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# Laser-Ultrasonic Monitoring of Temperature Distribution of Material Surface during Heating

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**Abstract**
A new method using laser ultrasound for monitoring temperature distribution on a material surface being heated is presented. The principle of the method is based on temperature dependence of the velocity of the surface acoustic wave (SAW) propagating on the material surface. To determine surface temperature distribution quantitatively, an effective method consisting of a SAW velocity measurement and an inverse analysis coupled with a one-dimensional finite difference calculation has been developed. To demonstrate the practicability of the method, a steel plate of 20 mm thickness having temperature distribution on the surface is evaluated. The SAW of each plate is continuously measured during heating using a laser ultrasound interferometer based on photorefractive two-wave mixing. The variation of the transit time of the SAW is then used for the inverse analysis to determine surface temperature distribution and its variation. It has been demonstrated that the ultrasonically determined results almost agree with those measured using an infrared camera.
**Keywords:** Surface temperature distribution, laser-ultrasound, surface acoustic wave, inverse analysis, finite difference calculation, heated plates

## 1. Introduction

In various fields of science and engineering, there are growing demands for measuring the temperature distribution and its variation of a material being heated. In particular, it is required to monitor the temperature distribution of materials being processed at high temperatures because the temperature state is a crucial factor influencing the quality and productivity of final products. Although thermocouple techniques are widely used for temperature measurements, they are not always acceptable for obtaining the spatial distribution of temperature 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.

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 [1-6]. In our previous work [7,8], an ultrasonic pulse echo method with a simple inverse analysis was developed and used to measure the temperature distribution inside a thick plate being heated. Although the ultrasonic method had successfully monitored the temperature distribution and its variation during heating, further improvement of the inverse analysis has been required to overcome some problems such as a restriction on the thermal boundary condition and time-consuming in the analysis.

In this work, an improved ultrasonic method that overcomes the problems mentioned above has been developed and applied to the monitoring of the temperature distribution on the material surface. The method consists of surface acoustic wave

(SAW) measurements and an inverse analysis combined with a one-dimensional finite difference calculation. To demonstrate the practicability of the method, a steel plate of 20 mm thickness having a one-dimensional temperature distribution on the surface has been evaluated. A laser ultrasound interferometer based on photorefractive two-wave mixing is used for measuring the transit time of the SAW on the surface of the steel being heated.

## 2. Ultrasonic determination of temperature distribution

### *2.1 Principle of temperature measurement by ultrasound*

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

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

where $L$ is the propagation distance, $v(T)$ is the ultrasonic velocity which is a function of temperature $T$. In general, the temperature dependence of velocity depends on material properties and may have an approximate linear relation with temperature for a certain temperature range. When the medium is being heated, the temperature distribution in the medium 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 medium. On the basis of equation (1), if an appropriate inverse analysis with a proper boundary condition is used, it could be possible to determine the temperature distribution from the transit time $t_L$ measured for the heated medium. In fact, such ultrasonic determination of temperature distribution of a heated silicone rubber plate was successfully demonstrated in our previous work [8]. It should be noted here that the inverse method proposed in the former work is useful only for the particular situation that the boundary conditions such as temperatures at both ends of the estimated area are held stable and known during the heating. Unfortunately, such thermal boundary conditions are often unstable and unknown for materials being processed at high temperatures. Therefore, it has been required to develop an improved method to overcome such problem.

### *2.2 Inverse analysis combined with a finite difference calculation*

Figure 1 shows a schematic of a one-dimensional temperature distribution on the surface of a flat plate whose single side is uniformly being heated. To investigate the temperature distribution, we consider a one-dimensional unsteady heat conduction with a constant thermal diffusivity. Assuming that there is no heat source in the plate, the equation of heat conduction in the $x$ direction on the surface is approximately given by [9]

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2} \quad , \tag{2}$$

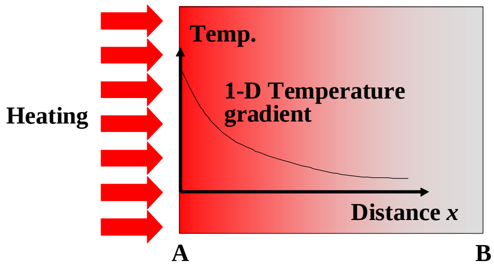


Figure 1. Schematic of a one-dimensional temperature distribution on the surface of a plate being heated.

where $T$ is temperature, $x$ is the distance from the heating surface A, $t$ is the elapsed time after the heating starts, $\alpha$ is the thermal diffusivity. The temperature distribution can be estimated by solving equation (2) under a certain boundary condition. In actual heating processes, however, the thermal boundary condition at the heating surface A is often unstable and unknown and therefore, the temperature distribution is hardly determined from equation (2).

