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Feasibility Study on Temperature Profile Monitoring of Solidification Process by Ultrasonic Method

金属凝固プロセスの超音波モニタリングに関するモデル実験

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1. Introduction

In materials manufacturing and processing, it is strongly required to measure the temperature and its transient variation of the material being processed at high temperatures because such temperature state crucially influences the quality of final products. 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 because the temperature gradient is closely related to the temperature state of the material being processed. Therefore, it is desirable to realize an appropriate technique for on-line measurements of such processes.

Recently, we have developed an effective ultrasounic method for monitoring tenperatude distribution of heated materials[1), 2)]. It is now quite meaningful to apply the ultrasonic method to a casting process monnitoring. In this work, the ultrasonic method is slightly modified to improve the accuracy in temperature determination and applied to the solidification process of a low melting metal. An attempt to monitor both internal temperature distributions of a melt and a die during cooling process has been made.

2. Ultrasonic Method for Determining Internal Temperature Distributions

The principle of temperature measurement by ultrasound is based on the temperature dependence of ultrasonic velocity in a medium. Assuming a one-dimensional temperature distribution in a medium, the transit time of ultrasonic pulse-echo in the direction of the temperature distribution can be given by

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

where L is half the transit distance of ultrasound, $v(T)$ is the ultrasonic velocity that is a function of temperature T. In general, T in a medium being heated can be given as a function of location x and time t. In a certain temperature range, the temperature dependence of ultrasonic velocity can be expressed in quadratic form as follows,

$$v(T) = \mathrm{A}T^2 + \mathrm{B}T + \mathrm{C}\,, \qquad (2)$$

where, A, B and C are constants obtained experimentally. It is expected that the use of quadratic form provides higher accuracy in determining temperature distribution.

We now consider a one-dimensional finite difference model consisting of a large number of small elements and grids, for the medium to be evaluated. Using a concept of trapezoidal integration, the transit time t_L given in equation (1) can be calculated from

$$t_L = h\left(\frac{1}{v_1^n} + \frac{1}{v_N^n}\right) + 2h\sum_{i=2}^{N-1}\frac{1}{v_i^n}\,, \qquad (3)$$

where h is the grid interval, N is the number of the grid, v_i^n is the ultrasonic velocity at each grid position, i and n are indices corresponding to spatial coordinate and consecutive time, respectively. Considering that the single side of the medium having a uniform temperature T^n at time step n is being heated, temperatures at each grid point in the medium at time step n+1 that is a very short elapsed time can be given by[3)]

$$T_i^{n+1} = T_i^n + r\left(T_{i+1}^n + T_{i-1}^n - 2T_i^n\right) \quad (i = 2, \cdots, N-1) \quad (4)$$

$$r = \frac{\alpha\tau}{h^2} \qquad (5)$$

where α is the thermal diffusivity, τ is the time step, and r is taken to be less than 0.5 according to the von Neumann stability criterion. Using equation (3) with (2), the temperature of the heated surface at time step n+1, T_1^{n+1}, can be given by

$$T_1^{n+1} = \frac{-\mathrm{B} \pm \sqrt{\mathrm{B}^2 - 4\mathrm{A}(\mathrm{C}-\mathrm{D})}}{2\mathrm{A}}\,, \qquad (6)$$

$$\mathrm{D} = \frac{1}{\dfrac{t_L}{h} - \left(\dfrac{1}{v_N^{n+1}} + 2\displaystyle\sum_{i=2}^{N-1}\frac{1}{v_i^{n+1}}\right)}\,, \qquad (7)$$

where t_L is the transit time of ultrasonic wave measured at the time step n+1. It is noted that the

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temperature of the other side of the medium, T_N^{n+1}, is assumed to be known because such temperature at a low temperature side can be easily obtained using any conventional techniques. Once the temperatures of all grid points in the medium at the time step n+1, $T_1^{n+1},\cdots, T_N^{n+1}$ are obtained, the temperature distribution at time step n+2 can also be determined by the same procedure using the transit time t_L measured at the time step n+2. Thus, we can continuously obtain the temperature distribution.

