Conf-9411239--1

UCRL-JC-117091
PREPRINT

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This paper was prepared for submittal to the
Photonics Technology Transfer Conference
Washington, DC, November, 9, 1994

November 9, 1994

Lawrence Livermore National Laboratory

DISCLAIMER

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ABSTRACT

We have developed a copper vapor laser based micromachining system using advanced beam quality control and precision wavefront tilting technologies. Precision microdrilling has been demonstrated through percussion drilling and trepanning using this system. With a 30-W copper vapor laser running at multi-kHz pulse repetition frequency, straight parallel holes with size varying from 500 microns to less than 25 microns and with aspect ratio up to 1:40 have been consistently drilled with good surface finish on a variety of metals. Micromilling and microdrilling on ceramics using a 250-W copper vapor laser have also been demonstrated with good result. Materialographic sections of machined parts show little (submicron scale) recast layer and heat affected zone.

INTRODUCTION

Laser micromachining has found expanded use in automobile, aerospace, and electronics industries. For example, lasers are used in precision hole drilling [1], micromilling [2,3], and fabrication of micromechanical components for dimensional tolerance of micron scale [4]. In microelectronics, lasers are employed to scribe wafers, trim passive film elements, and obtain alloy p-n junctions of semiconductors [5]. The advancements of laser micromachining are mainly due to the possibility of making small and unique structures that are difficult to achieve with conventional methods, and its applicability to traditionally hard-to-work materials such as ceramics, glass, and composite materials.

Despite the advantages of laser micromachining over conventional method, its advancement has been thwarted by the laggard development of advanced lasers suitable for this application. To meet the stringent precision requirement, the laser must have near-diffraction-limited beam quality with its wavelength shorter than 1 micron such that a circular laser focal spot with micron-scale size can be produced on the material's surface. To minimize the effects of material bulk heating and to produce a machined surface free of heat affected zone, the laser must have a relatively high peak power (greater than 10^8 W/cm^2) and short pulse duration (i.e., submicrosecond) such that the material removal is mainly through laser ablation instead of melting. Additionally, multi-kHz laser operation is preferred to remove the material in a more controllable fashion, such that the material removed during each pulse is small while the processing speed is maintained because of high pulse rate. To our knowledge, no existing laser system can meet all of these requirements except the copper vapor lasers (CVL) developed under Atomic Vapor Laser Isotope Separation (AVLIS) Program for the Department of Energy.

Over the past several years the AVLIS Program, in coorporation with several private industries, has examined the technical and economic feasibility of the applications of CVL technology developed at the Lawrence Livermore National Laboratory (LLNL) to micromachining. As a result, we have developed a new laser micromachining technique based on near-diffraction-limited CVL systems and a precision wavefront tilting technology. High-aspect ratio straight holes characterized by smooth side wall with negligible recast layer have been consistently produced. The use of a precision-wavefront-tilting technology greatly reduces the hole size and roundness error, typically to less than a few microns. Micromilling and microdrilling on a variety of ceramics have also been demonstrated with excellent result. This paper reports the new CVL based micromachining technology and its implementation in precision micromachining of metals and ceramics.

CVL MICROMACHINING SYSTEM

A CVL, with its high repetition frequency (4-30 kHz) and short output pulse (30-100 ns) in the visible spectrum, has been considered an ideal tool for laser micromachining [6,7,8] However, the difficulties in controlling CVL beam quality and in optimizing the processing parameters have prevented it from generating repeatable high-precision result. Our recent developments in near-diffraction-limited medium-power CVL oscillator and high-power CVL amplifier, and a precision wavefront tilting technology have revealed the potential of CVL in precision microfabrication.

