Optimization of Ultrasonic Measurement of Remelted Zone Thickness by Using Backscattered Waves

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Abstract

The present work is concerned with nondestructive evaluation of the thickness of the remelted zone formed on aluminum alloy castings by using ultrasonic backscattered waves. Remelted zones with different thicknesses were formed on the surface of an Al-Cu-Si alloy casting plate, and backscattered waves were measured at various positions on the plate by immersion method with different distances of the water path to obtain an optimum focal depth in the specimen. When the ultrasonic wave was focused on the boundary between the remelted zone and the matrix, the amplitude ratio of the backscattered wave from the matrix to that from the remelted zone reached a maximum. The longitudinal wave velocity and the density were measured with test pieces containing remelted zones to obtain acoustic impedances of the remelted zone and the matrix. The reflectivity at the boundary calculated from the acoustic impedances was less than 1.5% (-37dB).

Keywords: Backscattered wave; Aluminum alloy castings; Remelted zone; Acoustic impedance

1. Introduction

Surface strengthening techniques have been widely applied to alloy castings in this decade [1,2]. For instance, partial remelting on the surface of aluminum alloy castings by using a TIG arc welder or a laser beam can improve their hardness and wear-resistance [3]. Since the surface strengthening is largely influenced by the thickness and the width of the remelted zone, evaluation of the remelted zone size has been very important. So far, destructive metallographic examinations have provided a method to determine the remelted zone size in the aluminum alloy castings. However, the destructive method results in salable castings being sacrificed, offers no guarantee that all the other castings supplied are of the required quality, and is time consuming. Therefore, it is desirable to develop a suitable non-destructive evaluation procedure that is simple, fast and reliable.

The size of a treatment layer on a surface of iron and steel has been evaluated by using an ultrasonic wave reflected from a boundary between the matrix and the treatment layer [4,5,6]. For aluminum alloy castings, however, a remelting operation yields the same phases and similar structure in the remelted layer as in the matrix, and no reflection of the ultrasonic wave is expected from the boundary between the matrix and the remelted layer. Recently, the authors [7] have shown that the size of the remelted zone formed on the surface of aluminum alloy castings can be evaluated by using different amplitudes of backscattered wave from the matrix and the remelted zone. The ultrasonic method eliminates sectioning of specimens and preparation of samples for observation of microstructures. Furthermore, the measurement is carried out in several minutes for each point. These show the proposed method is cost effective. In previous reports [7], the measurement was carried out with a specimen containing remelted zones of a thickness of 6 mm and was not performed for other thicknesses of the remelted zone. And also the focal point of the probe was fixed on the surface of the specimen.

In the present study, changes in backscattered amplitudes were measured with aluminum alloy castings containing remelted zones of different thicknesses. The measurement was done with different distances of the water path to obtain an optimum focal depth for evaluation of the remelted zone thickness. Then a poor reflectivity at the boundary between the remelted zone and the matrix was confirmed.

2. Experimental procedures

2.1 Preparation of specimen

A plate of Al-4wt%Cu-5wt%Si alloy was prepared by a permanent-mold casting. An alloy melt heated at a temperature of 973K was poured into a metallic mold of 673K to obtain a plate of 120mm in length, 90mm in width and 20mm in thickness. Then the alloy plate was partly melted by a TIG arc welder to form remelted zones on the surface under the following conditions: 5～15L/min in flow velocity of Ar+He gas mixture, 150～275A in electric current, 10～30cm/min in moving speed of torch. By changing treatment conditions, remelted zones of different thicknesses (2.5～8.0mm) were obtained. Figure 1 shows a schematic representation of the alloy plate.

2.2 Ultrasonic measurement

The ultrasonic measurement was carried out by using a probe of focussing type generating a longitudinal wave of 10MHz in frequency. The diameter and focal distance in water of the probe are 10mm and 25mm, respectively. At different distances of the water path (the distance from the probe to the surface of the specimen), backscattered waves were measured from A to B in Figure 1 at an interval of 1.5mm.

