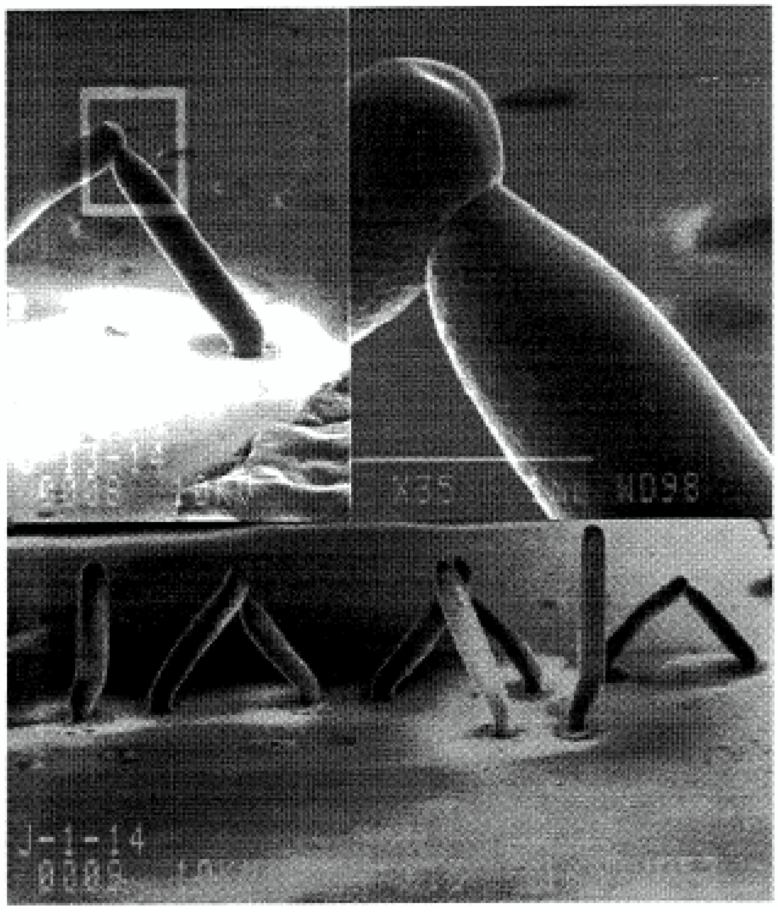

FIGURE 8. Sample rod welds.

3.4 Fiber Braiding

An aspect of fiber structure which is highly desirable in reinforcements is the ability to braid them. This option is compatible with both types of laser fabrication of angled rod, with the exception that the rod angle and direction is now required to change continuously. Preliminary results for this line of work is shown in Figure 10 where a 3-fiber braid was initiated atop a 1-level truss.

4 Conclusion

The main objective of the research exposed in this paper was to investigate the feasibility of fabricating trussed structures by means of 3-D LCVD. This approach is justified on the premise that rod growth is the only mode of LCVD with sufficient volumetric flow rate for free-form fabrication of centimeter size structures. The main issues addressed in this exploratory work were:

1. The ability to grow rods in arbitrary directions. This was achieved by scanning the laser focus parallel to the substrate during rod growth. Results pertaining to rod growth, scanning speed, angle and growth morphology were covered in Section 3.1.
2. The ability to butt-weld independently grown rods was demonstrated in Section 3.2. Though accurate location of the fiber tip remains a metrology challenge for this operation.
3. The ability to build meshes in a continuous fashion was explored in Section 3.3 with mitigated results. It appears though that this issue should be addressed with a better location system for the rod tip during growth.
4. Finally, the issue of braiding carbon fibers during growth was briefly investigated in Section 3.4.