The schematic of our copper laser based micromachining system is illustrated in Figure 1. An injection-controlled copper laser oscillator [9] with near-diffraction-limited beam quality is used in this system. A power-in-the-bucket measurement indicates ~73% of the laser output is within diffraction-limited beam divergence. This CVL beam quality is thus approximately 1.1 times diffraction limited based on Strehl ratio. The laser is designed to be operated between 4-9 kHz for various material processing requirements. This laser generates about 30-W output at wavelengths of 511 nm (60%) and 578 nm (40%). The self-terminated CVL used in our system typically has a pulse duration of 50-70 ns. For applications requiring higher laser power, the near diffraction-limited oscillator beam can be amplified to ~250 W through a CVL amplifier [10].

For micromachining applications, the laser beam is focused by a high-quality achromat on the work piece that typically generates a diffraction-limited spot size. As shown in Figure 1, a precision two-axis scanning mirror is used to tilt the laser wavefront before passing through the achromat with an angular resolution better than a few μrad. This scanning mirror is equipped with a feedback loop to compensate for hysteresis effects. The beam scanning frequency on the workpiece can be varied from 1 Hz to higher than 100 Hz depending on application requirement. A camera is used to examine the progress of material removal on the workpiece based on backscattered laser light.

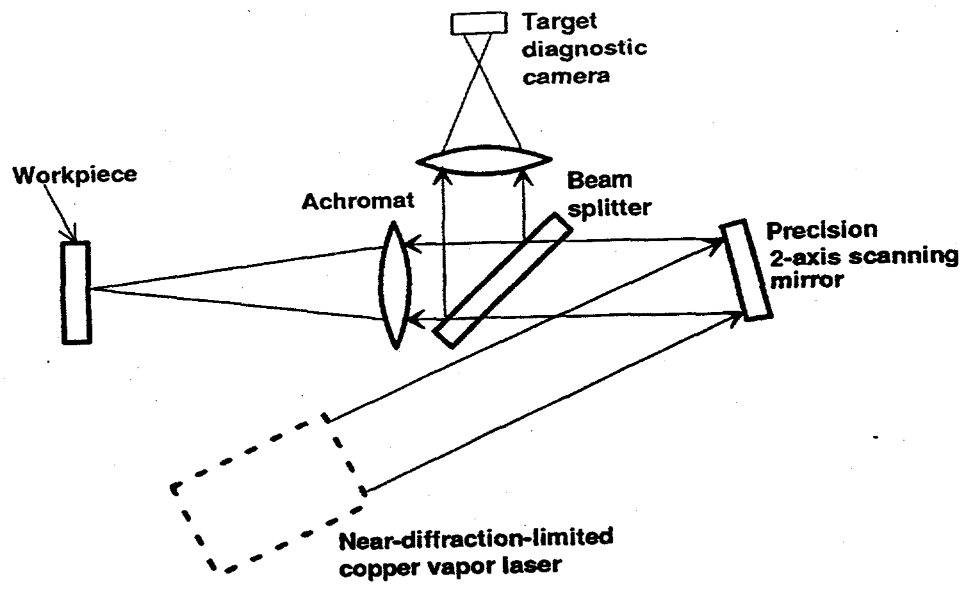


Figure 1. The schematic of a CVL micromachining system.

LASER MICRODRILLING

Laser drilling has been widely used in industry because of its high production rate and abilities of rapidly varying hole size, drilling holes at shallow angle, and drilling traditionally hard-to-work materials such as ceramics and composite materials. Most laser drilling systems are based on CW or long pulse CO_2 and YAG laser systems [1,11,12]. Material removal with these lasers is mostly through melt expulsion. This material removing mechanism normally leads to poor dimensional control and sizable recast layer with microcracks on the sidewall of drilled holes. The strong plasma-beam interaction at longer wavelength (i.e., 10.6 μm) due to inverse bremsstrahlung also makes the material removal during laser drilling less controllable. In addition, the reduced focusibility of the infrared laser beam makes it more difficult to produce micron-scale holes with large hole aspect ratio (i.e., hole depth to diameter). YAG laser systems have less pronounced plasma-beam interaction and shorter wavelength (i.e., 1.06 μm), but typically suffer from poor beam quality because of laser rod heating.