The remelted zone thickness was evaluated by using an energy integral method to improve the reliability of determining the remelted zone thickness from the change in the backscattered wave amplitude [7]. Since the energy of the wave is proportional to the square of the amplitude of ultrasonic wave, it can be defined as follows:

$$E(x)=\int_0^x[P(\xi)]^2\,d\xi \tag{1}$$

where $P(\xi)$ is the amplitude of the ultrasonic wave, and x is a distance from the specimen surface. The square of the amplitude of the backscattered wave was integrated. The remelted zone thickness was inferred from the inflection point of the energy integral curve, as shown in Figure 2.

2.3 Measurement of reflectivity at boundary

As shown in Figure 3, test pieces (20mm×12mm×12mm) with different remelted zone thicknesses were prepared from the alloy plate. The longitudinal wave velocity and the density of these test pieces were measured with the sing-around method in the center part of samples and Archimedes' principle, respectively. Then, the ultrasonic velocity V_R and the density ρ_R of the remelted zone were calculated with the following formulae:

$$\frac{1}{V_R}=\frac{1}{V_M}+\left(\frac{1}{V_0}-\frac{1}{V_M}\right)\frac{1}{S_R} \tag{2}$$

$$\rho_R=\rho_M+(\rho_0-\rho_M)/S_R \tag{3}$$

where S_R is a volume fraction of the remelted zone in the center part of test pieces, in which the remelted zone has a relatively uniform thickness; V_M and ρ_M are the velocity and the density of the matrix, respectively, and V_0 and ρ_0 are the velocity and the density of the test piece, respectively.

2.4 Metallographic examinations

After ultrasonic measurements, the plate was sectioned, polished and etched with a water solution of 2wt% NaOH. Then, the distance from the specimen surface to the boundary at which the grain size changed abruptly was measured as the remelted zone thickness. A typical optical micrograph of the boundary is shown in Figure 4.

3. Results and Discussion

3.1 Change in backscattered wave amplitude with water path and remelted zone thickness

The method proposed in the previous paper [7] is to use the change in backscattered wave amplitude to infer the remelted zone thickness in aluminum alloy castings. Obviously, the greater the change in backscattered wave amplitude at the boundary between the remelted zone and the matrix, the higher the reliability and the accuracy of measurement of the remelted zone thickness. To obtain a relation between the backscattered wave amplitude and the focal depth of the probe, backscattered waves were measured by changing the distance of the water path from 24mm to 4mm at an interval of 2mm. Figure 5 shows backscattered siguals obtained with a remelted zone thickness of 4.5mm under different distances of the water path. Figure 6 shows backscattered siguals for specimens with different remelted zone thicknesses under a water path of 24mm. The results shown in Figures 5 and 6 indicate that the change of backscattered wave amplitude at the boundary decreases with increasing remelted zone thickness and distance of the water path.

The ratio of the backscattered wave energy in the matrix to that in the remelted zone was calculated from the backscattered wave amplitude in the matrix and the remelted zone in a range of $\pm$1.8mm (as shown in Figure 7(a)) neighboring the boundary. The results are shown in Figure 7(b). The figure shows that the amplitude ratio is so small at a remelted zone thickness of 7.5mm and 8.0mm that no significant changes are obtained with the decrease in the water path. When the remelted zone thickness is 2.5mm to 5.5mm, the amplitude ratio is increased with decreasing water path, and it reaches a maximum in the range of measurement at a remelted zone thickness of 2.5mm to 4.5mm. Then the focal position in the specimen is inferred from the distance of the water path of the maximum amplitude ratio by using Snell's law. The results are shown in Figure 8. The estimated focal depth from the specimen surface is in good agreement with the remelted zone thickness. This demonstrates that when the ultrasonic wave is focused on the boundary, the amplitude ratio of the backscattered wave reaches a maximum and the reliability of the ultrasonic measurement becomes the highest.

