XIX IMEKO World Congress
Fundamental and Applied Metrology
September 6–11, 2009, Lisbon, Portugal

A NOVEL ULTRASONIC THERMOMETRY FOR MONITORING TEMPERATURE PROFILES IN MATERIALS

Ikuo Ihara [1], *Manabu Takahashi* [2]

[1] Dept. of Mech. Eng., Nagaoka University of Technology, Nagaoka, Japan, Ihara@vos.nagaokaut.ac.jp
[2] Graduate Student of Nagaoka University of Technology, Nagaoka, Japan, takaham@stn. nagaokaut.ac.jp

Abstract – A new ultrasonic method for monitoring the temperature distribution inside a material being heated or cooled is presented. The principle of the method is based on the temperature dependence of the velocity of ultrasonic wave propagating through a material. An effective inverse analysis coupled with a finite difference calculation is used to determine the one-dimensional temperature distribution inside a thick plate. To verify the practical feasibility of the ultrasonic method, experiments have been demonstrated. A single side of a steel plate of 30 mm thickness is heated by contacting with a heater of 200 ºC and subsequently cooled down by water. Ultrasonic pulse-echo measurements are then performed for the steel during the heating and cooling. A change in the transit time of longitudinal ultrasonic waves across the steel is continuously acquired and used to determine the temperature distribution inside the steel. The temperature distribution and its transient variation determined by the ultrasonic method almost agree with those obtained using thermocouples installed in the steel. Thus, it is verified that the present method can be a promising means for real-time monitoring of temperature profiles in materials being heated or cooled.

Keywords: ultrasonic thermometry, temperature distribution, inverse analysis

1. INTRODUCTION

In various fields of engineering and science, it is often required to measure internal temperature of a material being heated at high temperatures. This is because the temperature is an important factor which is closely related to material properties. In material industries, not only internal temperature but also its distribution inside the material is often required to be measured because such temperature distribution plays an important role in material productions. For example, in the cases of casting or moulding processes for metals and polymers, on-line information on temperature gradient inside the die or mould is indispensable for making an effective process control. It is known that such temperature gradient during material processing directly influences the productivity and quality of final products. Therefore, it is desirable to realize an effective technique for on-line measurements of the internal temperature distributions in materials being processed. Although a conventional thermocouple technique is widely used for temperature measurements, it is not always acceptable for obtaining the spatial distribution of temperature because of its limitation of installation to a die or mould. In addition, the thermocouple may not be appropriate for monitoring a transient variation of temperature because of its relatively slow time response in measurement.

Ultrasound is expected to be an effective means for monitoring the internal temperature and its gradient of materials because of its capability to probe the interior of materials and its high sensitivity to temperature [1]-[8]. The advantages of using ultrasound are considered that it may provide non invasive and quantitative measurements for the internal temperature of materials under heating or cooling. It is also attractive that ultrasonic measurements provide a faster time-response than conventional thermocouple techniques. In our previous works [9], [10], effective methods consisting of an ultrasonic pulse-echo measurement and an inverse analysis were proposed and applied to heated silicone rubber and steel plates to demonstrate the feasibility of temperature monitoring. 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 difficulty in using the thermal boundary condition of a material being heated and a time-consuming process in the analysis.

In this work, an improved ultrasonic method that overcomes the problems mentioned above has been proposed. The method consists of an ultrasonic pulse-echo measurement and an inverse analysis coupled with a one-dimensional finite difference calculation. The method has been applied to temperature distribution monitoring of a steel plate under heating and cooling.

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

ISBN 978-963-88410-0-1

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

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 have an approximate linear relation with temperature 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 (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 [9].

3. INVERSE ANALYSIS FOR DETERMINING TEMPERATURE PROFILE

In the present work, we attempt to perform an ultrasonic determination of the temperature distribution in a thick plate whose single side is being heated by contacting with a hot medium, or cooled with a cold medium. To investigate the temperature distribution of such plate, we consider a one-dimensional unsteady heat conduction problem with a constant thermal diffusivity. Assuming that there is no heat source in the plate, the equation of heat conduction is given by [11]

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

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 (2) under a certain boundary condition. In actual heating processes, however, the boundary condition is not always being held stable and often being changed transiently during heating. Such boundary condition is usually quite difficult to know and even to measure. Because of little knowledge about boundary condition, temperature distribution is hardly determined from (2). This kind of problematic situation often occurs when the plate is heated by contacting with a very hot medium such as molten metals.

