Ultrasonic Techniques for Imaging and Measurements in Molten Aluminum

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***Abstract*—In order to achieve net shape forming, processing of aluminum (Al) in the molten state is often necessary. However, few sensors and techniques have been reported in the literature due to difficulties associated with molten Al, such as high temperature, corrosiveness, and opaqueness. In this paper, development of ultrasonic techniques for imaging and measurements in molten Al using buffer rods operated at 10 MHz is presented. The probing end of the buffer rod, having a flat surface or an ultrasonic lens, was immersed into molten Al while the other end with an ultrasonic transducer was air-cooled to room temperature. An ultrasonic image of a character "N", engraved on a stainless steel plate immersed in molten Al, and its corrosion have been observed at 780°C using the focused probe in ultrasonic pulse-echo mode. Because cleanliness of molten Al is crucial for part manufacturing and recycling in Al processing, inclusion detection experiments also were carried out using the nonfocused probe in pitch-catch and pulse-echo modes. Backscattered ultrasonic signals from manually added silicon carbide particles, with an average diameter of 50 μm, in molten Al have been successfully observed at 780°C. For optimal image quality, the spatial resolution of the focused probe was crucial, and the high signal-to-noise ratio of the nonfocused probe was the prime factor responsible for the inclusion detection sensitivity using backscattered ultrasonic signals. In addition, it was found that ultrasound could provide an alternative method for evaluating the degree of wetting between a solid material and a molten metal. Our experimental results showed that there was no ultrasonic coupling at the interface between an alumina rod and molten Al up to 1000°C; therefore, no wetting existed at this interface. Also because ultrasonic velocity in alumina is temperature dependent, this rod proved to be able to be used as an in-line temperature monitoring sensor under 1000°C in molten Al.**

I. Introduction

In order to achieve net shape forming of aluminum (Al), processing in the molten state is often necessary. However, few sensors and techniques have been reported in the literature due to difficulties associated with molten Al, such as high temperature, corrosiveness, and opaqueness. The quality of Al products is frequently and critically associated with the presence of inclusions of nonmetallic materials within the molten Al during manufacturing steps. These inclusions can be oxide films together with other hard inclusions (particles) that are derived from the original smelting process or other reaction products such as flux particles. The size of these inclusions can vary from less than 1 μm to greater than 100 μm. The large, hard particles are, in particular, detrimental in forming thin-wall products such as cans, thin sheets, and large parts with thin walls. Part rejection due to defects of this type can be costly. In addition, these particles scratch or deform draw dies.

Filtration systems developed by the Al industry have been successful as an adjunct to the continuous casting process. However, any handling or movement of the filters can send entrapped particles down into the product. Various techniques, which currently are available for evaluating metal quality, are usually based on extraction of a metal sample followed by analysis in a laboratory. These approaches often are capable of providing the desired information regarding inclusion content. However, they require considerable sample preparation and analysis time to discover possible molten metal processing problems. In addition, the information often is obtained too late to make timely adjustments in the casting process.

Ideally, evaluation of cleanliness of molten metals would be conducted on large quantities, which could be rapidly analyzed with little or no sample preparation. This can be achieved only by analyzing the metal while it is still in the molten state. For Al processing, there is a commercial device available to measure the cleanliness, called the Liquid Metal Cleanliness Analyzer (LiMCA, ABB Bomen Inc., Quebec, QC, Canada) [1]. This device is commonly used and accepted in Al industry. The LiMCA is convenient but still suffers from several limitations. One limitation is that it uses an orifice with a diameter of 0.5 mm or less through which molten Al is pumped for measuring the size and counting the number of the particles. If the particle is larger than the diameter of the orifice, the orifice is blocked and must be replaced. The use of a small orifice also means that the LiMCA has little ability to detect particles larger than 100 μm. Another constraint of the LiMCA is that the volume of the molten Al used for cleanliness analysis is limited due to sampling through the small orifice. In addition, the LiMCA may not be suitable to monitor inclusions in the Al melt pool during continuous sand- and die-casting processes. Therefore, there is a need to develop other techniques for the inclusion detection in molten Al.

