

**OPTIMUM ENERGY AND DURATION IN PULSED LASER HEATING OF ORGANIC MATERIALS \***

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We have explored the minimum energy deposition necessary to drill a hole in a layer (or to cut a rod) of organic material by a pulsed CO<sub>2</sub> laser operating at 10.6  $\mu\text{m}$ . Applying equal amounts of energy over different time intervals gives rise to the appearance of two minima in an energy-time diagram. Current theoretical models for the melting process under laser irradiation yield a single minimum. Mass spectrometer tests of the vapors have localized dissociated molecular fractions strongly absorbing at 10.6  $\mu\text{m}$ ; thus hinting at the possibility that the second valley may be due to a strong absorption of the vapors. This was indeed the case, as verified by working with the 9.4  $\mu\text{m}$  emission band and with materials whose vapors are transparent in that region.

**1. Introduction — The model**

We have explored the minimum energy deposition to perform cutting operations on organic materials by CO<sub>2</sub> laser radiation. We were motivated by practical applications in industrial processes (drilling and cutting of plastics, processing of fabrics in textile industry, etc.) as well as by the biomedical relevance of such investigations with reference to the surgical use of the CO<sub>2</sub> laser.

When the effect is proportional to the total absorbed energy, as in a photochemical process (from photography to isotope separation) what matters is the so-called fluence ( $\text{J}/\text{cm}^2$ ). Indeed the energy versus exposure time curve of a photographic plate is practically flat, in the sense that the necessary power

scales with the reciprocal of exposure time.

On the contrary, when we have to break the continuity of solid matter, as in cutting a rod or drilling a hole through a thick material, and the local break of molecular bonds is not due to the intrusion of a harder body (the mechanical tool) but to a melting process via a local laser heating, we have also competing processes which may carry away the deposited energy. More specifically, let us refer to an ideal isotropic material characterized by uniform and constant thermal coefficients (as specific heats, thermal conductivities and latent heats of melting and vaporization).

Suppose we have defined the "optimal" energy deposition process, that is the minimum amount of energy corresponding to a pulse of given power and duration, necessary to perform the process. That means that, with a minimal influence of idle processes, the melting temperature has been reached up to

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the last section of the material. If we apply the same energy but with a longer pulse and smaller power, lateral diffusion processes have time to carry part of the energy away from the melting region (for sake of simplicity think of cutting a rod) so that the temperature in the working region does not reach any longer the melting value, thus requiring an extra amount of energy.

On the other hand, if we shrink the laser pulse to smaller duration and higher power, the local temperature increase on the exposed region is so high that a large amount of the material goes beyond the melting temperature and vaporizes, thus wasting energy as latent heat of vaporization.

From this qualitative description of the process we expect a rise of the energy curve both for long as well as for short times, as we move away from the optimum deposition time. Numerical solutions of a current theoretical model [1,2] justify this expectation. However, the experiments carried out by us [3] yielded strongly different results. In general rather than one minimum, our experiments consistently yielded curves with two minima. These deviations between model and experiments require new assumptions to modify the model. We have been able to formulate these new assumptions which yield a correct description of the phenomenon and to give an experimental support for them. The model proposed by Paek et al. [2] assumes that the thermal constants are independent of the temperature, the vapor is transparent to the laser beam and the liquid phase has no influence on the process. With these assumptions, the energy balance and heat conduction equations are

$$\rho L_v \partial Z / \partial t = K \partial T / \partial z |_{z=Z} , \tag{1}$$

$$\rho C_p \partial T / \partial t = b I \exp[-b(z - Z)] + K \nabla^2 T , \tag{2}$$

where  $t$  is the time,  $T$  the temperature,  $z$  the coordinate we assumed starting from the surface exposed to the radiation,  $Z$  the coordinate of the vaporization,  $K$  the thermal conductivity of the solid phase,  $\rho$  the density of the solid phase,  $L_v$  the latent heat of vaporization,  $C_p$  the specific heat of solid phase,  $b$  the absorption coefficient and  $I$  the laser intensity.

By solving these equations Paek et al. obtained the temperature distribution  $T(z)$  and the velocity  $v(t) = \partial Z / \partial t$  of the vaporization front as a function of time.

A numerical integration of  $v(t)$  yields the width

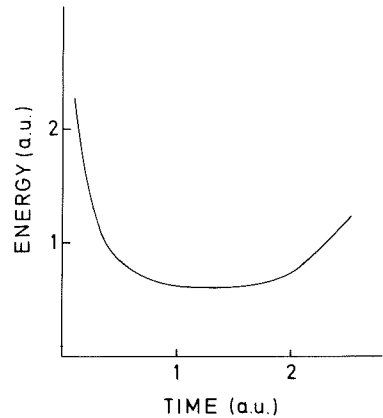


Fig. 1. Theoretical energy required to drill a hole through a plexiglas sheet as a function of the exposure time.

