LASER CUTTING OF CERAMIC COMPOSITE LAYERS*

Allan Lightman† and Gyoowan Han
University of Dayton Research Institute
Dayton, Ohio 45469-0150

ABSTRACT

The Laminated Object Manufacturing (LOM) process lends itself to use of a variety of materials that can be delivered in sheet format. Studies are underway to investigate the use of monolithic and fiber reinforced (composite) ceramic tapes. The laser cutting process presents a challenge due to the refractory properties of the fibers and, in some cases, their high thermal conductivity. The cw CO_2 laser's thermal degradation process currently used is not suitable for these materials. The evaluation of potential alternative lasers has focused on pulsed systems that use either photoablation together with thermal processes or thermal shock with thermal degradation. We will describe preliminary results achieved in our study of the photoablation process using a copper-vapor laser.

INTRODUCTION

As the technologies for solid freeform fabrication (SFF) mature, the new development emphasis is shifting from hardware to materials and applications. A major goal is the development of engineering materials which can be processed by SFF systems to develop mechanical properties equivalent to those derived from standard mass-production methods. This goal is being achieved on a limited scope and new materials are being developed. Another goal is the development of technologies that permit freeform fabrication using materials which traditionally require molds. This would eliminate the long delays and large expense associated with the production and testing of new parts made from these materials.

Objects fabricated from ceramics are desirable for many reasons, including their thermal properties and abrasion resistance. Production of ceramic parts traditionally requires the use of molds for casting the green part. Typically, the density of ceramic in the green part is on the order of 50% so the densification stage is accompanied by significant shrinkage and associated dimensional distortion. The result is that several iterations are usually required in order to approach the desired net shape after firing. Production of the initial molds and their subsequent modification during iterative development is time consuming and prohibitively expensive for consumer applications. Consequently, the use of ceramic parts has been limited to high value applications, such as military and aerospace, and to consumer applications having simple geometry and without stringent dimensional requirement, since few, if any, iterations would be required.

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† Author to whom correspondence should be addressed.

Realizing that development cost and time were limiting factors to the use of ceramic materials, DARPA initiated programs to develop new concepts for SFF production of ceramic materials. Particular interest focused on high-performance ceramics (non-oxide) and fiber-reinforced ceramic matrix composites (CMC). Laminated Object Manufacturing (LOM)[1] is particularly suited to the implementation of fiber-reinforced CMCs. The material is delivered to the build chamber in tape or sheet format, which permits fabrication of parts with traditional unidirectional or multidirectional fiber placements. The LOM process was developed using a cw CO_2 laser to cut the material layers (initially paper based). While this laser is suitable for cutting materials which can be thermally degraded (selectively burned), it proved to be unsuitable for use on the high-performance CMCs. Either the melt temperature of the fibers was too high to be reached under reasonable laser illumination (laser power and exposure time), or the heat conductivity of the fibers was so high that the thermal energy was quickly transported away from the interaction zone and degraded the surrounding material (or both).

One aspect of the current development program is the investigation of alternative laser sources for use in cutting the layers of CMC. This paper will focus on the results obtained using a copper-vapor laser - a high pulsed repetition frequency (PRF), medium-power, metal-vapor laser that can be tuned to operate in the green (511nm). The paper will show that the PRF can be the limiting factor for cutting speed, so this laser presents a good test bed to evaluate the LOM process. Pulsed Nd lasers converted to the visible or UV (frequency doubled [532nm], tripled [355nm], or quadrupled [266nm]) present intriguing alternatives, and their application is being studied. Preliminary results will be shown for comparison.

