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Noncontact Monitoring of Temperature Distributions of a Rotating Cylinder by Laser Ultrasound

レーザー超音波による回転円柱の温度分布の非接触モニタリング

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1. Introduction

There are growing demands for measuring temperature profiles of heated materials being processed at high temperatures. For instance, it is often required to measure surface or internal temperature distributions of rotating objects such as machining tools for drilling or friction stir welding, and columnar shaped work pieces for turning. Although an infrared radiation technique is applicable for temperature measurements of such rotating objects, it does not allow to make internal temperature measurements. Therefore it is highly required to develop a new technique that allows us to make a temperature profiling for both surface and inside of rotating materials being heated.

Ultrasound, due to its sensitivity to temperature, is expected to be a promising means for temperature measurements of heated materials. Because of advantage 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]-[5].

In this work, a new ultrasonic method for monitoring temperature distributions of rotating objects has been proposed. The method basically consists of non-contact ultrasonic measurements with laser ultrasonic techniques and an effective analysis for temperature profiling. To demonstrate the feasibility of the method, surface and internal temperature distributions of a rotating steel cylinder during heating are investigated.

2. Temperature Profiling of Rotating Cylinder

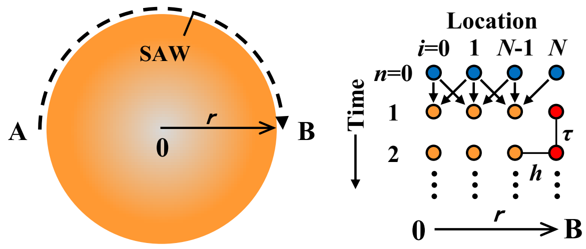
The principle of the temperature profiling by ultrasound is based on a combination of temperature dependence of ultrasonic velocity for surface acoustic wave (SAW) or longitudinal wave (LW) and heat conduction analyses [5]-[7]. This method is supposed that a columnar object to be estimated is uniformly heated at the outer surface as shown in figure 1(a). Assuming that a columnar has no internal heat source and no temperature distribution in a circumferential direction, one-dimensional equation of heat conduction in a radial direction of a columnar can be defined by

$$\frac{\partial T}{\partial t} = \alpha\left(\left(\frac{\partial T}{\partial r}\right)^2 + \frac{1}{r}\frac{\partial T}{\partial r}\right), \qquad (1)$$

where α is thermal diffusivity coefficient. Figure 1(b) shows a model for a finite difference calculation for the columnar. Internal temperatures, $T_0^{n+1} \sim T_{N-1}^{n+1}$, at a time step n+1 can be determined from finite difference analysis for eq. (1). Temperature at outer surface, T_N^{n+1}, can be determined from the velocity of the SAW propagating on the columnar surface. The velocity of SAW is given by

$$v_{SAW}(T) = \frac{L}{t}, \qquad (2)$$

where L is propagation distance of SAW, t is transit time of SAW, and v_{SAW} is the velocity of SAW which is a function of temperature T. In general, temperature dependence of the velocity depends on material property. For a certain temperature range such as between 20 °C and 200 °C for steel, it may



(a) (b)

Fig. 1 Analysis model used for temperature distribution estimation. (a) Schematic of a cross-section of a columnar object which is uniformly heated at outer surface. (b) Schematic of a model for finite difference calculation of a columnar.

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be expressed by a simple linear equation as

$$v(T) = aT + b, \tag{3}$$

where a and b are constants determined experimentally. From eqs. (2) and (3), temperature at the outer surface, T_N^{n+1}, can be determined by

$$T_N^{n+1} = \frac{1}{a}\left(\frac{L}{t} - b\right). \tag{4}$$

Thus, both surface and internal temperatures, *i.e.* temperature profile of the columnar can be determined by SAW measurements and a finite difference calculation. As long as the SAW measurements are continued, it is possible to monitor the variation in the temperature profile. In this method, a laser ultrasonic technique which provides noncontact ultrasound measurements for a rotating heated object has been employed.

3. Experiment and Results

Figure 2 shows a schematic of the experimental setup used. A steel cylinder of 100 mm diameter is used for a specimen and is rotated 300 min^{-1} using a stepping motor. The SAWs on the rotating steel cylinder are measured using a laser ultrasonic system. The SAWs can be generated at outer surface of the steel cylinder by a pulsed laser generator (Nd:YAG, wavelength 1064 nm, energy 180 mJ/pulse, pulse width 3ns) and SAWs propagating through the cylinder are detected using a laser Doppler vibrometer (He-Ne, wavelength 633 nm, power <1 mW). The center frequency of the SAWs is about 2 MHz. The transit time of each SAW is precisely determined by taking the cross correlation of the detected signal of SAW during heating, and then used for the analysis to determine both the surface and internal temperature distribution of the cylinder. In the experiment, the steel cylinder is heated using a gas burner. Temperature distributions of the side surface of the cylinder are measured using the infrared radiation camera to make a comparison with that estimated by the ultrasonic method.

Figure 3 shows the estimated temperature profiles of the steel cylinder and their variations with the elapsed time after heating starts, where the ultrasonically estimated results (left) are compared with those measured using the infrared radiation camera (right). It can be seen that both temperature distributions determined by the ultrasound and the infrared radiation agree well with each other. In this estimation, the temperature dependence of SAW of the steel columnar is found to be v_{SAW}=-0.4133T+3095.7 (m/s) and is used for the temperature estimation by the ultrasonic method.

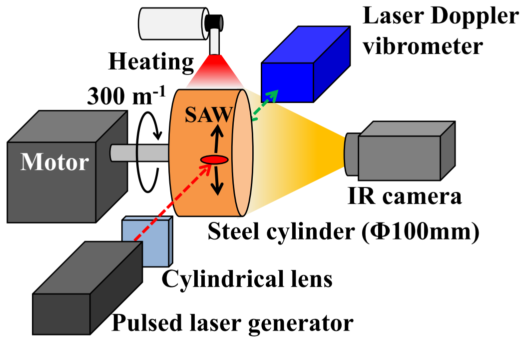

Fig. 2 Schematic of the experimental setup used.

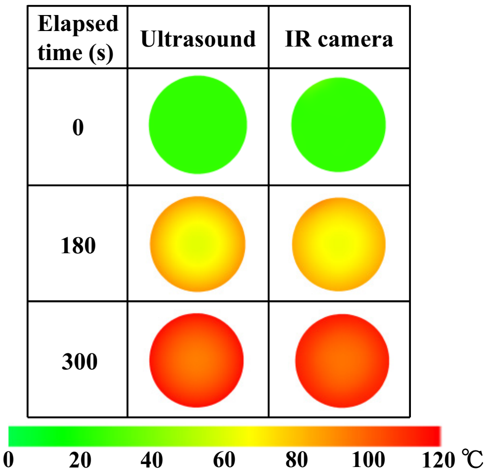

Fig. 3 Estimated temperature profiles of the rotating steel cylinder and their variations with the elapsed time after heating starts, by ultrasound (left) and infrared radiation camera (right).

Acknowledgment

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