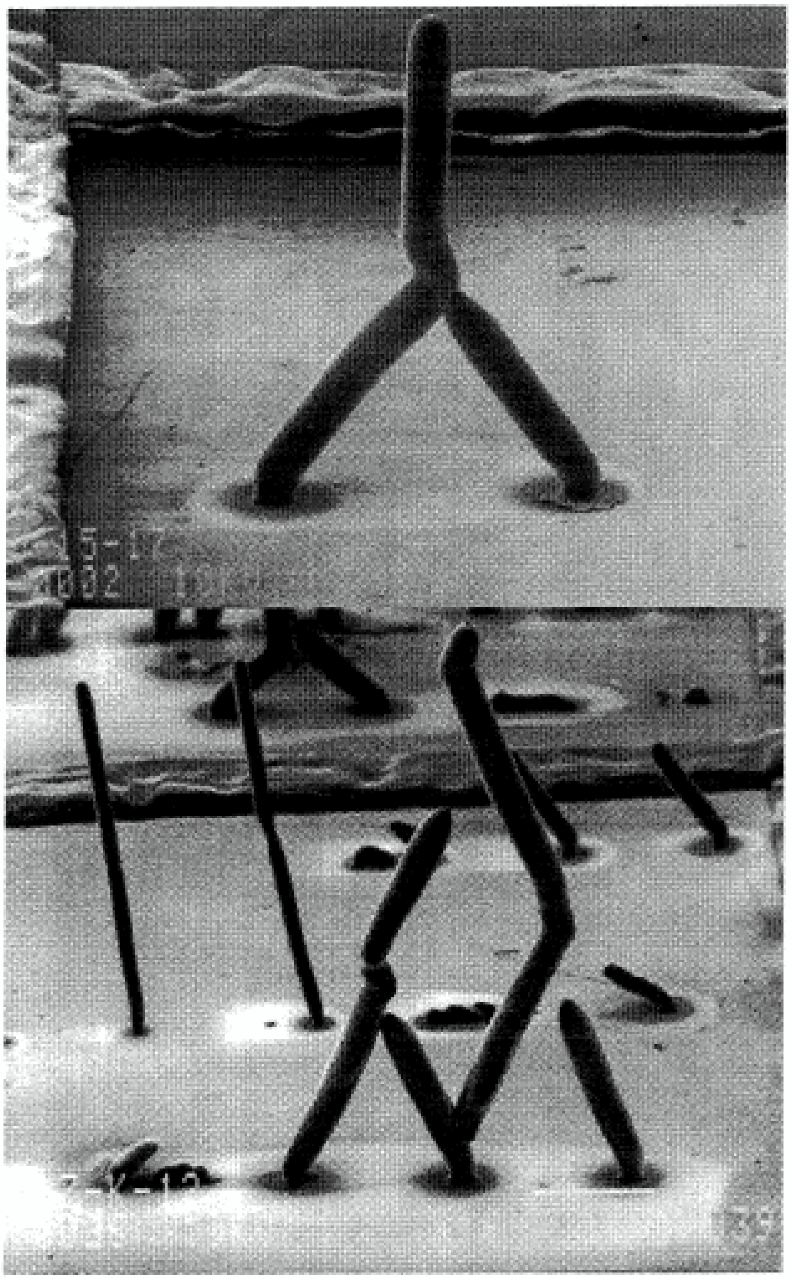

FIGURE 9. Sample micro-truss structures.

All the results exposed in this paper point to the fabrication of trussed structures using LCVD rod-growth as a viable approach to free-form fabrication of centimeter to possibly decimeter size objects.

The major interest of such an approach is in the material and size versatility of the process. About 80% of elements in the periodic table, as well as various intermetallic, oxides, and even functionally graded alloys can be deposited by LCVD. The wide range of volumetric deposition rates covers nearly 10 orders of magnitudes, thus allowing single stage fabrication of structures varying in size from micron to centimeter and possibly decimeter. Among its different operating modes (direct-write, rod growth, and SALD-VI) LCVD offers the prospect of a fully integrated, multi material, mesoscale fabrication.

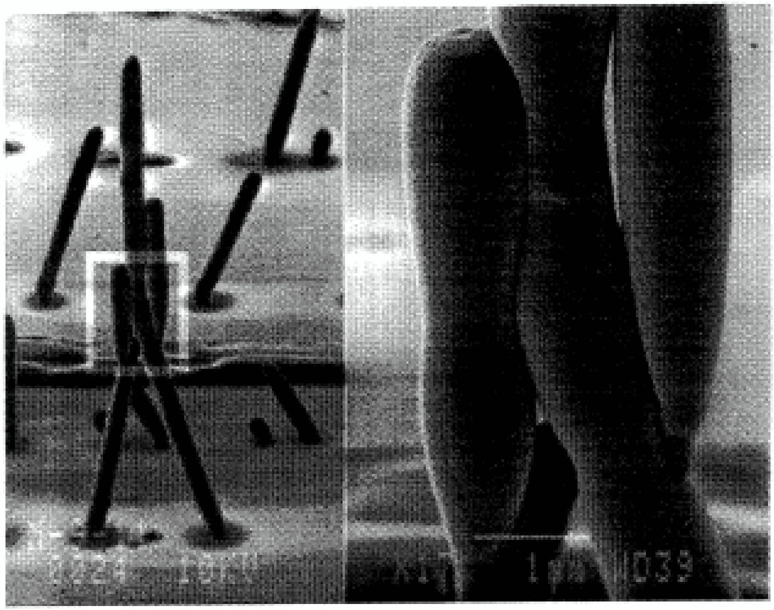

FIGURE 10. Sample 3-fiber braid atop a 1-level truss.

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