

In Situ Monitoring of Temperature Rise in Friction Surface Using Ultrasonic Technique

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Abstract — In this work, the feasibility of the use of ultrasonic thermometry for *in situ* monitoring of temperature rise in friction surface has been examined. The ultrasonic thermometry that is a method providing internal temperature measurements by ultrasound is applied to temperature measurements of a friction surface at which temperature rise occurs due to friction, and an attempt is made to demonstrate *in situ* monitoring of transient variations in the friction surface temperature and temperature distribution beneath the surface. Those temperatures near the friction surface are quantitatively determined by an effective method consisting of ultrasonic pulse-echo measurements and a finite difference calculation for estimating a one-dimensional temperature distribution along the direction of ultrasound propagation. The advantage of the method is that no boundary condition at the friction surface is needed. To demonstrate the practical feasibility of the method, the ultrasonic pulse echo measurements at 5 MHz are performed for a steel plate of 30 mm thickness whose single side is being rubbed with a felted fabric plate. The temperature at the friction surface and internal temperature distribution of the steel plate are measured during the rubbing process and the transient variations of the measured temperatures are obtained. Quick temperature rise of approximately 30 K at the friction surface is observed within a few seconds after the rubbing starts. It is noted that the temperatures measured by the ultrasonic method almost agree with those measured using thermocouples inserted into the steel plate. Thus, it has been demonstrated that the ultrasonic thermometry is a promising sensing means for *in situ* monitoring of temperatures at friction surface as well as beneath the surface.

Keywords- Temperature monitoring, Friction Surface, Ultrasonic thermometry, Temperature distribution, In situ measurement, Rubbing contact

I. INTRODUCTION

It has been known that surface and sub-surface temperatures generated by friction between two materials play an important role in understanding the tribological behaviors of the materials. This is basically because such temperatures are closely related to the mechanical and physicochemical properties of the materials [1]-[4]. Therefore, accurate knowledge about the temperature rise at the interface of the two sliding materials has long been a topic of great interest in the field of tribology as well as any other relating fields in science and engineering. Although there have been many theoretical and experimental works on the topics, few studies

on direct measurements of the temperature rise at the friction surface have so far been made. This is because of extreme difficulty in measuring such interface temperature. Little is known about the temperature rise at the interface of the two sliding materials. Therefore, measuring such temperature at a friction surface and understanding its variation comprehensively are important issues. In particular, *in situ* and real-time monitoring technique for the temperature could be quite beneficial not only for basic research in tribology but also for making an effective quality control of materials manufacturing processes with frictional behaviors.

Ultrasound, because of its capability to probe the interior of materials and high sensitivity to temperature, is considered to be a promising means for internal temperature measurements of materials. Since there are some advantages in ultrasonic measurements, such as non-invasive and faster time response, several studies on the temperature estimations by ultrasound have been made [5]-[11]. In our previous works [12]-[15], an effective ultrasonic methods for measuring internal temperature profiles of heated materials were developed and applied to internal temperature profiling of heated materials. Since the ultrasonic method, so-called ultrasonic thermometry, can determine surface temperature at a heated surface without using any thermal boundary conditions at the heated surface, it is quite attractive and highly expected to apply the ultrasonic thermometry to temperature measurements at a friction surface. In this work, the ultrasonic thermometry has been applied to the measurements of temperature rise at a friction surface and temperature distribution beneath the surface. An attempt to make an *in situ* monitoring of the transient variations in temperature rise during friction process has been made.

II. METHOD FOR DETERMINING TEMPERATURE DISTRIBUTION

Principle of Ultrasound Thermometry

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 t_L of an ultrasonic pulse-echo propagating in the direction of the temperature distribution can be given by

$$t_L = 2 \int_0^L \frac{1}{v(T)} dx, \quad (1)$$

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

where L is the thickness of the medium, and $v(T)$ is the ultrasonic velocity which is a function of temperature T . The temperature dependence of velocity depends on the material property and may be expressed by a simple equation such as a linear or quadratic function for a certain temperature range. In general, the temperature distribution in a medium being heated 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. Therefore, on the basis of Eq. (1), if an appropriate inverse analysis with a certain boundary condition is properly 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 demonstrated in our previous work [12].

