Time-resolved photoelasticity imaging of transient stress fields in solids induced by intense laser pulses

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Abstract. In this study, the spatial distribution of laser induced transient stress wave have been observed successfully by both shadowgraph and photoelasticity images using transparent materials. It has been found that photoelasticity images of polymer materials, such as epoxy resin, observed in laser irradiation under water provide clear images which would allow quantitative estimation of the magnitude of laser induced stress. Obtained photoelastic images show clear black-and-white patterns from which laser-induced stress distribution and its dynamical change can be deduced. When a metal film was coated on the surface of an epoxy block, obtained images from the sample indicate the interaction of laser with the metal surface. A semi-quantitative estimation of intensity of the laser-surface interaction has been carried out by comparing images to those obtained for designated pulse energies.

1. Introduction

Photo-induced surface reactions are important in many fundamental and technological processing [1]. Interaction between an intense laser pulse and a material surface is a key to understand and to control these processes. It is, however, difficult to study this interaction in detail because it occurs in a very small space and for a very short period. In addition, it is usually accompanied by plasma formation, which causes difficulties for most observation and measurement techniques. We have developed a time-resolved imaging technique, which uses a pulsed laser as a probe light and an ICCD camera as a recording device, and reported on the dynamic processes of laser ablation, laser cleaning, internal modification of transparent materials and electrical discharge machining [2, 3]. We also have successfully observed the spatial distribution of laser induced transient stress fields by both shadowgraph and photoelasticity images using transparent materials [4]. Laser-induced transient stress plays important roles in many practical applications such as laser induced ultrasound, laser hardening and laser microfabrication. The new method allowed the estimation of the effects of surface roughness and incident angles on the laser-matter interaction [4]. The results, however, have remained at the qualitative levels because obtained images are not clear enough to allow the quantitative estimations.

Recently, we have found that photoelasticity images of polymer materials, such as epoxy resin, observed in laser irradiation under water provide clear images which allow us to make the semi-quantitative estimation of the magnitude of the laser induced stress. These photoelasticity images show clear black-and-white patterns from which it is possible to deduce laser-induced stress distribution and its dynamical change. When a metal film is deposited on the surface of the block, images obtained would indicate the interaction of the laser with the metal surface. We can, therefore,
make the semi-quantitative estimates of the intensity of the interaction by comparing these images to those obtained for designated pulse energies.

2. Experimental
The measurement system was essentially the same as in our previous reports [2-4] and only roughly outlined here. Two Q-switched Nd:YAG lasers were used. One was operated at the fundamental wavelength and used as an excitation source. Another was operated at the second harmonic wavelength and used as monitoring light. Time interval of the two lasers was controlled by a delay generator. An ICCD camera with a band-pass filter of 532 nm captured the images at designated delay times. The series of images thus obtained would represent the time evolution of the laser-matter interaction. Laser pulse energy was adjusted by an attenuator and focused by a lens of f=30 mm.

Square pieces of epoxy-resin (25x25x6 mm) were used as samples. Epoxy-resin is essentially transparent for both the fundamental and the second harmonic radiations of the Nd:YAG laser and has a high photoelastic constant. One of the surface of the 6 x 25 mm was irradiated by focused laser pulses from the normal direction. The average sample roughness of the irradiated surface was Ra=0.1 μm. In addition, some samples were coated with graphite by a spray, with copper thin film by thermal evaporation in vacuum, or with aluminum or molybdenum thin films by adhesion by epoxy based adhesive. Underwater irradiation was carried out in a glass simple cell filled with distilled water.

For photoelasticity measurement, an optical components were arranged to construct the circular polariscope in which two quarter-wave plates were inserted between a polarizer and the sample, and between the sample and an analyzer, respectively. In this configuration, only the isochromatics can be observed.

3. Results and discussion
3.1.1. Enhancement of fringe pattern due to irradiation under water. Figure 1 shows examples of the shadowgraph and the photoelasticity images taken in atmospheric conditions as well as the photoelasticity image taken under water. Black vertical lines on the left part in (a) and (b) and at middle in (c) are sample surfaces, and the laser is focused at the middle of the surface from the left. In the shadowgraph image (a), two black-and-white semicircular lines, which start from the laser irradiated spot and propagate in opposite directions, are seen. The right-going one is a longitudinal stress wave (sound wave) propagating into the bulk while the left-going and only partly shown one is a shock wave propagating into air. Horizontal dark, irregular lines in the middle of the images are damages induced by the laser pulses. These damages indicate that part of the laser energy was transmitted into the bulk. The photoelasticity image in air (b) shows a smaller semicircle in addition to that in shadowgraph but fringes are not so clear [4]. On the other hand, the photoelasticity image obtained under water (c) clearly shows several fringes of isochromatics with complicated patterns which mainly appear inside a smaller semi-circle. The enhancement of fringe pattern observed in

![Figure 1](image-url)

Figure 1. Shadowgraph and photoelasticity images obtained for laser irradiated epoxy resin blocks. Laser pulse energy is 100 mJ and the delay time is 1300 ns. (a) Shadowgraph image taken in air, (b) Photoelasticity image taken in air, (c) Photoelasticity image taken under water. Vertical length of the image is 5 mm.
Figure 2. Time evolution of photoelasticity image obtained for epoxy resin irradiated by 100mJ pulse under water. Sample surface is at the middle and laser hit from the left at the centre. Vertical size of the image is 5 mm.

under water irradiation indicates the magnification of laser generated pressure due to the confinement of the laser induced plasma, plume and gas by water, which is far denser than air. This effect has been utilized in laser processing under water such like the laser peening in water [5].