3.2 Evaluation of remelted zone thickness in different distances of water path

Using the change in the backscattered wave amplitude, remelted zone thickness was evaluated with different distances of the water path of 25mm and 6mm from A to B in Figure 1. The results are shown in Figure 9. The remelted zone thickness was also measured by sectioning the specimen and observing microstructures as shown in Figure 9. Estimated remelted zone thickness is in good agreement with that of the section analysis for both distances of the water path. Also, regardless of the water path, scattering of data is almost the same. However, the reliability of the ultrasonic measurement increases with decreasing water path because of higher amplitude ratio of the backscattered wave.

3.3 Relationship between remelted zone thickness and acoustic impedance

The sound velocity and the density of test pieces with different remelted zone thicknesses are shown in Figures 10 and 11, respectively. In the figures, the sound velocity and the density of the remelted zone were calculated with equations (2) and (3). In both cases, they decreased with increasing remelted zone thickness.

Acoustic impedances of the matrix and the remelted zones were calculated from their sound velocity and density. And then, the reflectivity at the boundary between the matrix and the remelted zone was calculated from the acoustic impedances, as shown in Figure 12. The reflectivity at the boundary between the matrix and the remelted zone is less than 1.5% (-37dB). Therefore, although the ultrasonic wave is reflected from the boundary, the amplitude of the reflected wave is at the level of electronic noise or less, and is too small to be detected.

4. Conclusions

The main conclusions which can be drawn from the present study are as follows.

(1) The backscattered wave amplitude coming from the boundary between the matrix and the remelted zone increases with decreasing distance of the water path, but decreases with increasing remelted zone thickness. When the ultrasonic waves are focused on the boundary, the amplitude ratio of backscattered waves from the matrix and the remelted zone reaches a maximum.

(2) Regardless of the water path, the evaluated remelted zone thickness is in good agreement with the measured thickness.

(3) Reflectivity from the boundary between the matrix and the remelted zone is less than 1.5% (-37dB). This suggests that the reflection echoes from the boundary are indistinguishable from the scattered waves.

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List of Figure Caption

Fig. 1 Schematic view of specimen for ultrasonic measurement.

Fig. 2 Change in integral of square of ultrasonic wave amplitude with depth.

Fig. 3 Test piece for measurement of density and velocity.

Fig. 4 Typical optical micrograph at boundary between remelted zone and matrix.

Fig. 5 Relationship between scattered wave amplitude and water path (S: surface reflection wave; B: bottom reflection wave).

Fig. 6 Relationship between scattered wave amplitude and remelted zone thickness of (a) 3.0mm; (b) 4.5mm and (c) 6.5mm.

Fig. 7 (a) The integral range of backscattered wave amplitude; (b) Change in ratio (R_e) of backscattering wave energy of matrix to that of remelted zone with water path at different remelted zone thicknesses.

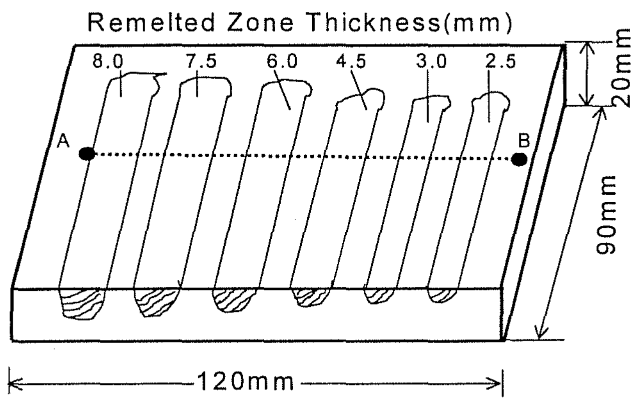
Fig. 8 Water path (D_{max}) at maximum ratio of scattering wave energy and estimated focal depth.

Fig. 9 Change in remelted zone thickness (t_R) with position of measurement.

Fig. 10 Change in sound velocity with remelted zone thickness.

