Summary

The generation of stress transients in liquids by laser impact has been investigated using special stress transducers. The observed time dependence and amplitudes of the pressure pulses are strongly dependent on the incident laser energy density and on physical properties of the liquid. This is explained by various interaction mechanisms involved. The results are in good agreement with theoretical models. For the pure thermoelastic process an analytical solution has been found where the laser impact is represented by a three dimensional heat pole.

Zusammenfassung

Die Erzeugung von Stosswellen in Flüssigkeiten durch Laserbeschuss wurde mit speziellen Drucksonden untersucht. Die Messungen zeigen, dass sowohl die Zeitabhängigkeit als auch Amplituden der Druckimpulse stark von der einfallenden Laserenergiedichte und von physikalischen Eigenschaften der Flüssigkeit abhängen. Dies wird anhand verschiedener Wechselwirkungs-Mechanismen erklärt. Die Resultate stimmen gut mit theoretischen Modellen überein. Für den rein thermoelastischen Prozess wurde eine analytische Lösung gefunden. Der Lasereinschuss wird dabei durch einen dreidimensionalen Wärmepol dargestellt.

Laser-supported Detonation Waves and Material Processing with Pulsed CO_2 Lasers

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The bulk reflectivity of most metals for CO_2 laser radiation is of the order of 95 % to 98 %. To melt or evaporate such metals with short laser pulses radiation intensities in the range of 100 MW/cm^2 are required. On the other hand, less than 10 MW/cm^2 may be sufficient to ignite a laser-supported detonation (LSD) wave in the ambient atmosphere near the surface of a target [1, 2]. Studies of ignition [2–5], propagation [2, 6–8], and decay [7, 9] of these absorption waves have been reported previously. The main properties of LSD waves in view of material processing are a very short absorption length for CO_2 laser radiation and a propagation velocity of about 1 cm/μs. Thus, energy transfer from the plasma to the target, which does play a role initially, is quickly replaced by efficient shielding [10, 11]. Consequently, very little material is removed while an LSD-wave lasts.

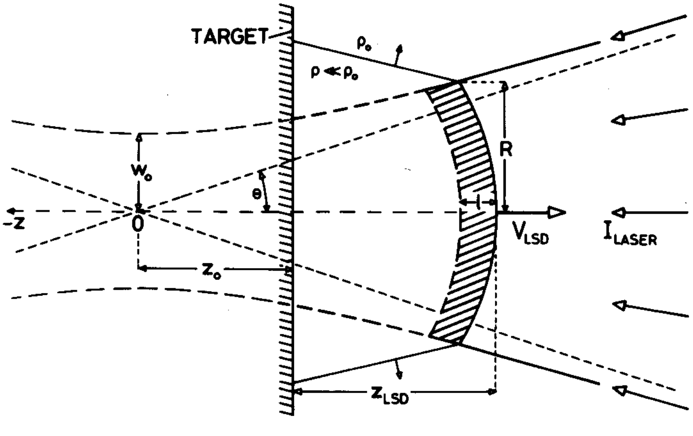

Figure 1
LSD-wave near a target in the focal region of a lens. Symbols are explained in the text.

However, it is well known that an LSD-wave can be maintained only if the incident laser intensity I is larger than a certain threshold value I_m [7, 9]. If I drops below I_m the LSD-wave evolves into an LSC-wave (laser-supported combustion wave) which is characterized by subsonic propagation and a much greater absorption length [12]. Experiments have shown recently that this transition of an LSD into an LSC wave can be very much accelerated by the use of a strongly focused TEM_{00} laser beam and by the choice of helium as ambient atmosphere [13]. In this paper a simple model is used to estimate the lifetime of an LSD-wave in such a situation. The results are then compared with experimental data.

Figure 1 gives a schematic representation of an LSD-wave propagating away from a target placed near the waist of a TEM_{00} laser beam. The laser intensity incident on the LSD-wave is given by

$$I(t, z_{\mathrm{LSD}}) = P_{\mathrm{Laser}}(t)/[\pi w_0^2 + \pi\theta^2(z_0 + z_{\mathrm{LSD}})^2] \tag{1}$$

with $P(t)$: laser power, w_0: beam radius at beam waist, z_0: target position relative to beam waist, θ: far field divergence angle, z_{LSD}: distance travelled by LSD-wave. For

$$\theta(z_0 + z_{\mathrm{LSD}}) > w_0 \tag{2}$$

the laser intensity I will drop quickly until at

$$I(\tau, \zeta) = I_m \tag{3}$$

(τ: lifetime of LSD-wave, ζ: maximum distance travelled by LSD-wave) the LSD-wave dies out.

