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Directivity Patterns of Ultrasound Generated by Evanescent light at the Interface between Prism and Aluminum Surface

エバネッセント光で励起した超音波の指向性に関する研究

Iwao Matsuya[1†], Kento Matozaki[2], and Ikuo Ihara[1] ([1]Dept. of Mech. Eng., Nagaoka Univ. Tech.; [2]Grad. School of Eng., Nagaoka Univ. Tech.)
松谷 巌 [1†], 的﨑健斗 [2], 井原郁夫 [1] ([1]長岡技科大, [2]長岡技科大院 工)

1. Introduction

Laser ultrasonic measurement is a sophisticated technique which enables the evaluation of the mechanical properties of material, crack detection, identification of temperature distribution and so on [1][2]. In this technique, the measurement resolution is limited by the diameter of incident light spot. Therefore, the novel method that overcomes the resolution limitation in laser ultrasonic measurement is strongly aspired. To extend this technique smaller than the diffraction limitation of light wave, utilizing the near-field optics is one of the promising alternatives to the conventional laser ultrasonic system. Ultrasonic near-field optical microscopy (UNOM) has been developed to provide nanoscale spatial resolution for ultrasound detection [3]. The UNOM technique allows local mapping of ultrasound with deep sub-optical wavelength spatial resolution. However, little attention has been given to the point that the generation of ultrasound utilizing near-field optics at local area. In this paper, the evanescent light during total internal reflection at prism surface is utilized for generating acoustic waves in aluminium plate and the characteristics of obtained acoustic waves are discussed by comparing the obtained directivity pattern with theoretical value.

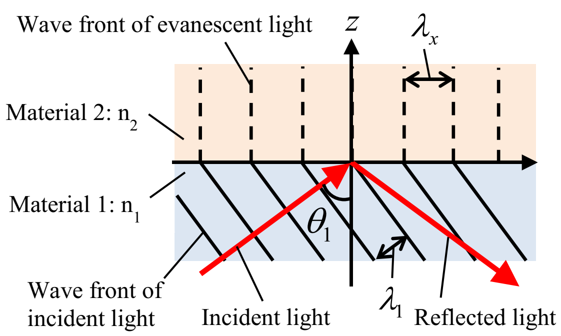


Fig. 1 Evanescent light during total internal reflection at prism surface.

matsuya@mech.nagaokaut.ac.jp

2. Theory

The evanescent light is a non-propagating electromagnetic wave that exhibits exponential decay with distance from the surface at which the total internal reflection of light is formed. **Figure 1** shows the evanescent light which penetrates inside the material 2. When the total internal reflection of the light is formed, the electric field of evanescent light decays exponentially from the prism surface [4]. The 1/e-penetration depth of evanescent light is calculated 480 nm in this experiment [5].

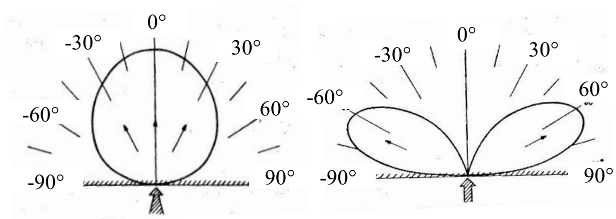
The directivity pattern (angular dependence) of the longitudinal wave by conventional laser ultrasonic technique in the ablation and thermoelastic regime are shown below. The directivity pattern for ablation mode is described by the theory of normal force excitation as follows [6][7].

$$U(\theta) \approx \frac{2k^2 \cos\theta (k^2 - 2\sin^2\theta)}{(k^2-2\sin^2\theta)^2 + 4\sin^2\theta(1-\sin^2\theta)^{1/2}(k^2-\sin^2\theta)^{1/2}} \quad (1)$$

The directivity pattern for thermoelastic mode is derived by heat conduction theory as shown below.

$$\frac{dU}{dr}\sin\theta \approx \frac{\sin\theta \sin 2\theta (k^2-2\sin^2\theta)^{1/2}}{(k^2-2\sin^2\theta)^2 + 4\sin^2\theta(1-\sin^2\theta)^{1/2}(k^2-\sin^2\theta)^{1/2}} \quad (2)$$

where k is the ratio between the longitudinal wave velocity and the shear wave velocity, and U is intensity of acoustic waves that varies with angle θ and absolute value r in the far field. **Figure 2** shows the theoretical results of directivity of longitudinal wave by using equations (1) and (2). Peak intensity is observed at 0° for ablation mode and 65° for thermoelastic mode.