$e(t)$  drilled as a function of time for different intensity values, that is

$$e(t) = \int_0^t v(t', I) dt' . \tag{3}$$

From eq. (3) it follows the time necessary to drill a hole through a given width and hence the energy deposition as a function of time. In fig. 1 the energy time curve is represented for the case of plexiglas.

## 2. Experimental arrangement and results

To investigate experimentally this problem we have used the experimental set-up shown in fig. 2.

Two beams, one of which provided by a CO<sub>2</sub> laser (100 W nominal power, TEM<sub>00</sub>) and the other by a He-Ne laser (5 mW), go through a shutter. When the shutter is open the He-Ne beam is in part sent over the photodiode 1, the signal of which sets the time counter, and in part goes to the back-surface of the workpiece. The photodiode 2 detects the reflection on the back-surface. The time counter consists of an oscillator and a pulse counter.

The CO<sub>2</sub> laser beam, going through a lens, drills the workpiece. At the moment when the hole through the material has been drilled, the signal of the photodiode 2 falls down and stops the time counter.

This system measures the time necessary to drill a

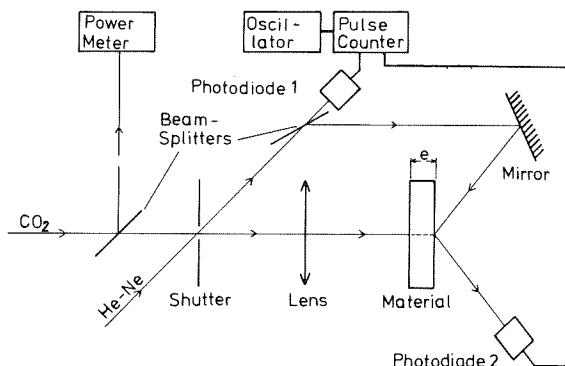


Fig. 2. Experimental set-up for measuring the time necessary to drill a hole through a slab of plexiglas.

thickness with an accuracy determined by the oscillator. In our case, the accuracy is 0.1 ms.

The CO<sub>2</sub> laser power is measured by a bolometer, before the beam reaches the shutter, with a relative precision better than 1%.

The results are shown in the graph of fig. 3. There is clear evidence of two distinct energy minima which are not predicted by the theoretical results. Further-

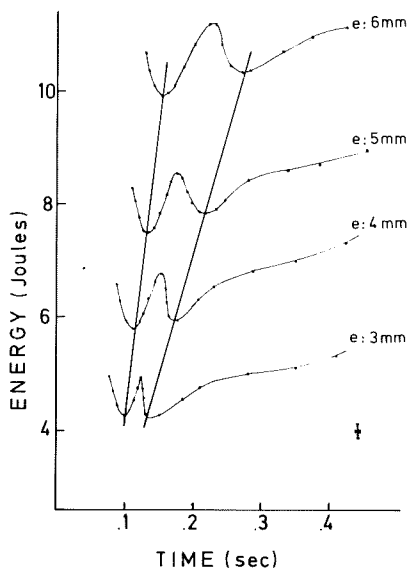


Fig. 3. Experimental energy versus time curves for different thicknesses of plexiglas with a 10.6  $\mu\text{m}$  CO<sub>2</sub> laser.

more, these minima are aligned on two constant power lines.

With this set-up, measurements were performed for different widths of plexiglas and cotton, with a N<sub>2</sub> jet and without, and results qualitatively similar were found.

To explain this phenomenon we must explore the influence of the assumptions made in the model and the existence of other interaction effects. In this sense, we made some mass spectrometer tests of the vapors and they localized dissociated molecular fractions. It was clear that the inter- and intra-molecular bonds were breaking during the interaction between the laser beam and the organic material as is described by Akulin [4].

As we show in fig. 4, those vapors are strongly absorbing at 10.6  $\mu\text{m}$  wavelength at which we perform our first experiments; thus hinting at the possibility that the two valley structure in the energy versus time diagram may be due to vapor absorption.

From fig. 4, it appears that plexiglas vapors absorb at 10.6  $\mu\text{m}$  but they are transparent at 9.3  $\mu\text{m}$ . This wavelength corresponds to the R(10) transition in the 9.4  $\mu\text{m}$  CO<sub>2</sub> laser band, so, it was possible to test the influence of the vapor absorption on the process, using a grating inside the cavity to select the emission band of the laser. The results obtained are shown in fig. 5 where it can be seen that the second valley is not present when the hole is made at 9.3  $\mu\text{m}$ , and that the energy necessary is always smaller than when the hole is made at 10.6  $\mu\text{m}$ , and the single minimum is found at shorter times, and hence for higher powers.

