

Pulsed CO₂ Lasers for the Surface Heating and Melting of Metals

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Abstract—We explore the possibilities of using pulsed electron-beam-excited CO₂ lasers for the generation of metal surfaces with improved properties through surface alloying or microsecond melting and thermal-conductance quenching (self quenching). Air plasma ignition yields enhanced thermal coupling to highly reflective metals, but is shown nevertheless to prohibit the melting of metals with lasers of reasonable size. Suppression of the air plasma by evacuation leads not only to unimpaired metal heating but to a new and little-understood mode of enhanced thermal coupling, with highly favorable characteristics. The surface melting of even refractory metals with single microsecond-duration pulses should be possible with pulsed CO₂ lasers of modest size.

I. INTRODUCTION

BEING economical sources of high-energy pulses at high repetition rates, pulsed electron-beam-excited CO₂ lasers are attractive for the surface heat treatment of metals, e.g., large-area surface alloying or microsecond surface melting and thermal-conductance quenching (self quenching), potentially producing surfaces of improved properties. They have seen, however, little use for this purpose because air plasma ignition at this wavelength interferes at intensities well below the levels required for surface melting. Metal heating will still occur, even with apparently increased efficiency (so-called plasma-enhanced thermal coupling [1]), but determination of the necessary laser pulse parameters for the melting of a metal surface is no longer a straightforward laser absorptance and metal heat flow calculation.

We will review here experiments on the heating of metals, primarily 2024-T3 aluminum alloy, with pulsed CO₂ lasers of pulse energies ranging from tens of joules to over 10 kJ. The results with air plasma ignition will lead to estimation of the CO₂ laser pulse requirements for metal surface melting in air, not only for aluminum but for metals in general, since plasma-mediated thermal coupling is insensitive to the identity of the irradiated metal. We will show that, due to air plasma ignition, metal surface melting with single CO₂ laser pulses is practical only on metals of very low melting temperatures.

The only adequate means of suppression of the air plasma, as will be shown by an analysis of plasma ignition, is by putting the metal specimen under vacuum. Modest vacuum levels (air pressure under ~ 2 torr) will be shown experimentally to be sufficient. Below this pressure, not only is the air plasma suppressed, but enhanced thermal coupling to high-reflectivity metals may still be observed, now with metal heating charac-

teristics far superior to those of air-plasma-enhanced thermal coupling. Microsecond surface melting of aluminum is easily achieved, even with modest (~ 15 J) lasers; no barrier to the surface melting of any metal by this process is apparent.

II. DESCRIPTION OF EXPERIMENTS

The thermal coupling experiments to be summarized here have been done with five different CO₂ lasers at three laboratories. Detailed descriptions would be tedious; further information can be found in cited references. All were transverse electron-beam-initiated sustainer-discharge machines, with pulse durations ranging from 1.8 to 40 μ s and maximum pulse energies from under 100 J to over 10 kJ. The pulse produced by these machines is preceded by a gain-switched spike 200–400 ns long and with intensity 3–10 times that of the pulse body.

Pulse energy was measured with commercial calorimeters or with a flat-plate calorimeter of anodized aluminum [2]. The pulse shape is observed with photon-drag or barium-titanate detectors. The greatest uncertainty in determination of the incident fluence and intensity of these high-energy pulses is in the measurement of the spot size. Direct measurements cannot be made at these levels, since air plasmas are ignited at any detector surface. Pyroelectric detectors can be used for small spots, using attenuators to reduce the intensity to tolerable levels, but are impractical on spots of very large area (>20 cm²). Attenuators for this wavelength and the longer pulses are themselves unreliable; plastic sheets are destroyed by the high laser fluence levels even at the laser aperture, while perforated metal screens are troubled by air plasma ignition at the perforation edges. Diffraction methods [3] have been attempted, but are impractical for spots of very large area in laboratories of finite dimensions. Our practice has been to estimate spot areas from burn patterns on thermosensitive material, but this is an imprecise procedure, with an uncertainty typically ± 30 percent. Fortunately, metal heating with air plasma ignition is not very sensitive to the incident intensity. The magnitude of the heat deposition on the metal specimens can be measured to ± 10 percent or better, and information about the spatial distribution also deduced, using arrays of simple chromel-alumel thermocouples [4].

III. AIR PLASMA IGNITION

Plasma ignition by CO₂ laser pulses at solid surfaces occurs at $\sim 10^6$ W/cm², far below the 10^9 W/cm² required for plasma ignition in clean air [5], [6]. Clean-air ignition is dominated by the requirement that an initially minuscule density of free

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electrons be cascade multiplied into the high density of a plasma [7]. An unpolished metal surface provides an initially high density by the heating of surface defects to thermionic emission temperature in time ~ 30 ns [8], causing other requirements to control ignition, as will be shown here. That metal defect heating (the temperature rise of the bulk metal is insignificant) is ample, for ignition by the 200–400 ns spike of our CO₂ lasers is demonstrated by ignition observations at oblique incidence [9]. At angle 80° from the normal, metal heating is reduced by a factor of two (the increase in aluminum absorptance with angle compensating partially for the cosine intensity variation), yet no change in threshold is detected (resolution ± 25 percent).

