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Enhanced failure of ceramics irradiated by combined pulse and c.w. lasers

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Several ceramic* materials were subjected to the combined irradiation of a 1.06 μm pulse and a 10.6 μm continuous wave (c.w.) laser. The duration of c.w. irradiation required to cause failure from the combined exposure is compared to that from c.w. irradiation alone. For example, thin Pyroceram and soda-lime glass plates burned through when exposed to the c.w. laser followed by the single pulse laser, in about one half the time required to cause fracture during exposure to the c.w. laser alone. Also, enhanced catastrophic fracture of thick soda-lime glass plates resulted when the c.w. irradiation followed the pulse within 0.3 sec. Finally, the effects of the combined pulse and c.w. exposure are compared with the effects of single or multiple pulses, and the apparent enhancement is discussed in terms of beam size and power.

1. Introduction

The influence of intense laser irradiation on a number of ceramic materials has been examined in a variety of experiments. Most of these experiments measured the damage thresholds of transparent laser optics by either single or multiple laser pulses [1–5] or a continuous wave (c.w.) laser beam [6–8]. Other studies determined the effects of irradiation on opaque materials [9–11]. However, prior to this study, the only report on the interaction of matrials with irradiation from a combination of pulse and c.w. lasers was one by Fox for metals [12]. Since he demonstrated that the penetration rate of metals could be enhanced by dual mode irradiation, this study was undertaken to determine if a similar reduction in time to fracture or burn-through of ceramics would occur.

2. Experimental procedure

Materials with differing optical properties were studied: Pyroceram 9606 (glass-ceramic) and Al-300 alumina, both of which, although intrinsically transparent at short wavelengths, are essentially opaque at both 1.06 and 10.6 μm due to surface and bulk scattering and soda-lime glass which is transparent at 1.06 μm. Plates of ~5 cm × 5 cm ceramic materials of varying thickness were irradiated by a 1.06 μm Nd^{3+} glass laser with a nominal energy on target of ~80 J and a pulse half-width of 0.5 msec and/or a 10.6 μm c.w. laser with a power of 325 W. The beams were aligned so as to expose the same spot on a specimen to the peak irradiance of both lasers (Fig. 1). The sample was exposed to both beams, singly, in series, or simultaneously by using a system of shutters and timers.

The irradiance of the pulse laser was focused at 0.6 to 5.0 MW cm^{-2} by either attenuation of the beam with filters or by changing the distance from the focus. The irradiance of the c.w. laser was varied from 0.7 kW cm^{-2} to 1.4 kW cm^{-2} by adjusting the focus, although most of the experiments were performed at the latter irradiance. Burn patterns in opaque plexiglass plates were used to establish the beam size and shape. The

*The term ceramics in this paper refers to non-crystalline (glasses) as well as single and polycrystalline ceramics.

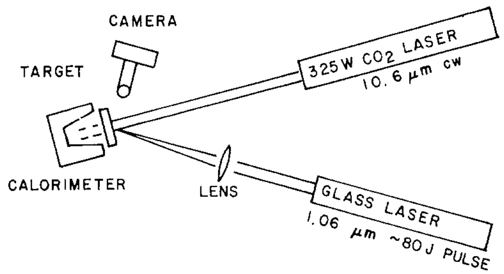

Figure 1 Schematic diagram of the experimental arrangement showing both the 80 J pulsed laser and the 325 W c.w. laser aligned on the target. Typical locations of the high speed motion picture camera and the rapid response calorimeter are shown.

energy output of the c.w. laser was monitored continuously by a power meter and the output of the pulse laser was checked periodically. A typical trace of the pulse temporal power distribution of the glass laser is shown in Fig. 2. In addition to these laser diagnostics, a rapid response power meter was used in conjunction with a visicorder to record transmitted energy and fracture or penetration time. A high speed (100 frames sec^{-1}) motion picture camera was used to observe the specimen during irradiation.

3. Results and discussion

3.1. Pulse irradiation alone

The combined fluence from several single pulses, $\sim 3\,kJ\,cm^{-2}$ and $6\,MW\,cm^{-2}$ each at a pulse rate of $\leqslant 1$ pulse per minute were required to penetrate opaque materials (Table I) such as 0.25 cm thick Pyroceram (5 pulses) and 0.32 cm thick alumina (> 6 pulses). The total fluence from these multiple pulses, $15\,kJ\,cm^{-2}$ and $18\,kJ\,cm^{-2}$ respectively, exceeded that predicted by a simple ablation model for penetration [9]. This extra energy was probably required because of one or more of the following: cool down between pulses, ionization of material, and/or the relatively small beam size [7, 9].

