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Laser Materials Processing Applications at Lawrence Livermore National Laboratory

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**Laser materials processing applications
at Lawrence Livermore National Laboratory**

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ABSTRACT

High power and high radiance laser technologies developed at Lawrence Livermore National Laboratory (LLNL) such as copper-vapor lasers, solid-state slab lasers, dye lasers, harmonic wavelength conversion of these lasers, and fiber optic delivery systems show great promise for material processing tasks. Evaluation of models suggests significant potential for tenfold increases in welding, cutting, and drilling performance, as well as capability for applications in emerging technologies such as micromachining, surface treatment, and stereolithography.

Copper and dye laser systems are currently being developed at LLNL for uranium enrichment production facilities. The goals of this program are to develop low-cost, reliable and maintainable industrial laser systems. Chains of copper lasers currently operate at more than 1.5 kW output and achieve mean time between failures of more than 1000 hours. The beam quality of copper vapor lasers is approximately three times the diffraction limit. Dye lasers have near diffraction limited beam quality at greater than 1.0 kW. Diode laser pumped, Nd:YAG slab lasers are also being developed at LLNL. Current designs achieve powers of greater than 1.0 kW and projected beam quality is in the two to five times diffraction limited range.

Results from cutting and drilling studies in titanium and stainless steel alloys show that cuts and holes with extremely fine features can be made with dye and copper-vapor lasers. High radiance beams produce low distortion and small heat-affected zones. We have accomplished very high aspect ratio holes in drilling tests ($> 60:1$) and features with micron scale (5 - 50 μm) sizes. Other, traditionally more difficult, materials such as copper, aluminum and ceramics will soon be studied in detail.

1. INTRODUCTION

Use of lasers for welding, cutting and drilling is well established in industry. Conventional CO₂ and Nd:YAG lasers have become technologies of choice for these applications. At Lawrence Livermore National Laboratory (LLNL), we have developed several new high power and high radiance lasers allowing a wider processing window for laser material processing due to improved beam-material interaction properties. This paper will discuss and compare laser material processing using copper vapor laser-pumped dye and copper vapor lasers. We also will discuss other technologies being developed at LLNL including diode laser pumped, slab Nd:YAG lasers, fiber optic delivery systems, and harmonic conversion of these lasers to ultraviolet wavelengths.

2. CUTTING THEORY

High radiance lasers can potentially provide significant productivity and precision improvements for industrial lasers. Short wavelength and improved beam quality lead to smaller beam spot size, while the pulsed beam format decreases the peak temperatures reached in the bulk material. These properties combined, make fabrication of micron-scale features feasible and decrease the volume of heat affected material outside the laser processing region.

To understand several important features of this process we use a steady-state solution of the thermal transport equation for a moving line heat source. This analytical approach was first used by Swift-Hook and Gick and others [1-2] to characterize electron-beam welding performance and has been shown to be a valid model for a wide range of materials and laser processing conditions.

Dimensionless speed and power parameters characterize the keyhole welding and cutting process as shown by the solution to the thermal transport equation, which is illustrated in Figure 1. Once a keyhole is established by sufficiently high peak fluxes ($>1 \text{ MW/cm}^2$), the typical energy transfer efficiencies to the material are high ($>70\%$), even for long wavelength CO_2 lasers. Data points on Figure 1 show cutting results using the dye laser system at LLNL with powers up to 600 W. The normalized speed function is

$$V_N = vw/D \quad (1)$$

where v is workpiece velocity,
 w is beam spot size, and
 D is the material thermal diffusivity.

The normalized power function is

$$P_N = nP_0/aS \quad (2)$$

where n is the laser coupling efficiency,
 P_0 is the laser power
 a is the material thickness and
 S is the material heat function.

The lower portion of the curve shows the parameter regime where heat flow from the line source is dominated by conduction into the base material. The upper portion of the curve is the parameter regime where energy is transported by convective flow. Comparison of high radiance copper vapor, dye and diode-pumped, Nd:YAG lasers with conventional industrial lasers shows that large increases in productivity and/or precision are gained as illustrated in Figure 2. This figure maps the laser parameters along with processing speed (productivity) and precision (kerf dimension) for 6mm thick 304 stainless steel. The figure accounts for parameters such as typical range of powers and radiance (kerf dimension) for commercial lasers and also shows laser pulse repetition frequency (PRF) requirements to maintain a reasonable laser spot overlap at a given speed. The Figure illustrates that high radiance lasers should provide an order of magnitude increase in processing capability.