The electrons liberated from the metal gain energy from the laser photons by inverse bremsstrahlung. A first ignition criterion is that the rate of energy gain de/dt must exceed losses to elastic collisions; in MKS units,

$$\frac{de}{dt} = \left[\frac{\Omega I_0 e^2}{m \omega^2} - \frac{2m\hat{\epsilon}}{M} \right] \nu_c > 0 \quad (1)$$

where ϵ is the electron energy, $\hat{\epsilon}$ is the mean energy near ignition (~ 5 eV, the ionization potential of metal vapor), Ω is the impedance of free space (377 ohms), ω is the laser angular frequency, I_0 is the incident laser intensity, e and m are the electron charge and mass, M is the mass of the ambient air molecules, and ν_c is the electron-neutral collision frequency [10]. (Note that $\omega^2 \gg \nu_c^2$ for $\lambda = 10.6 \mu\text{m}$ and ambient pressure atmospheric or less.) Electron losses by diffusion are negligible for these large-area ($r > 1$ cm) laser spots. Energy losses by inelastic collisions and oxygen capture are important, but difficult to incorporate, and unnecessary for obtaining the semi-quantitative results adequate here.

Smith [11] assumed that ignition was limited by the time required for the electron vapor to be sufficiently heated: $de/dt > N\Phi/\tau_p$, where N is the number of electron multiplications required, τ_p is the laser pulse duration (for our spike-led pulses, the spike duration, ignition invariably occurring either at the spike or not at all), and Φ is the ionization potential of air (~ 15 eV). Since $de/dt \propto \nu_c = N\sigma v$, σ being the scattering cross section, N the density of neutral molecules, and v the electron speed, this leads to an ignition threshold inversely proportional to the ambient pressure. This is not the case, as was first observed by Hall's Boeing group [12].

This result we confirmed in a recent experimental series with a 400 J, 12 μs laser pulse, with aluminum specimens irradiated at pulse-average intensity 2 MW/cm² (spike peak 6 MW/cm²), or twice the normal threshold of 1 MW/cm². Plasma ignition was not suppressed until the ambient pressure was decreased to 30 torr, or 0.04 atm. It follows from this weak pressure dependence that the rate of electron vapor heating does not control ignition at atmospheric pressure for this wavelength, pulse, and specimen surface state.

The controlling condition is, in fact, simply the requirement that the net energy balance be positive [see (1)], whence

$$I_0 > 8\pi^2 m^2 c^2 \hat{\epsilon} / M \Omega e^2 \lambda^2. \quad (2)$$

If $\hat{\epsilon} = 5$ eV, the ionization potential of metal vapor, this yields $I_0 > 9$ MW/cm², greater than the observed threshold (spike

peak magnitude) of 3–5 MW/cm². The remaining discrepancy may be accounted for by ignition at local spatial maxima, or perhaps by substitution of $\hat{\epsilon} = 1.5$ eV, corresponding to the temperature at which air becomes opaque [13] and the observed temperature of air plasmas [14].

A Lebedev Institute group also came to the conclusion that this condition, rather than the condition derived from the rate of electron heating, governs plasma ignition at a metal surface [6]. Thus, plasma threshold, for unpolished metal specimens and pulses characterized by a spike 200–400 ns wide, is expected to scale as $1/\lambda^2$ and be independent of target material. Ignition in our work is not detectably different for metals as different from aluminum as 4130 steel (a molybdenum-chromium alloy), 304 stainless steel, and a titanium alloy (6 percent Al–4 percent V). The Boeing group [12] found less than a factor of three difference in threshold among metals as diverse as copper, lead, and titanium. The wavelength dependence has not been confirmed, due to the very different pulse shapes of other infrared lasers (compare, e.g., Nichols and Hall [15]).

Equation (2) shows that there is little latitude for suppression of air plasma ignition. Elimination of the gain-switched spike, possible in oscillator–amplifier configurations, should permit a gain of a factor of three or so in the useable plasma-free laser intensity, but this is insufficient for the melting of high-conductivity, high-reflectivity metals, and for metals with high melting temperatures. Reduction in the density of surface defects, by polishing or by laser surface conditioning [12], can purchase some modest improvement. With the possible exception of extremely well-polished specimens, air plasma ignition at laser intensities high enough for metal surface melting can be suppressed only by removal of the air.

IV. METAL HEATING WITH AIR PLASMA IGNITION

Experiments at the Air Force Weapons Laboratory first revealed that air plasma ignition yielded an increase in the thermal coupling to (i.e., the effective absorptance of) highly reflective metals such as aluminum [16]. This is contrary to the CW laser experience, where the formation of a plasma terminates metal heating. In both cases, the plasma absorbs the laser energy totally [8]; however, for pulses only microseconds in duration, the plasma remains close enough to the surface to heat the metal itself. Theoretical analyses indicate that thermal reradiation, in the ultraviolet from the plasma at temperature $\sim 2 \times 10^4$ K, is responsible for the metal heating [17]–[19].