Quantitative Determinations of Temperature at Heated Surface and Temperature Distribution in Material

When a material slides over another material, heat is generated at the interface due to friction and the heat is transferred from the interface to each material. The generated heat and its transfer depends on the thermal properties of the materials and sliding conditions such as contact geometry and sliding speed. Figure 1 shows a schematic an internal temperature gradient in a material whose single side is uniformly heated due to friction. To investigate the temperature gradient, a one-dimensional unsteady heat conduction with a constant thermal diffusivity is considered. Assuming that there is no heat source in the material, the equation of heat conduction is given by [16]

where T is temperature, x is the distance from the heated or cooled surface, t is the elapsed time after the heating or cooling starts, α is the thermal diffusivity. It is known that the temperature distribution can be estimated by solving Eq. (2) under a certain boundary condition. In actual heating process such as frictional heating, however, the boundary condition is quite difficult to know and often being changed transiently during heating. Such boundary condition can usually not be measured. Because of little knowledge about the boundary condition, temperature gradient is hardly determined from Eq. (2). This kind of problematic situation usually occurs in frictional heating processes. To overcome the problem mentioned above, we have applied an effective method, so-called the ultrasonic thermometry [13-15], to the evaluation of the temperature of the friction surface as well as the temperature distribution beneath the surface. This method consists of an ultrasonic pulse-echo measurement and an inverse analysis coupled with a one-dimensional finite difference calculation. The advantage of the method is that no boundary condition at the heating surface is needed. A one-dimensional finite difference model consisting of a large number of small elements and grids is used for analyzing heat conduction in the heated material. Using two information, the initial temperature distribution and the temperature dependence of the ultrasonic velocity of the material to be evaluated, not only the temperature at the heating surface but also the temperature distribution in the material can be determined by the method. Temporal variations of the determined temperatures can also be obtained as long as the transit time of ultrasound propagating in the direction of temperature gradient of the heated material is continuously being measured using any ultrasonic transducer as shown in Figure 1. It is noted that both the temperature at B which is the outer surface and the temperature dependence of the material should be given as known information in the inverse analysis. The detailed procedure of the method is described in References [13-15].

III. EXPERIMENTAL SETUP

To demonstrate the feasibility of the proposed method, an attempt to measure the temperature of a friction surface of a plate as well as its internal temperature distribution has been made. A steel plate of 30 mm thickness is used as a specimen and its surface is rubbed with a felted fabric of 5 mm thickness so that the rubbed surface of the steel plate is heated by frictional heat.

Figure 2 shows a schematic of the experimental setup used. This system provides not only ultrasonic pulse-echo measurements but also internal temperature measurements of the steel plate using thermocouples inserted in the plate, so that the validity of the ultrasonically determined temperatures can be verified by comparing with those measured using the thermocouples. Five thermocouples, TC1, TC2, TC3, TC4 and TC5, are inserted at different locations, 0.5, 1.5, 2.5, 10 and 20 mm from the rubbed surface, respectively. Another thermocouple, TC6, is placed on the top surface of the plate to measure the surface temperature which is used as a known

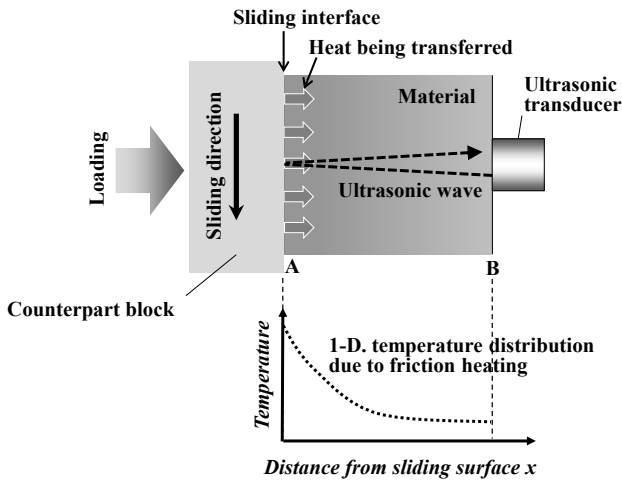


Figure 1 Schematic of a one-dimensional temperature distribution in a material whose single side is heated by friction.