To overcome the problem mentioned above, an effective method for evaluating the internal temperature distribution is proposed. The 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 a thick plate. Considering that the single side of the plate having a uniform temperature T^n at time step n is heated by contacting with a hot medium, temperatures at each point inside the plate at time step n+1 that is a very short elapsed time, can be given by [12]

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

$$r = \frac{\alpha\tau}{h^2} \qquad (4)$$

where, N is the number of the grid, 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. r is taken to be less than 0.5 according to the stability requirement called the von Neumann stability criterion. τ is the time step and h is the grid interval. We define i=1 as the heated surface that is contacted with a hot or cold medium and define i=N as the other side that has no heat source. It is now required to obtain the temperatures at the both sides of the plate, $T_1^{\,n+1}$ and $T_N^{\,n+1}$, so that the temperature distribution of the plate could be totally determined. It is possible to assume the temperature $T_N^{\,n+1}$ to be a known value because such temperature at a low temperature side can easily be obtained using any conventional technique such as a thermocouple. However, the temperature at the heated surface, $T_1^{\,n+1}$, is usually difficult to know. Although the $T_1^{\,n+1}$ is unknown unless the thermal boundary conditions at both ends of the plate are given, it is possible to estimate the $T_1^{\,n+1}$ if the finite difference calculation is coupled with the transit time of ultrasound propagating through the plate. Using a concept of trapezoidal integration, the transit time t_L given in (1) can be approximately calculated from

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

From (5) and the relation between temperature and ultrasonic velocity, the temperature of the heated surface at time step n+1, $T_1^{\,n+1}$, can be given by

$$T_1^{n+1} = \frac{t_L^{n+1} - t_L^{n}}{\mathrm{A}h} - T_N^{n+1} + T_1^{n} + T_N^{n} - 2r\left(T_1^{n} - T_2^{n} - T_{N-1}^{n} + T_N^{n}\right) \qquad (6)$$

where, t_L^{n} and $t_L^{\mathrm{n+1}}$ are the transit times measured at the time step n and n+1, respectively. It should be noted that (6) is derived under the assumption that the temperature dependence of ultrasonic velocity has a linear relation shown as follows,

$$\frac{1}{v(T)} = \mathrm{A}T + \mathrm{B}\;, \qquad (7)$$

where, A and B are constants obtained experimentally. Thus, the temperature of the heated surface at time step n+1, $T_1^{\,n+1}$, can then be determined from (6) when the transit times t^{n} and $t^{\mathrm{n+1}}$ are measured. Once the temperatures of all grid points in the plate at the time step n+1, $T_1^{\,n+1}$,···, $T_{\mathrm{N}}^{\,n+1}$, are determined, we can determine the temperature distribution at next time step n+2 from the same procedure using the transit times $t^{\mathrm{n+1}}$ and $t^{\mathrm{n+2}}$ measured at the time step n+2. According to such procedure, we can continuously obtain the internal temperature distribution as long as the ultrasonic transit time measurement is continued. Fig. 1 shows the flowchart of the inverse analysis for determining the temperature distribution.