These issues have prevented the advancement of high-quality precision laser microdrilling. Lately, because of the advancement of low-power waveguide excimer lasers and frequency-quadrupled Nd-YAG lasers, precision microdrilling has been demonstrated on nonmetallic materials [3,4,5]. UV laser ablation on most nonmetallic materials is basically a non-thermal process by breaking structure bond without melting (photolytic). Laser ablation in metals, although achievable with higher laser peak power, is still a thermal process that includes rapid melting and vaporization of material illuminated by laser beam. The condensation of ablated material on the surface further complicates this process, especially for high-aspect-ratio machining. A more sophisticated processing control is thus required for high-quality microdrillings in metals.

CVL Percussion Drilling

In CVL percussion drilling, a stationary laser beam is used to drill through a stationary workpiece. Straight parallel holes with aspect ratio better than 40:1 have been repeatedly produced in a variety of steels. Figure 2 shows a section of three 20-25 micron diameter holes percussion drilled on stainless steel (1-mm thickness). Because material removal in this case was mainly through laser ablation, these holes show no measurable heat affected zone and the hole quality is distinctively superior to those drilled with long pulse CO_2 and Nd:YAG lasers. Smaller hole sizes can also be achieved using lower laser power and faster focusing optics, but this also reduces material penetration with the possibility of generating tapered holes. Since the coupling between the sidewall of a drilled hole and the laser beam is very poor due to high incidence angle, our experience indicates that the laser peak power on the hole entrance must be more than a few GW/cm^2 to avoid hole taper.

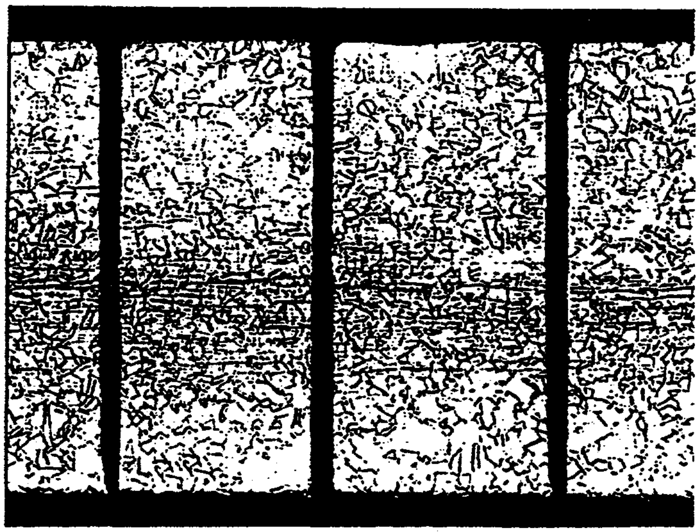


Figure 2. Section of CVL percussion drilled holes on a 1-mm thick stainless steel with hole diameter 20-25 microns. These holes show no measurable heat-affected zone. Note that the minor taper on the hole bottom was actually caused by section error. The hole sizes measured on the top and the bottom are less than 10% different.

Assist gas was not found to be essential in CVL microdrilling, but there is evidence that oxygen increases drilling speed because of exothermic reactions. Although straight holes free of recast layer can be produced by a simple CVL percussion drilling at a fairly fast speed, the hole dimensional control and hole repeatability are generally not satisfactory for high precision applications. Typically a tolerance of hole size and roundness of approximately 5-10% of its diameter is expected. Higher precision microdrilling must be accomplished by laser trepanning.