The LSD-front leaves behind a volume of hot gas, the density ρ of which is much smaller than ρ_0 of the ambient atmosphere. In fact, it may be less than the threshold for reignition of the LSD-wave [14]. In this case the remainder of the laser pulse is available for further heating of the target. In order to estimate the duration τ we have used Raizer's formula [7] for the velocity v_{LSD} of an LSD-wave:

$$v_{\mathrm{LSD}} = [(\gamma^2 - 1)2\delta I(t, z_{\mathrm{LSD}})/\rho_0]^{1/3}. \tag{4}$$

γ is the ratio of specific heats behind the detonation front and the factor

$$\delta \simeq (1 + l/R)^{-1} \tag{5}$$

takes account of energy lost radially from the front. (l: absorption length for laser radiation in the front, R: radius of front).

In the following calculations the radial distribution of laser intensity due to the TEM_{00}-mode structure is ignored and the maintenance intensity I_m as well as the correction factor δ are assumed to be constant. Numerically it is then a straight-forward matter to determine τ by integrating Eqns. (1) and (4) simultaneously until condition (3) is satisfied.

To obtain an analytical formula, the expression $[w_0^2 + (\theta z)^2]^{1/3}$ was approximated by $w_0^{2/3}[1 + \frac{1}{3}(z\theta/w_0)^2]$ for $z\theta < w_0$ and by $(z\theta)^{2/3}[1 + \frac{1}{3}(w_0/\theta z)^2]$ for $z\theta > w_0$, $z = z_0 + z_{\mathrm{LSD}}$. The additional error introduced by this procedure is negligible. The lifetime τ of an LSD-wave is then given by

$$\int_{t_0}^{t_0+\tau} [p(t')]^{1/3}\,dt' = \frac{1}{v_m}\left\{\frac{3}{5}\left[\frac{P_p}{\pi\theta^2 I_m}\right]^{1/2}[p(t_0+\tau) - I_r]^{5/6} - \frac{w_0}{\theta} I_r^{1/2}[p(t_0+\tau) - I_r]^{-1/6} + \frac{w_0}{\theta} I_r^{1/3} F(z_0)\right\} \tag{6}$$

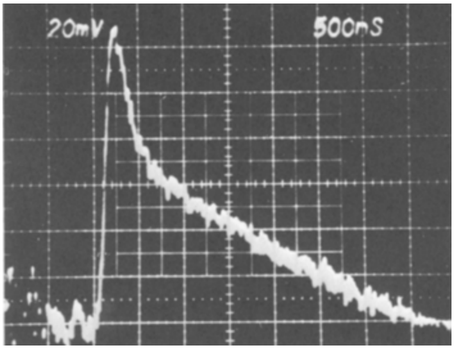

Figure 2
Laser power vs. time of UV-preionized TEA-CO_2 laser emitting in TEM_{00} mode.

where $v_m = [(\gamma^2 - 1)2\delta I_m/\rho_0]^{1/3}$
$I_r = \pi w_0^2 I_m / P_p$

$$F(z_0) = \begin{cases} 136/45 + (w_0/\theta z_0)^{1/3}[1 - (3/5)(\theta z_0/w_0)^2], & z_0 < -w_0/\theta \\ 68/45 - (\theta z_0/w_0)[1 + (\theta z_0/3w_0)^2], & -w_0/\theta < z_0 < +w_0/\theta \\ (w_0/\theta z_0)^{1/3}[1 - (3/5)(\theta z_0/w_0)^2], & w_0/\theta < z_0 \end{cases}$$

P_p = peak power of laser pulse
$p(t)$ = normalized laser power, such that $P(t) = P_p p(t)$
t_0 = time interval from beginning of laser pulse to ignition of LSD-wave.