Our objective here is estimation of the laser pulse requirements for the achievement of single-pulse surface melting on any given metal. The discovery of enhanced thermal coupling appears to be encouraging evidence that pulsed CO₂ lasers of moderate size could be used for microsecond surface melting even on highly reflective metals, such as aluminum, despite the apparent problem of air plasma ignition. Fig. 1 shows an example of such plasma-enhanced thermal coupling, this work done with an Avco-Everett Research Laboratories laser delivering up to 150 J energy in a 12 μs pulse and 300 J in a 30 μs pulse. Upon air plasma ignition, the total thermal energy deposited in these unpolished 1100 alloy (commercially pure) aluminum specimens increases sharply to 17 percent of the

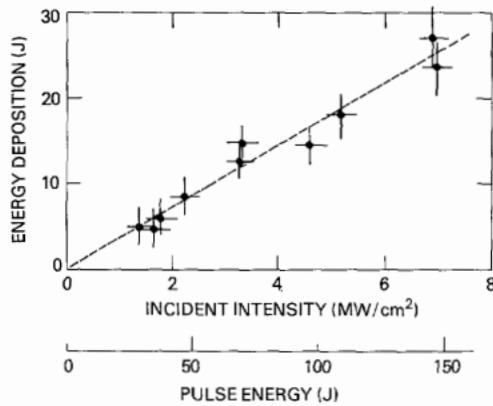


Fig. 1. The total thermal energy deposition in aluminum specimens, with air plasma ignition; spot area 1.4 cm^2 . The energy rises in direct proportion to the incident pulse energy with coupling coefficient 17 percent.

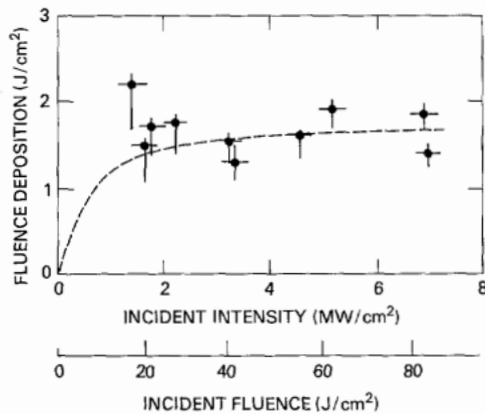


Fig. 2. The thermal fluence deposition at laser spot center for the same shots as Fig. 1; this does not increase appreciably above ignition threshold, showing that the thermal energy is merely deposited over a steadily increasing area as the incident intensity increases. The dashed line is a fit based on the model described in the text.

incident pulse energy versus the normal absorptance of 2.5 percent observed below threshold.

But Fig. 2 shows that an increase in pulse intensity does not necessarily yield an increase in the concentration of heat delivered to the metal. The thermal fluence deposition rises sharply upon plasma ignition, but does not increase thereafter. Increasing the pulse energy merely increases the area of thermal deposition [4], [14].

The magnitude of the thermal transient at the metal surface produced by the plasma must be deduced from the time-integrated total thermal energy and thermal fluence deposition data, such as shown in Figs. 1 and 2. The brilliant plasma prevents direct observation of the metal surface, while thermal probes inserted from the rear [1] involve materials of thermal conductivity much lower than solid metal, thus changing the magnitude of the thermal transient. These probes also fail at relatively modest thermal fluence depositions, due to the increased temperature rise over the low thermal conductivity insulating component.

The surface temperature response can be calculated from these time-integrated data, such as shown in Figs. 1 and 2, given a model for the time dependence of the thermal flux from the plasma to the metal surface. Assumption of continuous heat deposition during the pulse is inaccurate. It is

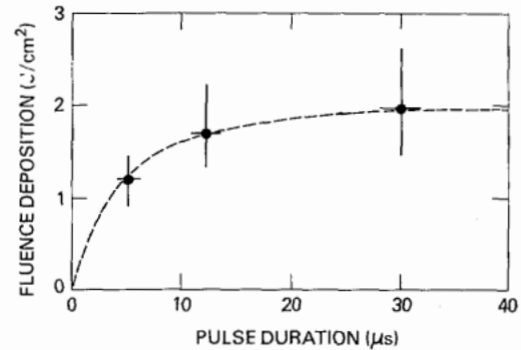


Fig. 3. The plasma-mediated thermal fluence deposition in aluminum for three different pulse durations, the fluence deposition at each pulse duration being independent of intensity. Increasing the pulse duration beyond a few microseconds adds little to the metal heating. The dashed line is based on the model described in the text.

evident from Fig. 3, showing the fluence deposition for three different pulse durations, that most of the fluence deposition must take place early in the pulse. This is observed directly in surface-thermocouple measurements [1].