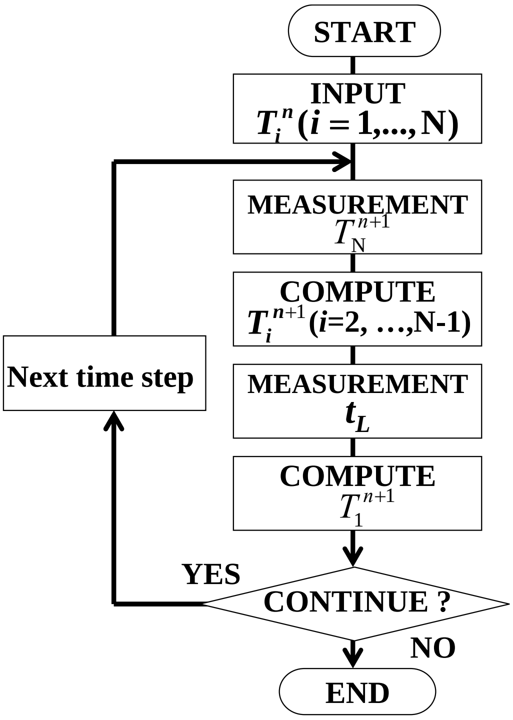

Fig. 1 Flowchart of the inverse analysis for determining the temperature distribution.

4. EXPERIMENT

In order to verify the feasibility of the proposed method for determining temperature distribution, the method has been applied to a thick steel plate being heated and cooled. Fig. 2 shows a schematic diagram of the experimental setup used. This system provides not only ultrasonic pulse-echo measurements but also temperature distribution measurements using thermocouples, so that we can verify the validity of the ultrasonically determined temperature distribution, by comparing with that measured using the thermocouples. A steel plate (JIS type: SKD61) of 30 mm thickness is used as a specimen. At first, the bottom surface of the plate is heated by contacting with a heater of 200 ºC for a period of 50 s, and then the surface is cooled by water. An ultrasonic transducer of 2 MHz is installed on the top surface of the steel plate to make pulse-echo measurements for the steel. To obtain a reference value of the temperature distribution inside the plate, five thermocouples, TC1 - TC5, are inserted into the plate. In addition, another thermocouple TC6 is used to measure the temperature at the top surface of the plate. Ultrasonic pulse-echo measurements are performed during the heating and cooling, and echoes reflected from the bottom surface and temperatures at each position are continuously acquired every 0.2 s with a PC based real-time acquisition system. The sampling rate of ultrasonic signal is 100 MHz. Signal fluctuation due to electrical noise in measurements is reduced by taking the average of ten ultrasonic signals.

5. RESULTS

Fig. 3 shows ultrasonic echoes reflected from the bottom surface of the plate during heating. We can see a high signal-to-noise ratio even in the second echo. The transit time through the steel plate can be precisely determined from the time delay between the first and second echoes, by taking a cross-correlation between them.

Fig. 4 shows the variation of the temperature at 5 mm from the bottom surface of the steel during heating and cooling. As we expected, the temperature rapidly increases with measurement time immediately after the contact of the heater, and then markedly decreases just after the water cooling starts. The variation of the transit time of ultrasonic

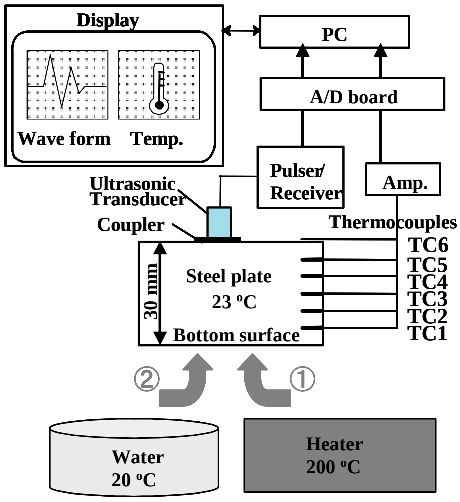

Fig. 2 Schematic of the experimental setup for ultrasonic temperature monitoring.

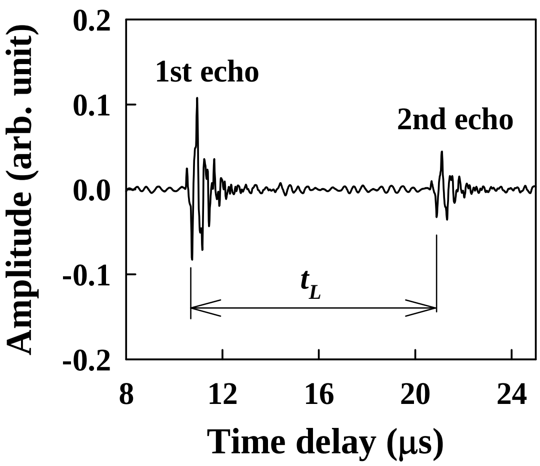

Fig. 3 Ultrasonic echoes reflected from the bottom surface of the steel plate.

