3-D LASER SHAPING OF CERAMIC AND CERAMIC COMPOSITE MATERIALS

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ABSTRACT

A versatile, automated, laser-based system, capable of producing complex three-dimensional shapes of ceramic and ceramic composite materials, through either controlled layer ablation or solid freeform fabrication, is currently under development. The system comprises a 1.2 kW CO_2 laser, positioning system, beam scanner, non-contacting positioning sensor, beam conditioner and CAD/CAM system. This paper reports progress in relating machine parameters (scan rate, feed, beam power and polarization) to process measurables (material removal rate and surface roughness), and demonstrates the potential for rapid prototyping and direct manufacturing of: (a) rotationally symmetric components based on ablative ceramics such as Si_3N_4 and (b) graphite fuel cell plenums.

INTRODUCTION

Advanced ceramic and ceramic composite materials based on, for example, Si_3N_4, SiC, SiAlON, AlN, are candidate materials for automotive engine components, bearings, cutting tools, pump components, valves and valve-train components for conventional piston engines, turbochargers, recuperators, heat exchangers and hot gas filters.[1-5] Currently, the high costs and difficulties of shaping such brittle ceramics by diamond grinding, waterjet cutting, ultrasonic machining, sintering, and near-net shape processes, such as hot isostatic pressing, are major factors limiting their widespread deployment. In this research, the laser based system under development offers the potential not only for rapid prototyping but also for economical, direct manufacturing of full strength, structural ceramic components.

BACKGROUND

The laser shaping system under development in this program is based on patents developed by Copley, Bass and Hsu[6] and by Bass and Copley[7]. More than a decade of research has shown that for optimized, reproducible, laser machining of complex, three-dimensional ceramic shapes, closed-loop control of beam mode, polarization, beam power, beam speed, beam feed, and laser firing in synchronization with translational, rotational and tilt stages will be required.[8-24] Discoveries by Copley, Bass and Hsu[6] have identified conditions for removing layers of ablative ceramics with controlled wall angles (perpendicular or sloping) at all positions along the bounding wall of a closed contour.[6] Parameters for laser machining Si_3N_4 surfaces with arithmetic average surface roughnesses of 3 μm,[19] and post laser machining treatments, which restore the mechanical properties of the laser machined surfaces to those of the as-ground material, have been identified.[22]

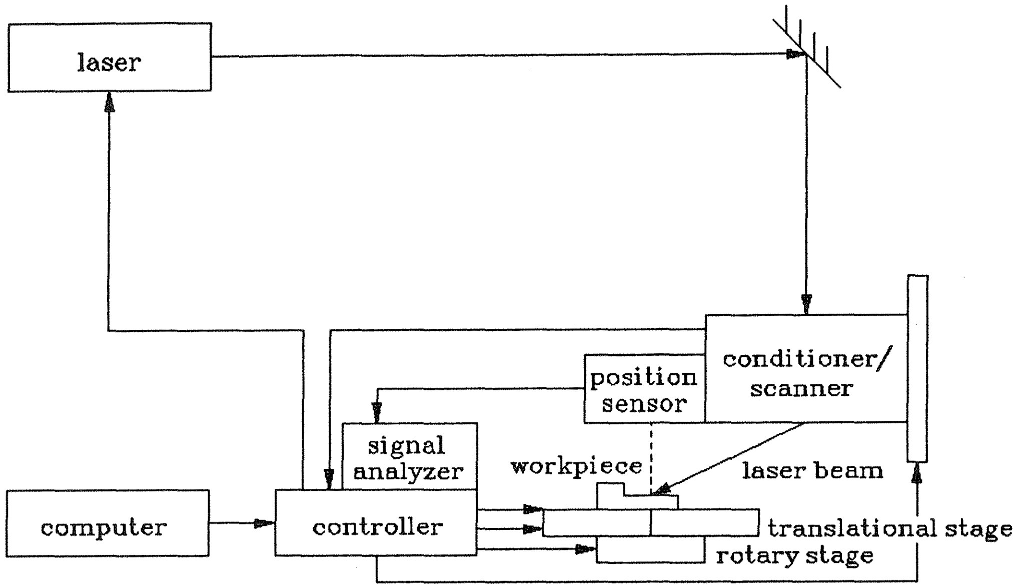


Figure 1: Prototype laser shaping system.