CVL Precision Microtrepanning

Laser trepanning has long been applied in industry to either improve the hole accuracy or to generate large holes, mostly for hole aspect ratio less than 1:1. Precision microtrepanning for high-aspect-ratio holes has rarely been accomplished because of difficulties in material penetration and removal. In our investigation, laser trepanning is achieved by periodically tilting the X-Y scanning mirror such that the laser spot generates a circular pattern on the workpiece. A typical laser beam scanning pattern is illustrated in Figure 3, which shows a circle with diameter of 180 microns. Figure 3 also illustrates a well defined kerf ablated by a CVL focus spot. Note that the coloration along the side of the kerf was burned by the side lobes of the far-field spot.

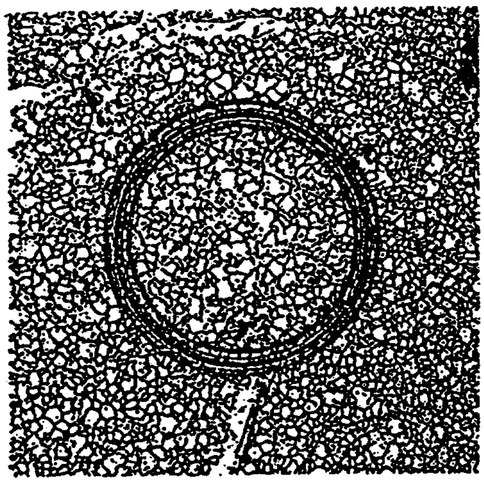
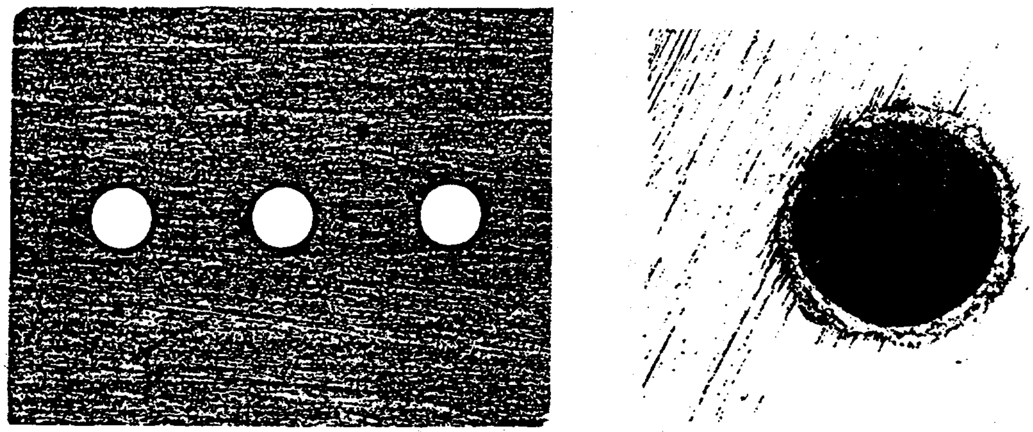


Figure 3. A circular laser scanning burn pattern (180 micron diameter) on the workpiece for micro trepanning.