In parallel to the LiMCA development, ultrasonic techniques have been reported as on-line methods to monitor molten metal properties [2]–[12]. The merits of ultrasound are that it can propagate in the molten metals without much attenuation, and when there are inclusions in the molten metals, the ultrasonic propagation properties (such

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as velocity and attenuation) will change, and the ultrasonic energy will be scattered by the inclusions. This means that the variation of the velocity, attenuation, and scattered energy of the ultrasound propagating in the molten metal may be used to characterize inclusion properties such as its population density. Because the variation of the velocity and attenuation is not sensitive to small amounts of inclusions (<30 ppm), which is of our interest, the detection of the scattered energy from each individual particle [13] will be the focus in this study.

Ultrasonic probes used in the earlier studies were composed of an ultrasonic transducer and a buffer rod with no cladding [2]–[12]. Due to the lack of cladding, the signal-to-noise ratio (SNR) of the ultrasonic signal in such nonclad buffer rods was poor. The SNR is defined as the strength of desired signals divided by the strength of the spurious signals (unwanted signals) produced in the rod because of mode conversion, diffraction, etc. Recently, our works have demonstrated that the cladding improves ultrasonic guidance in the probe and increases the SNR [14]–[16]. The inclusion detection sensitivity is directly related to the SNR. The higher the SNR, the better the detection sensitivity.

Furthermore, we also have used an ultrasonic lens to focus the ultrasonic energy for ultrasonic imaging and inclusion detection in molten zinc (Zn) [13]. In that study, the lens enhanced the spatial resolution and the capability to detect small particles. In principle, using higher ultrasonic frequencies also can provide proportionally higher resolution if the SNR is not deteriorated due to the higher ultrasonic attenuation in the melt. In this study, we will use an ultrasonic imaging experiment to evaluate the performance of the ultrasonic lens in molten Al. It is our expectation that ultrasonic imaging of objects in molten Al would be beneficial for on-line inspection of defects in vessels containing molten Al such as cracks and of the graphite electrodes in an Al electrolytic cell, because the removal of molten Al for inspection might be time consuming and costly. However, no ultrasonic imaging attempts have been reported to inspect objects in molten Al. It is noted that, because the ultrasonic velocity in molten Al is almost twice that of molten Zn [17], the spherical aberration of the lens [18] in molten Al is much more serious than that in molten Zn. In addition, wetting conditions, corrosion rate of our probe, and ultrasonic attenuation in molten Zn are different from those in molten Al.

In this paper, ultrasonic imaging and particle detection in molten Al using a clad steel buffer rod with a flat surface or an ultrasonic lens on the probing end of the rod will be investigated in order to evaluate the capability of the buffer rod as a probe to carry out process monitoring in molten Al. Furthermore, we also will use the ultrasonic technique to evaluate the wetting behavior at the interface between molten Al and alumina at elevated temperatures, which is related to corrosion resistance; because the alumina has high corrosion resistance to molten Al, it is commonly used as the container material for molten Al in laboratories. A higher corrosion resistance means a poorer wetting, which gives a poorer ultrasonic coupling. If the wetting exists, which means that the ultrasound can be propagated from the alumina into the molten Al, then we may use the alumina rod as the buffer rod in molten Al.

Throughout the experiments, longitudinal wave ultrasonic transducers (UT) with a center frequency of 10 MHz were used, and an Al alloy of A356 or A357 which contains 7% silicon (Si), 0.1% iron (Fe), and 0.4–0.5% magnesium (Mg) served as molten Al.