In the case of laser pulses of constant power, i.e. $p(t) = 1$, satisfying $I_r \ll 1$ Eqn. (7) is reduced to

$$\tau \simeq \frac{3}{5}\left[\frac{\rho_0}{2\delta(\gamma^2 - 1)I_m}\right]^{1/3}\left[\frac{P_p}{\pi\theta^2 I_m}\right]^{1/2} \qquad (7)$$

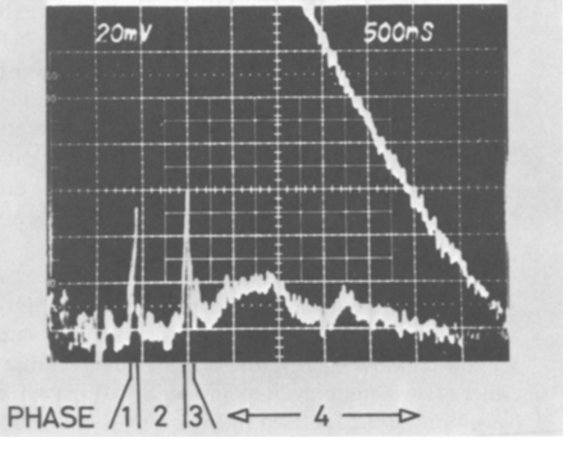

Figure 3
Laser power reflected from metallic target; Upper trace: without interaction; Lower trace: with interaction (same scale as upper trace).

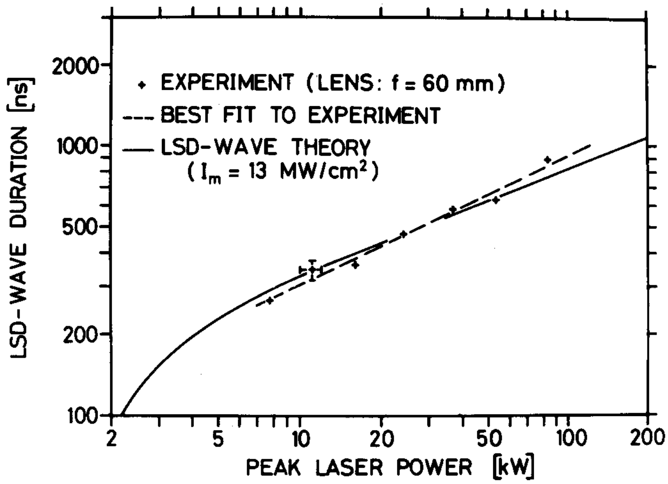

Figure 4
LSD-wave lifetime vs. peak laser power for copper target.

Of course, laser pulses of constant and high enough power are difficult to generate with CO_2 lasers. Nevertheless, this simple formula provides some insight into the behaviour of τ as a function of most of the relevant parameters.

Experiments are now being conducted to check the validity of the model. The LSD-wave lifetime is measured directly by monitoring the specular reflection from polished metal targets during interaction with a pulse from a UV preionized TEA-CO_2 laser [14]. The pulse shape is shown in Figure 2. A typical example of a reflection signal is shown in Figure 3 on the lower trace. The duration of the LSD-wave is identified as phase 2 of the interaction, when the specularly reflected laser power drops below the detection limit. A series of such measurements of τ as a function of peak laser power is shown in Figure 4, together with a numerical calculation based on the same pulse shape. In this and all following calculations we have assumed $\delta = 0.5$ (Eqn. (5)), which roughly agrees with our experimental situation. The only parameter available to fit theory and experiment is the maintenance intensity I_m, which has no influence on the slope of the curve. We found $I_m \simeq 13$ MW/cm^2. This value is lower than the result published by Barchukov et al. [16] ($\simeq 20$ MW/cm^2) but higher than the lowest ignition thresholds ($\simeq 6$ MW/cm^2) reported by Maher et al. [2]. Considering the uncertainty of the reported values of I_m and the simplifications involved in the model the agreement between calculated and measured values of τ as shown in Figure 4 is acceptable. In particular it should be noted that both curves very closely obey a power law, as predicted by Eqn. (7). The exponents are 0.48 and 0.41 for the measured data and the equivalent set of calculated points, respectively. The deviation from the predicted value of 0.5 (Eqn. (7)) is caused mainly by the pulse shape.

Apart from direct measurements of LSD-wave lifetime we have also investigated the influence of LSD-waves on target damage. The latter was quantified by the ratio of crater volume and total pulse energy, and designated as drilling yield y. Measurements of y at constant pulse energy in vacuum, helium and air are displayed in Figure 5 as a function of normalized target position $z_0\theta/w_0$ (defined in Figure 1). Also included in Figure 5 are calculated curves of LSD-wave lifetime in helium and air.

