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INTRODUCTION

An ultrasonic technique was developed to detect and characterize laser damage in critical optics. During normal usage, sub critical flaws induced by high laser fluence can grow to critical size and potentially can cause unanticipated failure of the optics. This ultrasonic technique monitors the optic in situ and provides a quick, reliable way to quantify the location, number and, ultimately, the size of defects that may initiate and grow during firing of the laser.

The feasibility of detecting and sizing laser-induced damage with an ultrasonic technology was theoretically and experimentally demonstrated. An experiment was conducted whereby ultrasonic data was acquired in situ on an optic as it was damaged by a laser. This monitoring of laser induced damage clearly demonstrated the potential for ultrasonic monitoring of critical optics for laser-induced damage.

EXPERIMENT

Laser damage was ultrasonically monitored during the growth of a single damage site on a large fused silica optic, see Figure 1. A single laser damage site was grown in a fused silica window measuring. The damage was grown to over 7 mm in diameter during the course of 21 shots of a 1.053 μm pulsed laser. After each shot, an effective diameter for the damage site was calculated from the front-view optical image by averaging the maximum horizontal and vertical dimensions of the site. In addition to the optical images, acoustic data were acquired after each shot by the standard ultrasonic measurement method known as the pulse-echo technique [1]. A single transducer was placed on the top edge of the fused silica plate, at a range of 280 mm from the damage site. In the glass slab, the damage manifests as a central pit with cracks that radiate into the glass. The combined interaction of the central pit and the radiating cracks with the acoustic beam has profound effects upon the signal content. By developing a better understanding of how these effects manifest, we can begin to utilize increasing amounts of the information contained in the signal as a result of these interactions.

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NUMERICAL SIMULATIONS

The laser damage experiments were accompanied by numerical simulations of elastic wave scattering from idealized models of damage spots in a glass slab [2]. The results reinforce the physical interpretation of the experimental data and allow a closer examination of the scattering mechanisms. In addition, simulations can provide model data for situations that would be difficult or impossible to realize experimentally. The net result is a better understanding of the effects of damage morphology on the scattered ultrasonic signal and, therefore, on experimentally measured data.

A simulator has been developed, using a modification of a previous finite difference time domain (FDTD) elastic wave code, which incorporates the full physics of elastic wave propagation including compressional and shear waves, mode conversion at interfaces, and diffraction and scattering from surface pits with complicated geometries[3,4]. The simulator is capable of incorporating realistic models of acoustic transducers and measured input pulses, and can simulate damage spots with complicated morphologies. The modified code incorporates free surface boundaries on all sides of the computational domain to allow it to simulate elastic wave propagation in a freely suspended slab, which approximates the conditions for an optical window in a high powered laser.

RESULTS AND DISCUSSION

Experimental monitoring of laser damage

It is known that the shape and morphology of laser damage sites can vary widely, depending upon the experimental conditions, and often include radiating or circumferential cracks [5]. The effects of these variations in shape and morphology, and of the presence of cracks around the central damage site, upon the characteristics of any diagnostic signal must be well characterized before that diagnostic technique can be used for online monitoring of the damage. Laser damage is a combination of a central pit, or crush zone, surrounded by a network of cracks [2]. These cracks around the base of the central pit lead to the manifestation of coherent interference effects in an acoustic (ultrasonic) beam reflecting from the damage site. At the nominal frequency used in this study, 5 MHz, the wavelength is ~1.2 mm. Thus, for damage ranging from a fraction of a millimeter to several millimeters in diameter, the various features of the damage site are distributed over an acoustic path length on the order of up to a few wavelengths. This implies that, upon reflection from a non-uniform discontinuity, components of the beam reflected from features separated by several millimeters of path length can interfere coherently.

Evaluation of the peak-to-peak amplitude versus defect diameter for the full range of laser damage sizes, shown in Figure 2, indicates that the coherent interference effect can be severe as the damage site grows through this range of diameters. In these data the amplitude of the primary echo does not increase monotonically as the damage grows. In fact, the amplitude shows a repeating pattern of abrupt increases and decreases, with a generally increasing trend. This behavior was qualitatively reproduced over several laser damage experiments, and is attributed to the interference between different portions of the acoustic beam as they reflect from different features within the damage site. In contrast, similar experiments performed on hemispherical, machined-in damage (i.e. clean pits without radiating cracks) from 0.5 to 5 mm in diameter yielded a linear increase in signal amplitude with pit diameter, [6] This provides strong evidence that the oscillatory behavior shown in Figure 2 arises from the presence of the pit/crack combination.

