Experimental study on laser-induced plasma shock waves in transparent solid media

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By means of an optical fiber sensor based on beam deflection technique, the laser-induced plasma shock waves propagating in transparent organic glass are systemically investigated in experiments. Under the condition of free attenuation of shock wave, the temporal and spatial variations of some important parameters on the shock fronts are obtained by analyzing the experimental data. The experimental results reveal that shock waves, in the same medium, attenuate more slowly with the increase of laser energy; at the same time, propagation distance of shock waves increase when they have changed into sound waves.

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Shock waves feature a strong dissipation of energy during propagation[1]. The dissipated energy changes the state of the matter behind the shock front, and is thus related to the shock processing technique. The shock-wave propagation, which occurs when a powerful laser beam is brought to focus, has been investigated theoretically and experimentally for solids[2.3]. Nowadays, there are two conventional experimental methods exploited for the diagnosis of the propagating shock waves in solids. One is schlieren photography[4], which records the time when the shock fronts reach the rear face of the target. The other method is similar to the first one, except that a polyvinylidene fluoride (PVDF) thin film pressure cell, instead of a steak camera, is utilized to measure the time[5,6]. But it is terribly inconvenient to detect shock waves by means of these two techniques, because we have to change the targets with different thickness continuously. In this work we present a simple and effective detection technique based on fiber-coupling optical beam deflection principle to probe laser-induced shock wave in transparent organic glass. Compared with other methods, this system is much more compact, sensitive, and easy to adjust.

In this method, we adopt a He-Ne laser beam to intersect the propagating shock wave. The probe laser is deflected in the direction of density gradient so that a corresponding transient angular deflection will create a signal in a position-sensitive detector[7]. The experimental arrangement is shown in Fig. 1. The shock waves are generated by a Q-switched Nd:YAG laser (wavelength of 1.06 μm, pulse width of 30 ns) after pulse beam is expanded and collimated. Here the laser beam is focused perpendicular to the flat face of solid organic glass. In the detection region, the He-Ne laser as a probe source (wavelength of 0.67 μm, output power of 5 mW), is focused by an aspherical lens (f_1=30 mm) used for eliminating the spherical aberration. In order to detect the transient impact, the probe beam is focused parallel to the bare polished flat face of the organic glass. Here the probe beam passes through the transparent solid medium. The transmitted beam is focused by a microscope objective (f_2=4 mm) into a single-mode optical fiber that is mounted on a five-dimensional fiber-regulating-stand with 0.1−μm resolution. The output beam from the fiber is put into a photomultiplier (Hamamatsu 5773 with 2 −ns rise time) and displayed on a digital oscilloscope (Tektronix 730A, 1 Gs/s). A part of the scattered laser is fed into a PIN photodiode with 0.1−ns rise time to generate the trigger signal In order to increase signal-to-noise ratio, a narrow-band filter is used before the transmitted beam is coupled into the fiber.

In order to adjust the distance of laser focus to the boundary, we designed a console with the minimum movement distance of 10 μm. It can control synchronously the movement of He-Ne laser, aspherical lens, microscope objective, interference filter, 5-axis fiber-regulating-stand, and single-mode optical fiber in the direction perpendicular to the organic glass surface. Taking into consideration that the material surface could be

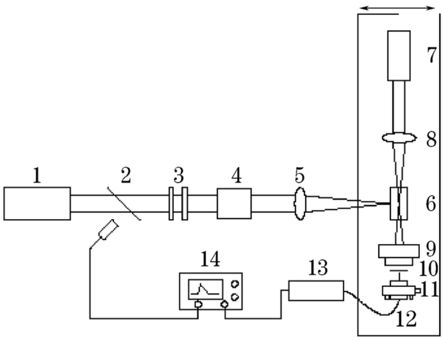

Fig. 1. Diagram of experimental setup. (1: Q-switched Nd: YAG laser; 2: beam splitter; 3: attenuator group; 4: concave lens; 5: convex lens; 6: organic glass; 7: He-Ne laser; 8: aspherical lens; 9: microscope objective; 10: interference filter; 11: 5-axis fiber-regulating-stand; 12: single-mode optical fiber; 13: photomutiplier; 14: digital oscilloscope; 15: PIN photodiode; 16: console.)