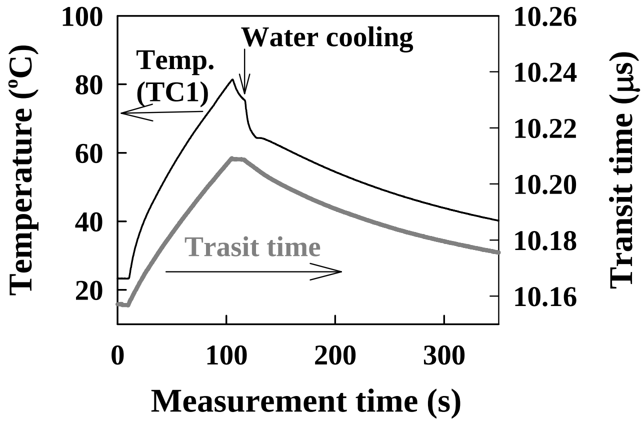

Fig. 4 Variations of the transit time of the ultrasonic wave and temperature in the steel plate during heating and cooling.

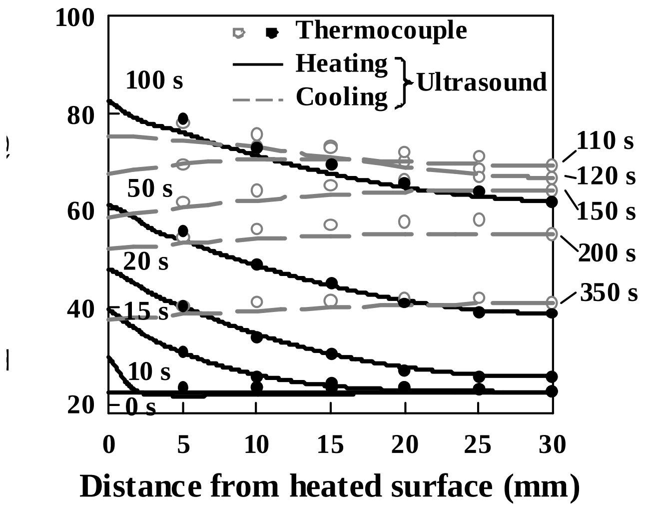

Fig. 5 Variation of temperature distribution in the steel plate with elapsed time, estimated by the ultrasonic method and thermocouples. The numbers in the figure denote the elapsed time after heating starts.

wave in the steel is also shown in Fig. 4. We can see that the tendency of the variation of the transit time during heating and cooling is similar to that of the temperature. However, we can also see the difference of their variation rates between the heating and cooling. In particular, the decrease rate of temperature in the beginning of cooling is quite different from that of transit time, which is much significant than the difference between their increase rates in heating. This is because of the difference of the temperature gradient inside the steel between heating and cooling processes.

The transit times measured during the heating and cooling are used for the inverse analysis to determine the temperature distribution and its variation. Since the prior information on the temperature dependence of ultrasonic velocity is needed for the analysis, we examine the relationship between the velocity and temperature for the steel in the temperature range up to 250 °C. It has been found that the velocity change is almost linear with temperature in the temperature range and therefore the temperature dependence is approximately given to be

$$v(T) = -0.636T + 5917.6\ ,\ \text{(m/s)} \qquad (8)$$

Using the transit time shown in Fig. 4 and the temperature dependence of (8), the variation of temperature distribution in the plate is estimated from the proposed inverse analysis. In the estimation, the temperature of the steel before heating, 23.3 °C, is used as the initial condition. Also, the temperature TC6 is used as the known value. The estimated temperature distributions are shown in Fig. 5, where the ultrasonically estimated results are compared with those measured using thermocouples. The time shown in Fig. 5 denotes the elapsed time after the heating starts. It can be seen that the temperature distribution estimated ultrasonically and its variation almost agree with those measured using thermocouples, while there are discrepancies between them in the range of high temperatures. Although the reason for the discrepancy is not clear at this moment, it is interesting that the proposed ultrasonic method seems to be effective to monitor a transient variation in internal temperature distribution of materials being heated or cooled. It is noted that it takes about 8 ms to calculate a temperature distribution at each time step from the measured ultrasonic data, which is fast enough to make a real-time monitoring.