LASER SHAPING SYSTEM

The laser shaping system shown in Figure 1 comprises: (a) a 1.2 kW CO_2 laser capable of both continuous wave and pulsed mode operation; (b) a beam conditioner to control the beam polarization ratio, $r = x/(1 - x)$, where $x = I_n/I_o$; I_n = intensity of the laser beam's electric vector oriented normal to the plane of incidence, and I_o = incident beam intensity; (c) a custom-designed polygonal scanner to give linear beam speeds exceeding 100 cm s^{-1} (Figure 2); (d) x, y and z axis translational stages; (e) a motion controller, capable of up to 16 axes of control and equipped with a laser firing card; (f) a non-contacting position sensor for accurately sensing the position of the machined surface; and (g) a CAD/CAM system which generates scan patterns (Figure 3) and beam paths for layer removal to create a three dimensional shape. Note that,

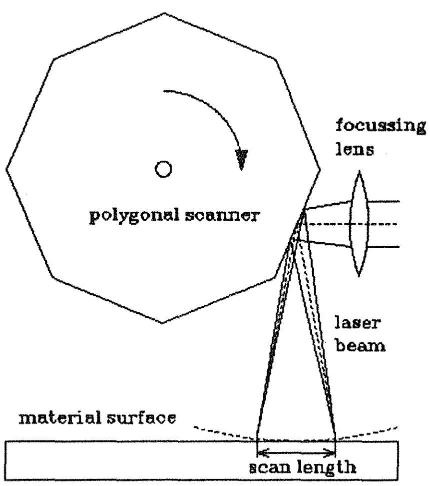


Figure 2: Beam scanner.

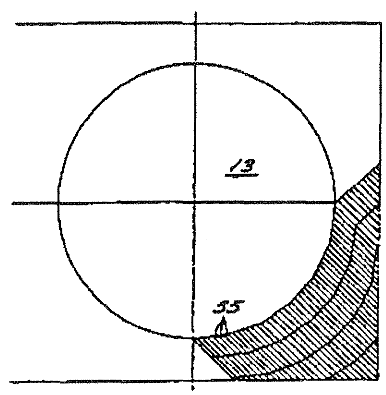


Figure 3: Plan view for layer removal in a single quadrant to produce a piecewise linear approximation of a convex spherical contour. The beam is scanned in a single direction.

unlike solid free form fabrication, additional controls are incorporated in this system to select the terminal angle at which the laser beam contacts the component surface for wall slope control. The system is capable of generating shapes by ablating material from oversized ceramic preforms or by solid free form fabrication for prototyping or direct manufacturing of components.

MATERIALS

The materials used in the present study were Ceralloy 147-31E sintered reaction bonded Si_3N_4 supplied as blocks and 10 mm diameter bar, Allied Signal GS-44 Si_3N_4 (blocks), Noralide NCX-5102 HIPed Si_3N_4 (10 mm diameter bar), and nuclear grade graphite received from Oak Ridge National Laboratory.

PARAMETRIC STUDIES

Material removal rates for single grooves and layers machined in both Si_3N_4 and graphite were studied as a function of beam velocity, beam polarization, position of the focal plane and beam feed to groove width ratio (f/a). Figure 4 compares MRR data for Allied Signal GS-44