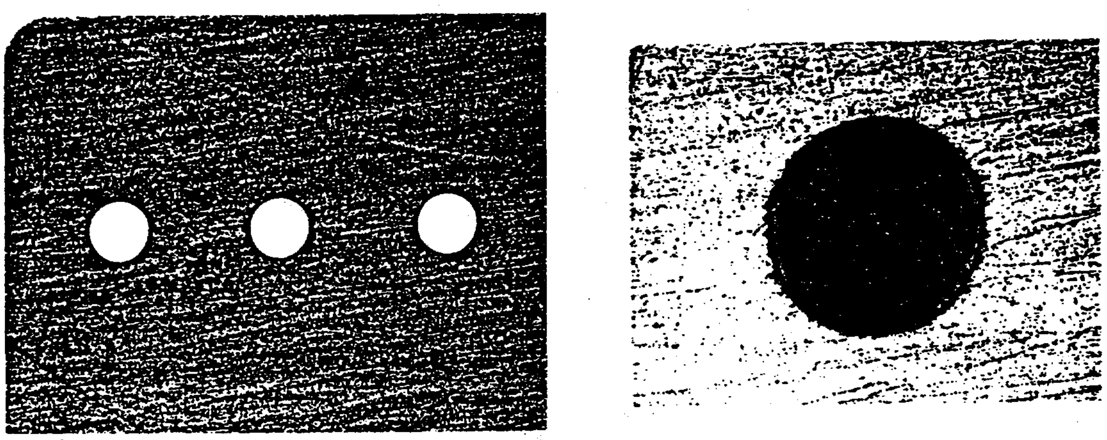
Figure 4a illustrates three CVL trepanned holes with 185 micron diameter on a 1-mm stainless steel. The sample was ultrasonic cleaned after drilling without additional post processing. Minor edge erosion with depth less than 10 microns was found on the laser entrance side as shown in Figure 4b. However, materialographic examination of sectioned holes indicates the material underneath of this area was not affected. The holes on the laser exit side, shown in Figure 5, demonstrate extremely well defined circular hole pattern without erosion. Measurements indicate that both the entrance and exit holes have a roundness error of about 5 microns caused mainly by the residue hysteresis of our scanning mirror system. Laser beam polarization state is also known to have some effects on exit hole geometry, especially for high-aspect-ratio hole drilling.

Repeatability of hole dimension has been significantly improved with CVL trepanning as demonstrated in Figures 4 and 5. The variations of hole size and shape were almost impossible to measure based on our microscope measuring system. This striking improvement on hole repeatability is believed to be mainly due to the fact that laser trepanning not only performs material removal during the initial drilling phase, but also engages in material trimming and sidewall polishing during the later drilling phase.



(a) (b)

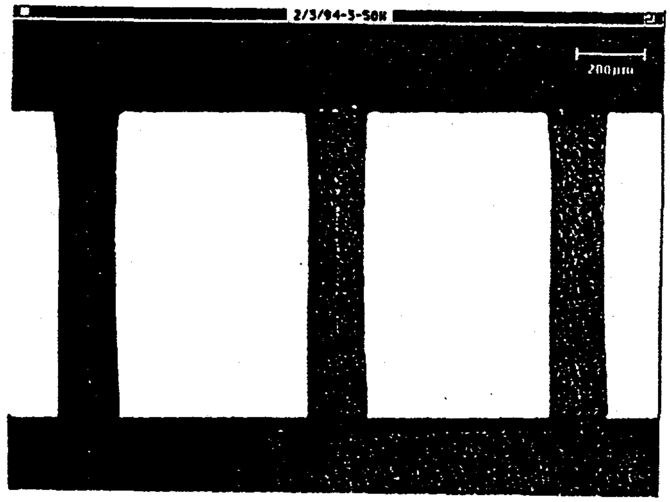
Figure 4. Precision laser trepanned holes (laser entrance side) on a 1-mm thick hardened steel with hole diameter of 185 microns. One of the holes is further magnified, as shown in (b).



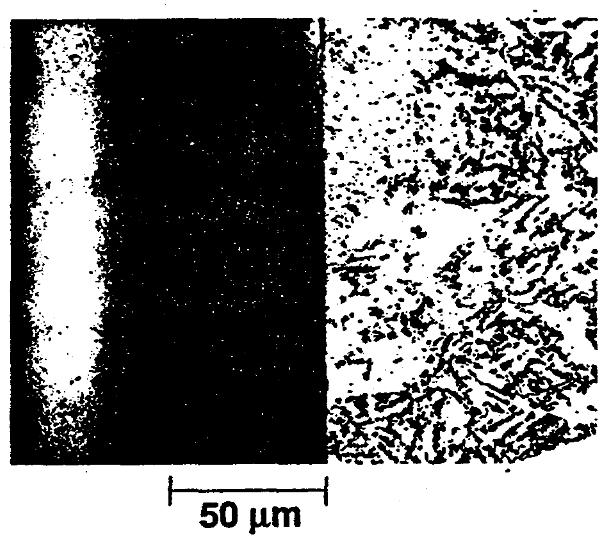
(a) (b)

Figure 5. Precision laser trepanned holes (laser exit side) on a 1-mm thick hardened steel with hole diameter of 185 microns. One of the holes is further magnified, as shown in (b).