Detailed theoretical analyses of plasma-enhanced coupling [17], [18] show that this decrease in thermal coupling with time is due to the decay of the plasma pressure. These analyses do not yield easily tractable methods of estimation of the metal surface thermal transient. We have devised a very simple model [20], [21] which, while not accurately reflecting the physics, agrees in qualitative form with the correct analyses. In the proper theory, plasma radiation to the metal surface decreases rapidly after time a/c , where a is the spot radius and c is the sound speed in the plasma. In the simple model, the decrease occurs as the plasma, a radiating disk of radius a , propagates vertically from the metal surface; the radiation level at the surface decreases rapidly after time a/c , where c , in this case, is the propagation speed of the plasma. It is this similarity in behavior which makes the simple model a useful mathematical form to which the data can be fit, and which will yield rough estimates of the thermal transient at the metal surface.

According to this model, the peak metal surface temperature ΔT_p is

$$\Delta T_p = \alpha I_0 (a/\pi c \delta)^{1/2} / \rho C \quad (3)$$

where α is the total-energy coupling coefficient, I_0 is the incident laser intensity, and C , ρ , and δ are the metal heat capacity, density, and thermal diffusivity, respectively. Reaching this temperature requires that the pulse duration τ_p be greater than $0.64a/c$. The value of c may be determined from the fluence deposition, given by the model as

$$F_d = \alpha I_0 [\tau_p + a/c - (\tau_p^2 + a^2/c^2)^{1/2}]. \quad (4)$$

From the data of Figs. 1 and 2, $\alpha = 0.17$ and $c = I_0/\gamma$, where $\gamma = 17 \text{ J/cm}^3$. Then

$$\Delta T_p = \alpha (a \gamma I_0 / \pi \delta)^{1/2} / C \rho \quad (5)$$

as long as $\tau_p > 0.64a/c$, or about $2 \mu\text{s}$ for this experiment. For the maximum-energy pulse, $\Delta T_p \sim 400 \text{ K}$, well short of the melting even of aluminum.

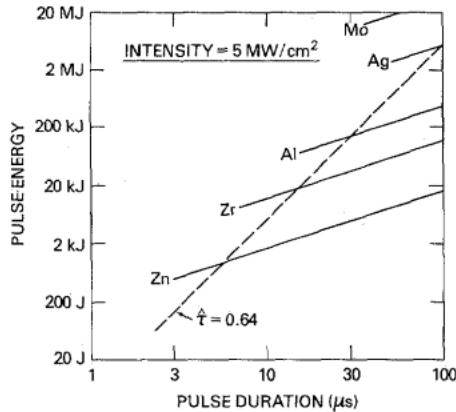


Fig. 4. Estimated laser pulse energy required to achieve metal surface melting for several elements, with air plasma ignition, according to the model described in the text. A laser operating point must lie to the right of the $\hat{\tau} = 0.64$ line for the peak temperature to be reached, and must be above the melt line of the appropriate metal. For most metals of interest, the required pulse energy is impractically large.

The intensity I_0 cannot be increased indefinitely; above $I_0 \sim 10 \text{ MW/cm}^2$ a supersonic detonation wave, rather than the subsonic combustion wave, is produced, reducing surface heating [17]. Equations (3) and (4) show that the thermal transient can be further increased only by increasing the spot radius a .

Thermal coupling experiments were accordingly done using two larger CO₂ lasers at the Avco-Everett Research Laboratories, with pulse energies up to over 10 kJ, providing plasma ignition with spot areas over 100 cm². These large-spot data yielded even less gain in metal heating than the dependence promised by (5). The fluence deposition results, on 2024-T3 aluminum alloy but not significantly different for 304 stainless steel and 4130 molybdenum steel, can be summarized by the empirical equation

$$F_d = (I_0 I_s)^{1/2} [\tau_p + a/c - (\tau_p^2 + a^2/c^2)^{1/2}] \quad (6)$$

where $I_s = 4.35 \times 10^4 \text{ W/cm}^2$ and $c = 0.45 \text{ cm}/\mu\text{s}$. The factor I_s and the square-root dependence are entirely empirical.

The thermal transient is then

$$\Delta T_p = (I_0 I_s a / \pi c \delta)^{1/2} / C_p \quad (7)$$

which, even for the 11 kJ, 140 cm², 2 MW/cm² pulse of [21], amounts to only 325 K on 2024 aluminum alloy. This equation can be solved for the pulse energy required to achieve any desired temperature:

$$Q = \pi^4 c^2 \delta^3 \hat{\tau} (C_p \Delta T_p)^6 / I_0^2 I_s^3 \quad (8)$$

where $\hat{\tau} = c\tau_p/a$, i.e., the ratio of the pulse duration to the spot-radius sonic transit time. Fig. 4 shows this pulse energy as a function of pulse duration. A laser operating point must lie to the right of the diagonal line indicating $\tau_p = 0.64a/c$. The near-horizontal lines are the melting-point loci for a number of metallic elements; achieving melt requires that the operating point be above this line.