(a) Ablation (b) Thermoelastic

Fig. 2 Directivity of longitudinal wave.

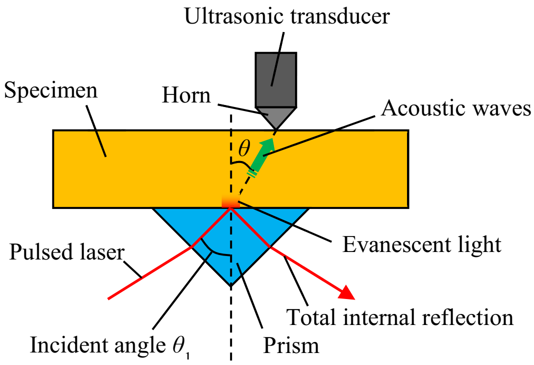


Fig. 3 Schematic diagram of experimental setup.

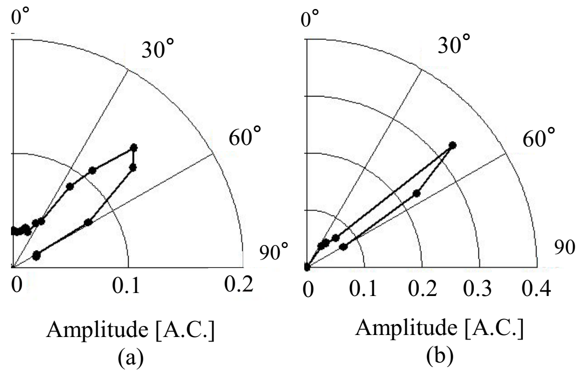


Fig. 4 Directivity patterns of ultrasound by (a) direct laser irradiation and (b) evanescent light.

3. Experimental setup

Figure 3 shows the schematic diagram of experimental setup for measuring the generation of acoustic waves. The well-polished aluminum plate with 5 mm thickness is used as a specimen. The right angle prism is in close contact with the specimen. The evanescent light is formed during the total internal reflection at prism surface by using the pulsed laser. The incident angle of the pulsed laser is determined to be 58° which is more than the critical angle of 53.9° derived from Snell' s law. Pulsed Nd:YAG laser (maximum power 180 mJ) is operated at 1064 nm optical wavelength, with duration time of 3～5 nsec. Lens with 100 mm focal length is used to focus the pulsed laser onto the specimen. To detect acoustic waves, the ultrasound transducer with horn is arranged on the other surface of the specimen with proper pressure as shown in figure 3. The ultrasound transducer is longitudinal wave type with 10 MHz band frequency. The power density of pulsed laser is measured by using a power meter to evaluate acoustic waves quantitatively. Laser power is controlled to be 10 mJ, and distance from lens to aluminum is arranged 130 mm which is longer than the focal length of lens to enlarge the irradiated area on the specimen. Because damaged region will be introduced inside the prism due to perfectly focused laser, we intended to control the energy density (laser power / irradiated area) of pulsed laser carefully. Although the spot diameter of laser is usually estimated by $1/e^2$ (13.5%) power as compared with the beam center, we utilized the simple method this time. The irradiated area is estimated by drawing an ellipse over the damaged region on the sensitized paper. The irradiated area is estimated 1.47×10^{-2} cm^2, so the energy density is calculated 0.68 J/cm^2. To draw the directivity pattern of acoustic waves, the ultrasound transducer is displaced parallel to the specimen. Angular measurement range is controlled to be 0 ～ 63°. For comparison, the experiment without prism is also carried out.

4. Results

Figure 4 shows obtained directivity pattern generated by direct laser irradiation and the evanescent light. The gains of 30 dB and 59 dB are applied to the original signals generated by the direct laser irradiation and the evanescent light respectively. For fair comparison, these gains are canceled after the data processing. The highest signal of the acoustic waves generated by evanescent light is approximately 1/12.6 as large as the one generated by the conventional pulsed laser. Peak intensity is observed at approximately 45° for direct laser irradiation and 50° for the evanescent light as shown in Fig. 4. The acoustic waves with the evanescent light are considered to be generated by thermoelastic effect. It is required examining the reason why the difference between experimental value and the theoretical value is caused.

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