A section of three trepanned holes is illustrated in Figure 6a. It shows fairly straight sidewalls with surface roughness measured within 1-2 microns (i.e., peak to valley), which is comparable to the high end of mechanically drilled holes. A minor curvature on the sidewall was caused by the caustic surface of the focused laser beam and can be corrected with a longer focus lens. Detailed examination of the hole section reveals that the recast layer and heat-affected zone are minimized to a nonmeasurable level (i.e., submicron), as illustrated in Figure 6b.



(a)

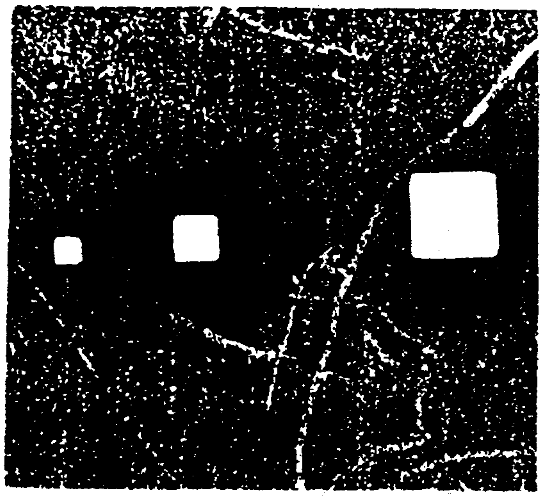


(b)

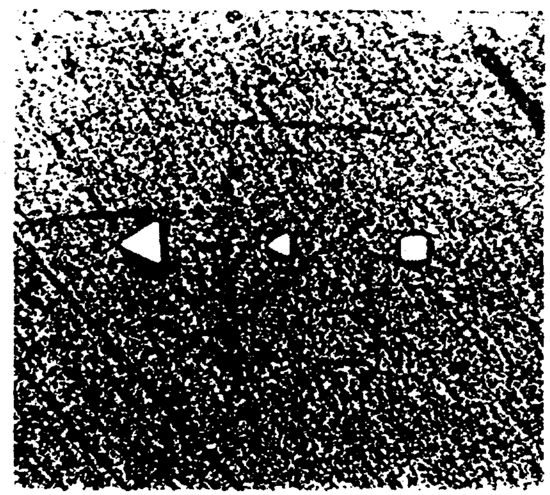
Figure 6. (a) A section of three CVL trepanned holes on a 1-mm thick hardened steel. (b) Materialographic section shows good surface finish with no heat-affected zone on the sidewall.

CVL Micromachining of Noncircular Holes

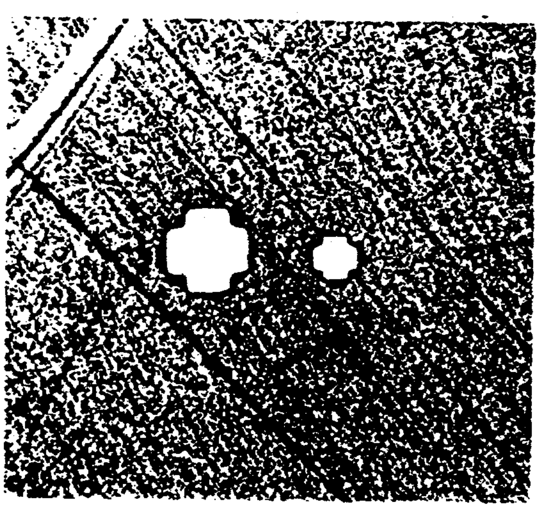
In addition to circular holes, we have demonstrated trepanning noncircular holes with various geometries on a 1-mm thick stainless steel, as illustrated in Figure 7. These holes were cut by modifying the scanning pattern of the trepanning system to draw the desired shape on the target. Hole aspect ratio higher than 10:1 with no taper has been achieved with these non-circular trepanned holes. The corner rounding effect shown in Figure 7 becomes more severe as hole size was reduced to smaller than 100 micron. This effect primarily arose from the size of the CVL far-field beam footprint. It can be improved by using faster focus lens when smaller hole aspect ratio is required. This demonstration of noncircular microholes with high aspect ratio reveals the great potential in laser microtrepanning applications,, which may have significant impact on engineering design that was traditionally limited to circular holes.