This is obviously only a rough estimate, a crude extrapolation of existing data with an uncertain model; it is nevertheless clear that, despite the apparent advantage of plasma-enhanced

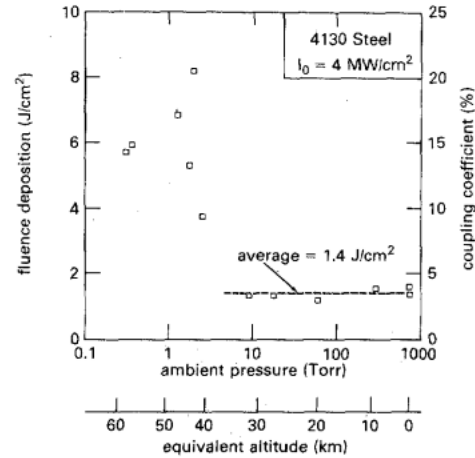


Fig. 5. Thermal fluence deposition in 4130 steel as a function of ambient pressure, for a 12 μs , 400 J laser pulse, spot area 8 cm². Pressure reduction to about 10 torr has no effect on the fluence deposition. Below about 3 torr the air plasma gives way to a vacuum plasma, and the fluence deposition rises to values well above the 4.5 J/cm² that would result from simple infrared absorption.

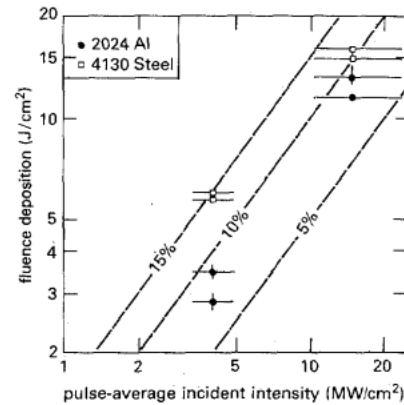


Fig. 6. Fluence deposition in 2024 aluminum and 4130 steel in vacuum (0.5 torr), for the 12 μs , 400 J pulse, with spot areas 8 and 2.7 cm². The coupling remains high at high intensity, in contrast to the case with air plasma ignition.

thermal coupling, achieving surface melting with single microsecond-duration CO₂ laser pulses requires enormous lasers.

V. PULSED METAL HEATING IN VACUUM

It is clear that it is the air plasma, despite the apparent advantage of plasma-enhanced thermal coupling, that makes the melting of metal surfaces with single microsecond-duration CO₂ laser pulses difficult or impractical. The analysis of air plasma ignition (Section III) showed that only complete removal of the air can prevent ignition at the high laser levels required for metal melting.

Suppression of air plasma ignition does not lead merely to simple infrared absorption. Fig. 5 shows the thermal fluence deposition to 4130 steel as a function of ambient pressure, data obtained with a 400 J, 12 μs pulse from an Avco-Everett Research Laboratories laser. With a spot area of 8 cm², the pulse-average intensity was 4 MW/cm² and the spike-peak intensity was 17 MW/cm². Below approximately 3 torr residual air pressure ($4 \times 10^{-3} \text{ atm}$), the thermal coupling increases to

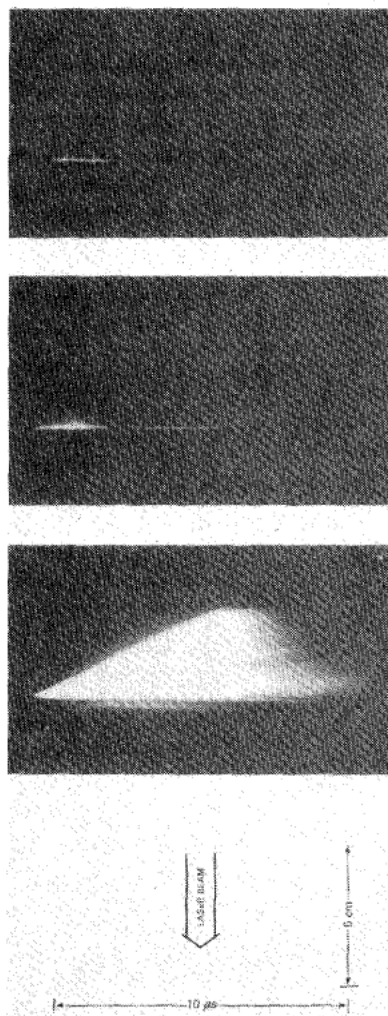


Fig. 7. Streak photographs of the plasma at an aluminum surface produced by the $12\ \mu\text{s}$, $400\ \text{J}$ pulse. Time goes from left to right; the metal surface is horizontal, the laser beam incident from the top. The top photograph shows the plasma in vacuum for the $8\ \text{cm}^2$ spot; next down, the $2.7\ \text{cm}^2$ spot (spike-peak intensities 17 and $50\ \text{MW}/\text{cm}^2$, respectively). The metal-vapor plasma in vacuum propagates no more than $2\ \text{mm}$; compare the air plasma at atmospheric pressure, third photograph. The vapor plasma vanishes long before the end of the laser pulse, yet excellent thermal coupling results.

values well above the 9 percent of ordinary absorption. This is the phenomenon of enhanced thermal coupling in vacuum which has been observed previously [1], [22], [23]. (The observation in [1] we had previously thought to be plasma ignition in the residual air, the vacuum level being an order of magnitude lower than in [22] and [23]; the present results show that the modest vacuum of [1], $0.5\ \text{torr}$, was adequate for the true vacuum effect.)