II. Ultrasonic Imaging

We expect that ultrasonic imaging could be useful for on-line inspection of conditions of containers and electrodes immersed in molten Al. However, this type of application has not been explored because no imaging probe and technique were available. It is understood that a buffer rod can be used as a probe to perform ultrasonic measurements in molten metals [2]–[13]. However, the well-known problem in using a long buffer rod in ultrasonic pulse-echo measurements is the presence of spurious echoes, namely, trailing echoes [19], appearing at almost constant time intervals. The causes of these spurious echoes are mainly wave diffraction and mode conversion in the rod of finite diameter and specific shape. Other spurious echoes might be scattering echoes from random grains and/or voids in the rod materials. The spurious echoes are unwanted because they interfere with desired signals from a sample inspected and make the SNR of the desired echo worse. In our previous work, we found that a taper shape of the buffer rod significantly reduced the trailing echoes [20]. In addition, the presence of a cladding cannot only reduce the trailing echo but also enhance the ultrasonic guidance, which results in better SNR [14]–[16].

In this section, the ultrasonic imaging in molten Al is performed using pulse-echo techniques to evaluate the SNR and focusing ability of ultrasonic probes using a clad steel buffer rod with a double-taper shape in molten Al. Endurance of the rod in molten Al also is investigated.

A. Experimental Setup

Fig. 1(a) shows a double-taper shape clad buffer rod, consisting of a mild steel core and a stainless steel (SS) cladding, used in the experiment. One end has a spherical concave ultrasonic lens, as shown in Fig. 1(b), to focus ultrasonic energy in molten metals; the other end has a flat surface to which a UT is attached. The ultrasonic lens was machined using a ball-end mill so that a lens with the desired radius of curvature was easily fabricated. The SS cladding was fabricated outside of the steel core by thermal spray technique [14], [15]. The dimensions of the rod are as follows: the length is 276 mm with taper angle of 2°; the diameters at the middle and at the ends are 24 mm and 14 mm, respectively; and the radius of curvature and the aperture diameter of the lens are 6.35 mm and 12 mm, respectively. The thickness of the cladding is 1 mm. The

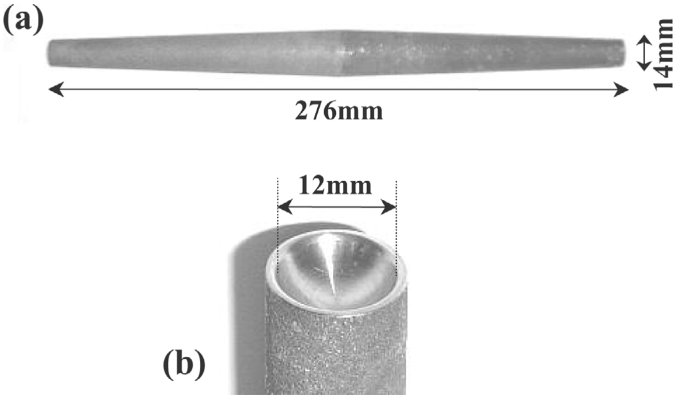

Fig. 1. Double-taper shape clad buffer rod: (a) external view, and (b) spherical ultrasonic lens fabricated at the probing end of the rod.

TABLE I
EVALUATION OF FOCUSED ULTRASOUND IN WATER AT 23°C AND IN MOLTEN AL AT 780°C AT 10 MHZ USING A STEEL BUFFER ROD WITH AN ULTRASONIC LENS.

	In water at 23°C	In molten Al at 780°C
$v_{\mathrm{steel}}/v_{\mathrm{liquid}}$	4.0	1.1
λ	149 μm	462 μm
F	8.5 mm	59.4 mm
dr	0.11 mm	2.33 mm
dz	0.53 mm	80.23 mm

detailed design of the rods such as taper angle and the rod evaluation were presented elsewhere [14]–[16], [21].