110 µm 190 µm 350 µm



156 µm 84µm 90 µm



350µm 180 µm

Figure 7. CVL trepanned holes on a -mm thick stainless steel shows that a variety of hole geometries can be drilled with hole aspect ratio larger than 10:1.

CVL MICROMACHINING ON CERAMICS

Advanced fine ceramics have many excellent physical and chemical properties for usage in high-density electronics fabrication and packaging. Nonetheless, their hardness and brittleness make them difficult to machine even with diamond tools. The noncontact nature of laser micromachining precludes the problem of tool wear and also minimizes any unacceptable microstructure change. However, the laser machined method using long-pulse CO_2 and YAG lasers has a disadvantage of developing thermal-stress induced cracks on ceramics. The use of high-radiance short-pulse CVL minimizes the material bulk heating such that a crack-free micromachining processing becomes feasible.

Figure 8 illustrates laser milled grooves on a piece of silicon carbide (i.e., 1.25 mm thick) with about 40 W of CVL. The grooves are 120-micron wide and 120-micron deep in the part. Detailed examination of the grooves showed straight sidewalls and fairly flat bottom. The holes in the part were trepanned with 70 W of CVL. The hole diameters in the part are 1.25 and 2.5 mm. The hole roundness is perfect and no material crack has been observed. Micromachining on alumina and silicon nitride has also been demonstrated with promising result. This crack-free machining of a variety of ceramics represents a great potential for using our CVL based micromachining system in electronics industry.

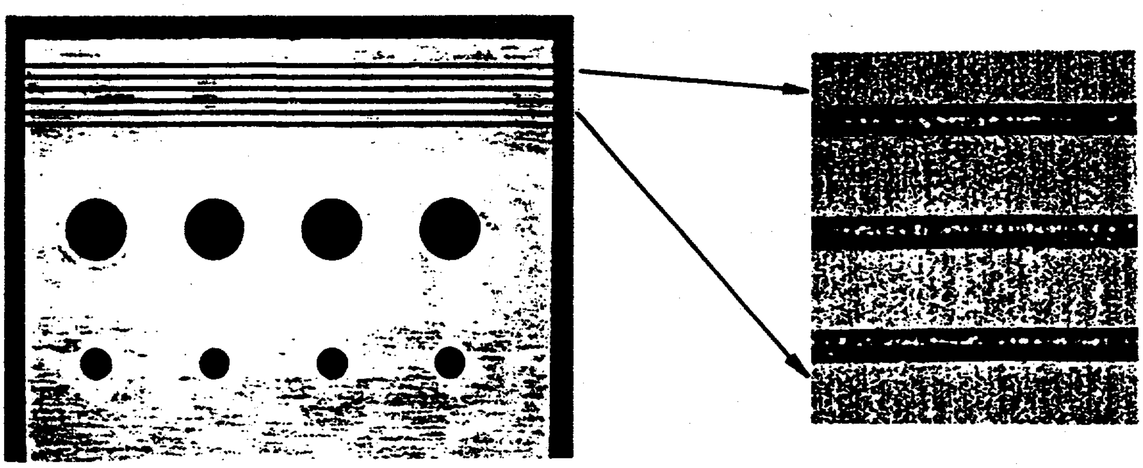


Figure 8. CVL machined grooves and holes on a piece of silicon carbide. The hole sizes are 1.25 and 2.5 mm, the grooves are 120 μm wide and 120 μm deep.