EXPERIMENTAL SIMULATOR

A table-top LOM (TTLOM) system was constructed to simulate fabrication with the commercial hardware and provide ready access to all components of both hardware and software. The system, Figure 1, is stabilized by tying all components to an optical table and a rigid build platform. Material is fed by hand into the build stage, permitting the use of limited supplies of the materials under development. The LOM process[2] cuts out the periphery of the part layer by

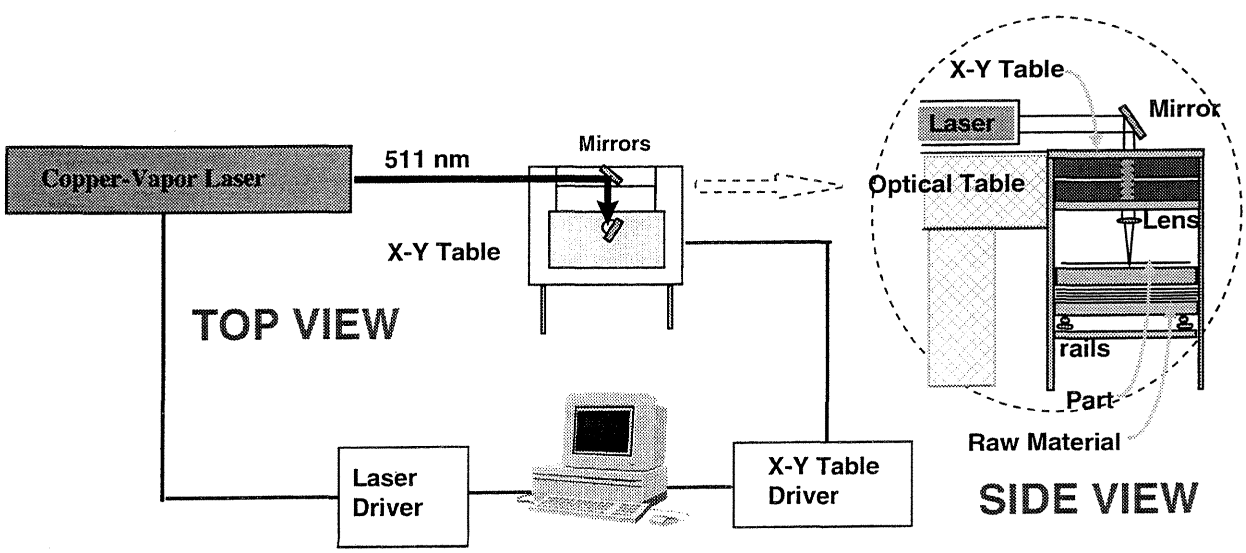


Figure 1. Schematic diagram of the TTLOM system.

layer, by moving the focused laser spot across the material layer via an X-Y table under computer control. In the TTLOM, the X-Y table provides a working space of 20"x20" and a positioning accuracy better than 0.001". The material is introduced into the build chamber by rolling out the build stage (roller bearing and precision rail support), removing a sheet of material from beneath the build platform and attaching it to the top of the construction material on top of the build platform (thus maintaining the top layer at the same height), and then sliding the platform back until it contacts the fixed stops which accurately registers it under the X-Y table.

The copper-vapor laser was custom designed for this study[3] using an unstable resonator to provide higher energy per pulse and better beam quality than would be achieved using standard stable resonator configurations. Prior studies of laser-material interactions indicated that deposition fluence would be a critical parameter. Thus, it was important to develop a high beam quality so that the beam could be tightly focused. The output beam has a flat intensity profile, 18mm nominal diameter, and a divergence of 0.3mrad[‡]. The beam is focused with a 100mm lens and the focused spot is characterized, using a scanning knife-edge, in X and Y (Figure 2). Note the hot-spot 85μm from the center in the X profile. This hot-spot does not emerge from within the beam until near the focus, so it is difficult to remove by spatial filtering. It is thought to result from the geometry of the unstable cavity.