To utilize this methodology for monitoring and sizing laser damage in a large system, a quantitative understanding of the effects leading to the amplitude/size behavior in Figure 2 must be developed. As indicated above, the behavior has been qualitatively established as coherent interference effects within the ultrasonic beam. It has been shown that the laser damage manifests in such a fashion as to provide features consistent with this behavior, cracks radiating out from a central pit, and that the characteristics of the ultrasonic signal used in this study (wavelength, bandwidth, and ring-down time) are consistent with the proposed phenomenon. To develop a more rigorous understanding of the behavior observed in these experiments, numerical modeling was used to investigate the effects of damage shape and size upon simulated ultrasonic data.

Numerical simulation of damage in a fused silica slab

To illustrate the basic features of the scattering from a crack/pit combination that results from laser damage, the results from a 2 mm diameter pit with a single 1 mm long crack projecting from the pit at a 60° angle toward the transducer are shown in Figure 3. A simulation sequence was performed to investigate the effect of the overall size on the acoustic return from a crack/pit combination that grows in a self-similar fashion (i.e. the shape stays constant). The sequence starts with a 0.5 mm radius pit combined with a 0.5 mm long crack oriented at 60° towards the transducer. The dimensions of each are increased in 0.5 mm increments until the pit radius and crack length are both 3.5 mm (i.e. until the pit diameter is 7 mm). Figure 4 shows the amplitude of the simulated waveforms as a function of defect diameter. These data represent a two dimensional simulation of a highly idealized representation of the actual laser damage geometry: a hemispherical pit with a single elliptical crack. The simulated data qualitatively exhibit the major features of the experimental data shown in Figure 2. The variation in amplitude is not monotonic, and exhibits a maximum at an intermediate size. The amplitude variation seen in the (two-dimensional) simulated data in Figure 4 is directly attributable from the combined interaction of the acoustic beam with both the radiating crack and the central pit. This phenomenon agrees with the experimental results.

CONCLUSION

Laser damage growth was ultrasonically monitored on a large fused silica optic. The ultrasonic measurements were performed in the pulse-echo mode between shots of the laser. The experiment was accompanied by numerical simulations of the elastic wave scattering from idealized models of damage spots in a fused silica slab. The results of the simulations indicate that the observed ultrasonic signals are a result of the effect of cracks radiating from the bottom of the damage pit. Thus an algorithm can be developed to correlate ultrasonic signal parameters with laser damage size. The algorithm will account for destructive interference caused by the reflection from the crack interacting with the reflection from the pit when calculating the size of the damage.

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Figure Captions

Figure 1: Experimental schematic showing: a) fused silica window, b) incident laser pulse, c) ultrasonic transducer, d) laser damage site, and e) front view camera.

Figure 2: Amplitude versus diameter during growth of the laser damage site. Each datum represents one pulse of the laser. The amplitude variation with size is attributed to coherent interference from the crack features.

Figure 3: Model pit/crack configuration used in the numerical simulation. The dark line is the nominal geometry, the shaded area is the actual slab boundary of the finite difference grid.

Figure 4: Simulated data showing amplitude versus size during self similar growth of the pit/crack geometry shown in Figure 3. The diameter refers to that of the pit.