6. CONCLUSIONS

A new ultrasonic method for monitoring internal temperature gradient of materials is presented. The advantage of the method is that no boundary condition at the heating surface is needed for the monitoring. The feasibility of the method has been demonstrated through an experiment with a steel plate being heated and cooled. An uncertainty analysis is now being done to estimate the accuracy in the present method and the result will be reported in the near future. Although further technical improvements in the measurement and analysis are needed, it is highly expected that the method could be effective in the on-line monitoring of the transient variation of the temperature profile of materials being processed at high temperatures. It should be noted that non-contact thermometry with the proposed ultrasonic method is also possible if any non-contact ultrasonic measurement technique such as a laser-ultrasound is employed.

ACKNOWLEDGMENTS

Financial supports by the Grant-in-Aid for Scientific Research (B19360330) from the Japan Society for the Promotion of Science, and Toyota Motor Co. are appreciated.

REFERENCES

[1] T.-F. Chen, K.-T. Nguyen, S.-S. Wen and C.-K. Jen., "Temperature measurement of polymer extrusion by

ultrasonic techniques" *Meas. Sci. Technol*., 10, pp.139-145 (1999).

[2] K. Balasubramainiam, V. V. Shah, R. D. Costley, G. Boudreaux and J. P. Singh, "High temperature ultrasonic sensor for the simultaneous measurement of viscosity and temperature of melts", *Rev. Sci. Instrum.*, 70-12, pp.4618-4623 (1999).

[3] W.-Y. Tsai, H.-C. Chen andT.-L. Liao, "An ultrasonic air temperature measurement system with self-correction function for humidity", *Meas. Sci. Technol.*, 16, pp. 548-555 (2005).

[4] K. Mizutani, S. Kawabe, I. Saito and H. Masuyama, "Measurement of temperature distribution using acoustic reflector", *Jpn. J. Appl. Phys*., 45-5B, pp. 4516-4520(2006)

[5] F. L. Degertekin, J. Pei, B. T. Khuri-Yakub, and K.C. Saraswat, "In-situ Acoustic Temperature Tomography of Semiconductor Wafers", *Appl. Phys. Lett*., 64, pp.1338-1040 (1994).

[6] K. N. Huang, , C. F. Huang, Y. C. Li and M. S. Young, "High precision, fast ultrasonic thermometer based on measurement of the speed of sound in air", *Rev. Sci. Instrum.*, 73-11, pp. 4022-4027(2002).

[7] P. Ingleby, and M. D. Wright, "Ultrasonic imaging in air using fan-beam tomography and electrostatic transducers", *Ultrasonics*, 40, pp.507-511 (2002).

[8] C. Simon, P. VanBaren, and E. Ebbini, "Two-Dimensional. Temperature Estimation Using Diagnostic Ultrasound", *IEEE Trans. on Ultrasonics, Ferroelectrics, and Frequency*. *Control*, 45-.4, pp.1088-1099 (1998).

[9] M. Takahashi, and I. Ihara, "Ultrasonic Monitoring of Internal Temperature Distribution in a Heated Material", *Jpn J. App. Phys*., 47, pp.3894-3898 (2008).

[10] M. Takahashi, and I. Ihara, "Ultrasonic Determination of Temperature Distribution in Thick Plates during Single Sided Heating", *Modern Physics Letters B*, 22-11, pp. 971-976, (2008).

[11] G. E. Myers, *Analytical Methods in Conduction Heat Transfer*, McGraw-Hill, NY, pp.10 (1971).

[12] W. Press, S. Teukolsky, W. Vetterling and B. Flannery, *NUMERICAL RECIPES in C++*, pp.849, Cambridge Univ., NY (2003).