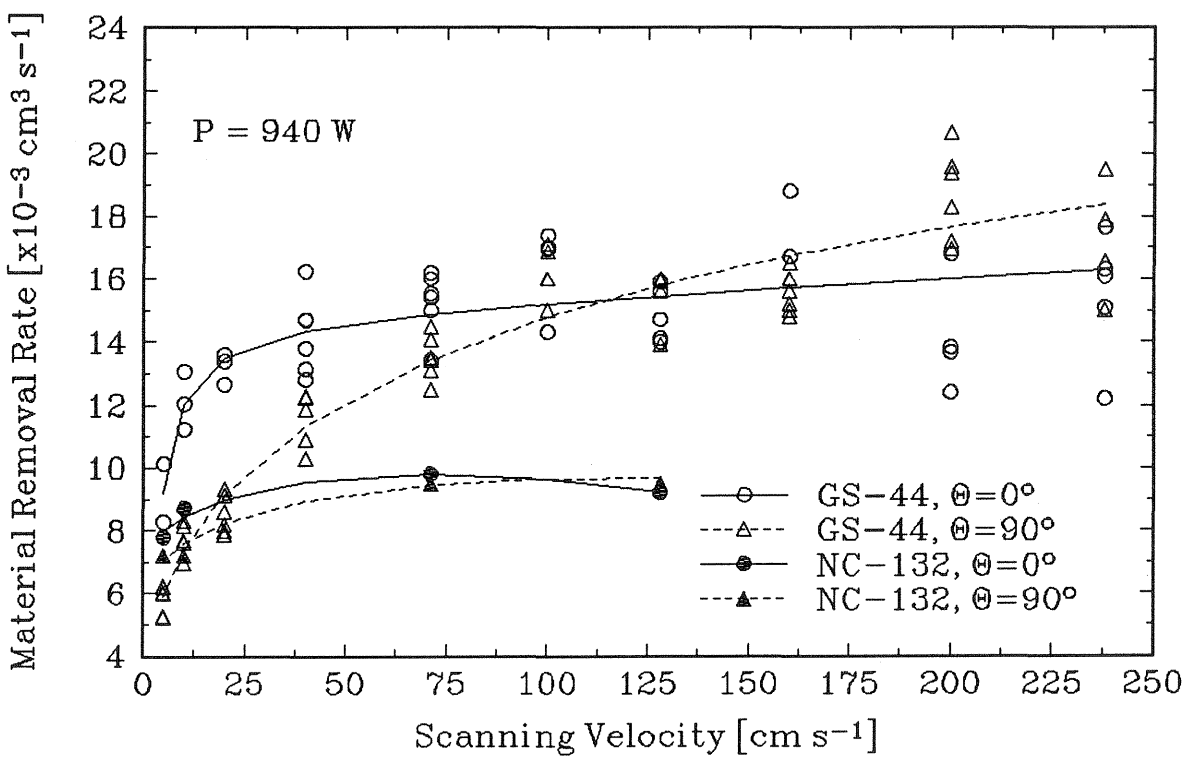


Figure 4: Comparison between material removal rates determined for Allied Signal Si3N4 #8, GS-44 MOR bars (present study) and Norton NC-132 MOR bars (Copley et al.) for beam velocities from 5 to 240 cm s^{-1}, and electric vector parallel (0°) or perpendicular (90°) to the scan direction.

machined at 940 W with prior data for Norton NC-132 collected by Wallace[10] and Wallace et al,[17] and shows that removal rates were approximately doubled for the GS-44 material. A material removal rate of 15 x 10^{-3} cm s^{-1} is equivalent to removing 1 cm^3 of material in 67 seconds. Figures 5a, 5b show single layers machined in GS-44 with f/a ratios of 0.9 and 0.3. Twelve passes of the laser beam can be clearly seen in Fig. 5a (f/a = 0.9). Reduction of the f/a ratio to 0.4 (Fig. 5b) resulted in a significantly smoother surface. Note that although the entrance surfaces were covered with a layer of silicon in the above example, silicon build up was minimized during multi-layer removal through optimization of beam power, speed and feed.

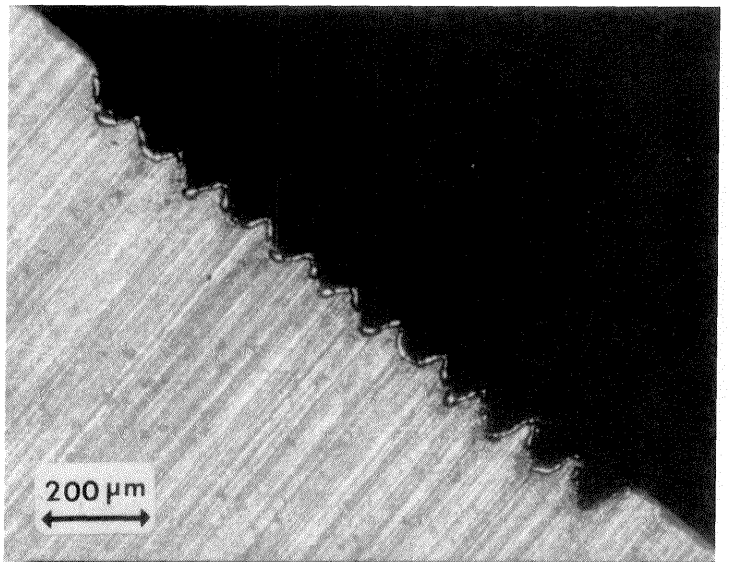


Figure 5a: Single layer laser machined in GS-44 with f/a ratio of 0.9.

