Two-dimensional monitoring of surface temperature distribution of a heated material by laser-ultrasound scanning

I Ihara, H Yamada and M Takahashi
Department of Mechanical Engineering, Nagaoka University of Technology, Nagaoka, Niigata 940-2188, JAPAN,
E-mail: ihara@mech.nagaokaut.ac.jp

Abstract. A non-contact method with a laser-ultrasonic technique for measuring two-dimensional 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. The surface temperature is basically determined from a temperature dependence of the velocity of the surface acoustic wave (SAW) propagating on a material surface. One-dimensional surface temperature distributions are determined by an inverse analysis consisting of a SAW measurement and a finite difference calculation. To obtain a two-dimensional distribution of surface temperature on a material surface, SAW measurements within the area of a square on the surface are performed by a pulsed laser scanning with a galvanometer system. The inverse analysis is then applied to each of the SAW data to determine the surface temperature distribution in a certain direction, and the obtained one-dimensional distributions are combined to construct a two-dimensional distribution of surface temperature. It has been demonstrated from the experiment with a heated aluminum plate that the temperature distributions of the area of a square on the aluminum surface determined by the ultrasonic method almost agree with those measured using an infrared camera.

1. Introduction
Temperature is one of the fundamental and important parameters to be measured in the various fields of materials science and engineering. This is basically because the properties and behaviour of materials often show any temperature dependence and therefore, measuring temperature and its comprehensive understanding are indispensable for developing and processing of materials. Since a temperature state 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 thermocouple techniques are widely used for temperature measurements, they are not always acceptable for obtaining the spatial distribution of temperature in a material because of its limitation of installation. In addition, the thermocouple technique may not be appropriate for monitoring a transient variation of temperature because of its relatively slow time response in measurement. To overcome such problem, an infrared radiation technique is used for measuring temperature distribution and its variation on a material surface. Since this method enables noncontact measurements, it is convenient for on-line measurements of surface temperature. In this method, however, accurate temperature measurements are often hindered by the different emissivity and reflection of infrared radiation from other heat sources. Such influences due to the emissivity and reflectivity result in the deterioration of measurement accuracy.
Ultrasound, because of its high sensitivity to temperature, is expected to be an alternative means for measuring the temperature of materials. Because of advantages of ultrasonic measurements such as non-invasive and faster time response, some works on the application of ultrasound to temperature estimations have been made extensively [1]–[6]. In our previous works [7] [8], an ultrasonic pulse echo method with an inverse analysis was developed and used to measure internal temperature distributions of a thick plate being heated. It was shown that one-dimensional temperature distributions inside materials being heated can be successfully determined by the ultrasonic inverse method coupled with a one-dimensional finite difference calculation [8]. The advantage of the method is that no information on the thermal boundary condition at the heating surface is needed for inversion. Recently, the ultrasonic method is modified to be adapted to surface temperature determination by surface acoustic wave (SAW) [9].

In this work, a new method with a laser-ultrasonic technique for measuring a two-dimensional 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 to measure the SAW of the plate during heating.

2. Method

2.1. Ultrasonic determination of temperature distribution

It is known that the velocity of ultrasonic wave propagating through a material changes with the temperature of the material. The principle of temperature determination by ultrasound is based on the temperature dependence of the ultrasonic wave velocity. Assuming a one-dimensional temperature distribution on a material, the transit time of ultrasonic wave propagating in the direction of the temperature distribution can be given by

$$t_L = \int_0^L \frac{1}{v(T)} \, dx,$$

where $L$ is the propagation distance, $v(T)$ is the ultrasonic velocity which is a function of temperature $T$. It is noted that the temperature $T$ may change with location $x$. When the material is heated, the temperature distribution in the material can be given as a function of location $x$ and time $t$. Such a temperature distribution $T(x, t)$ is subjected to the thermal boundary condition of the heated material. On the basis of equation 1, if an appropriate inverse analysis with a proper boundary condition is employed, it could be possible to determine the temperature distribution from the transit time $t_L$ measured for the heated material. In fact, the validity of such ultrasonic determination of internal temperature distribution was successfully demonstrated through an experiment with a heated silicone rubber plate in our previous work [7]. In addition, an improved ultrasonic inverse method coupled with a one-dimensional finite difference calculation was developed to determine one-dimensional temperature distributions of materials being heated [8].

2.2. Quantitative evaluation of surface temperature distribution

Recently, the ultrasonic inverse method mentioned above has been modified to be adapted to surface temperature determination by SAW [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 an inverse analysis coupled with 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 for inversion. 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 two-dimensional mapping of surface temperature distribution.

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 E₁ to E₁₃ 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 using a laser interferometer based on photorefractive two-wave mixing (Nd:YAG, λ=532 nm, energy 200 mW). An aluminum 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 are measured within the square of 60 mm x 60 mm as shown in figure 1. Since the scanning time from E₁ to E₁₃ 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 °C. 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 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 (upper) are compared with those measured using the infrared camera (lower). It can be seen that both temperature distributions

![Figure 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.](image-url)
determined by the ultrasonic method and the infrared camera almost agree with each other. It is noted that the temperature dependence of the Rayleigh wave velocity (m/s) of the aluminum, \( v = -0.7557T + 2981.7 \), where the temperature \( T \) is in degree Celsius, is used for the inverse analysis.

4. Conclusions
A non-contact method with a laser-ultrasonic technique for measuring two-dimensional temperature distribution on a material surface is presented. The practicability of the proposed method is demonstrated through the experiment with aluminum plate heated up to 120 ºC. Although further improvements in the analysis and the resulting accuracy are necessary, it is highly expected that the method will be effective in the on-line monitoring of the transient variation in the surface temperature of the material processed at high temperatures.

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