3. DESCRIPTION OF EQUIPMENT

3.1. Material processing laser system

Our copper and dye laser systems are high radiance laser sources because of their visible wavelength, near diffraction limited beam quality, and high-average power. They show promise in improving material throughput and in increasing precision, particularly with fine-hole drilling and cutting. We are currently using both high-power dye and copper laser beams to map out precision cutting and hole drilling operating regimes. In addition, we are developing diagnostics to better understand the high-radiance-laser/material interactions.

The copper laser system at LLNL consists of 12 chains operating continuously. The copper lasers operate at nominally 4.5 kHz, with 50 ns pulse widths and produce 20 W at near the diffraction limit from oscillators and $>250 \text{ W}$ from each amplifier. Chains consist of an oscillator and three amplifiers and produce $>750 \text{ W}$ average, with availabilities $>90\%$ (i.e., $>7900 \text{ h/y}$). Development of advanced copper laser hardware has resulted in chains that produce more than twice these power levels ($>1,500 \text{ W}$). The total copper laser system power averages $\sim 9000 \text{ W}$ and has operated at over 10,000 W for extended intervals. The 12 copper lasers beams are multiplexed and delivered to the dye laser system where they pump multiple dye laser chains. Each dye laser chain consists of a master oscillator and three or four power amplifiers. The master oscillator operates at nominally 100 mW with a 50 MHz single mode bandwidth. Amplifiers are designed to efficiently amplify the dye beam with low ASE content and high optical quality. Sustained dye chain powers are $>1000 \text{ W}$ average with dye conversion efficiencies $>50\%$, ASE content $<5\%$, and wave front qualities correctable to $<\lambda/10 \text{ RMS}$, using deformable mirrors. Since the timing of the copper laser chains can be offset, the dye laser system is capable of repetition rates which are 4.4 kHz, up to 26.4 kHz, limited by the dye pumping system.

A commercial, 3-axis computer controlled workstation capable of 40 cm per second speed and $7\mu\text{m}$ precision was attached to our dye and copper vapor laser beamlines for process testing. Both beams travel several hundred feet through a

conventional optical train to reach this workstation and are stabilized by an active pointing and centering system to minimize vibrational motion of the laser beams. We can access either the dye laser beam at powers up to ~1 kW or up to two copper laser chains at 1.5 kW of power. Details on the pointing and centering system and the dye and copper laser systems are available in other papers in this conference [3-4].

We developed two sets of diagnostic tools for material processing studies, a beam measurement system and a penetration detector. These tools were important instruments for making accurate measurements during material processing studies. The beam measurement system used on copper vapor and dye laser beams allows low power beam spot size measurements on a very fine scale. The z-axis of the workstation is moved to find the smallest (focal) spot size. This measurement system also allows beam profile measurements to be made outside the focal spot. This data is especially valuable when processing thick sections to determine the proper placement of the focal spot to produce the smallest tapers in holes and kerfs. The penetration time detector uses two photodiodes to sense the light reflected from the workpiece surface and light when it penetrates through the section.

3.2. Future additions to laser material processing laboratory

We will shortly be testing a 1 kW diode pumped, slab Nd:YAG laser developed at LLNL. This laser is expected to have beam quality on the order of two to five times diffraction limited and robust semiconductor diode laser pumping. Its multiple pulse formatting capability will allow us to optimize parameters for several material processing operations.

We have developed technology to pass high power visible beams through fiber optics and are presently working on optical solutions to enhance beam quality when using fiber optic delivery. The use of fiber optic delivery systems has helped commercial lasers gain widespread acceptance in industrial applications. Reducing the number of conventional optics needed to move light to a processing operation makes using lasers much easier and more robust in industrial environments.

Harmonic conversion of visible and infrared lasers into ultraviolet wavelengths may allow processing of special and difficult materials with high precision. These lasers could be more robust than other types of ultraviolet lasers. We presently have converted visible light to ultraviolet wavelengths with efficiencies of 15 to 20 percent. Our models indicate that 50 percent conversions may be achieved [5].