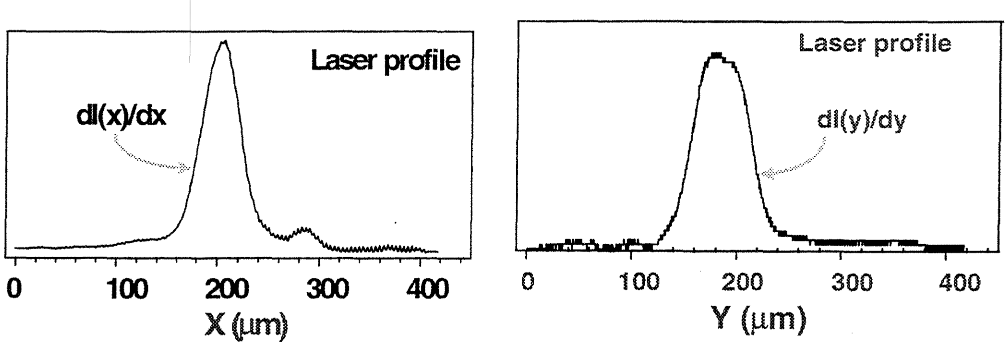


Figure 2. Copper-vapor laser profiles at the focal spot.

The laser's maximum power is 20W at 8 kpps (20ns pulse), delivering 2.5mJ per pulse to the material. The laser focus spot is an oval with axes of 80μm x 100μm, yielding a peak deposited fluence of $4x10^9 W/cm^2$. Two types of experiments are initially performed when testing a material. The material removal rate is determined as a function of the energy per pulse and the residual material, in the vicinity of the cut, is studied as a function of the energy deposited per pass. The first study establishes the threshold for material removal[4] which determines the optimal cutting rate. The second study determines the depth of material removal per pass that is possible without damaging the material. Successive passes are required to cut through the full layer.

The copper-vapor laser is a discharge heated system, best operated at full rated power. In order to characterize the dependence of material removal vs. fluence, a set of custom neutral density (ND) filters is needed (standard ND filters are destroyed under exposure to this laser).

‡ Note: This is a metal vapor laser so it is subject to beam degradation as the metal is redeposited within the laser cavity [the same as the HeCd laser used in stereolithography].

The filters, inserted in the optical path at the laser head, are made from screen mesh and they scatter the beam. As a result, the laser spot broadens, requiring that the focus be remeasured under each operating condition.

The material removal rate per scan is varied by controlling the scanning speed of the X-Y table, since the speed determines the overlap of the laser spots. Overlap reduction is achieved by increasing the scanning rate. Retracing does not impact the ultimate through-cut rate which is only a function of the laser-material interaction, as long as there is no overhead time associated with retracing. Studies were made at different scanning speeds and the slowest speed, with no material damage, was selected. Studies of the cut depth as a function of the number of scans were made to investigate potential beam guiding effects and material damage from cumulative buildup.

Two materials were investigated. The first is a tape composed of SiC particles and chopped Nicalon fibers. The material is held together with a polymer binder. The solids loading is 65% - 70% by volume. This material was formulated to provide high ceramic volume density so that the part dimensions will remain stable when the binder is burned out. The second material was developed from a Nicalon tow, with the continuous fibers distributed into a quasi-uniform sheet. The material was held together with a sparse application of polymer binder. This material was developed using a novel concept for implementing fiber reinforcement and is the most challenging material for the laser cutting applications.

MATERIAL REMOVAL

Single Pass (vary Fluence)

Material removal processes have been studied in a variety of operating conditions. Srinivasan[4,5] has performed considerable analyses of laser-material interactions in the UV using excimer laser sources. These studies provided the initial motivation for the studies reported here. While the excimer laser has the desirable property of operating in the deep UV (less than 200nm, depending on gas used), it can only be used as a flood source, since it requires an exposure pattern mask to define the illumination pattern. It is not suitable for use as a focused spot to be scanned in an arbitrary profile that changes from layer to layer. The copper vapor laser can be focused and it has a high PRF, but it operates in the visible (511nm, 578nm). Srinivasan's[4] results using XeCl (308nm) showed material effects similar to his deep UV studies (173nm and 193nm), indicating that it might be possible to extend this mode of interaction into the visible. The results indicate that the laser is absorbed according to a traditional Beers' law profile. This model should apply as long as the laser pulse is shorter than the time needed for the effluent plume to be developed. Otherwise, the laser would get absorbed away from the surface, heating the plume and potentially damaging the bulk material. Results of our study on the Nicalon tape are shown in Figure 3.

