Laser-induced stresses versus mechanical stress power measurements during laser ablation of solids

Mark A. Shannon[a)]
Department of Mechanical and Industrial Engineering, University of Illinois at Urbana–Champaign, Urbana, Illinois 61801

Richard E. Russo
Lawrence Berkeley National Laboratory, M.S. 90-2024, Berkeley, California 94720

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Laser-induced stresses resulting from high-power laser-material interactions have been studied extensively. However, the rate of change in mechanical energy, or stress power, due to laser-induced stresses has only recently been investigated. An unanswered question for monitoring laser-material interactions in the far-field is whether stress power differs from stresses measured, particularly with respect to laser-energy coupling to a solid target. This letter shows experimental acoustic data which demonstrate that stress power measured in the far field of the target shows changes in laser-energy coupling, whereas the stresses measured do not. For the ambient medium above the target, stress power and stress together reflect changes in laser-energy coupling. © *1995 American Institute of Physics.*

Laser-induced stresses resulting from high-power laser-material interactions have been studied extensively.[1–5] During high-power, short-pulsed laser-material interactions, very high stresses result from thermal expansion and phase change, as well as recoil momentum and shock waves induced by high velocities of the ablation products. Important information on the nature of specific laser-material interactions is contained in stress wave propagation. Stress monitoring of laser ablation processes has been investigated to determine mass removal, displacement, and pressure.[6–9] Stresses, by themselves, do not reveal how much laser energy is coupled mechanically to the target. However, the stress times the rate of change of stress is a measure of mechanical energy propagating through a medium. Moreover, the power carried mechanically via stress propagation can be directly related to the total energy balance during laser-material interactions.[10] Recently, the rate at which energy carried by the mechanical stress propagating through a target was introduced for monitoring laser energy coupling with materials.[11] The mechanical stress power P in the far field was measured acoustically to determine if changes in laser-energy coupling in the near field could be detected during nano- and picosecond laser ablation of metals. Notable changes were reported in the measurement of P versus laser power density in air, He, and Ar atmospheres at varying pressures. However, stress power was not compared with simultaneous measurements of stress to determine if the responses differed significantly.

The purpose of this letter is to report that a significant difference exists in the far-field acoustic measurements of stress versus stress power as functions of laser power density. Locally, the power carried mechanically has an explicit dependence on heat transfer and the rate of change of internal energy $\dot{e}$, such that

$$P=\rho r-\operatorname{div}\,\mathbf{q}-\rho\dot{e}, \tag{1}$$

where ρ is the density, r is all heat sources, and div $\mathbf{q}$ is the divergence of the heat flux.[12] Stress power P is defined as $P=\mathbf{T}\cdot\mathbf{L}$, where $\mathbf{T}$ is the Cauchy stress tensor $\tau_{ij}\mathbf{e}_i\otimes\mathbf{e}_j$, and $\mathbf{L}$ is the velocity gradient tensor $\partial\mathbf{v}/\partial\mathbf{x}=v_{i,j}=\partial v_i/\partial x_j$: $(i,j=1,2,3)$. Therefore stress power is directly related to the stress τ_{ij}. If the velocity gradient depends on stress, then P may have a nonlinear dependence on τ_{ij}. Since laser-induced stresses depend on laser power density, then P may grow nonlinearly with laser power density, even if the stresses do not.

Acoustic emission monitoring of stresses in the far field was performed using transducers that produce a voltage proportional to the average stress in the element volume. Dividing this average stress by the volume gives a transient stress per unit volume. For an averaged scalar stress, stress power is $2C\sigma\dot{\sigma}$, where C is a proportionality constant and σ is the average stress in the transducer. Therefore, the average stress power at any time in the transducer is a function of the stress and the rate of change in the stress. The average power contained in the acoustic emission signal $s(t)$ is calculated by integrating in the frequency f domain, such that

$$P=2C\int f\Sigma(f)\Sigma^*(f)df=2C\int f\Sigma^2(f)df, \tag{2}$$

where $\sigma\propto s$, $\Sigma(f)$ is the Fourier transform of $\sigma(t)$, and Σ^* is the complex conjugate.