4. EXPERIMENTAL RESULTS

We completed several cutting and drilling studies on both Ti-6Al-4V and AISI 304 stainless steel using both copper vapor and dye lasers. These studies to date have used a wide range of thicknesses and power levels. Copper vapor laser material processing studies have recently been initiated at low powers (< 20 W) and thin section sheet material.

4.1. Results of cutting studies

In thin materials (100 to 500 μm) the dye laser has typically produced cuts with kerfs ranging between 10 to 50 micrometers in width. The copper vapor laser produces kerfs in the same materials that range from 20 to 50 micrometers in width. Plots of some dye laser data and their correlation with the curve generated by Swift-Hook and Gick are shown as the datapoints in Figure 1.

Early studies with dye laser cutting generated kerfs that exhibited rough surfaces with a large amount of vapor and liquid droplet redeposition on the surface. The copper vapor laser and more recent dye laser generated kerfs have been smooth and similar to those found when using Nd:YAG and CO₂ lasers. Representative SEM photomicrographs of both types of kerf are shown in Figure 3.

Microstructurally, the heat-affected zones associated with cuts made using dye and copper vapor lasers are very small or nonexistent. Figure 4 shows the lack of a heat-affected zone in a cut made through AISI 304 stainless steel. Although stainless steels typically show recrystallization and twinning as effects of heating, no signs of either are noted in the edge of the cut shown.

4.2. Results of drilling studies

Studies done on drilling have shown two regimes: a region where thickness penetrated is roughly a linear function of the time needed to produce holes and an equilibrium region where material removal appears to be approximately balanced by material redeposition and further penetration is difficult. Holes of 50 μm diameter made in Ti-6Al-4V and AISI 304 stainless steel alloys have both exhibited this phenomena and other studies have also found the equilibrium condition to occur when drilling with commercial lasers [6]. Figure 5 shows data generated using a dye laser in both regimes.

Microstructurally, the heat-affected zones associated with holes made using dye and copper vapor lasers are very small. The edge quality is also very good with minimal taper exhibited in holes, although through use of defocusing techniques, taper can be added to holes. Figure 6 shows a series of holes made in 304 stainless steel using a low power (6 W) copper laser beam. Hole diameters are 35 μm through 380 μm thick sheet. Very little taper is found in the holes and the straightness is excellent. Figure 7 shows the precision allowed by using high radiance, copper-vapor laser for hole drilling. This hole size is approximately the same as the grain size of the material and exhibits excellent roundness.

5. SUMMARY

This work shows that the new generation lasers under development at LLNL with short wavelengths and high beam quality can be used to cut and drill fine features in engineering materials. The hole aspect ratios generated in these studies were very high, up to 60:1. This technology opens capabilities for micromachining of parts never before available for commercial applications.

6. ACKNOWLEDGMENTS

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- Normalized speed depends on:
 - Velocity (v)
 - Kerf width/laser spot size (w)
 - Material diffusivity (D)
- Normalized power depends on:
 - Laser power (P_0)
 - Penetration depth/thickness (a)
 - Material heat fuction (where K is thermal conductivity)

$$S = \int_{T_0}^{T_1} K dT = \bar{K} \Delta T$$

Fig. 1. Swift- Hook and Gick analysis of penetration, power and speed. Data points show how cuts made with dye laser system compare to the theoretical model, which is based upon a steady state solution of the thermal transport equation for a moving line heat source.

Fig. 2. Nominal material processing performance comparison for various laser sources and the expected capabilities of high radiance lasers under development at LLNL.

(a)

0.01"

(b)

0.002"

Figure 3. SEM photomicrographs of kerf surfaces from (a) dye and (b) copper vapor laser cuts. These kerfs show that choice processing parameters and systems can greatly affect finished cut quality.

Figure 4. High magnification photomicrograph showing lack of heat-affected zone in a dye laser cut. The kerf width was $100\text{ }\mu\text{m}$.

Fig. 5. Penetration time as a function of thickness for dye laser drilling of 50 μm diameter holes. Laser power and penetration time are roughly linear until equilibrium occurs between material removal and material redeposition at larger thickness and aspect ratio.

Beam exit

Figure 6. Series of holes drilled in AISI 304 steel alloy using copper vapor laser. Holes are of excellent quality with very little taper and small heat-affected zone.

0.02 mm

Figure 7. Hole made in AISI 304 stainless steel alloy showing the extreme precision possible with high radiance, copper vapor lasers.

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