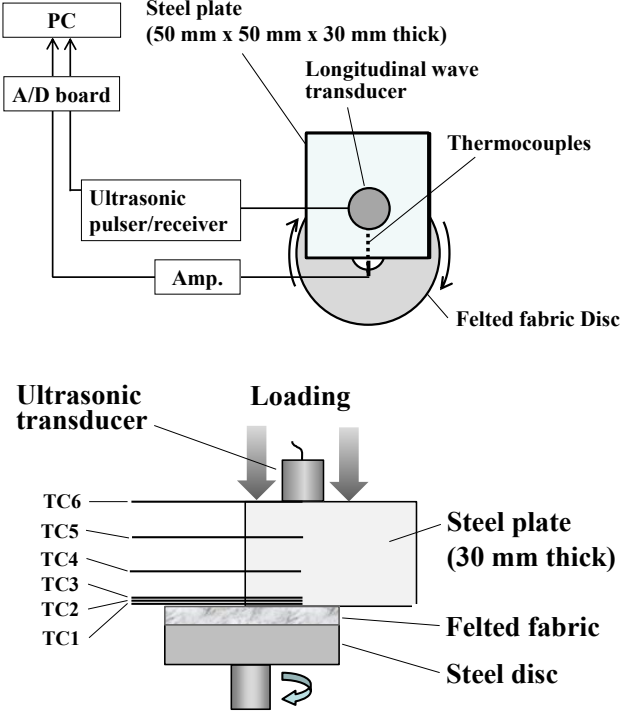


Figure 2 Schematic of the experimental setup: steel plate on a rotating felted fabric disc and schematic diagram of measurement system (upper); cross sectional view of the setup (lower).

data in the ultrasonic thermometry. The thermocouples type K of 0.15 mm in diameter are used. As shown in Figure 2, the steel plate is rubbed with a rotating felted fabric disc. The pressing force between the plate and the felted fabric is approximately 100 N. The rotating speed of the disc is approximately 1050 min^{-1} (rpm) and the sliding speed between the steel and fabric is approximately estimated to be 2.2 m/s. A longitudinal ultrasonic transducer of 5 MHz, 10 mm in diameter is installed on the top surface of the steel plate and ultrasonic pulse-echo measurements are performed. Ultrasonic pulse-echoes from the bottom surface (friction surface) of the steel plate are continuously acquired every 25 ms with a PC based real-time acquisition system. The sampling rate of ultrasonic signals is 100 MHz. Signal fluctuation due to electrical noise in measurements is reduced by taking the average of fifty ultrasonic signals. The acquired ultrasonic signals are used for determining the temperatures at the friction surface and inside of the steel plate.

IV. RESULTS

Figure 3 shows ultrasonic pulse echoes measured for the steel plate during rubbing process. Two clear echoes, the first and second reflected echoes from the bottom (friction surface) are observed. In addition, a series of small echoes from the thermocouples in the steel are also detected. The transit time of ultrasound through the steel can precisely be determined from the time delay between the two echoes by taking a cross-

correlation between them. Using the transit times acquired during the rubbing process, the temperature at the friction surface and internal temperature distribution of the steel are estimated as a function of elapsed time. It is noted that the temperature dependence of the longitudinal wave velocity of the steel plate used, $v(T) = -0.5827T + 6003$ (m/s) and the initial temperature of the steel plate before the rubbing, 21.3 $^{\circ}\text{C}$, are used in the temperature estimations.

Figure 4 shows the estimated temperature distribution and its variation with elapsed time, where the numbers shown in Figure 4 denote the elapsed time after the rubbing starts. It can be seen in Figure 4 that the temperature at the friction surface measured by ultrasound rapidly increases and the temperature distribution near the friction surface also changes significantly. Although the temperatures measured using thermocouples have also similar tendency to the ultrasonic results, there are discrepancies between them in the early stage of the frictional heating. Thus, it has been found that the ultrasonic method seems to function properly in measuring temperature rise due

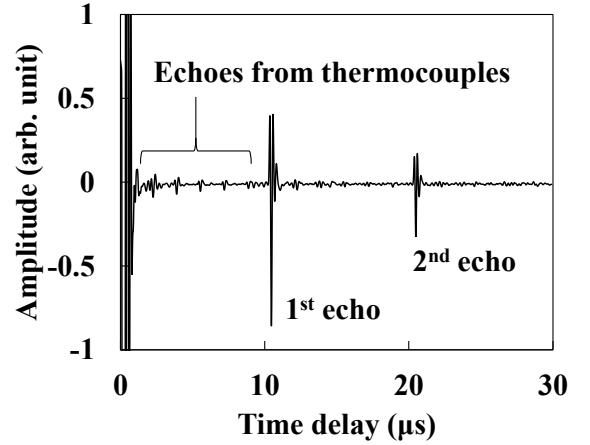


Figure 3 Measured ultrasonic pulse echoes from the bottom surface (friction surface) of the steel plate of 30 mm thickness.