The experimental apparatus is shown in Fig. 1 and has been previously described.[11] The excimer laser is a Questek model 2860 at $\lambda=248$ nm with a 30 ns pulse length. A new location on the target was used for each energy level and spot size by shifting the target relative to the beam and transducers. The targets are 3 mm thick by 8 cm^2 6061 Al in T6 condition. A 1 in. diameter acoustic emission transducer (AET) with a -3 dB frequency response from 10 kHz to 18 MHz was placed at the rear of the target along the center line

[a)]Electronic mail: mas1@uiuc.edu

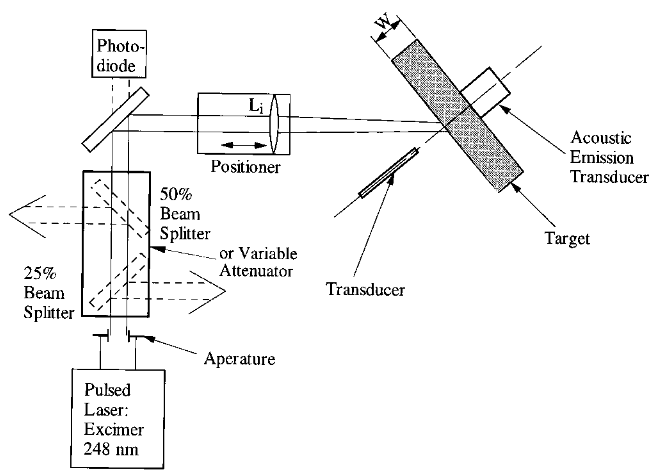

FIG. 1. Experimental apparatus for measuring stress waves propagating through the target, and in the atmosphere in front of the target.

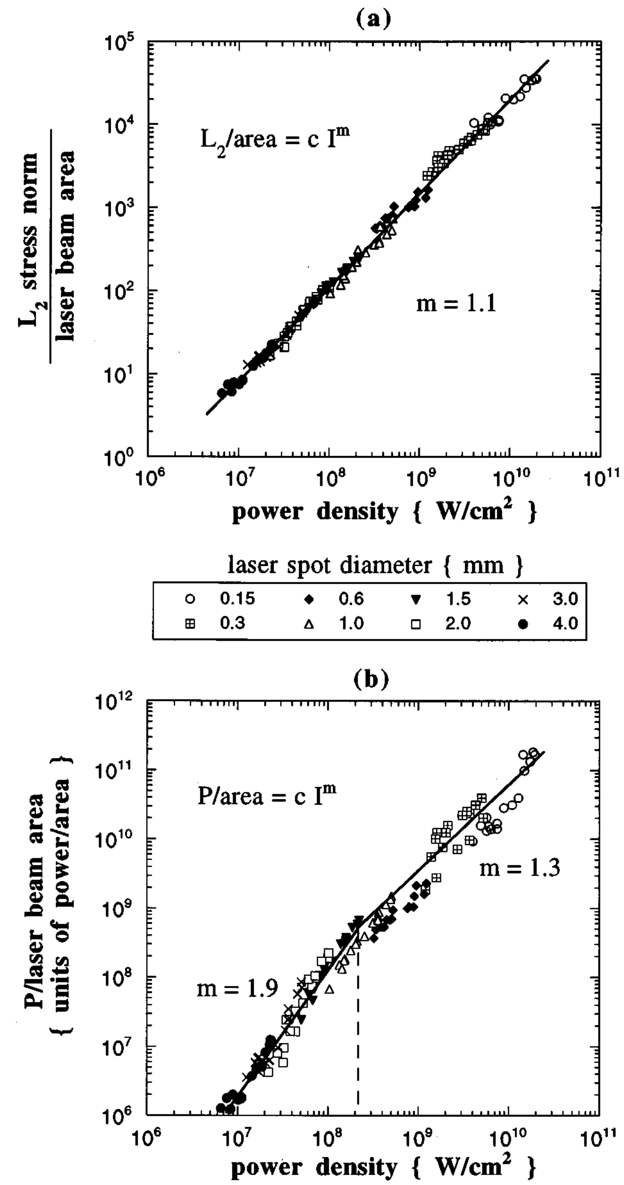

FIG. 2. (a) The L_2/laser area stress norm in the target vs laser power density shows a near linear dependence. (b) Stress power normalized to the laser beam area shows two distinct regions of dependence on laser power density.