In vacuum no LSD-wave is possible and, correspondingly, the drilling yield is highest. In helium of atmospheric pressure the maximum yield is only about half as large, and in air no more

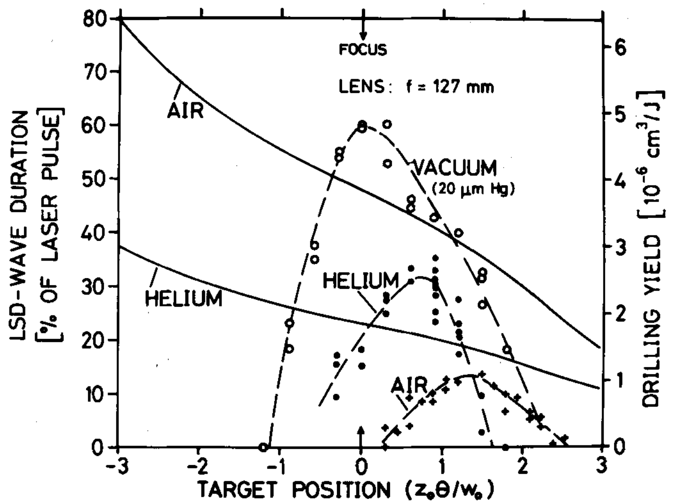

Figure 5
Drilling efficiency as a function of target position in focal region compared with LSD-lifetime. Target material: copper.

than 25 % of the vacuum value were achieved. These differences are well correlated with the LSD-wave duration, which is about twice as long in air as in helium at corresponding optimum target positions. The shift of these positions away from the focus towards the lens observed in helium and air is caused by the monotonous decrease of LSD-wave lifetime with z_0.

In conclusion, our experiments have shown that with CO_2-laser pulses there is a strong dependence of drilling yield on focusing geometry and ambient atmosphere. Both effects can be explained qualitatively by the influence of LSD-wave duration. A simple model has been developed that allows to calculate LSD-wave duration as a function of experimental parameters. The results are in satisfactory agreement with measurements.

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Summary

The processing of metals with short CO_2 laser pulses is strongly influenced by an air-breakdown plasma (LSD-wave). Material removal is possible only if the duration τ of this LSD-wave can be kept short compared with the length of the laser pulse. A simple model for the calculation of τ is developed allowing the derivation of an analytic formula and leading to good agreement with experimental data.

Zusammenfassung

Die Bearbeitung von Metallen mit kurzen CO_2-Laserpulsen wird von einem Air-Breakdown-Plasma (LSD-Welle) stark beeinflusst. Materialabtragung ist nur dann möglich, wenn die Dauer τ dieser LSD-Welle wesentlich kürzer ist als die gesamte Pulslänge. Es wird ein einfaches Modell für die Berechnung von τ entwickelt. Daraus lässt sich ein analytischer Ausdruck herleiten. Die Resultate stehen in guter Uebereinstimmung mit experimentellen Daten.

Laser Drilling in Heat Sensitive Components

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1. Introduction

Two properties make lasers particularly attractive for machining of heat sensitive components, as for instance semiconductor devices: Their energy can be highly concentrated in time and space, and the rate of energy deposition can be precisely controlled.

In this paper we show how laser radiation can be used for the production of a diffusing reflector in Light Emitting Diodes (LED).

Figure 1 displays a cross-section of a GaAs LED structure. It consists of an opaque GaAs substrate (about 300 μm thick) and a transparent $GaAs_{1-x}P_x$-layer of about 20 μm, both consisting of n-type epitaxial material. A small p-type region is diffused into the transparent layer forming the p–n junction. The distance between the GaAs substrate and the p-type region is about 15 μm. A considerable part of the light produced in the p–n junction is emitted in the backward direction or reflected from the front surface and subsequently absorbed in the substrate. If a diffusing reflector can be made near the interface of GaAs–$GaAs_{1-x}P_x$, a part of the impinging light energy is scattered into the small solid angle of 34° required for transmission

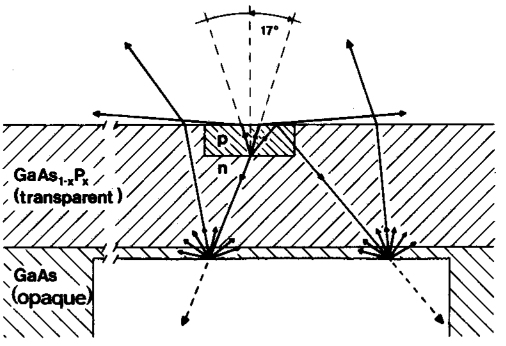

Figure 1
Light paths in a GaAs-luminescence-diode. ——— with a diffusing reflector behind the active region and – – – without reflector.