Plasma formation in these reduced-pressure tests was monitored with a TRW image-converter streak camera, viewing the specimen surface through a $10\ \text{nm}$ wide optical filter centered at $500\ \text{nm}$. At spot area $25\ \text{cm}^2$ (spike-peak intensity $5\ \text{MW}/\text{cm}^2$), no plasma was detected, and the thermal coupling to both 2024 aluminum and 4130 steel was normal infrared absorptance. At $8\ \text{cm}^2$ area, the coupling to both metals increased sharply (Fig. 6), coincident with the appearance of a plasma at the metal surface (Fig. 7). The behavior of this

plasma in vacuum was dramatically different from that of the air plasma (also shown in Fig. 7); the transition from one to the other with decreasing air pressure was abrupt, the propagation distance of the air plasma increasing to $>15\ \text{cm}$ at low pressure, while this metal-vapor plasma expands $<0.2\ \text{cm}$. Upon further decrease of the spot area to $2.7\ \text{cm}^2$, the coupling remained high (Fig. 6) while the plasma was little changed (Fig. 7).

The emission evident in Fig. 7 is too bright to be merely metal vapor at $\sim 3 \times 10^3\ \text{K}$, as is predicted for simple vaporization [24]. The camera was set for proper exposure of the air plasma at temperature $\sim 1.8 \times 10^4\ \text{K}$, at which temperature blackbody emission at $500\ \text{nm}$ is $\sim 10^3$ times the emission at the lower temperature.

In our opinion, this enhancement in thermal coupling is due to the metal-vapor plasma. The thermal coupling value observed is similar to the total-energy thermal coupling from air plasmas (Fig. 1), the major difference being the absence of significant plasma propagation in the vacuum case. Plasma expansion in air causes heat deposition well outside the laser spot; in vacuum, the thermal energy deposition is confined to the laser spot.

The Lebedev group [22] proposed that the increased coupling was merely the infrared absorptance of liquid metal heated to an extreme temperature. However, the coupling coefficients observed on aluminum exceed the absorptances to be expected even at the vaporization temperature [23]. Another possibility is the conversion of the metal into an absorbing dielectric [25], but the predicted laser intensity threshold for this effect is ~ 20 times the threshold observed here. Both these models assume extensive metal liquefaction and vaporization, inconsistent with the superficial melting observed on our specimens irradiated near threshold.

The plasma appears at the start of the pulse, presumably during the spike; but the temperature rise of the metal surface during this spike is far short of metal melting, much less vaporization (compare an observation of anomalously low reflectance at $10.6\ \mu\text{m}$ [26]). Vapor for plasma formation is no doubt provided by the same surface defects responsible for air plasma ignition [8]. Models based on the assumption of a defect-free metal surface [24], [27] are unlikely to provide applicable results.

The reason for the very small distance of plasma propagation is obscure. Expansion at sound speed, which for this metal-vapor plasma should be comparable to or greater than the $0.45\ \text{cm}/\mu\text{s}$ of air plasmas, would yield a much larger distance than observed, even allowing for the premature ($\sim 3\ \mu\text{s}$) expiration of the plasma. Even an ordinary vapor expansion rate [24] would lead to a distance at least twice that detected. One possibility is rapid acceleration of the plasma to very high speed and low density [28], but some trace of the higher temperature phase ought to be apparent. Another possibility is a discontinuous decrease in temperature and density at a Knudsen layer boundary [29], but the vapor temperatures within the Knudsen layer predicted by this model are so low that the vapor would be invisible. A density drop below the critical density for wavelength $10.6\ \mu\text{m}$ would not lead to a cold, invisible vapor, since vapor remains highly absorbing at densi-