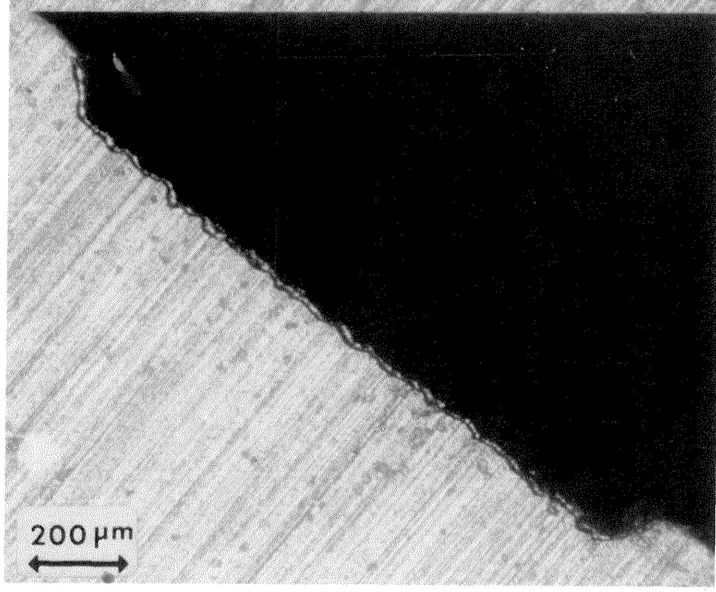


Figure 5b: Single layer laser machined in GS-44 with f/a ratio of 0.3.

Material removal of graphite was investigated at 940 W in the velocity range 10 to 20 cm s^{-1} and found to increase (a) with increasing velocity, and (b) as the position of the focal plane was changed from 0.5 to 1.0 or 1.5 mm below the specimen surface (Fig. 6). Interestingly, the material removal rates were similar in magnitude to those for Si_3N_4. When groove and layer morphologies were observed, material removal rates and surface roughnesses were optimized using a velocity of 10 cm s^{-1}, focal plane position of -1 mm and f/a of 0.35.

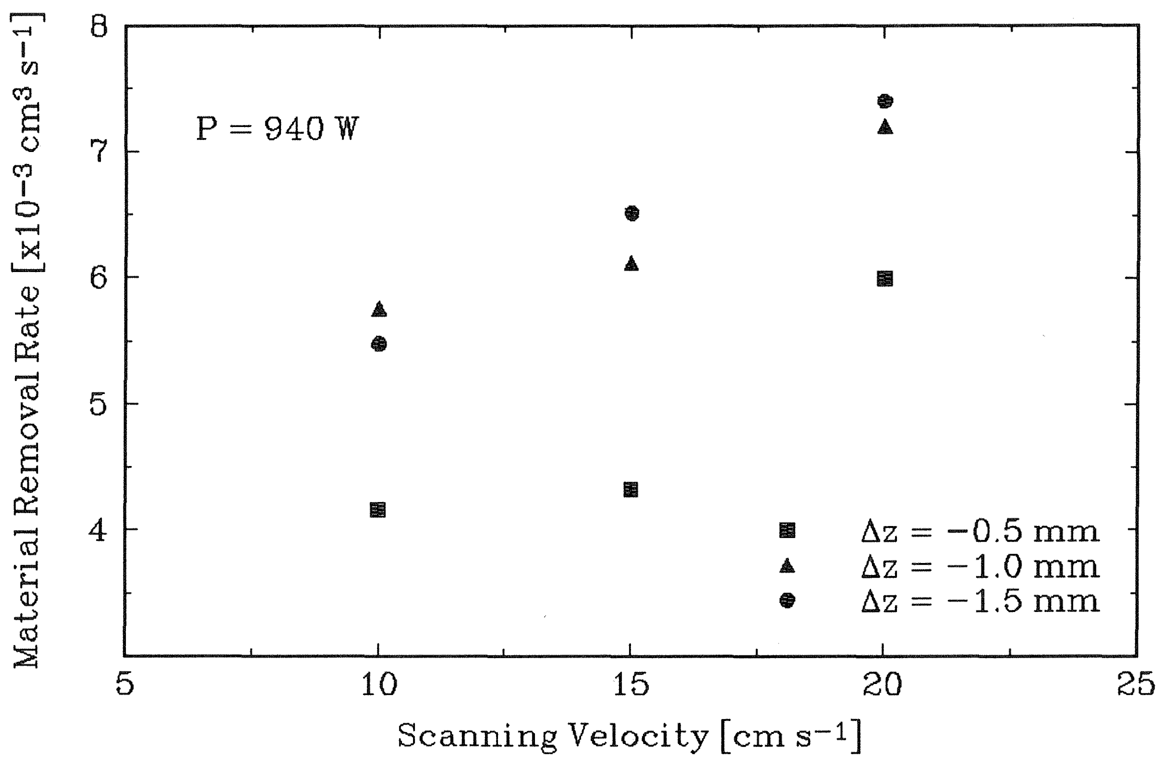
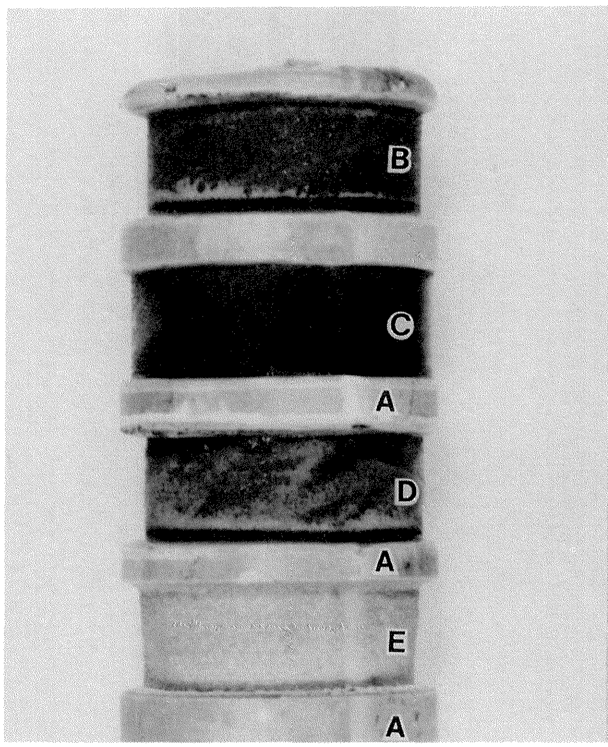