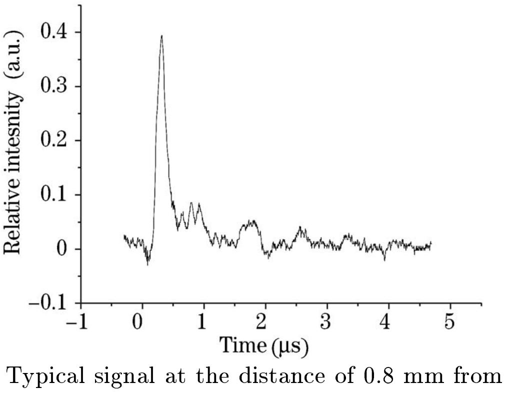

Fig. 2. Typical signal at the distance of 0.8 mm from probe He-Ne beam to the solid surface at the laser energy 95 mJ.

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out-off-flatness under the intense laser radiation, we parallelly move the organic glass to avoid the occurrence of the phenomenon. Figure 2 displays the pressure spikes for a laser-induced plasma shock wave in organic glass.

The expressions for the momentum, energy, and mass conservation at the shock front in a coherent medium are described as[8]

$$\begin{cases} \rho(u_\mathrm{s}-u_\mathrm{p}) = \rho_0 u_\mathrm{s} \\ p_\mathrm{s} = \rho_0 u_\mathrm{s} u_\mathrm{p} \\ e = \frac{1}{2} p_\mathrm{s}(\tau_0-\tau) \end{cases} , \qquad (1)$$

where u_s is the velocity of shock front, ρ the density of the shock front, p_s the pressure of the shock front, and e is the specific internal energy, u_p is the particle velocity behind the shock front, ρ_0 represents the density and internal energy of the medium when it is at rest. And the shock-wave velocity u_s can be expressed as a linear experimental function of u_p, the particle velocity behind the shock front[9]:

$$u_\mathrm{s} = c_0 + \lambda u_\mathrm{p} , \qquad (2)$$

where c_0 and λ are two constants which are defined by a large number of experiments. In this work, to the organic glass, $c_0 = 2901$ m/s, $\lambda = 1.481$, $\rho_0 = 0.915$ g/cm ^{3}.

From the experimental data, the distance r of the shock front from the emission center is plotted in Fig. 3 as a function of flying time t. The incident laser energies are 55 and 185 mJ, respectively. Then we get the shock wave velocity distribution versus propagation distance, which is shown in Fig. 4. It indicates that the plasma shock waves decay exponentially to sound waves after the end of the laser pulse. Induced by laser pulses at lower energy, shock waves have a smaller maximum velocity at a shorter distance away from the emission center and decay faster. Fitting the data with least-squares procedure as a function of $v = v_0 + Ce^{-Ax}$, the attenuation index of velocity is attained.

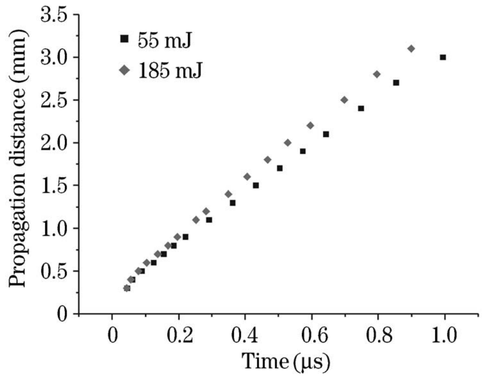

Fig. 3. Shock wave propagation distance versus time at incident laser energies of 55 and 185 mJ.