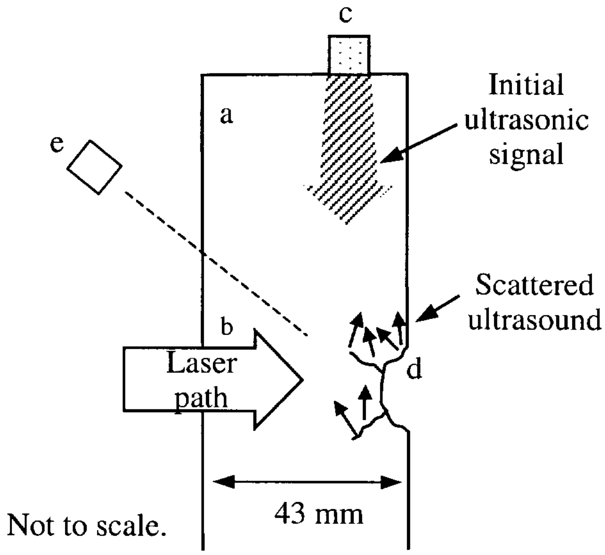

Figure 1

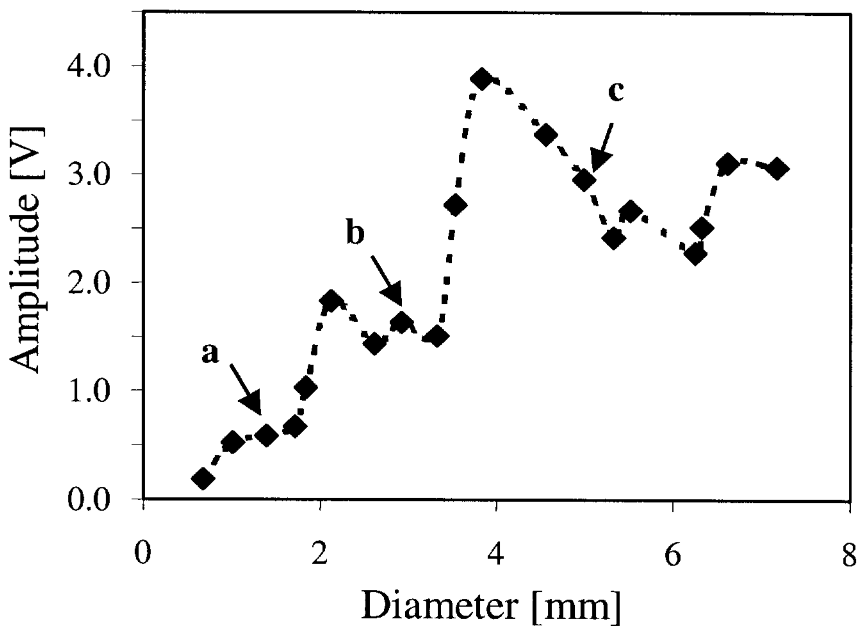

Figure 2

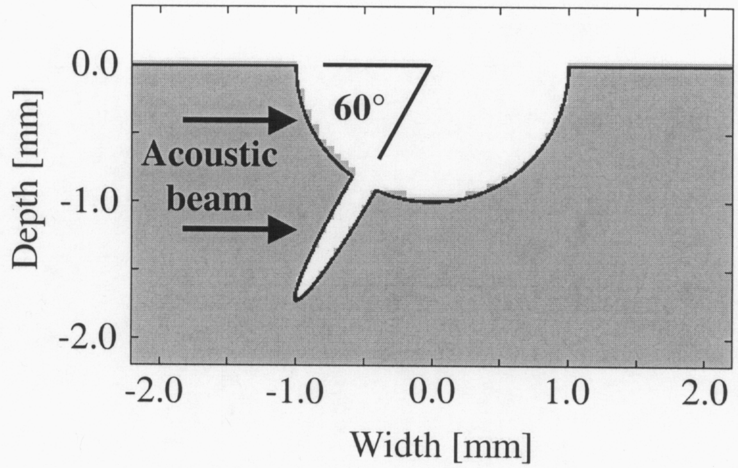

Figure 3

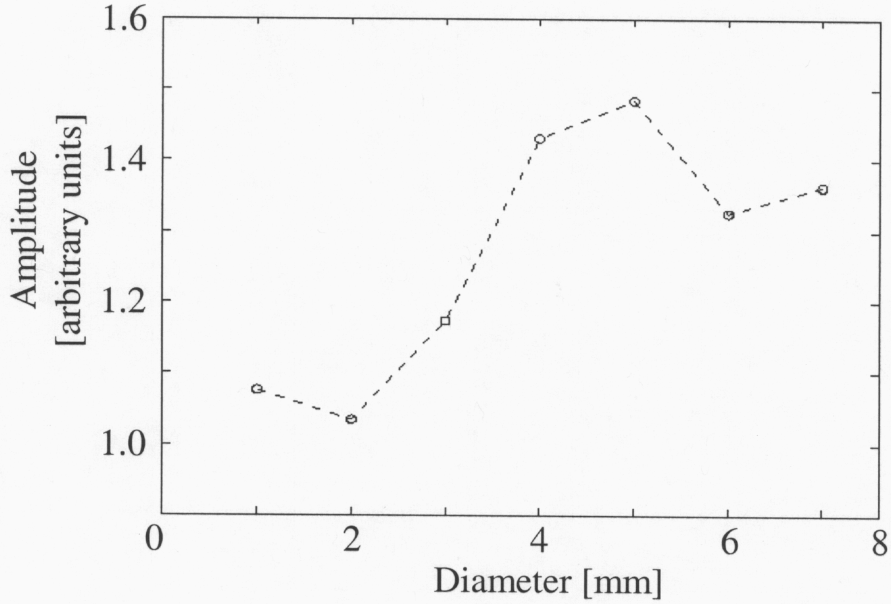

Figure 4