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Ultrasonic Temperature Monitoring near Heating Surface by Measuring Oblique Incident Bulk Waves Using Laser Ultrasound

レーザー超音波を用いた斜入射バルク波計測による加熱面近傍の温度モニタリング

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1. Introduction

Ultrasound, because of its high sensitivity to temperature, has the potential to be an effective means for measuring temperatures of heated materials in the fields of science and engineering. Because of advantages of ultrasonic measurements such as non-invasive and faster time response, several works on the applications of ultrasonic temperature measurements have been made extensively.[1-4)]

In our previous works, an ultrasonic method for measuring temperature distributions of heated materials, so called ultrasonic thermometry, was developed and its feasibility and accuracy were demonstrated.[5-8)] This method can measure internal and surface temperature distributions using a longitudinal wave and a surface acoustic wave, respectively. In the ultrasonic thermometry for measuring internal temperature distribution, ultrasonic transmitter and receiver are needed to be located at a surface opposite the heated surface. Therefore, it is impossible to apply the ultrasonic thermometry to measure the temperature when there are restrictions on the location for the installation of ultrasonic sensors because the fixing of test pieces and tools in machining processes is needed.

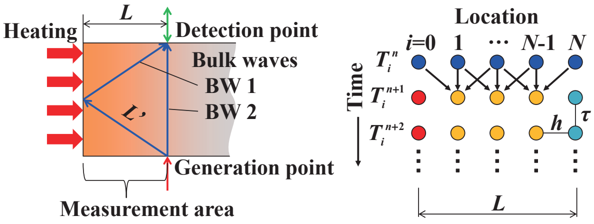
In this work, a laser ultrasonic method for monitoring temperature distributions near a heated surface based on the use of oblique incident bulk waves is proposed. Considering the propagation direction of bulk waves generated by laser at a surface perpendicular to the heated surface, the temperature distribution near the heated surface is determined. To demonstrate the feasibility of the proposed method, an experiment with a single side heated material is carried out. In addition, the influence of using the oblique incident bulk waves on the temperature estimation is examined.

2. Temperature determination of ultrasonic thermometry using oblique incident bulk wave

The principle of temperature profiling using ultrasound is based on a combination of a temperature dependence of ultrasonic velocity of bulk waves and heat conduction analyses. This method is supposed that an object is uniformly heated at one side as shown in **Fig. 1(a)**. Assuming that an object has no internal heat source, one-dimensional heat conduction equation can be defined by

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2} \qquad (1)$$

where α is thermal diffusivity coefficient. **Figure 1(b)** shows a finite difference model for determining temperature distributions in a measurement area. If all temperatures at a time step n are known as initial condition, internal temperatures, $T_1^{n+1} \sim T_{N-1}^{n+1}$, at a time step n+1 can be determined by a finite difference analysis of eq. (1). Temperatures, T_0^{n+1} and T_N^{n+1}, are determined using bulk waves. When a pulse laser is irradiated to a surface perpendicular to the heated surface, two bulk waves, BW 1 and BW 2, propagating as shown in **Fig. 1(a)** are generated and detected using a laser interferometer at the opposite side. From the generation point, an oblique incident bulk wave, BW 1, propagates to the heated surface and reflects to the detection point. And another bulk wave, BW 2, propagates from the generation point to the



(a) (b)

Fig. 1 Analysis model used for temperature distribution estimation using oblique incident bulk waves. (a) Schematic of an object which is uniformly heated at one-side surface. (b) Schematic of a model for finite difference calculation of an object.

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detection point, directly. Therefore, temperatures, T_0^{n+1} and T_N^{n+1}, are determined from the two bulk waves, BW 1 and BW 2, respectively. Temperature at $i=N$ can easily be determined from ultrasonic velocity measurement and temperature dependence of the velocity of BW 2 because BW 2 propagates at uniform temperature. On the other hand, transit time of BW 1 is given by

$$t = 2\int_0^{L'} \frac{1}{v(T(x))} dx \qquad (2)$$

where L' is the propagation distance of oblique incident bulk wave from the generation point to the heated surface and v is the velocity which is a function of temperature, T. To determine the temperature at the heated surface from eq. (2), finite difference model shown in **Fig. 1(b)** is used. Thus, temperature at the heated surface, T_0^{n+1}, can be determined from a combination of eq. (2) and temperatures at all points except a point at the heated surface as shown in **Fig. 1(b)**. It is noted that propagation distance of the oblique incidence bulk wave, L', is not the same as the size of finite difference model, L. As long as the bulk wave measurements are continued, it is possible to monitor the variations in the temperature distribution of the measurement area.

3. Experiment and results

Figure 2 shows the schematic of the experimental setup. An aluminum cylinder is used for a specimen and one of its end surfaces is heated by a heater at 400 °C. Laser from a pulsed laser generator (Nd:YAG, wavelength 1064 nm, energy 200 mJ/pulse, pulse width 3 ns) is irradiated at 16 mm from the heated surface, and then generated bulk waves are detected by a laser Doppler vibrometer (He-Ne, wavelength 633 nm, power <1 mW) at the opposite side. **Figure 3** shows the measured waveform before the heating starts. A direct longitudinal wave and an oblique incident transverse wave are clearly seen in **Fig. 3**, and used for estimating temperature distributions in the cylinder as BW2 and BW 1, respectively. Infrared radiation camera is used for obtaining reference values of temperature distributions.

Figure 4 shows the estimated temperature distributions at 0, 5, 15, 30, and 60 s after the heating starts. The spatial resolution and time resolution of the present ultrasonic estimation are 8 mm and 0.167 s, respectively. Temperature distributions estimated by the ultrasonic method almost agree with those measured by the infrared radiation camera. Although the transverse wave propagates obliquely to the direction of the temperature gradient, it is found that the influence of the oblique propagation on the temperature estimation can be negligible in the experiment.

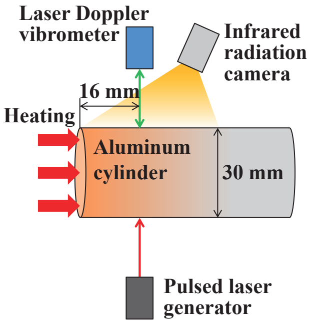

Fig. 2 Schematic of experimental setup.

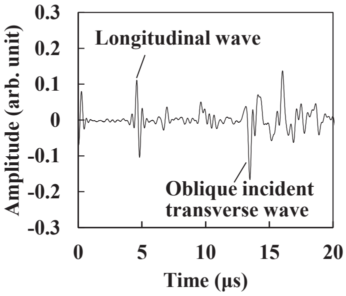

Fig. 3 Measured waveform before heating.

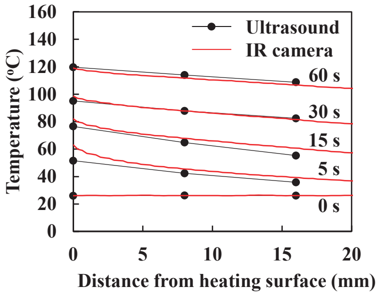

Fig. 4 Variations in the estimated temperature distributions of the single-side heated aluminum cylinder.

Acknowledgments

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