of the irradiated spot to detect longitudinal and shear waves propagating through the material. A Valpey–Fisher model VP-1093 Pinducer with a 0–1.2 MHz range was placed 5 mm from the surface along the center line normal to the spot to detect the density wave propagating through the air. The Pinducer's response is linear up to approximately 2000 atm, when saturation is reached. The data were captured with a Tektronix model 602A 2 G sample/s digitizing oscilloscope. The peak frequencies and pressures recorded in the far field were all well within the limits of the transducers, and the data acquisition exceeded the Nyquist criteria by at least three times.

As a measure of the laser-induced stresses, a L_2 norm (root mean square) of the stress over 20 μs is divided by the laser beam area. Figure 2(a) shows the L_2/laser area norm of the stress waves propagating through the Al target versus laser power density. Over more than 3 decades of laser power density, the stress norm increases near linearly with $m=1.1$ for a power law fit $\propto I^m$. This fit occurs for eight different laser pulse energies from 20 to 100 mJ, and eight laser spot diameters from 0.15 to 4.0 mm. The laser-induced stresses propagating through the target, therefore, follow a near-linear dependence on laser power density.

As a measure of laser-induced stress power, P [calculated from the same stress data used for Fig. 2(a)] is also normalized by the laser beam area. P/laser area versus laser power density in Fig. 2(b) shows two distinct regions for the power law $\propto I^m$, with $m=1.9$ for the lower power region, and $m=1.3$ for the higher power region. The decrease, or rolloff, in m occurs at about $2\times(10^8)$ W/cm^2. Several points are noted. First, the stress power in the lower power region is growing near quadratically with laser power density, while the stress is growing near linearly. This result is consistent with **L** having a linear dependence on stress. Second, in the higher power region the growth in stress power with laser power density has rolled off to only 1.2 times that of the stress. These results imply that the dependence of **L** on stress has changed, and/or that nonconservative attenuation in P is occurring. Either of these explanations strongly suggest that the laser-energy coupling to the solid is changing. A complete investigation into stress dependence and dissipation mechanisms is beyond the scope of this letter, and will be the subject of future publications.[13] A final point is that the stress power was observed to rolloff with laser power density at the same laser power density as previously reported for mass removal rates for Al targets irradiated with UV nanosecond lasers.[14] Reduction in the efficiency of mass ablated per unit laser energy is strongly correlated with laser energy coupling to the solid, and the target stress power shows the change, whereas the stress data do not.

Figure 3 shows the (a) stress and (b) stress power response to laser power density 5 mm above the target surface. Unlike the stresses in the target, the L_2 norm in air shows two regimes. L_2/laser area for the stress in the medium