Fig. 11 Change in density with remelted zone thickness.

Fig. 12 Change in acoustic impedance (Z) of remelted zone (deduced) and matrix (measured) and reflectivity at boundary with remelted zone thickness.



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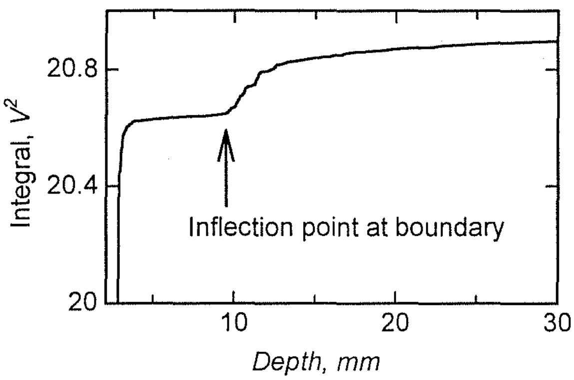
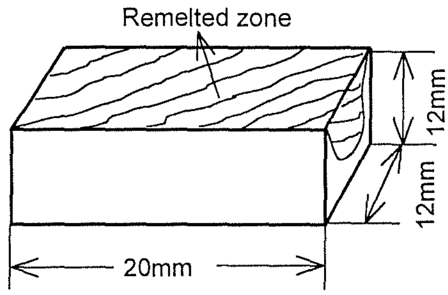


Fig.2 Change in integral of square of ultrasonic wave amplitude with depth.



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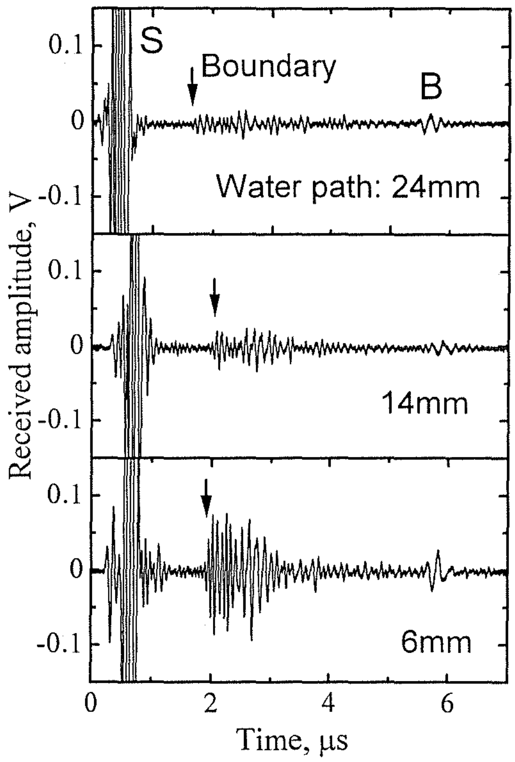

Fig.5 Relationship between backscattered wave amplitude and water paths (S: surface reflection wave; B: bottom reflection wave).

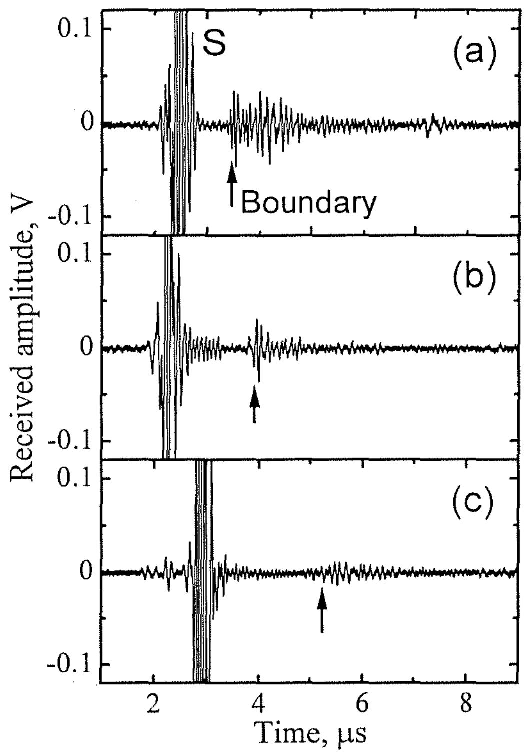

Fig.6 Relationship between scattered wave amplitude and remelted zone thickness of (a) 3.0mm, (b) 4.5mm and (c) 6.5mm.

