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Modeling of Material Removal by Solid State Heat Capacity Lasers

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Pulsed lasers offer the capability of rapid material removal. Here we present simulations of steel coupon tests by two solid state heat capacity lasers built at LLNL. Operating at 1.05 μm, these deliver pulse energies of about 80 J at 10 Hz, and about 500 J at 20 Hz. Each is flashlamp-pumped. The first laser was tested at LLNL, while the second laser has been delivered to HELSTF, White Sands Missile Range. Liquid ejection appears to be an important removal mechanism.

We have modeled these experiments via a time-dependent code called THALES, which describes heat transport, melting, vaporization, and the hydrodynamics of liquid, vapor, and air. It was previously used, in a less advanced form, to model drilling by copper vapor lasers [1]. It was also used to model vaporization in beam dumps for a high-power laser [2]. The basic model is in 1D, while the liquid hydrodynamics is handled in 2D,

The geometry of the model is shown in Fig. 1. From left to right, the model describes heat conduction in the solid, a moving melt line, heat conduction and liquid motion in the melt, a moving ablation surface, a thin Knudsen layer of molecular flow, the hydrodynamically expanding vapor, a moving vapor/air boundary, the hydrodynamically expanding air, and a shock front. Reasonable estimates for temperature-dependent material properties (primarily the thermal conductivity and the absorptivity) are employed. Since typical vapor temperatures are only a few thousand degrees, absorption in the vapor is negligible. In reality, absorption may occur in ejected liquid blobs, but this is not handled here.

In the liquid model, the fluid is pushed inward (to the left) and toward the radial edges by the recoil pressure of the ablated vapor, as shown by the streamlines in Fig. 1. The fluid reaching the edges is considered to be removed from the system. This picture is embodied in the following solution for 2D incompressible, potential flow [3]:

$$v_z(z,t) = -2\beta(t)[z - z_m(t)], \quad v_r(r,t) = \beta(t)\, r,$$

where z is to the right in the figure and $z_m(t)$ is the position of the melt surface. The function $\beta(t)$ responds to the central pressure just beneath the surface via

$$d\beta / dt + \beta^2 = (2/\rho a^2)\, p_0(t),$$

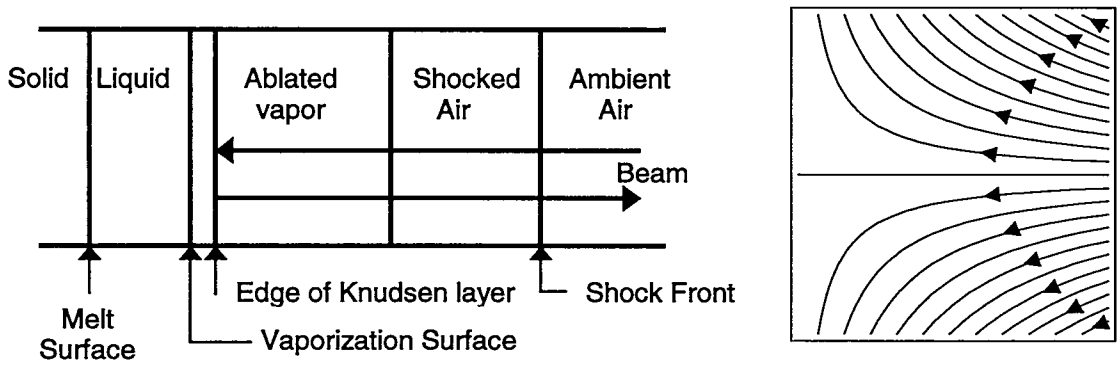

Fig. 1. Left: geometry of the model (not to scale). Right: streamlines in the liquid.

where ρ is the liquid density and a is the beam radius. Since the model does not describe the flow up the edges, it is most appropriate for shallow holes, such as those considered here.

The extracted pulse of the first laser consisted of a 400-μs train of relaxation oscillations (Fig. 2). After focus to a spot of about 0.09 cm^2, the beam had a fluence of about 900 J/cm^2 and a maximum intensity of about 27 MW/cm^2. It penetrated a 2.3 mm steel coupon in about 13 pulses. Although the removal certainly increased with successive pulses, we use the average (175 μm per pulse) as a very rough estimate of the depth expected for the first pulse.

If the removal mechanism were entirely vaporization, then the maximum depth achieved by a pulse would be of order $\alpha F / \rho H_v$, where α is the surface absorptivity, F is the fluence, and H_v is the heat of vaporization. This amounts to only about 30% of the depth estimated from experiment. Thus we are led to consider removal in the form of liquid ejection. This interpretation is also suggested by photographs of bright streaks emanating from the coupon.