Here we evaluate the focusing ability of ultrasound in molten Al using this probe at an ultrasonic frequency, f, of 10 MHz in order to estimate spatial resolution for imaging with comparison of that in water, as water is one of the ideal couplants in ultrasonic measurements. The water wets our probe well without significant corrosion on the probes during imaging measurements. The lateral resolution, dr, and focusing depth, dz, are approximately calculated using the following equations [22]:

$$dr \cong 1.02\lambda \cdot \frac{F}{D}, \tag{1}$$

$$dz \cong 7.1\lambda \cdot \left(\frac{F}{D}\right)^2, \tag{2}$$

where λ is the wavelength of ultrasound in liquid, F is the focal length, and D is the aperture diameter of the lens. The λ and F are calculated by $\lambda = v_{\mathrm{liquid}}/f$ and $F = R/(1 - v_{\mathrm{liquid}}/v_{\mathrm{steel}})$, respectively, where v is longitudinal wave velocity and R is a curvature radius of the lens. The calculated results are summarized in Table I. The values of v_{liquid} for Al and v_{steel} at 780°C are 4617 m/s [23] and 5170 m/s [24], respectively; the values of v_{liquid} for water and v_{steel} at 23°C are 1491 m/s [25] and 5923 m/s [24], respectively. It is predicted that, because the ratio of the velocity of the steel over that of the molten Al is only 1.1, spherical aberration [18] is large for this imaging lens configuration and causes the resolution to be poorer in molten Al than in water. The dr estimated in molten Al is 2.33 mm, which is about 20 times larger than that in water.

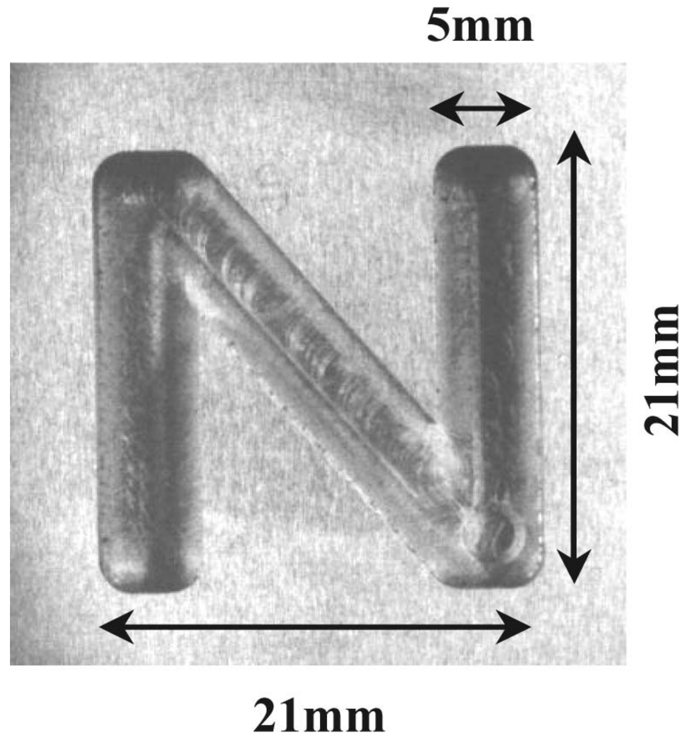

Fig. 2. Photograph of the character "N" engraved on a stainless steel plate for the imaging experiment in molten Al.

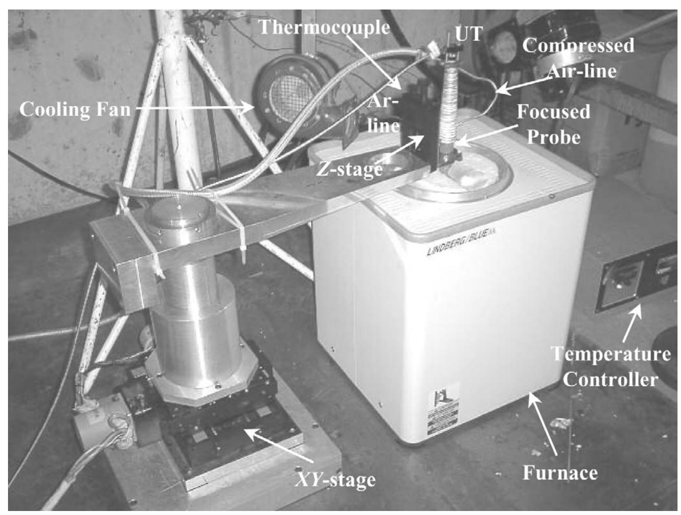

Fig. 3. Experimental setup for ultrasonic imaging in molten Al.