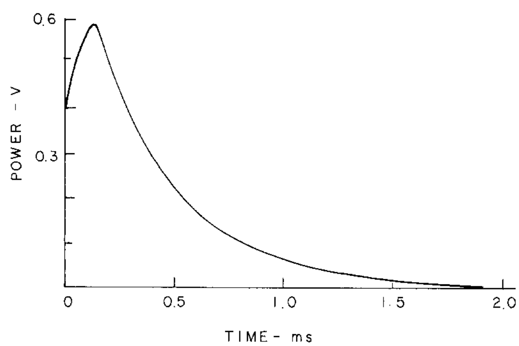

Figure 2 Temporal profile of the output power from the 1.06 μm, 80 J, pulse laser.

A single pulse produced both front and rear surface sub-critical radial cracking in all thicknesses of soda-lime glass exposed at irradiances of 2 to $50\,MW\,cm^{-2}$, with the damage in the rear generally being greater, as would be expected due to increased absorption [1–5] with the explanation of Crisp [3] appearing the most probable. However, both the occurrence and the type of damage which is similar to that resulting from impact (Hertzian cracks), suggests a contribution by impulse loads from the pulse [11] as opposed to thermal response alone.

3.2. C.w. alone and c.w. followed by one pulse

The failure thresholds of Pyroceram and soda-lime glass exposed to the c.w. laser at an irradiance of $1.4\,kW\,cm^{-2}$ for various lengths of time alone or followed by an 80 J pulse at an irradiance of $1.6\,MW\,cm^{-2}$ are summarized in Tables I and II. Exposure of control samples of 0.25 cm thick Pyroceram to the c.w. beam alone resulted in longer times to fracture (~ 11 sec) than those observed previously (~ 4 sec) at equivalent irradiance with larger lasers (3 to 100 kW) [9]. This is most likely due to the low beam size [9]. However, the combination of c.w. exposure followed by the pulse resulted in a relative enhancement of failure in Pyroceram since penetration which did not occur from the 325 W beam alone could be brought about if the target was irradiated by a 14 J, $1\,MW\,cm^{-2}$ pulse after a minimum of 4 sec

TABLE I Type of laser irradiation

Material	C.w. (325 W, $1.4\,kW\,cm^{-2}$)		Pulse (80 J, $6\,MW\,cm^{-2}$)		Combined lasers	
	Exposure time (sec)	Result	Exposure No. pulses	Result	Exposure time (sec)	Result
Pyroceram (0.25 cm thick)	11 ±1.5	Fracture	5	Penetration	4.1 ± 0.2	Penetration
Alumina (0.3 cm thick)	2.1 ± 1.4	Fracture	>6	Penetration		

TABLE II Type of laser irradiation of soda-lime glass

Thickness (cm)	C.w. (325 W; 1.4 kW cm^{-2})		C.w. + pulse		1 pulse + c.w.		1 pulse + delayed c.w.		Pulse (80 J; 6 MW cm^{-2})	
	Exposure time (sec)	Result	Exposure time (sec)	Result	Exposure time (sec)	Result	Exposure time (sec)	Result	Exposure No. pulses	Result
0.3	1.4 ± 0.2	Fracture	1.4 ± 0.4	Fracture	1.0 ± 0.4	Fracture	1.1 ± 0.4	Fracture	1	Cracking
	10 ± 5	Fracture	6 ± 5	Burn-through	11 ± 3	Fracture				
0.6	5 ± 1	Fracture	4 ± 0.5	Fracture	0.2 ± 0.1	Fracture	7 ± 1	Fracture	1	Cracking

of c.w. irradiation. After 4 sec, the sample is molten through most of its thickness and the penetration time is only slightly less than that predicted for burn-through by the total energy required to heat, melt, and vaporize the material. The pulse acts to drive the melt out of the cavity as illustrated in Fig. 3.

A bimodal distribution of the time to fracture of 0.3 cm thick glass from c.w. irradiation alone was observed (Table II). This behaviour is probably due to a bimodal flaw distribution in the glass, which increases the difficulty of data analysis. While the slight reduction in time to failure observed for 0.6 cm thick soda-lime glass is statistically insignificant (Table II), 0.3 cm thick targets lasting longer than ≈ 2 sec could be penetrated in 6 sec by use of the pulse laser compared with 10 sec for the c.w. laser alone, similar to the behaviour of Pyroceram. The time for penetration of both thicknesses from this type of dual mode irradiation coincides roughly with the time at which the glass was softened through most of its thickness. Thus, above the penetration threshold, the impulse from the pulsed laser probably caused the softened glass to be ejected from both sides of the sample.