Figure 6: Material removal rates determined for graphite for beam scanning velocities from 5 to 20 cm s^{-1}, electric vector parallel (0°) to the scan direction, and three different focal plane positions.

APPLICATIONS

Rotationally Symmetric Si_3N_4 Components

The material removal rate data collected above were applied to demonstrate feasibility of concept for laser machining rotationally symmetric Si_3N_4 components, such as valve stems and injector nozzles. Layers were laser machined from the 10 mm diameter Ceraloy 147-31E and Noralide NCX-5102 HIPed Si_3N_4 bars. It should be noted that the NCX-5102 HIPed bars were bowed, out of round and exhibited two seams and a flat on the external surface. Figure 7a shows as-laser machined (940 W, 100 cm s^{-1}) surfaces of NCX-5102, with the seam on the original surface labelled A. Regions B, and D were machined to cylinders, eliminating the surface features and out-of round shape. Note that region C was a shallower depth which was insufficient to eliminate the surface seam. Conditions which retained the surface profile with depth were also identified. Region E has been machined to the same depth as region D, but the surface seam is now clearly visible. Minimal silicon build was observed on the sample, unlike the continuous silicon films shown on individual layers of GS-44 in Figures 5a, 5b. Surfaces B, C and D also exhibited a smooth, brown film, thought to be a silicon oxy-nitride. Residual silicon was removed by an etching treatment but the time was insufficient to completely remove the brown film (Figure 7b). Studies to optimize etching conditions are now in progress.



