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Laser-induced shock effects in Plexiglas and 6061-T6 aluminum

Jay A. Fox and Dallas N. Barr

*United States Army Mobility Equipment Research and Development Center,
Fort Belvoir, Virginia 22060*

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The mass removal per unit area from Plexiglas and 6061-T6 aluminum targets irradiated in air with a giant pulsed laser is presented as a function of incident fluence. This quantity appears to be a strong function of the focal length of the focusing lens. Air breakdown in the presence of a target occurs at fluences greater than 380 J/cm^2 for Plexiglas targets and 159 J/cm^2 for aluminum targets. Photographic evidence of the back-face spallation of a 0.1-cm-thick aluminum sample irradiated in vacuum is presented. The mirror-finished target was inclined at 45° to the incident beam and irradiated with a fluence of approximately 5000 J/cm^2 .

The purpose of this letter is to report the results obtained by the authors while performing a recent series of experiments at Battelle Columbus Laboratories, Columbus, Ohio. This letter will deal with mass removal from Plexiglas and aluminum targets irradiated in air with a 30-nsec pulse from a Nd:glass laser. We shall also report on the fluences (energy density) necessary to cause air breakdown in the presence of these targets. Finally, we shall present evidence of back-face spallation in an aluminum target irradiated in vacuum with a 1-nsec laser pulse. We believe this to be the first published report of laser-induced back-face spallation of an uncoated metal.

The Q-switched glass laser is a Compagnie d'General Electrique Vare D 640 oscillator-amplifier system. The oscillator and five amplifier stages were used to produce energies in the 300- to 450-J range at 30 nsec and in the 100- to 150-J range at 1 nsec. The laser pulse shape and energy were monitored for each shot by means of a photodiode and calibrated calorimeter, respectively. The procedures may be found elsewhere.¹

Since clear Plexiglas is nominally transparent to $1.06\text{-}\mu$ radiation, another choice had to be made. Various types of colored or coated targets were tested for absorptivity and damage effects. Optimum coupling into the Plexiglas as measured by mass removal was achieved by using a transparent sample of smoky gray color. Communication with the manufacturer² has revealed that this appearance is due to a suspension of fine carbon particles in the Plexiglas. Absorptivity measurements with a YAG laser showed that 67% of the $1.06\text{-}\mu$ light would be absorbed. (It is interesting to note that a thin spray coating of Krylon ultraflat black paint onto clear Plexiglas proved totally ineffective in inducing mass removal of the Plexiglas. The effect of irradiating such a target with 316 J/cm^2 was simply to blow off the coating and leave the Plexiglas practically undamaged.)

The stock aluminum samples were of the 6061-T6 alloy and were nominally of 0.2- and 0.1-cm thicknesses. The front surface of each target was prepared by hand sanding with 320 grit paper.

The experimental setup consisted of a lens to focus the beam onto the target, a target holder, and two cameras to record the event. Lens focal lengths of 1.0 and 0.5 m were used and, as will be soon demonstrated, it was found that the results depended strongly on this length. One camera was an ordinary device with a Polaroid back, the other was a 6B TRW high-speed framing cam-

era capable of taking three pictures at 500-nsec intervals. The target was offset about 10° to the incident beam so that the specular reflection would not present a hazard to the laser. Mass measurements of the target were performed with a Mettler H20T balance.

The results of the mass removal experiment are presented in Fig. 1, where mass removal per unit irradiated area is presented as a function of fluence. These fluences have been corrected for transmission losses and thus represent the actual energy density incident on the target. The estimated experimental error in quoted fluences ranges from 10% for fluences of about 100 J/cm^2 to 20% for fluences as great as 900 J/cm^2 . The spot diameters ranged from 0.60 to 1.50 cm. The precision of these and other diameter measurements was $\pm 0.05 \text{ cm}$. The magnitude of the mass removal was in the 5.0×10^{-4} - to 1.0×10^{-1} -gm range for Plexiglas, while for aluminum the range was from 1.04×10^{-3} to 2.88×10^{-3}

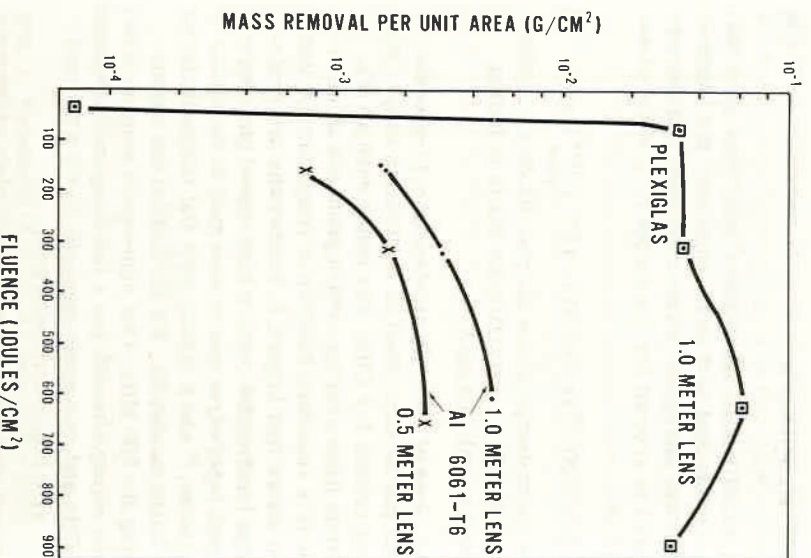


FIG. 1. Mass removal per unit irradiated area for Plexiglas and aluminum targets as a function of incident laser fluence.