Fig. 2 shows a photograph of a SS character sample used in the experiments. The character "N" was engraved on the SS plate (S304) with a dimension of 38 mm × 51 mm × 13 mm. The area of the character was 21-mm square, and both the line thickness and the depth of the character were 5 mm. The experimental setup is shown in Fig. 3. The basic setup was almost the same as in our previous work in molten Zn [13]. The UT (Model A127S, Panametrics Inc., Waltham, MA), which radiates and receives pulsed-ultrasound with a pulser-receiver (Model 5072PR, Panametrics Inc.), was attached to the UT end of the buffer rod that had an air-cooling system. The buffer rod was mounted on a manual vertical-translation stage (Z-stage) to adjust the distance between the probing end and the sample, and it was transferred horizontally using a XY-stage driven by stepping-motors. A SS tube coil, inside of which compressed air flows, was attached outside of the buffer rod in order to lower the temperature of the rod. Furthermore, blowing air by fans cooled the UT directly.

The Al contained in a SS crucible was heated and melted by an electric resistance furnace. The character sample was fixed on the bottom of the crucible by welding. A temperature controller controlled the temperature of molten Al using the temperature values measured by a thermocouple (Type K, Omega Inc., Stamford, CT) immersed in the molten Al. Argon (Ar) gas was continuously supplied above the Al to prevent oxidation of molten Al because creation of an Al oxide would disturb the propagation of the ultrasound and would make the SNR worse for the desired echoes. The ultrasonic signals were recorded using a data acquisition board (Model CS12100, Gage Applied Science Inc., Montreal, QC, Canada) with a resolution of 12 bits and a sampling rate of 100 MHz.

B. Experimental Results

The experiment was carried out first in water, then that in molten Al was conducted using the same probe and sample; the image in water represents the best possible result obtainable in molten Al. Figs. 4(a) and (b) show observed ultrasonic signals in water at room temperature and in molten Al at 780°C, respectively. The signals from the top surface [indicated by "Top" in Fig. 4(a)] were the echoes reflected from the nonengraved area of the SS plate, and those from the bottom surface (indicated by "Bottom") were from the engraved area of character "N" (see inset in Fig. 4). The first round trip echoes of longitudinal waves in the rod, indicated by L^1, were observed at the time delay of about 93 μs as shown in Figs. 4(a) and (b). The echo L^1 was spread due to the spherical concave shape of the probing end. The spurious echo appearing at the time delay of about 4 μs after the echo L^1 was probably the first trailing echo. However, the further trailing echoes were eliminated due to the taper shape and cladding of the rod. Therefore, the desired echoes for imaging purpose, as indicated by "Top" or "Bottom" in Fig. 4, reflected from the character sample were clearly observed with the sufficient SNR.

In the case of water, the focal position was set on the top surface of the sample. The desired echo from the bottom surface of the character (indicated by "Bottom" in lower curve) was about 20 dB smaller than that from the top surface of the sample (indicated by "Top" in upper curve) as shown in Fig. 4(a). This is because the focusing depth, dz, of 0.53 mm in water, as described in Table I, was much