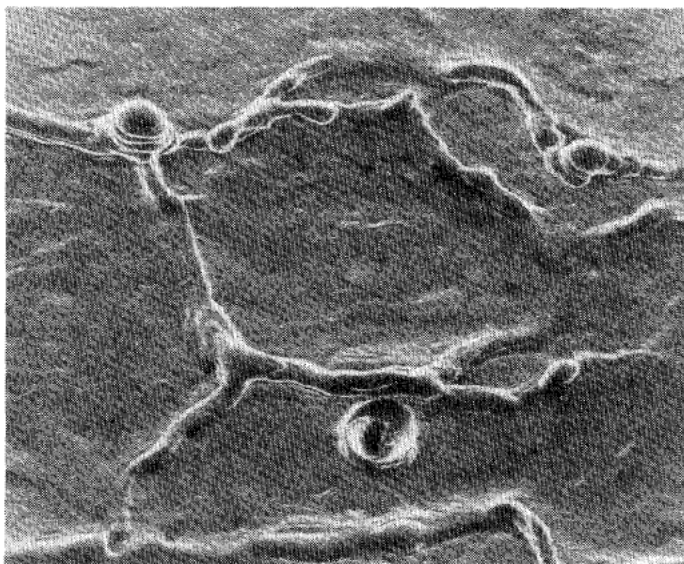


Fig. 8. Scanning-electron-microscope photograph of a 3003 aluminum alloy surface after melting by a $1.8 \mu\text{s}$ laser pulse, showing the frozen-in ripples and domes. The total width of this view is 2.0 mm; the ripple ridges are about $45 \mu\text{m}$ wide. The pit at bottom center is a location marking point, not an artifact of the laser processing.

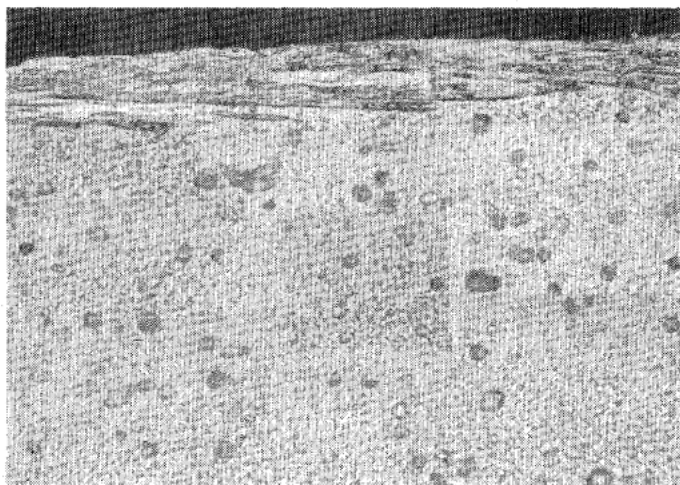


Fig. 9. Cross-section of the 3003 aluminum alloy surface after melting by the $1.8 \mu\text{s}$ laser pulse. The melt layer is about $10 \mu\text{m}$ thick. The many inclusions apparent in the unmelted material, possibly different alloy phases, have been forced into a structure of thin layers in the melted portion. This surface shows significantly improved resistance to HCl corrosion.

ties far below critical (as shown by the absence of any great effect on air plasmas as the ambient pressure is dropped so low that complete single ionization would leave the plasma a factor 10 below critical density).

Whatever the origin of the enhanced coupling in vacuum, the effects on metal heating are dramatic. Surface melting over large areas is easily achieved, in contrast to the case in air; the enhancement of coupling indicates that even highly reflective metals can be surface melted with relatively high efficiency. There appears to be no upper limit to the useable intensity [23]; and the heat deposition is confined to the laser spot area, preserving one of the practical advantages of laser heating, tight control of the heated area.

Our earlier work [23] was not at all controlled for the production of improved aluminum surfaces. Nevertheless, the 3003 alloy aluminum (97 percent Al, 1.2 percent Mn) surface-melted by the $1.8 \mu\text{s}$ pulses well above the $70 \text{ MW}/\text{cm}^2$ threshold already show favorable results. Fig. 8 is a scanning electron microscope view of the refrozen surface, which exhibits metal flowing and rippling. The ripples and bumps are clearly frozen-in flow waves; similar ripples are seen on metal surfaces rapidly melted by CW lasers [30], but the flow of liquid metal under pulsed irradiation must be affected also by the very high pressures produced [31], [32].

The rapid melting and resolidification modifies the microstructure of the metal (Fig. 9). Particles of second alloy phases, evident in the unmelted metal body, resolidify in a layered structure. The total melt thickness is about $10 \mu\text{m}$. These specimens showed reductions of 30–50 percent in corrosion rates in hydrochloric acid [33].

VI. SUMMARY

Electron-beam-excited CO₂ lasers are efficient, economical sources of high energy pulses, attractive for the microsecond melting and thermal-conductance quenching of metal surfaces, a process which can yield improved surface properties by modifying the surface structure or alloy state. However, the relatively long wavelength of the CO₂ laser leads to air plasma ignition at intensity levels far short of those required for the melting of most metals. Air plasma ignition does yield an apparent enhancement of thermal coupling, but this increase in thermal coupling coefficient is itself valid for only a limited range of laser intensities, still insufficient for metal surface melting. Increasing the laser pulse duration beyond a certain point also contributes nothing to the peak surface temperature.

