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Non-contact Monitoring of Surface Temperature Distribution by Laser Ultrasound Scanning

レーザー超音波スキャニングによる表面温度分布の非接触モニタリング

Hiroyuki Yamada[1], Akira Kosugi[1‡] and Ikuo Ihara[1] ([1]Nagaoka University of Technology)
山田　浩之[1]，小杉　祥[1‡]，井原　郁夫[1]（[1]長岡技術科学大学）

1. Introduction

Since a temperature field of a material being heated or cooled is transiently changed, it is often required to monitor not only the temperature at a certain point but also its distribution in a certain area of the material. Although some conventional methods using thermocouples or infrared radiation are widely used for temperature measurements, they are not always acceptable for some applications because of the limitation of the ability.

Ultrasound, because of its high sensitivity to temperature, is expected to be an alternative means for temperature measurements. Because of advantages of ultrasonic measurements such as non-invasive and faster time response, several works on the applications of ultrasound to temperature measurements have been made extensively [1]–[6]. In our previous works [7] [8], ultrasonic pulse echo methods for measuring internal temperature distributions were developed. Temperature distributions inside heated materials were then successfully determined by the ultrasonic method coupled with a one-dimensional finite difference calculation [8]. Recently, the ultrasonic method is modified to be adapted to surface temperature determination by surface acoustic wave (SAW) [9].

In this work, a method with a laser-ultrasonic technique for measuring a temperature distribution on a material surface is presented. The method consists of a laser-ultrasonic measurement of a one-dimensional temperature distribution on a material surface and its two-dimensional area mapping by a pulsed laser scanning. To demonstrate the practicability of the method, surface temperature distribution for aluminum plate being heated is investigated. A laser interferometer based on photorefractive two-wave mixing [10] is used for measuring the SAW of the plate during heating.

2. Ultrasonic Method for Determining Surface Temperature Distribution

The principle of temperature determination by ultrasound is based on the temperature dependence of the ultrasonic wave velocity. Recently, an effective ultrasonic method for determining a one-dimensional temperature distribution was developed [7][8] and the method was modified to be adapted to surface temperature determination [9]. In the modified method, one-dimensional unsteady heat conduction with a constant thermal diffusivity is considered for the surface of a flat plate whose single side is uniformly heated. Assuming that there is no internal heat source in the plate, the one-dimensional equation of heat conduction in a certain direction on the surface can approximately be defined. The temperature distribution can be estimated by solving the heat conduction equation under a certain boundary condition. In actual heating processes, however, the thermal boundary condition at the heating side is often unstable and unknown, and therefore, the temperature distribution is hardly determined by solving the heat conduction equation analytically. To overcome the problem, we developed an effective method consisting of a SAW measurement and a one-dimensional finite difference calculation. The advantage of using the method is that no information on the thermal boundary condition at the heating side is needed. It was demonstrated through an experiment with a heated plate that the method with SAW is useful for measuring surface temperature distribution in a certain direction [9]. In this work, the method has been applied to an area mapping of surface temperature distribution, using a laser-scanning system.

3. Experiment and Result

Figure 1 shows a schematic of the experimental setup used. This system provides non-contact measurements of SAWs on a heated plate using a laser-ultrasonic system. SAWs are generated at different positions from E_1 to E_{13} consecutively by pulsed laser scanning irradiation (Nd:YAG, λ=1064 nm, energy 200 mJ/pulse, pulse width 3 ns) using a two-dimensional galvanometer scanner, and each SAW is detected at position D

E-mail address: ihara@mech.nagaokaut.ac.jp

using a laser interferometer based on photorefractive two-wave mixing (Nd:YAG, λ=532 nm, energy 200 mW). An aluminium plate of 30 mm thickness is used for a specimen. The center frequency of the SAW is about 2 MHz. Because of such pulsed laser scanning, SAWs can be measured within the square of 60 mm x 60 mm as shown in figure 1. Since the scanning time from E_1 to E_{13} is about 0.9 s, the scanning irradiation can be performed every 1 s, while the left end of the plate is being heated by contacting with a heater of 300 ºC. The transit time of each SAW is precisely determined by taking the autocorrelation of the detected signal of SAW during heating, and then used for the inverse analysis to determine the one-dimensional surface temperature distribution in the direction of SAW propagation. The obtained thirteen temperature distributions are combined together to construct the surface temperature distribution of the square area at transient moment. An infrared camera is used to measure the reference data of the surface temperature distribution for comparison purpose. Figure 2 shows the estimated surface temperature distributions and their variations with the elapsed time after heating starts, where the ultrasonically estimated results (right) are compared with those measured using the infrared camera (left). It can be seen that both temperature distributions determined by the ultrasonic method and the infrared camera almost agree with each other. It is noted that the temperature dependence of the aluminium is found to be v= - 0.7557T + 2981.7 (m/s) and is used for the temperature estimation by the ultrasonic method.

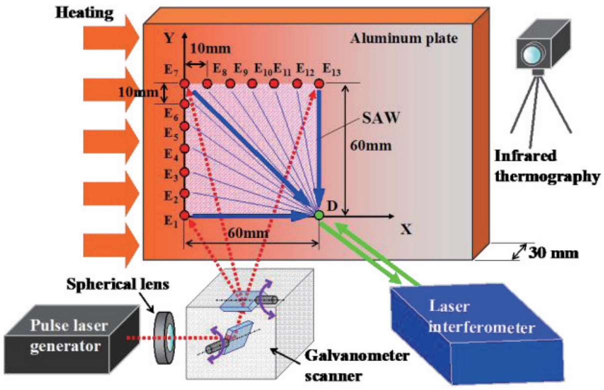

Fig. 1 Schematic of the laser ultrasonic system with a pulsed laser scanning used for measuring SAWs in the area of a square on the surface of a heated plate.

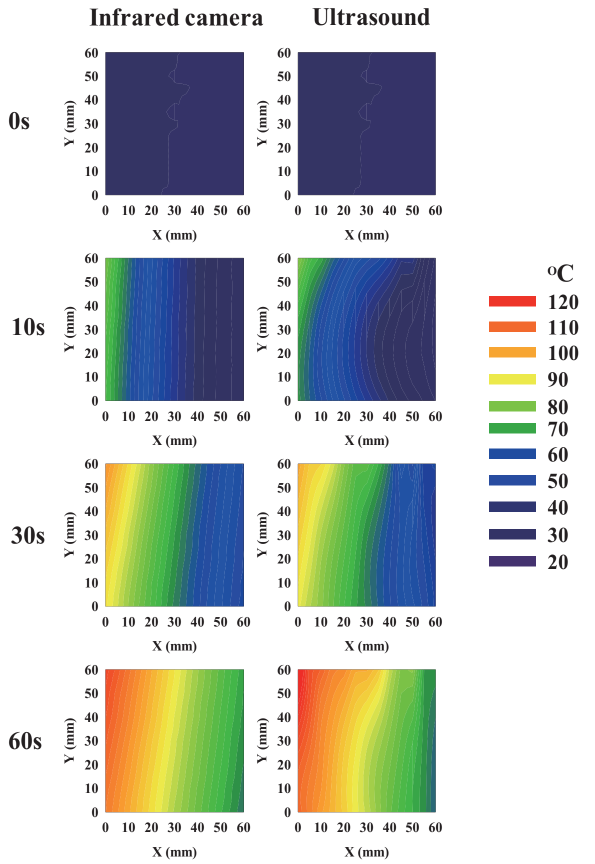

Fig. 2 Variations in surface temperature distribution of an aluminum plate with heating time, estimated by ultrasound (right) and infrared radiation (left).

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