The simulated removal is shown in Fig. 2. The depth is about 180 μm, agreeing with the estimated depth. The melt layer increases to a maximum of 16 μm before disappearing after application of the pulse. About 80% of the material is removed as liquid, with the remainder as vapor.

The edge temperature of the liquid is predicted to oscillate with the pulse, reaching a maximum of about 5000 C, as shown in Fig. 3. This behavior also holds for the first laser. The figure also shows a typical thermal profile. At this time (262 μs), the heat has penetrated about 250 μm from the original solid surface. The profile in the liquid increases almost linearly. On a much longer time scale (~10 ms), the temperature distribution in the coupon is no longer 1D.

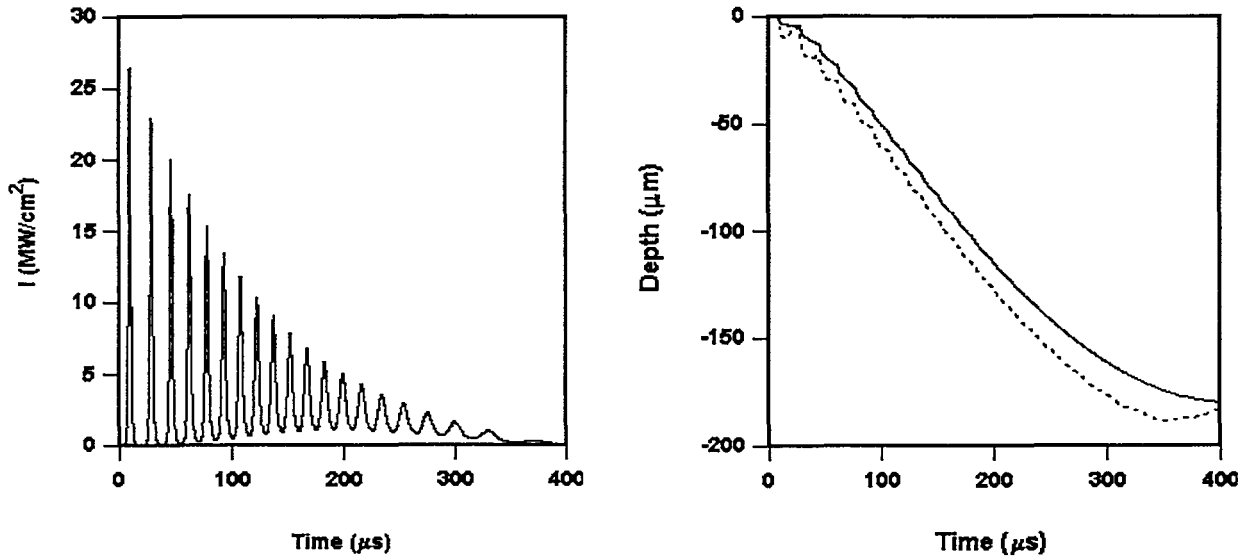

Fig. 2. Left: Intensity of first SSHCL during coupon tests. Right: Simulated removal in steel. The solid line and dotted line show the liquid/vapor and solid/liquid interfaces, respectively.