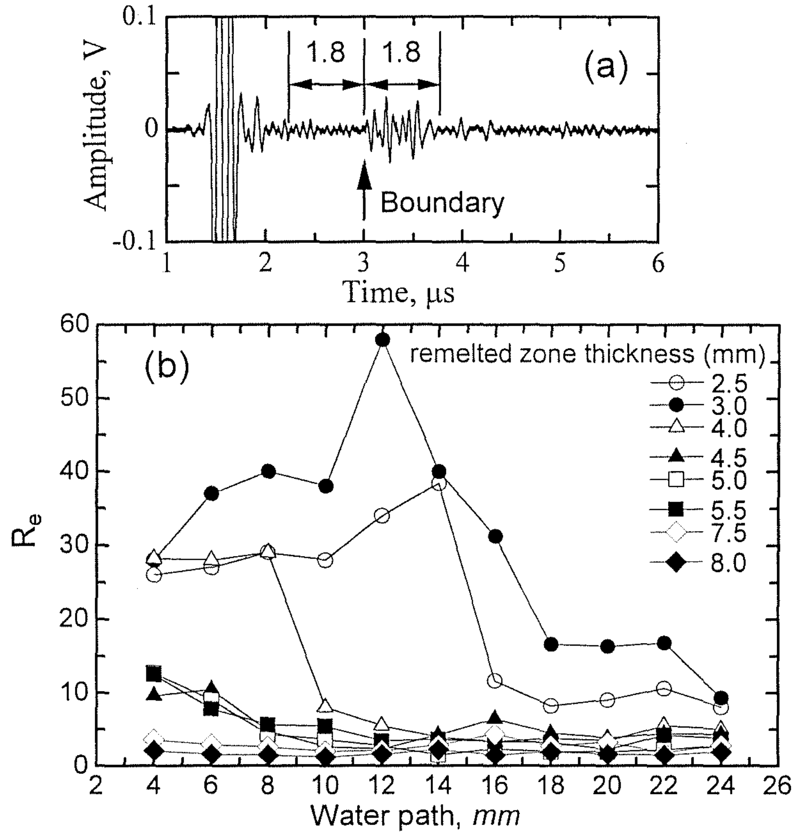

Fig.7 (a) The integral range of backscattered wave amplitude; (b) Change in ratio (R_e) of backscattered wave energy of matrix to that of remelted zone with water path at different remelted zone thicknesses.

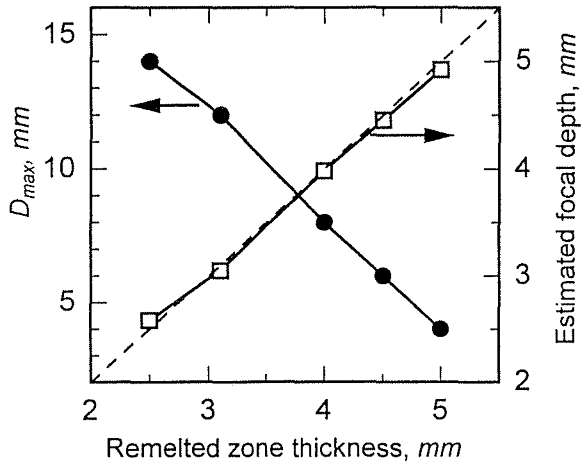

Fig.8 Water path (D_{max}) at maximum ratio of scattered wave energy and estimated focal depth.