To overcome the problem, we proposed an effective method consisting of a SAW measurement and an inverse analysis coupled with a one-dimensional finite difference calculation. A one-dimensional finite difference model composed of a large number of small elements and grids is used for analyzing the temperature distribution in the $x$ direction shown in Fig. 1. We assume that the surface of the plate has a uniform temperature $T^n$ before the heating starts. Considering that the single side of the plate is started to heat at time step $n$, the temperature of each grid point on the surface at time step $n$+1 that is a very short time elapsed after the time step $n$, can be given by [10]

$$T_i^{n+1} = T_i^n + r\left(T_{i+1}^n + T_{i-1}^n - 2T_i^n\right) \quad (i = 2, \Lambda, N-1) \tag{3}$$

$$r = \frac{\alpha\tau}{h^2} \tag{4}$$

where, $N$ is the total number of the grid points, $i$ and $n$ are indices corresponding to spatial coordinate and consecutive time, respectively. $T_i^n$ is the temperature of each grid point $i$ at time step $n$. The coefficient $r$ is taken to be less than 0.5 according to the stability requirement from the von Neumann stability criterion given in equation (4). $\tau$ is the time interval and $h$ is the interval between adjoining grid points. It should be noted that the temperatures at two ends, $T_1^{n+1}$ and $T_N^{n+1}$, are not given in Eq. (3). We define $i$=1 as the heating surface A and $i$=$N$ as the other side B that has no heat source. Since we can calculate the temperatures $T_i^{n+1}$ ($i$=2, ···, $N$-1) from equation (3), it is now required to obtain the temperatures at the both grid points, $T_1^{n+1}$ and $T_N^{n+1}$, so that the temperature distribution on the surface at time step $n$+1 could be fully determined. It may be reasonable to assume that the temperature $T_N^{n+1}$ can be known because such temperature of a low temperature side can easily be obtained using any conventional technique such as a thermocouple or an infrared radiation. However, the temperature at the heating surface, $T_1^{n+1}$, is usually difficult to know. Although the $T_1^{n+1}$ is unknown unless the thermal boundary conditions at the both ends of the plate are given, it can be possible to estimate the $T_1^{n+1}$ if the finite difference calculation is coupled with the transit time of ultrasound propagating through the distance between the two ends, A and B. Using a concept of trapezoidal integration, the transit time $t_L$ given in equation (1) can be approximately calculated from

$$t_L = \frac{1}{2}h\left(\frac{1}{v_1^{n+1}} + \frac{1}{v_N^{n+1}}\right) + h\sum_{i=2}^{N-1}\frac{1}{v_i^{n+1}} \ , \tag{5}$$

Using equation (5) and the relation between temperature and SAW velocity, the temperature of the heating surface at time step $n$+1, $T_1^{n+1}$, can be given by

$$T_1^{n+1} = -\frac{1}{\mathrm{A}\left\{\frac{2t_L}{h} - \left(\frac{1}{v_N^{n+1}} + 2\sum_{i=2}^{N-1}\frac{1}{v_i^{n+1}}\right)\right\}} + \frac{\mathrm{B}}{\mathrm{A}}, \tag{6}$$

where, $t_L$ is the transit time measured at the time step $n$+1. It should be noted that equation (6) is derived under the assumption that the temperature dependence of SAW velocity has a linear relation shown as follows,

$$v(T) = -aT + b \ , \tag{7}$$

where, $a$ and $b$ are constants determined experimentally. The SAW velocity $v_i^{n+1}$ at each grid point in equation (6) can be estimated from equation (7) since the temperature at each grid point can be obtained from equations (3) and (4). The temperature $T_N^{n+1}$ is considered to be known as mentioned above. Therefore, the temperature $T_1^{n+1}$ can then be determined from equation (6) when the transit time $t_L$ is given as a measured value. Once the temperatures of all grid points in the plate at the time step $n$+1 are determined, we can then determine the temperature distribution at time step $n$+2 in the same procedure using the transit time $t_L$ measured at the time step $n$+2. Thus, we can continuously obtain the temperature distribution on the surface as long as the SAW measurement is continued and the temperature at B is known. The advantage of the proposed method is that no boundary condition at the heating surface A is needed.