3. Experiments and Results

Figure 1 shows a schematic diagram of the experimental setup for measuring ultrasonic pulse-echoes for a die and melt. A low melting metal that can be melted by boiled water is employed to make a simple simulation of casting process. An ultrasonic transducer of 5 MHz is attached on the outer surface of a steel die and ultrasonic pulse-echo measurements are then performed while the low melting alloy is being solidified in the die. To obtain a reference value of the temperature during solidification process, an IR-camera is used.

Figure 2 shows B-mode result showing the variation in the reflected echoes with the elapsed time during casting process. We can see both echoes reflected from the inner surface of die (A) and through the alloy (B). The echo B is appeared at 45 s at which the solidification starts and moves to left side because of the velocity change in the alloy being solidified.

The temperature dependences of the longitudinal ultrasonic velocities of the die and the alloy are estimated experimentally and can be approximated to be

$v(T)$=-6.04x10$^{-4}T^2$-0.542T+5931.7 (m/s) for die (8)

$v(T)$= - 0.029T^2+0.906T+2395.6 (m/s) for alloy. (9)

Using the transit time in the die and equation (8), the temperature distribution in the die is determined. Furthermore, the temperature distribution in the alloy is determined from the transit time in the alloy, equation (9) and the temperature of the die. **Figure 3** shows the variations of the estimated temperature distributions with the elapsed time. Thus, it seems that the proposed method can monitor the temperature profiles in both the die and the alloy during solidification.

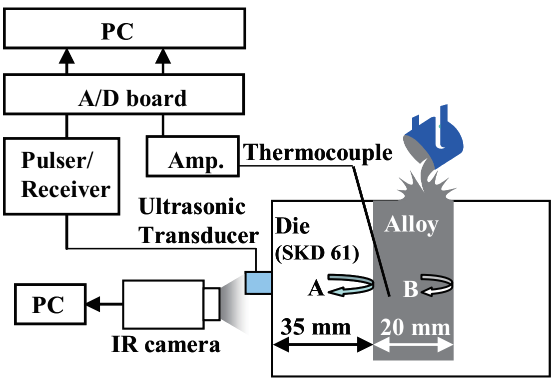

Fig. 1 Experimental setup for monitoring a casting process.

Acknowledgment

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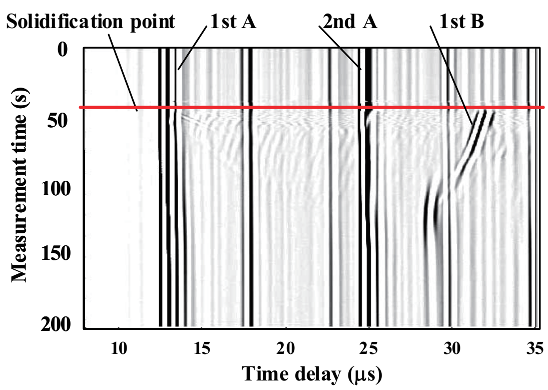

Fig. 2 B-mode result showing the variation in the reflected echoes with the elapsed time during casting process.

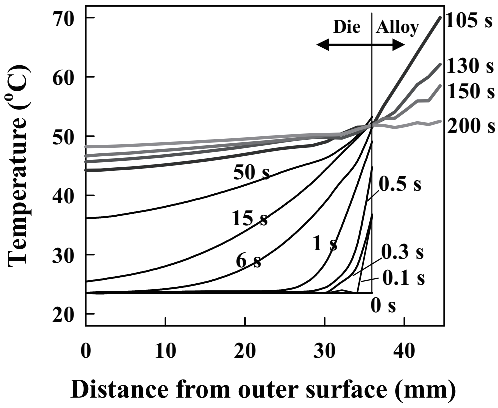

Fig. 3 Variation in temperature profiles in the die and the alloy during casting process, estimated by the ultrasonic method.