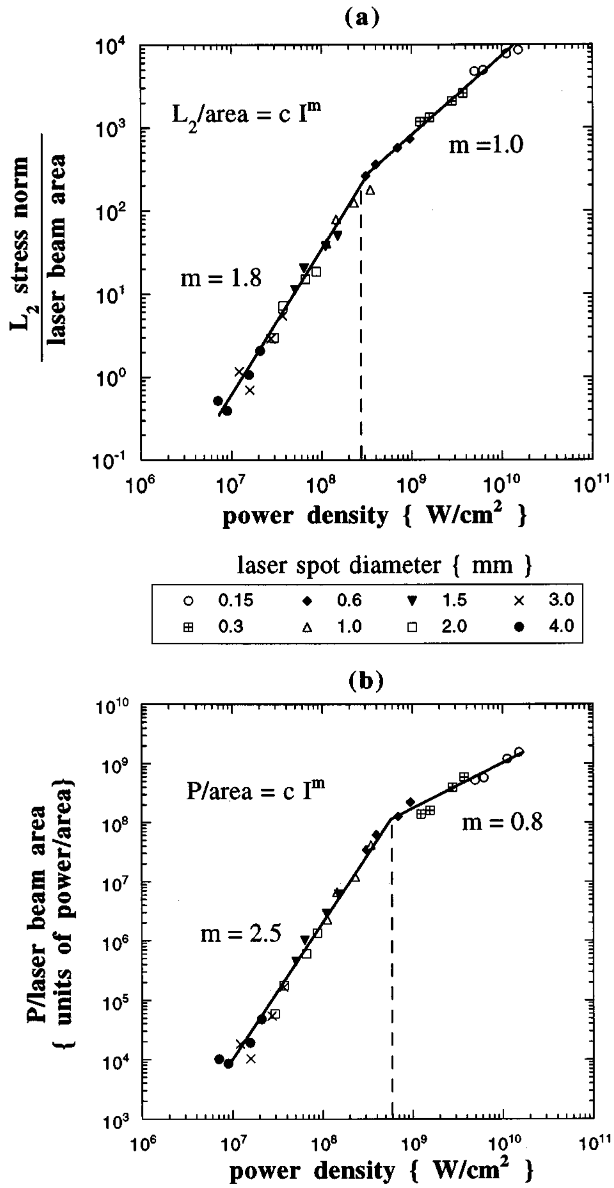

FIG. 3. (a) The L_2/laser area stress norm in air above the target versus laser power density shows two distinct regions of dependence on laser power density. (b) P/laser beam area vs power density shows different dependencies of stress power on laser power density than in (a).

grows near quadratically at $m=1.8$ for the lower power regime, and rolls off to a linear dependence above about $3\times(10^8)$ W/cm^2. P/area also shows two regimes with $m=2.5$ for the lower power regime and $m=0.8$ for the higher power regime. Stress waves above the target result primarily from pressure due to vaporization of the target material, as well as heating of vapor and gas products directly from the laser light. At sufficiently high pressures, shock waves occur. For a mass flux that increases linearly with laser energy density, the pressure increase would be linear for a steady-state flux. However, when expansion is constrained by shock expansion of the contact surface into the quiescent medium, the resulting pressure pulse is higher for the transient mass flux. Accordingly, the stress growth rate is superlinear below the rolloff point, where the mass flux is assumed to be proportional to laser power density. Above the rolloff point the rate drops, implying that mass removal efficiency declines.

The stress power in the air depends on the pressure pulse, as well as the rate of change in the pressure pulse, which is related to the velocity gradient of the contact surface. The dependence of the velocity gradient on pressure is less than or equal to one. For a linear increase in pressure with laser power density, the stress power dependence should be quadratic or less. The dependence of 2.5 observed in Fig. 3(b) for P/area below the rolloff point is consistent with the stress dependence being greater than one in Fig. 3(a). Above the rolloff point, the stress growth rate is linear with power density, implying that the pressure now increases linearly with laser power density. The stress power data above rolloff drop from superquadratic to sublinear. If the pressure is increasing linearly with power density for this region as suggested in Fig. 3(a), then either the velocity gradient is decreasing, and/or there is significant power dissipation in the expanding plume. Both explanations reflect changes in laser energy coupling.

This study demonstrates that stress power differs from stress in the far field versus laser power density. Of value for monitoring complicated laser energy coupling into a target is that the change in P is directly related to the general energy balance, and stress is indirect. Therefore, P may show that the rate of laser energy coupling into the target is changing, when stress measurements themselves do not. For laser energy coupling into the medium, monitoring stress and stress power away from the surface also show that laser-energy coupling may change, which cannot be inferred from the stress data alone. Further study of the role of stress power, as well as stresses, in high-power laser-material interactions is needed to better understand laser-energy coupling mechanisms.

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