CONCLUSION

Precision micromachining has been demonstrated using LLNL developed high beam quality CVL and precision wavefront tilt technology under the AVLIS program. In the area of microdrilling, straight holes with sizes varying from 20 microns to 500 microns have been consistently drilled with hole aspect ratio up to 1:40 on a variety of metals. CVL percussion drilled holes typically show a hole dimension error of 5-10% of its diameter. When higher precision is needed, CVL microtrepanning is applied to improve the dimensional error to less than a few microns. Noncircular holes have been drilled by simply changing the laser scanning pattern. The repeatability of trepanned holes is excellent when the drilling parameters, which are laser power, scanning frequency, scanning geometry, focus position, laser polarization, and processing time, are well maintained. Surface roughness inside trepanned holes was measured within 1 to 2 micron peak to valley. Materialographic sections of the drilled holes indicate little heat affected zone or recast layer because of an effective laser ablation process owing to the short pulse and high peak output power (10^8-10^{10} W/cm^2) of a CVL. These characteristics of a CVL also enabled us to demonstrate crack-free micromilling and microdrilling on a variety of ceramics.

This CVL micromachining system represents a great potential in precision microfabrication industry. Its machining capability in ceramics surpasses not only conventional diamond tools but also long-pulse CO_2 and YAG laser machining systems because of crack-free machining. The quality of micro trepanned holes on metals using this system is found to be comparable or better than that done by EDM (i.e., Electrical Discharge Machining). With the flexibility in hole geometry and size, and scalability to higher production speed, this micromachining system offers a technique superior to EDM machines that are currently widely used in industry. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

REFERENCES

1. H. Treusch and G. Herziger, "Metal precision drilling with lasers," SPIE, Vol. 650, pp. 220-225, 1986.
2. A. van Krieken, J. Schaarsberg, and H. Raterink, "Laser micro machining of material surfaces," SPIE, Vol. 1022, pp. 34-37, 1988.
3. C. Paul Christensen, "Waveguide excimer laser fabrication of 3D microstructures," SPIE, Vol. 2045, pp. 141-145, 1994.
4. E. Wiener-Avnear, "Laser cut microscopic paths with major potential," Laser Focus World, pp. 75-80, July 1993.
5. J. Hobbs, "Electronics makers switch to precise micro machining tools," Laser Focus World, pp. 69-72, March 1994.
6. R. Kupfer, H. Bergmann, M. Lingenauer, "Material influence on cutting and drilling of metals using copper vapor lasers," SPIE, Vol. 1598, pp. 46-60, 1991.
7. H. Bergmann and M. Hartmann, "Drilling of metals with copper vapor lasers," Laser Processing Proceedings, TMS Annual Meeting, Denver, 1993.
8. R. Pini, R. Salimbeni, M. Vannini, and G. Toci, "Copper vapor laser high aspect ratio drilling process on transparent materials," Presented in CLEO'92, Los Angeles, 1992.
9. J. Chang and M. Solarski, "A self-imaging injection-controlled copper laser oscillator," CLEO'93 Digest, p. 458, 1993.
10. J. Chang, "Pressure dependence of copper laser output characteristics," Applied Optics, Vol. 32, pp. 5230-5235, 1993.
11. S. Tam, C. Yeo, S. Jana, M. Lau, L. Lim, L. Yang, and Y. Noor, "Optimization of laser deep-hole drilling of Inconel 718 using Taguchi method," J. Materials Processing Tech. v. 37, pp. 741-757, 1993.
12. S. Takeno, M. Moritasu, and S. Hiramoto, "Laser drilling by high-peak pulsed CO_2 laser," ICALEO'92 Proceedings, pp. 459-468, 1992.