The achievement of metal surface melting with thermal coupling enhanced by an air plasma requires an immense laser. Only by increasing the laser spot radius to very large values can high surface temperatures be reached; but this is a very laser-expensive procedure, the required pulse energy increasing as the cube of the spot radius, while the peak surface temperature increases only as the square root of the radius.

The air plasma can be suppressed by evacuation to a modest level, easily produced by ordinary mechanical pumps. At pulse intensities a few times greater than the threshold for air plasma ignition, a metal-vapor plasma appears in vacuum. Coincident with the appearance of this plasma, the thermal coupling coefficient increases to 10–15 percent, well above the normal infrared absorptance of high-conductivity metals such as aluminum. Whether this plasma is cause or consequence of the coupling enhancement cannot be determined from the available experimental data.

In contrast to the case with the air plasma, metal heating with vapor-plasma formation in vacuum remains confined to the laser spot, and there seems to be no upper limit to the useable laser intensity. Metal surface melting is easily achieved, even with modest pulsed lasers; no obstacle to the melting of any metal, including refractory types, is apparent.

Note added in proof: The plasma ignition analysis of Section III leads to a λ^{-2} dependence of the intensity threshold

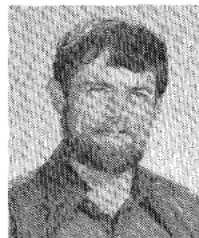
[see (2)]. Some recent data [34] reveal in fact a dependence of form λ^{-1} , showing that our analysis is deficient.

Smith [11] obtained a λ^{-1} form by assuming that the rate of inverse-bremsstrahlung energy gain was proportional to the vapor density, rather than the air density, and further that the vapor density was proportional to the laser intensity. The inverse-bremsstrahlung energy absorption rate then takes the form $I_0^2 \lambda^2$ instead of $I_0 \lambda^2$, and a λ^{-1} dependence may follow, depending on the form of the energy loss term. Because Smith's estimated vapor densities are well below atmospheric, this procedure seemed to us to be unwarranted.

We have implicitly assumed vapor densities below atmospheric, with the inverse-bremsstrahlung interaction thus dominated by collisions with air molecules. The new experimental data bring this assumption into question. A recent theoretical analysis of ignition by CO₂ laser pulses at aluminum surfaces [35], including in detail the role of thermally isolated defects, yields vapor densities above atmospheric, and may therefore justify Smith's approach. This theoretical analysis does not permit ready determination of wavelength or ambient-pressure dependences for comparison with experiment.

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Intensity of Hot Spots in Multimode Laser Beams

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Abstract—The conditions for occurrence of local intensity maxima (hot spots) due to interference of several resonator modes are examined. Simple expressions for upper bounds of the intensity and probability of hot spots are derived.

ASSUMPTIONS

The electric field of the transverse mode TEM_{mn} ($m, n = 0, 1, 2, \dots$) can be written as [1], [2]

$$E_{mn}(x, y, t) = A \exp \{i[\omega + (m+n)\Omega]t\} f_m(x) f_n(y) \\ f_m(x) = (2/\pi)^{1/4} (2^m m! w)^{-1/2} \\ \cdot \exp(-x^2/w^2) H_m(\sqrt{2}x/w), \\ f_n(y) \text{ analogously.} \quad (1)$$

THE application of laser pulses in such diverse fields as laser annealing and laser damage studies requires accurate knowledge and control of beam intensity distribution both in space and time. It is well known that the simultaneous oscillation of several oscillator modes [1] leads to local maxima in intensity, commonly referred to as hot spots. The main reason to utilize multimode radiation is that suppression of all but the lowest mode (usually achieved by means of beam-limiting apertures within the resonator) results in a substantial loss of available beam energy.

In what follows we derive simple estimates for the intensity and probability of hot spots in terms of only two physical parameters: the spot radius w of the TEM_{00} mode (which is uniquely determined by the resonator data [1]) and the actual beam radius b (which is determined by the apertures). All beam properties are discussed with respect to a target plane perpendicular to the beam axis, it being understood that both w and b are referred to that plane.

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Here, x and y are coordinates in the target plane with the beam axis at $x = y = 0$, ω is the frequency of the TEM_{00} mode, and Ω is the frequency separation of adjacent transverse modes [1]. H_m are Hermite polynomials. The prefactors in (1) are chosen such that the integral of the intensity $|E_{mn}|^2$ over the whole plane is the same ($=A^2$) for each mode. Phase factors that are irrelevant for the following have been omitted in (1). Actual fields are superpositions

$$E(x, y, t) = \sum_{m,n} c_{mn}(t) E_{mn}(x, y, t) \quad (2)$$

with complex weight factors $c_{mn}(t)$ describing the contributions of individual modes thought to vary slower than the fields in (1). In the following we consider time intervals τ short enough so that the c_{mn} can be assumed constant. The integral

$$\iint |E(x, y, t)|^2 dx dy = A^2 \sum_{m,n} |c_{mn}|^2 \quad (3)$$

representing the total beam power is then constant. The maximum number of excited modes can be estimated from the