In fixed energy per pulse systems like the copper-vapor laser, the existence of a threshold fluence (F_{TH}) for material removal establishes an optimum fluence for the cutting process. In operation, this optimal exposure is achieved by selecting the focusing lens to provide the calculated focal spot diameter. The maximum cutting rate can be shown to occur when

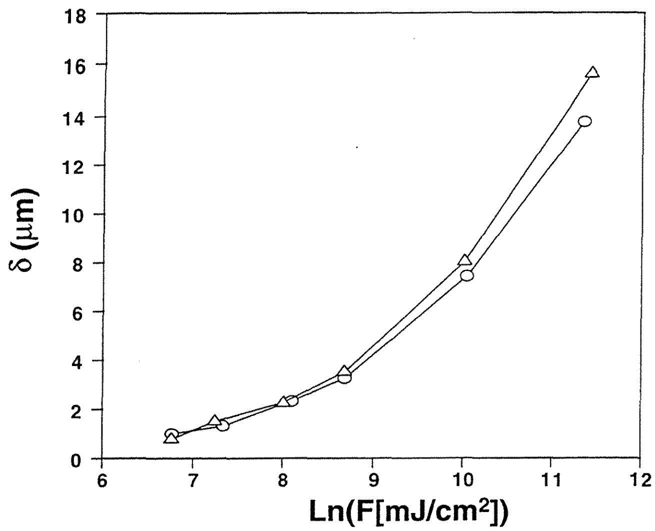


Figure 3. Material removal depth as a function of the laser fluence. (The line serves only as a guide.)

$$F = 7.4\,(F_{TH}). \qquad (1)$$

Satisfying (1) impacts the choice of laser operating conditions. In typical SFF applications, such as LOM, it is desired to maintain a kerf on the order of 200μm. This fixes the illumination area. If the system is to be operated at optimum fluence, the energy per pulse is then also determined. If the laser's operational envelope is only limited by average power, then the optimum operating condition will occur when the PRF is adjusted so that the energy per pulse is that determined using Eq. (1). For the Nicalon tape used in this study the threshold fluence is about $1 J/cm^2$. Eq. (1) determines that optimum cutting will occur when the laser pulse delivers 2.3mJ into the 200μm focus. For most lasers, it is not possible to vary the PRF and change the energy per pulse while maintaining the average power. Currently, Nd lasers are limited to PRFs on the order of 100pps by system considerations (heating) and the energy per pulse can exceed the optimum described above. The excess energy will then couple into the material, degrading the cut quality. (Figure 4) Energy per pulse reduction is only achieved at the expense of laser performance. Further laser development is required to provide a range of operating parameters allowing selection of the best laser for the application. The energy per pulse of the copper-vapor laser is about the desired level and its high PRF results in faster cutting for the materials used in this program.

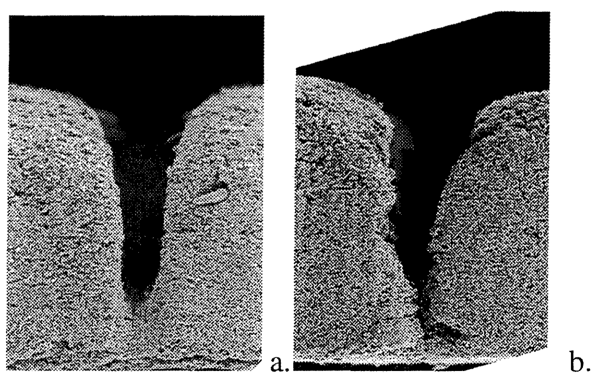


Figure 4. Laser cut profiles for different laser operating conditions. (a) Copper-vapor laser - 1.8mJ per pulse at 511nm (14W, 8kpps, 20ns, 5 overlap, 7 pass). (b) Nd:YAG tripled - 25mJ per pulse at 355nm (0.5W, 20pps, 3ns, 2 overlap, 3 pass).