To have a complete overview on the phenomena, we have taken a high velocity movie picture (500

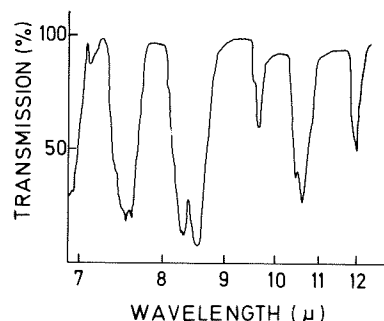


Fig. 4. Absorption spectrum of plexiglas vapors formed by a CO<sub>2</sub> laser.

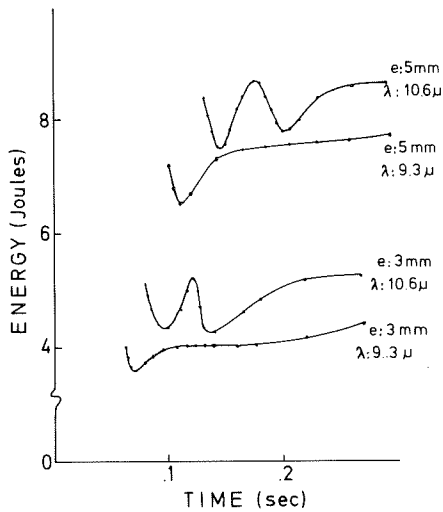


Fig. 5. Experimental energy versus time curves for plexiglas exposed at two different CO<sub>2</sub> laser wavelengths (Data refer to two thicknesses).

frames/s) which gives us the velocity of the vaporization front as a function of time. As shown in fig. 6 the velocity reaches a maximum and then does not decrease uniformly for all the intensity values, but it has irregular oscillations before it arrives to a steady state value.

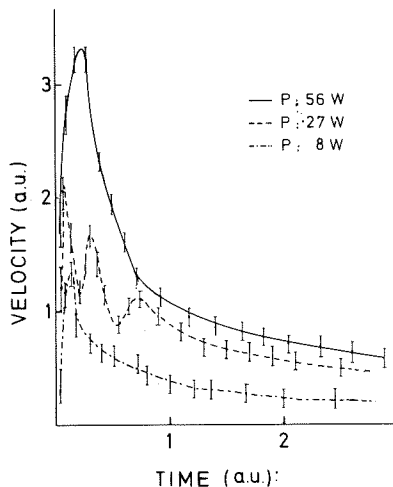


Fig. 6. Velocity of the vaporization front versus time for different power values with the P(20) transition of a CO<sub>2</sub> laser. Curve obtained by fast cinematography.

### 3. New assumptions and relative experimental support

We attempt here a qualitative interpretation of our plots. We expect that for a given energy deposition at an "optimal" time, there is a local temperature increase at the focal spot up to the melting point.

For sake of simplicity in this model we think of a standard continuous material undergoing the ordinary phase transition solid to liquid to vapor. However, the transition responsible for bonds breaking, may not be necessarily a solid-liquid transition when the sample is made of long polymeric molecules, but may be a local softening due to intramolecular or intermolecular breaking induced by vibrational motions [4].

As we said above, for a very low power pulse a large amount of energy is carried away by lateral diffusion. Hence, the energy required increases. At short times and higher powers, the energy losses increase due to the vaporization of the material and absorption of these vapors. This interpretation is supported by the fact that this relative minimum is not present when the vapors do not absorb the laser radiation (fig. 5).

Taking into account that the vaporization is obtained by removing energy from the region near the front surface, it is clear that this cooling mechanism can cause the maximum temperature to lie inside the solid material and, if the process is not rapid enough, the maximum temperature may be so high as to produce a vaporization of an inner portion of material. In this case, the pressure arising from the vaporized material produces an explosion. After the explosion has occurred, the process begins again and the hole is completed after several microexplosions. This process explains the oscillations on the velocity curves of fig. 6. In this case, the process is very efficient, more than when the hole is made by melting or vaporization of the whole material [1-5], so the required energy decreases.

For very high intensities, the possibility of explosions vanishes because the rapidity of the vaporization front (see the velocity versus time curve for 56 W in fig. 6). As a result the energy necessarily increases because the vapor absorption becomes more and more important. The attribution of this energy increase fundamentally to the vapor absorption is supported by the fact that the minimum was found at shorter times, and at higher powers, when the interaction succeeds at 9.3 μm.

#### 4. Conclusions

The experimental results show that the disagreement between experiments and theoretical model in the problem of laser drilling of organic materials, depends mainly on the vapor absorption and not on the temperature dependence of the thermal constants.

A corresponding more refined theory is possible by suitable modification of the model equations (1) and (2) to include for at least two phases, namely vapor and solid. In this way, we can obtain a two valley energy time curve in qualitative agreement with the experiment.

More details on the calculations and on the experiments will appear in a larger report.

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