## 3. Experiment and results

Figure 2 shows a schematic of the experimental setup used. Two SAWs, SAW1 and SAW2, are generated at positions A and B, respectively, using a pulse laser generator (Nd:YAG, $\lambda$=1064 nm, energy 20 mJ/pulse, pulse width 10 ns) with a polarizing beam-splitter, and detected at position C using a laser ultrasound interferometer based on photorefractive two-wave mixing (Nd:YAG, $\lambda$=532 nm, energy 200 mW). A steel plate (JIS type: SKD61) of 20 mm thickness is used as a specimen. The single side of the plate is being heated by contacting with a heater of 350 ºC. Taking the difference in the transit time between SAW1 and SAW2, the transit time of the SAW propagating through the distance between A and B can be determined. An infrared camera is used to obtain a reference value of the temperature distribution on the surface.

Figure 3 shows the variations of the temperatures and the transit time of SAW on the steel surface during heating. As we expected, the temperatures start to rise just after the heating starts. The rising rate becomes higher in the vicinity of the heating surface. The transit time of the SAW increases drastically because of the rise in temperature of the plate. The variation of transit time is smoothed by averaging and the smoothed curve is then used for the inverse analysis to estimate the temperature distribution on the steel surface. Figure 4 shows the variations of the estimated temperature distributions with the elapsed time after the heating starts, where the ultrasonically estimated results are compared with those measured using an infrared camera. In this analysis the

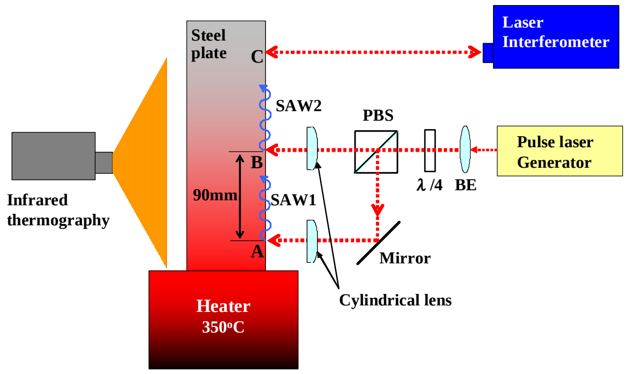


Figure 2. Schematic of the laser ultrasonic system used for monitoring SAWs of a steel being heated.

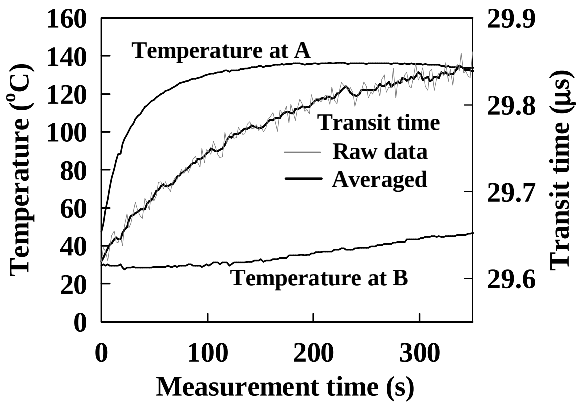


Figure 3. Variations of the temperatures and the transit time of the SAW on the steel surface during heating.

temperature dependence of SAW for the steel, $v_{SAW}$=-0.691T+5920.5 (m/s), is used. It can be seen from Fig. 4 that both temperature distributions determined by the proposed ultrasonic method and the infrared camera almost agree with each other. Thus, it is demonstrated that the proposed method provides surface temperature monitoring of a material being heated, with no use of any information on heating conditions.

## 4. Conclusions

This paper presents a new ultrasound inversion method for determining a one-dimensional surface temperature distribution on the surface of a material being heated. The advantage of the method is that no information on the thermal boundary condition of the heating surface is needed for the inversion. Although there are some discrepancies in the result between the ultrasound method and infrared camera, the method is believed to be effective in monitoring the transient variation of the surface temperature distribution of materials being processed at high temperatures.

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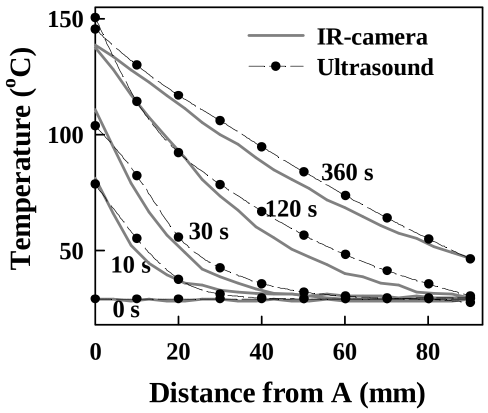


Figure 4. Comparison between temperature distributions determined by the proposed ultrasonic method and using an infrared camera.

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