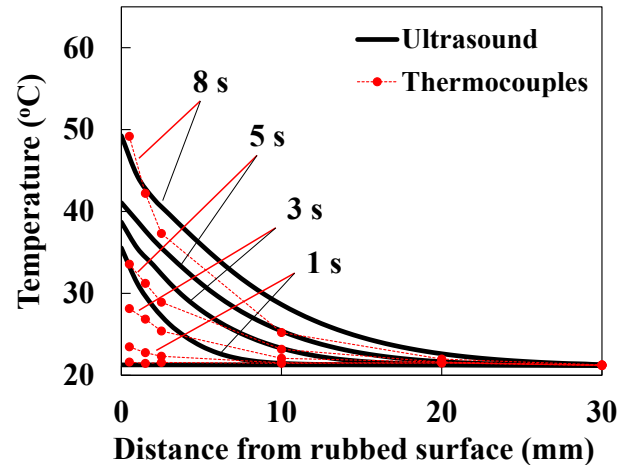


Figure 4 Temperature distributions inside the steel plate and their variations with elapsed time after the rubbing starts, measured by the ultrasonic method and thermocouples.

to friction between the steel and felted fabric.

Figure 5 shows the measured temperature variations at the friction surface and 0.5 mm beneath the surface of the steel plate. A rapid change in the surface temperature is clearly observed in the results by the ultrasonic method. It has been found that an immediate sharp increase in the surface temperature occurs within a few seconds immediately after the rubbing starts. The surface temperature reaches almost 48 °C due to the friction heating by the rubbing process for 10 s, and then shows a rapid drop when the rubbing is stopped. Thus, the steep rise in the surface temperature during the rubbing process and the rapid drop in the temperature after the rubbing are observed by the ultrasonic method as shown in Figure 5. It has also been found that the temperature at 0.5 mm beneath the surface is slightly lower than that of the surface and the variation with elapsed time is very similar to that of the surface temperature. On the other hand, the rising rate of the temperature measured by the thermocouple is lower than that

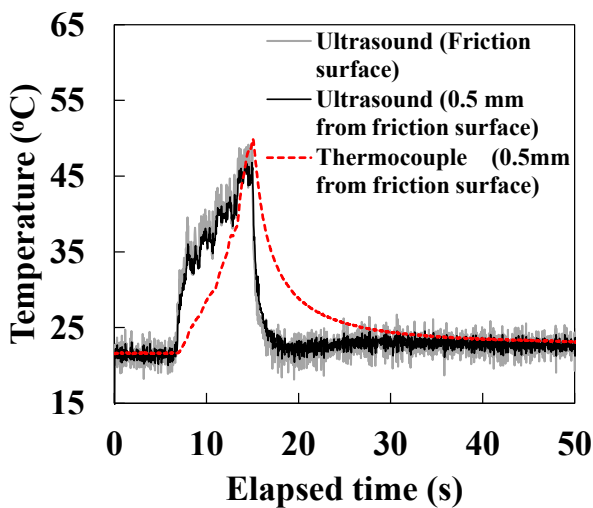


Figure 5 Temperature variations at the friction surface and 0.5 mm beneath the surface of the steel plate, measured by the ultrasonic method and thermocouple.

measured by ultrasound and the declining rate of the temperature by the thermocouple has also the same tendency as shown in Figure 5. Thus, the ultrasonic method has a higher sensitivity than the thermocouple in measuring temperature rise due to friction heating.

V. CONCLUSIONS

An ultrasonic thermometry has been applied to temperature measurements of a friction surface at which temperature rise occurs due to friction, and an attempt is made to demonstrate *in situ* monitoring of transient variations in the friction surface temperature as well as the temperature distribution beneath the surface. It has been demonstrated with the ultrasonic method

that a rapid temperature rise of approximately 30 K at the friction surface is observed within a few seconds immediately after the rubbing starts. Although further study is necessary to improve the practicability and robustness in the method, it is highly expected that the ultrasonic method could be a useful means for *in situ* monitoring of temperatures at friction surface as well as beneath the surface.

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