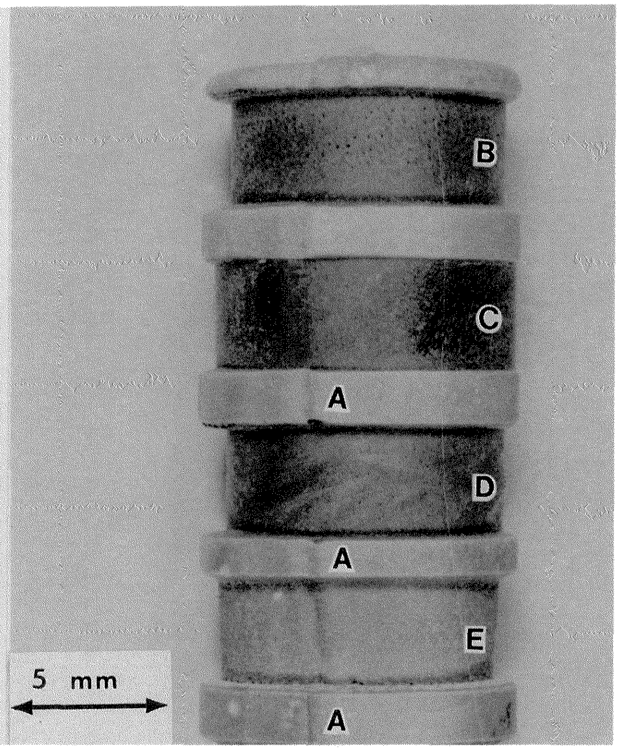


Figure 7a: As-laser machined surfaces of Noralide NCX-5102 HIPed Si_3N_4.

Figure 7b: Etched surfaces of Noralide NCX-5102 HIPed Si_3N_4.

Fuel Cell Plenums

Fuel cells convert chemical energy directly into electrical energy by oxidation of the fuel which flows through a complex array of channels in the plenum. Multiple plenums, typically made of graphite, are assembled to make the fuel cell stack. Each plenum contains channels approximately 1 mm in width, depth and spacing. Machining the complex array of channels is slow, produces carcinogenic graphite dust, and is expensive, even with CNC milling machines, since excessive force or speed results in chipping of the graphite. Plenums containing developmental 1 x 1 inch arrays of channels were conventionally machined for IIT's fuel cell program at a cost of $500 each.

In contrast, laser machining offers an economical and clean method for two- and three-dimensionally shaping graphite. Using the parameters developed above, a prototype fuel cell was machined as shown in Figure 8. Production costs, based on laser operating costs of $100.00 per hour, were estimated at approximately $8.00.

SUMMARY

The above studies demonstrate the potential for direct manufacturing of laser machined components of Si_3N_4 and graphite. The research on fuel cells is being scaled up

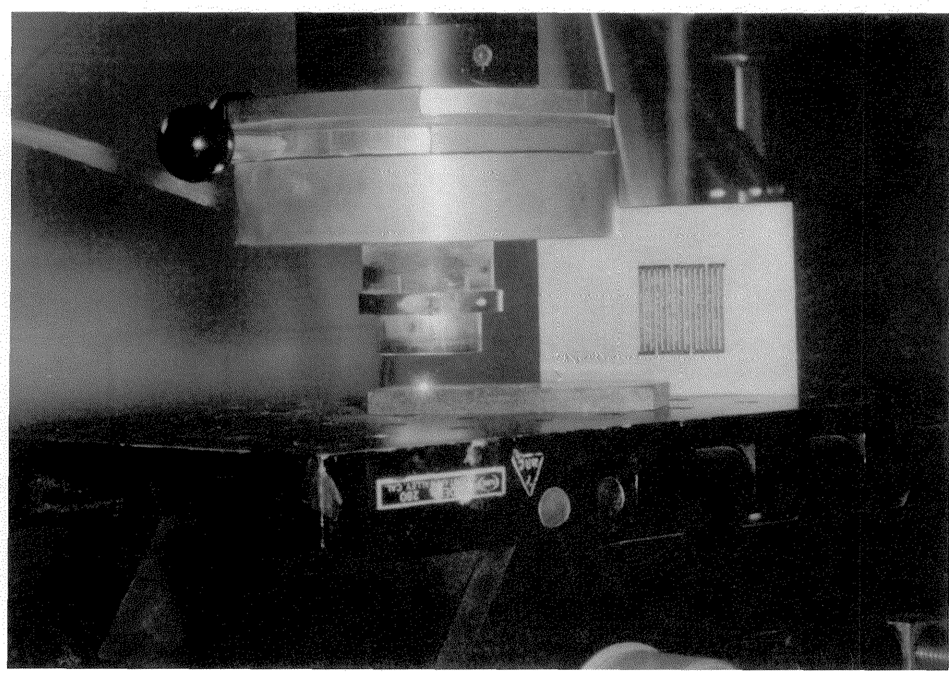


Figure 8: Laser machining a graphite fuel cell plenum.

for technology transfer to industry, while development of the laser shaping system continues for the production of complex three dimensional shapes of Si_3N_4.

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