Multiple Pass (vary Overlap)

Preliminary studies were made with the Nicalon tapes. The cut surface was examined for a recast layer or other indications of damage to the material. It is important that the cut surface present open porosity after binder burnout so the part can be infiltrated. The edge surface, Figure 5, shows a clean cut with ceramic powder, binder, and fibers clearly evident, indicating no thermal damage to the edge.

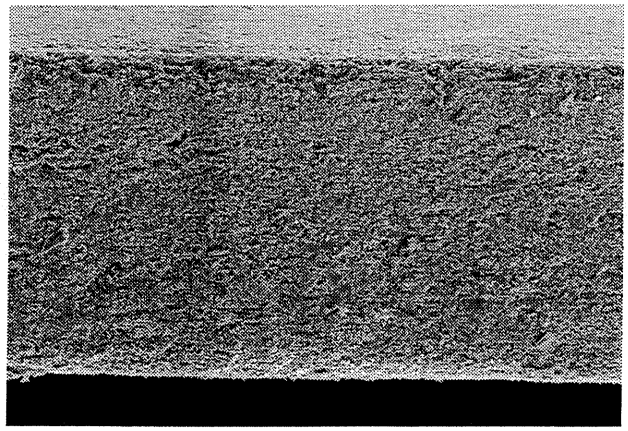
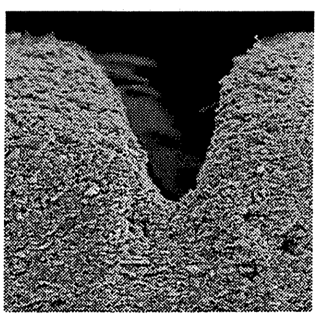
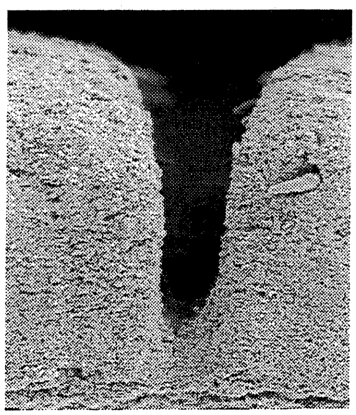


Figure 5. Cut edge of Nicalon tape by copper-vapor laser, 1.75mJ per pulse, 5 pulse overlap, 11 passes. Tape is about 350μm thick.

The copper-vapor laser was used to cut the Nicalon tape and the fibers derived from the tow (16 spot overlap). Scanning electron microscope (SEM) pictures of the cut profile (Figures 6a, b, c) were used to study the linearity of the material removal under multiple rescanning. Figure 7 shows initial linearity but as the depth increases there is evidence that another phenomena is occurring which blocks the laser's direct access to the material. This occurs at depths approaching 400μm when the laser kerf is about 80μm, indicating that there may be a maximum aspect ratio of about 5:1 for clean cuts. Another series of studies was made on Nicalon fibers spread into a tape from a tow. Preliminary results show successful laser cutting (Figure 8). Experiments using a Nd:YAG laser were performed and the data is under study. Preliminary results show that deposition of too much energy per pulse damages the material, just as seen in Figure 4 with the tape.



a.



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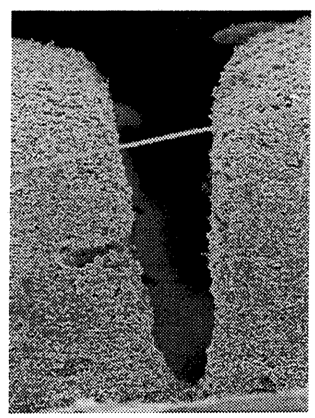

c.

Figure 6. Multiple pass material removal, copper-vapor laser and Nicalon tape. (a) 4 passes. (b) 7 passes. (c) 10 passes. Laser kerf is about 80 μm.