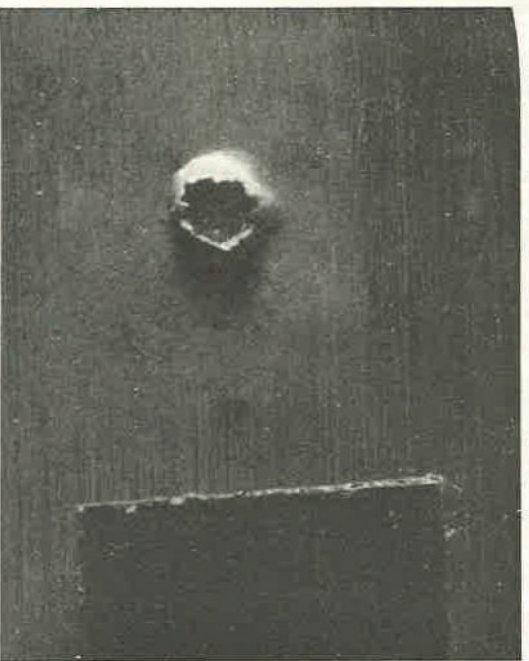


FIG. 2. Back-face spallation of a 0.1-cm-thick aluminum target irradiated under vacuum conditions by a fluence of approximately 5000 J/cm^2 . The nominal diameter of the spalled region is 0.6 mm.

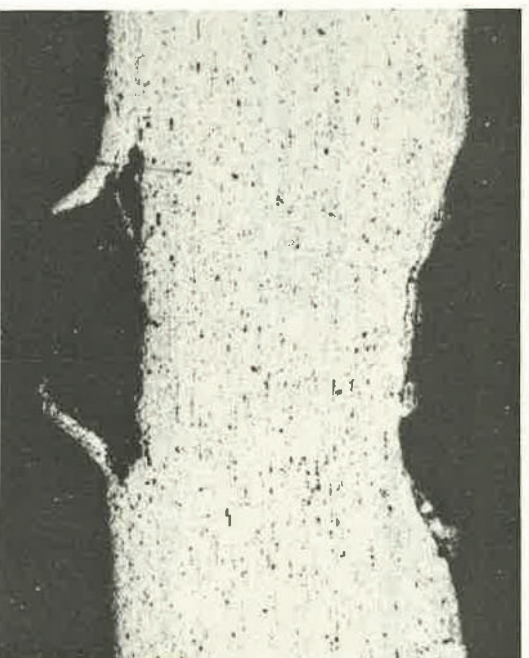


FIG. 3. Sectioned view of the sample shown in Fig. 2. The laser beam was incident from the left-hand side at an angle of 45° to the normal.

gm. Repeated mass removal measurements yielded identical results to within 3% in the worst case. Some interesting phenomena are illustrated in Fig. 1. Plexiglas removal per unit area attains a sharply defined local maximum at less than 100 J/cm^2 and does not substantially change at fluences of almost 900 J/cm^2 , apparently reaching a peak at approximately 600 J/cm^2 . The curves for aluminum appear to be both qualitatively and quantitatively different. It was observed that the mass removal of aluminum depends strongly on the focal length of the lens used to focus the beam onto the target. About twice as much mass is removed for the same energy and spot size using the 0.1-m lens as compared to the removal with the 0.5-m lens. This large and consistent mass difference cannot be ascribed to experimental error. The authors plan further investigation of this effect and thus will defer until a later date conference as to its cause.

The breakdown threshold for clean air irradiated with short ($< 5 \times 10^{-8}$ -sec) $1.06\text{-}\mu$ laser pulses have been reported³⁻⁶ to be in the 1000- to 4000-J/cm^2 range. It has also been noted^{7,8} that the presence of a target reduces the breakdown level still further because of the intense ultraviolet radiation emitted during the formation of the plasma created at the surface of the target. We were able to verify this reduction of breakdown level with the aid of the previously mentioned cameras. The sparks from the air breakdown were clearly visible in the photographs taken by the framing camera and less evident (but still visible) in the other photographs. The sparks extended out as far as 8 cm from the surface of the target and in the direction of the laser pulse rather than normal to the target surface. (Recall that the target was inclined $\sim 10^\circ$ to the laser beam.) This was also reported by Ref. 8 and was explained as local absorption of the laser energy at the plasma boundary. With Plexiglas as a target, no air breakdown was observed for four shots at fluence below 325 J/cm^2 . Breakdown occurred during each of four single shots at higher fluences ranging from

380 to 890 J/cm^2 . Aluminum targets lowered the threshold value still further. Breakdown was observed at fluences as low as 159 J/cm^2 and for each of four other shots at fluences ranging from 165 to 649 J/cm^2 . No breakdown was observed for shots at 149 and 20 J/cm^2 . The 1-m lens was used for all but two of these shots. In all cases the laser pulse width at half-maximum amplitude was 30 nsec.

Several high-fluence ($> 1000\text{-J/cm}^2$) shots of 1- to 2-nsec duration each were taken at aluminum targets under vacuum ($< 10^{-4}$ Torr) conditions. In order to protect the laser against the possibility of back reflection from surface irregularities, it was necessary to turn the target away from the incident beam direction by 45° and also to polish the surface to a mirror finish. A complete metallurgical analysis of these irradiated samples has not yet been made; however, we wish to call immediate attention to the results of a particular shot in this series. Figure 2 shows the back surface of a 0.1-cm-thick aluminum sample irradiated with a fluence of approximately $(5 \pm 2) \times 10^3 \text{ J/cm}^2$ and a spot diameter of between 0.1 and 0.15 cm. A clear indication of complete back-face spallation is seen. Figure 3 shows a view of the sectioned sample. The nominal diameter of the spalled region is 0.6 mm, while the diameter of the front face crater is about 1.6 mm.

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