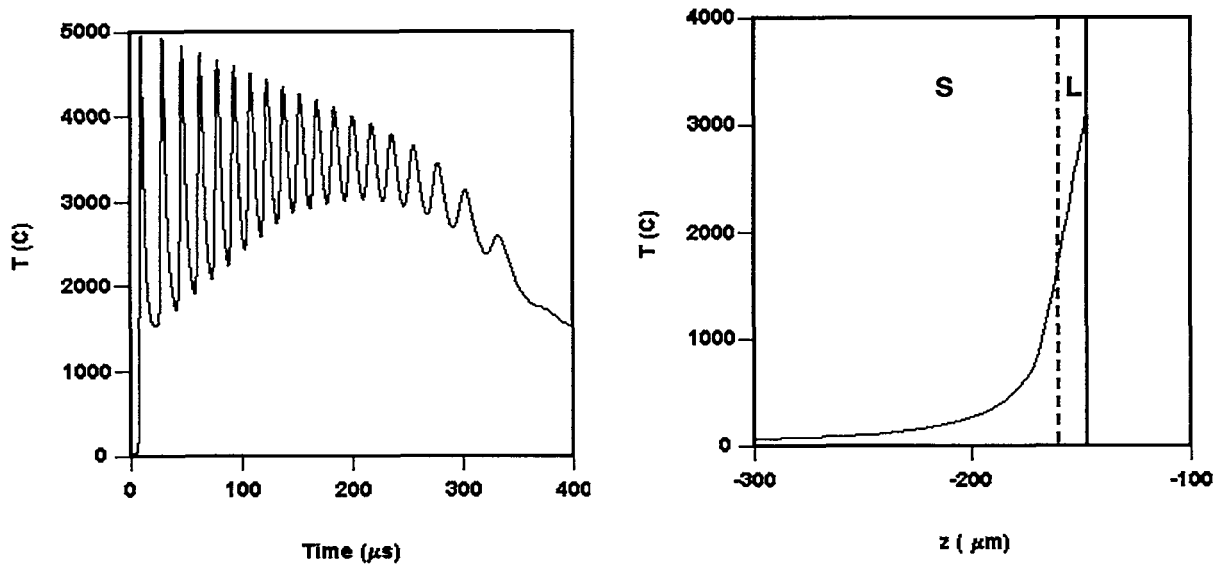

Fig. 3. Left: Edge temperature of the liquid during coupon test. Right: Thermal profile in solid and liquid at 262 μs ($z = 0$ corresponds to the original solid surface).

For the second (10 kW) laser, the waveform from a stable cavity is a large initial spike, followed by a smooth pulse with small superimposed spikes (Fig. 4). The initial spike accounts for about 5% of the energy. In the shot considered here, the area of the focal spot is about 0.25 cm^2, for a fluence of 2000 J/cm^2. As shown in Fig. 4, the predicted removal depth is about 300 μm. The melt layer is again very thin (12-16 μm). In this case, about 63% of the material is removed as liquid.

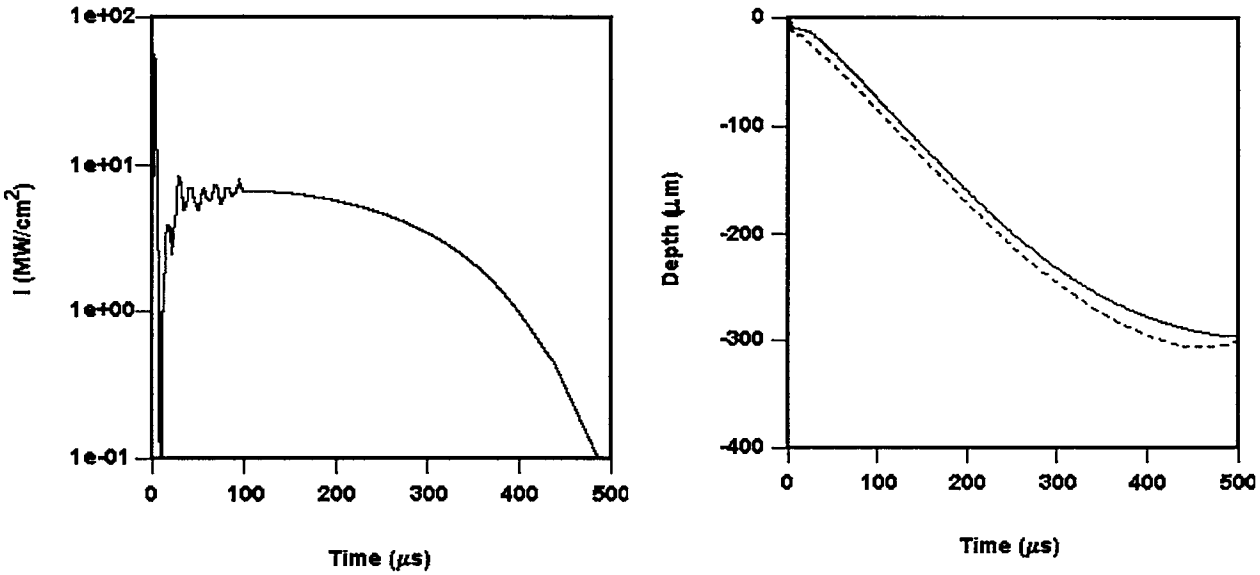

Fig. 4. Left: Intensity of 10 kW SSHCL during a coupon test (note logarithmic scale). Right: Simulated removal in steel by the first pulse. The lines are defined as in Fig. 2.

Compared to the shot by the first laser, the removed mass decreases relative to the beam energy. The resulting Q* is 8.5 kJ/g, as compared to 6.3 kJ/g for the first laser.

In conclusion, coupon tests by two SSHCLs have been modeled by a hydrodynamics code which gives a combined treatment of the solid, liquid, and vapor phases. The removal agrees with an experimental estimate for the first laser. Liquid ejection appears to play a dominant role.

Acknowledgments

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