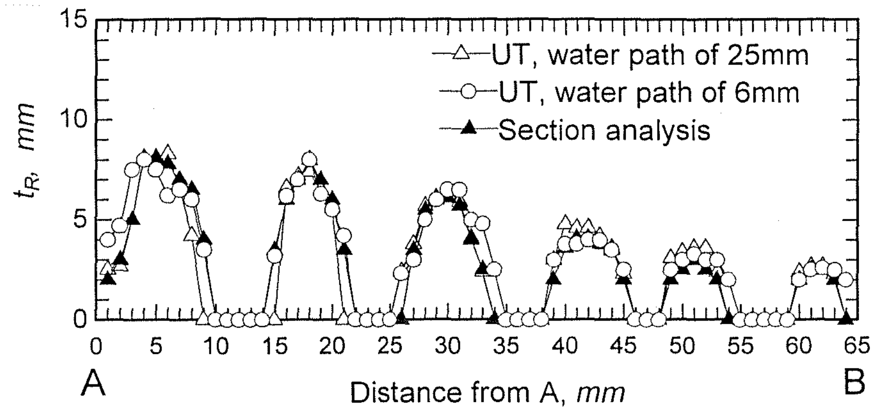

Fig.9 Change in remelted zone thickness (t_R) with position of measurement.

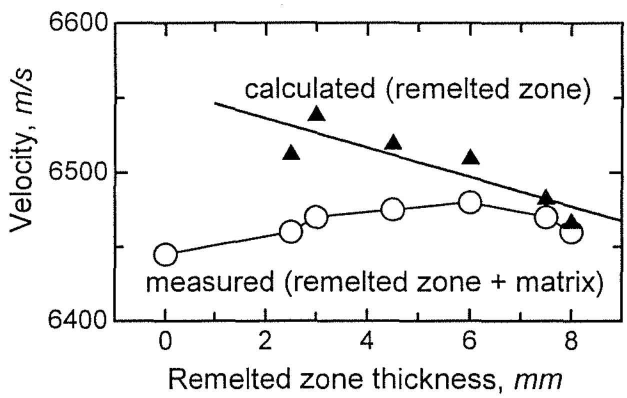

Fig.10 Change in sound velocity with remelted zone thickness.

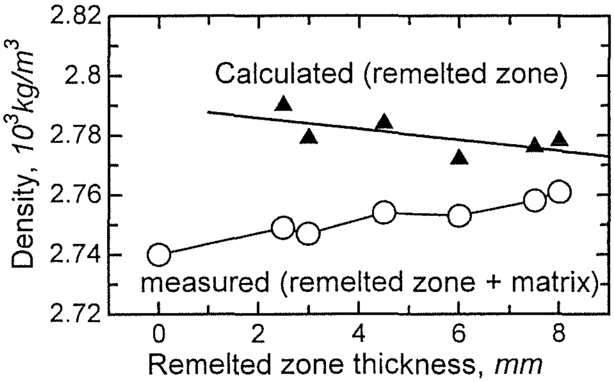

Fig.11 Change in density with remelted zone thickness.

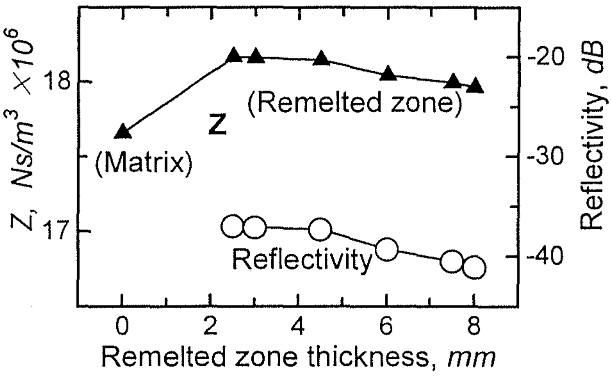

Fig.12 Change in acoustic impedance (Z) of remelted zone (deduced) and matrix (measured) and reflectivity at boundary with remelted zone thickness.