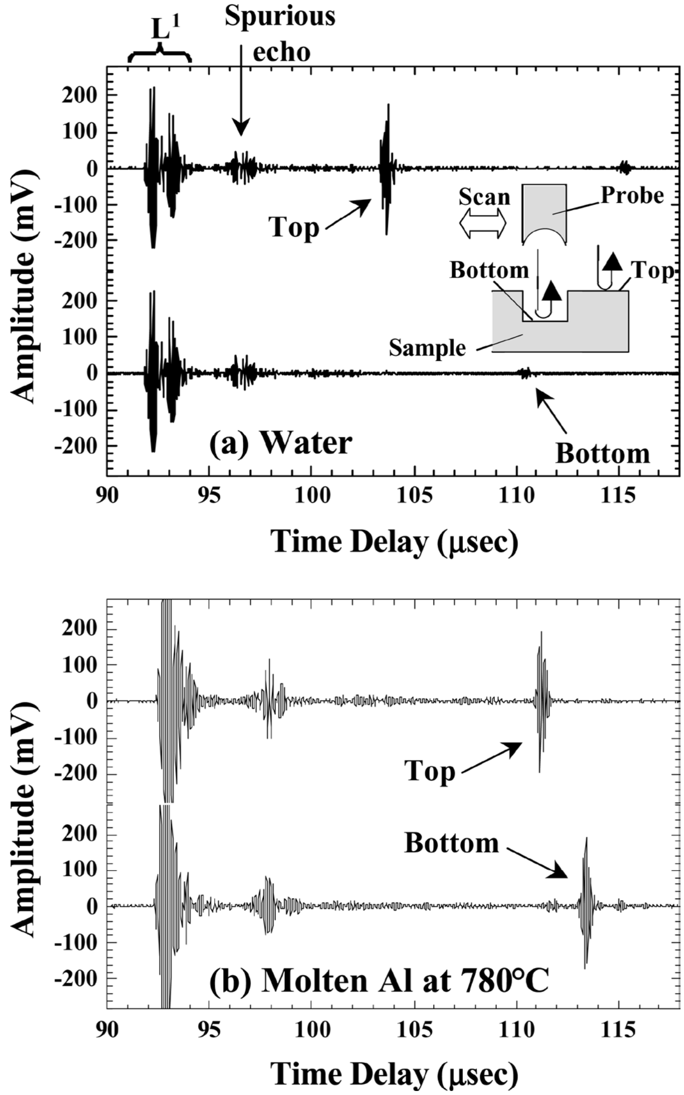

Fig. 4. Reflected signals from the rod and the sample in water at room temperature (a) and in molten Al at 780°C (b).

shorter than the character line depth of 5 mm. On the contrary, in the case of molten Al, the focal position was not as clear as in water, and the echoes from the top surface and those from the bottom surface of the character had almost the same amplitude due to the longer dz of 80 mm as shown in Table I. Furthermore, the time delay of the echoes from the sample in molten Al was greater than in water, even though the longitudinal velocity in molten Al is three times faster than in water. This is due to the fact that the focal length in molten Al was seven times longer than in water, as shown in Table I. A SNR of more than 33 dB was obtained for the echo from the sample surface at the focal position in molten Al.

Figs. 5(a) and (b) show the ultrasonic images measured in water and in molten Al, respectively. It took about 30 minutes for a 25 mm by 25 mm area scan with a scan step of 500 μm in our measurement condition. The upper and lower figures were constructed from the amplitude and time delay of the echoes from the sample surface, respec-