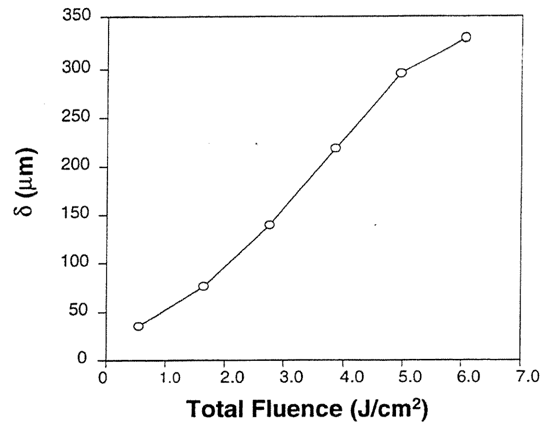

Figure 7. Material removal rate (Nicalon fiber) as a function of total fluence deposited for the copper vapor laser. (The line is only a visual guide.)

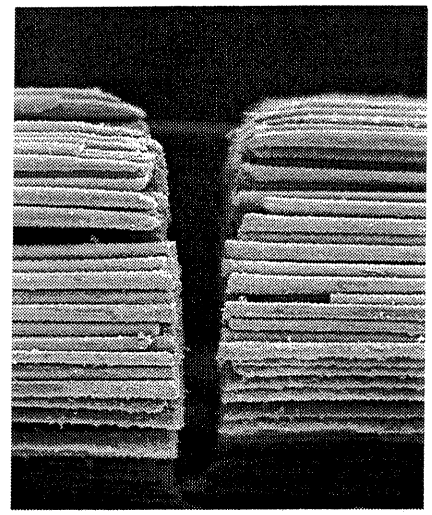

Figure 8. Copper-vapor laser penetration of Nicalon fibers. Median kerf is 80μm and fiber diameter is about 10μm. (511nm, 14W, 8kpps, 20ns, 5 overlap, 13 pass)

Preliminary results using the frequency multiplied Nd:YAG indicate there is a difference in the interaction of the Nd laser and the copper-vapor laser (Figure 9). The principal difference in the operating conditions is that pulse length of the Nd is 3ns versus the 20ns of the copper-vapor. The Nd laser focal spot has not yet been fully characterized so the observed differences in the rate of ablation cannot be attributed at this time. The computed fluences were based on the optical system parameters, assuming a diffraction limited focus. The measured kerf was in agreement with the assumptions.

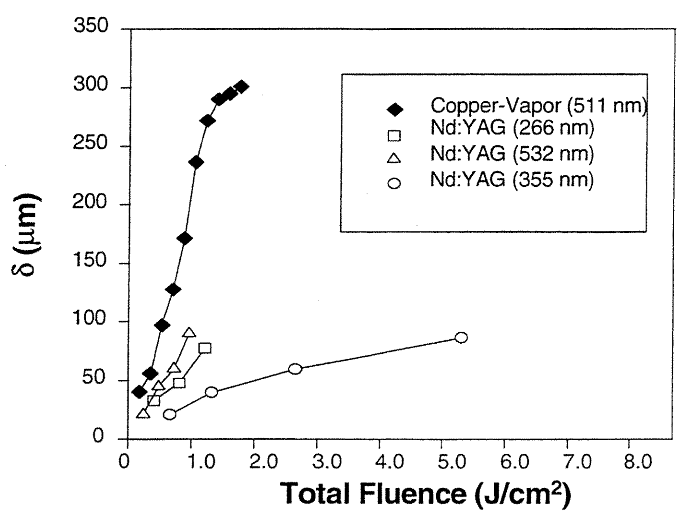

Figure 9. Observed depth of material removal as a function of laser fluence. Graph compares measurements of copper-vapor and frequency-converted Nd.

CONCLUSIONS

A copper-vapor laser successfully cut through fiber reinforced ceramic tapes and tapes composed entirely of ceramic fibers. The operating performance of the copper-vapor laser is closely matched to the desired parameters for optimal performance with the materials used. Comparative studies of material removal rate using a frequency converted Nd laser indicate that the material interaction is dependent on both wavelength and pulse length. The laser-material interaction has not been conclusively determined and further studies are needed.

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