3.1.2. **Photoelasticity image.** The photoelasticity image obtained under water consists from three distinctive futures as seen in figure 1 (c): (1) Sharp black-and-white semicircular image which propagates into the bulk, (2) smaller semi-circular image which propagates with a speed about half of (1) with broader black or white line and complicated patterns within it, and (3) distorted circular pattern, the sides of which elongate faster than propagation at its centre. In the shadowgraph image, contrasts corresponding to (1) are clearly identified but those for (2) and (3) are not observed or only weakly identified for higher pulse energies even for irradiations under water. Figure 2 shows the time evolution of the photoelasticity images obtained for 100 mJ pulses irradiated under water. In the early stage, rather weak, overlapping circular images aligned along the laser incident axis appear. These images represent stress waves originating from the laser induced damages made along the laser axis. About 300 or 400 ns after laser irradiation, the semicircular images which started from the irradiated surface spot become clear and are the dominant futures in the later stages. The propagation speed of (1) is about 2.49 x 10³ ms⁻¹ and remains the same for all the measurement conditions and is in good agreement with the typical sound velocity in the epoxy resin of 2.4 to 2.9 x 10³ ms⁻¹. The speed of (2) is estimated to be 1.12 x 10³ ms⁻¹ and in good agreement with the reported speed of transverse (shear) stress wave 1.1 x 10³ ms⁻¹ [6]. In photoelasticity, the number of fringes reflects the magnitude of stress: greater number of fringes indicates greater stress, and their spacing are related to the change in the magnitude of the stress. But the photoelasticity pattern is not the stress fields itself. The pattern is related to the difference between two principal stresses. At free boundary, the fringe order can give one of the principal stress values, but unfortunately the fringe patterns at free boundary in these images are distorted due to the diffraction from the sample edge, the interference from the water part and the residual edge stress. It is not straightforward to deduce the actual stress distribution from the pattern and theoretical simulation is now under progress.

3.1.3. **Semi-quantitative estimation of the intensity of laser-matter interaction at metal surfaces.** The photoelasticity images observed under water can be used in semi-quantitative estimation of laser-matter interaction during laser ablation. Even though the pattern does not represent the stress field directly, these images have been taken under the same conditions, i.e., the same pulse energy, delay time and geometry of irradiation. Therefore, obtained images can be compared with one another. Figure 3 shows examples of such estimations. As an intensity standard, we used the epoxy blocks irradiated sides of which were coated by graphite film, so that we could assume that all of the laser energy would be absorbed at the surface. We irradiated the graphite coated samples at several pulse energies between 3 to 100 mJ and recorded the corresponding photoelasticity images. Figure 3 (a) is the image obtained at 40 mJ. Figure 3 (b) is the image obtained for an epoxy block (without the graphite coat) at 100 mJ. The laser induced damage causes interferences to the pattern but the fringe number that appeared amongst wave (2) and (3) are equal and hence we can estimate that the intensity of the stress should be roughly equal to one another. Therefore, the amount of laser energy reflected at
the surface and transmitted into the bulk might be up to 60% of incident energy. Figure 3 (c) is the image for copper coated sample at 40 mJ. The fringe order seems a little higher than that for the graphite coated one shown in (a). This may be caused by the fluctuation of laser intensity. For the case of aluminium or molybdenum, even though we glued metal films by epoxy adhesive carefully, some images suggest that there may be imperfect contact between the epoxy block and the films. Thus, the rather weak laser induced stress for aluminium may be due to these imperfections as well as the effect of film thickness.

We must admit that our estimate is too clued to make any decisive quantitative discussions and more accurate discussions should be postponed until the theoretical analysis of these images is done.

4. Concluding remarks
The custom-designed time-resolved photoelasticity imaging technique provided clear images which can make it possible to reduce transient stress field induced by an intense laser pulse. Semi-quantitative estimation of the coupling between laser radiation and the sample materials are presented but more detailed theoretical analysis of the photoelasticity images need to be carried out to make more accurate, quantitative discussions. Converting the photoelasticity patterns to the actual stress fields is, however, not straightforward because the photoelasticity reflects the difference between the principal stresses and not the stress itself. In addition, the obtained image is a two dimensional projection of the three dimensional stress field for which we must apply the inverse Abel transformation. The theoretical analysis is now underway.

It has been demonstrated that this method has high temporal and spatial resolutions sufficient to examine the dynamics of laser-matter interactions in detail.

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