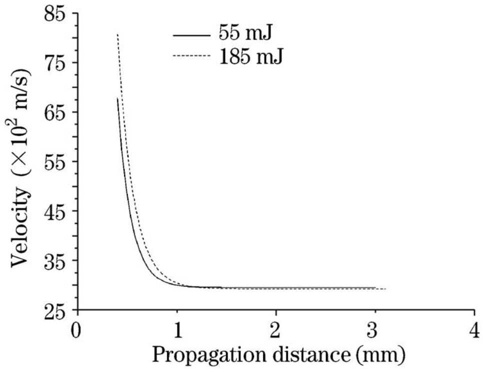

Fig. 4. Shock wave velocity distribution produced by 55- and 185- mJ laser pulses.

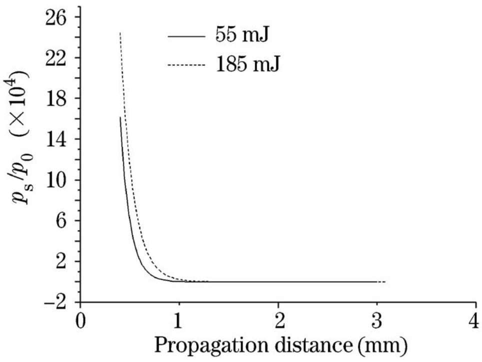

Fig. 5. The ratio of shock wave pressure with static pressure as a function of distance.

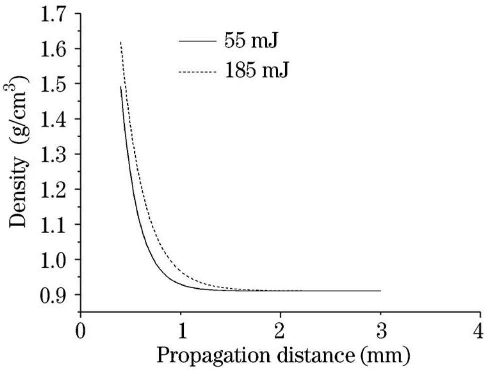

Fig. 6. Shock wave density as a function of distance.

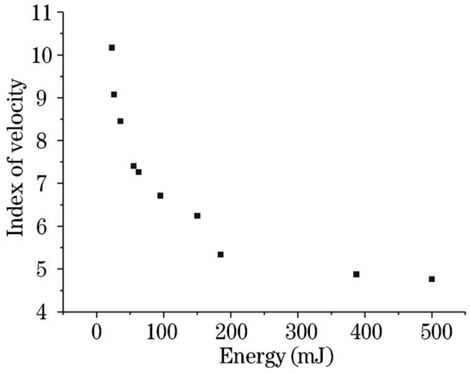

Fig. 7. Attenuation index of shock wave velocity at various incident laser energies.

The pressure and density on the shock fronts are linked with the shock wave velocity u_s by Eqs. (1) and (2). p_s/p_0 (p_0 denotes the static pressure) and ρ distribution as functions of propagation distance are shown in Figs. 5 and 6, respectively. As expected, they all decay more slowly in the far field than in the near field. They also decrease exponentially. Figure 7 demonstrates that the attenuation index of shock wave velocity on the shock fronts decrease with increasing incident laser energy in transparent organic glass.

Proposed in this paper is a new wide-band sensitive optical fiber sensor based on fiber-coupling optical beam deflection technique. The optical fiber is employed as a position-sensitive sensor in shock wave detection system. It offers new possibility for the nondestructive examination of shock waves in many transparent media, whether the media is gas, liquid, or solid. Using of this technique, the laser-induced plasma shock waves propagating in transparent solid are systemically investigated in experiment. The experimental results reveal that the laser-induced plasma shock wave propagates freely and the following decay process presents an exponential way in organic glass. Shock wave will have the velocity of an acoustic wave in organic glass after a certain distance. The distance increases with rising laser pulse energy i.e. shock waves attenuate more slowly. The values of peak pressure and velocity are greater for higher incident laser energy. These results indicate that the energy density within the plasma increases with increasing pulse energy. These research results will provide the theoretical and experimental reference to laser processing, laser medicine, and other corresponding fields.

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