3.3. Pulse followed by c.w.

The greatest reduction in failure times occurred when 0.6 cm thick soda-lime glass sheet was

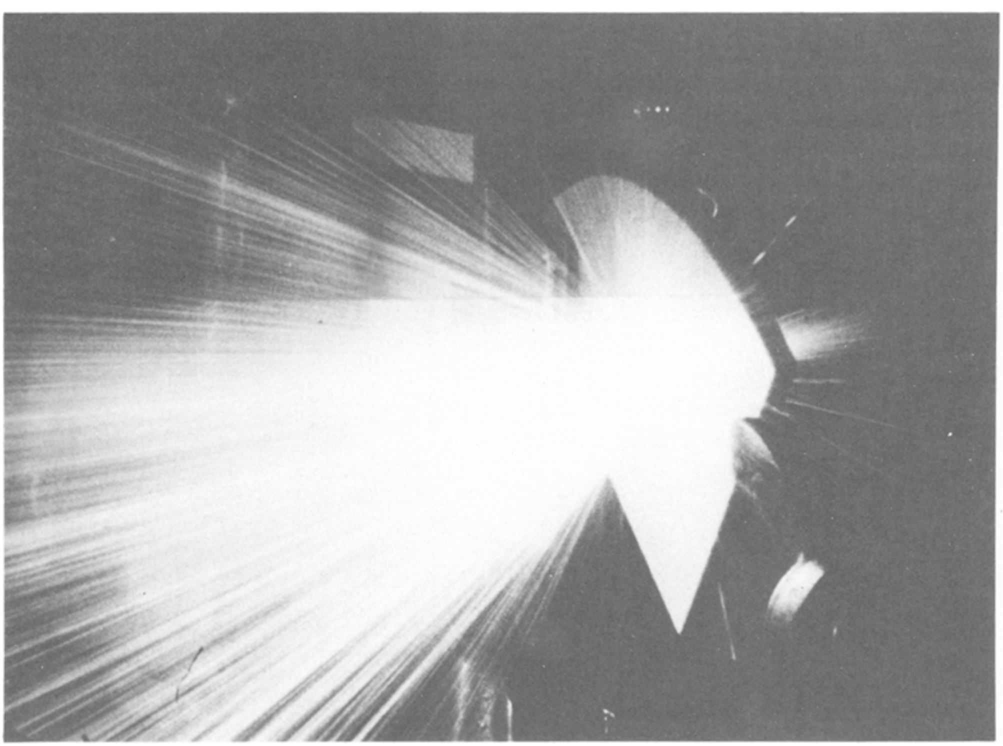

Figure 3 Penetration of a 0.25 cm thick Pyroceram plate by the 1.06 μm pulse after c.w. irradiation. The plume in the rear is a result of melt being expelled by the pulse.

exposed first to an 80 J pulse followed immediately by the 325 W c.w. beam (Table II). With this combination, the 0.6 cm glass failed in 0.01 sec when the 1.4 kW cm^{-2} c.w. irradiation was begun within 0.3 sec after exposure to a 6 MW cm^{-2} pulse.* However, if the introduction of c.w. irradiation was delayed 2 sec or more, fracture of the glass did not occur until after ~ 7 sec exposure to c.w., the same time at which failure occurred from c.w. alone. These observations suggest that when the c.w. follows the pulse there is a maximum time interval in which the superposition of stresses can cause catastrophic failure. This threshold time (~ 2 sec) is probably due to the decay of the impulse stress. The lack of enhancement following the delayed exposure occurs even though rear surface cracks result from the pulse. While there is no enhancement of failure time, more extensive cracking occurs when exposure to c.w. is delayed due to the greater amount of stored elastic energy.

No similar fracture enhancement occurred from pulse followed by c.w. irradiation of 0.3 cm thick soda-lime glass. This is probably due to the decreased absorption of the thinner plates at 1.06 μm.

These experiments suggest that fracture of materials which are generally opaque at both the pulse and c.w. wavelengths would be expected to be enhanced over either irradiation alone if the observed behaviour is primarily from impulse. Fracture of (0.6 cm thick) soda-lime glass coated with graphite (making it opaque to the pulse) in the same times as uncoated glass, while not conclusive, suggests that the impulse mechanism is quite important to the enhancement. On the other hand, the lack of fracture enhancement with the thin (0.3 cm thick) soda-lime glass suggests that the transparency at 1.06 μm is also important. Further experiments at different wavelengths are necessary to differentiate the mechanisms.

4. Summary and conclusions

One clear and statisically meaningful enhancement of failure occurred in these experiments: 0.6 cm soda-lime glass fractured catastrophically within 0.01 sec when an 80 J, 1.06 μm pulse was followed within 0.3 sec by c.w. exposure. Also, within the limited range of laser powers and energies available, the threshold for penetration failure of 0.25 cm Pyroceram and 0.3 cm soda-lime glass was reduced ~ 50% from that observed for fracture from c.w. irradiation alone if the c.w. exposure was followed immediately by a single 6 MW cm^{-2} pulse. There is some indication that the use of a larger c.w. laser in conjunction with a larger pulse would produce further significant reduction in times to failure of Pyroceram and soda-lime by either burn-through or fracture. However, the degree of enhancement is probably a function of both laser wavelength and power, so that additional experiments which include combined exposure to both large CO_2 pulse and c.w. lasers will be necessary to resolve ambiguities.

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*Below ~ 4 MW cm^{-2} pulse irradiance, the pulse followed immediately by c.w. irradiation results in times equivalent to c.w. irradiation alone.