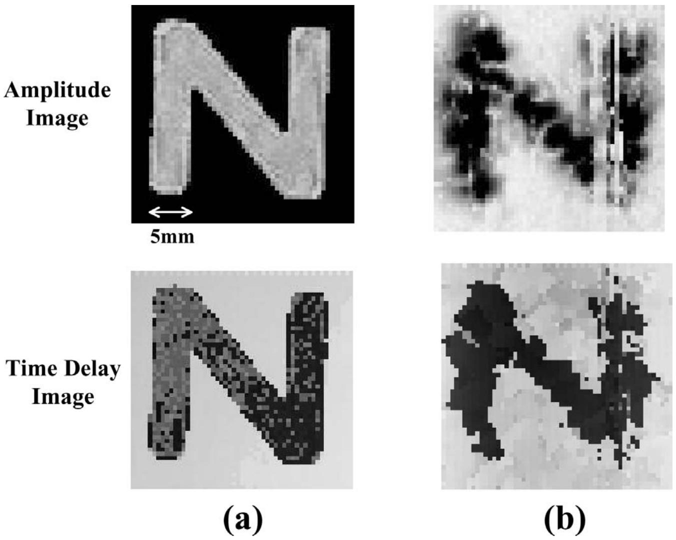

Fig. 5. Ultrasonic images of the character "N" obtained in water at room temperature (a) and in molten Al at 780°C (b) using amplitude and time delay of signals reflected from the sample surface.

tively. The darker color shows the larger amplitude and longer time delay for amplitude and time delay images, respectively. In the case of water [Fig. 5(a)], the amplitude and time delay of the largest echoes from the sample surface were used for the images. The images of the character "N" were clearly observed.

In the case of molten Al [Fig. 5(b)], although the quality of the images is poorer than that in water because of larger lateral resolution as predicted, we can clearly recognize the character "N". For the time-delay images (lower figure), the time delay of the largest echoes from the sample surface was used. For the amplitude image (upper figure), only the echoes from the bottom surface (engraved area) of the character were used because the amplitude of the echoes from the top and bottom surfaces were almost the same in molten Al as shown in Fig. 4(b). This is why the contrast of the amplitude image in molten Al is reversed when compared with that in water.

C. Discussion

Fig. 6 shows ultrasonic three-dimensional images in molten Al constructed by the same signals used for the images shown in Fig. 5(b). It is obvious from Fig. 6 that the values of amplitude over the area of the character "N" were not stable, and the edges of the character were not clear and sharp in both images. One of the reasons of the poorer quality of the image in molten Al is the larger lateral resolution compared to the water as discussed in Section II-A. In our previous work [13], we obtained better ultrasonic images of the characters, even with a character line thickness of 1 mm—which was five times less than the present sample—in molten Zn at 600°C. Because the velocity in molten Zn (2800 m/s) is slower than in molten Al, a higher spatial resolution was obtained in molten Zn. The lateral resolution can be improved using a lens with a smaller value of F/D according to (1). According to (1), a lateral resolution of 2.20 mm could be achieved at 780°C with a lens having an aperture diameter twice the curvature radius used for the present combination of molten Al and steel rod. In addition, higher frequencies and rod materials, such as ceramics, with a larger longitudinal velocity can improve the quality of the image due to better spatial resolution. However, it should be taken into account that higher frequencies have greater ultrasonic attenuation and that ceramics have poor thermal shock resistance.

It should be noted that, on the scanning lines around $Y = 20$ mm, the values of amplitude suddenly increased more than 400 mV, as seen in Fig. 6. This is due to the manual cleaning of the lens surface just before these lines. The cleaning was done using a steel ball with the same diameter as the lens, in order to remove some depositions on the lens surface that might be Al oxide. Such inclusions as oxide particles and films drifted in molten Al, and disturbed and partially blocked the ultrasound propagation in molten Al, which made the detected ultrasonic signals unstable.

Here, we will consider the additional reasons for poorer quality of images in molten Al. Figs. 7(a) and (b) show photographs of the ultrasonic lens at the probing end of the rod and the SS character sample, respectively, immersed in molten Al for 6 hours. It is observed that surfaces of the lens and the sample were corroded significantly in molten Al. The steel reacted with molten Al because of the solubility of iron in molten Al and formation of intermetallic compounds such as Fe_2Al_5 and $FeAl_2$ [26], [27]. Such a corrosion of the lens gradually deteriorates the focusing effect of the probe. Coating materials can improve the corrosion resistance of steel rods, but they may reduce wettability [26]. So far, although it is difficult to explain completely the phenomena at the interface between the probe end and the molten Al, the reaction between steel and molten Al resulted in achieving good ultrasonic wetting between the probing end and molten Al. The reaction may be more active at a higher temperature. Further investigations such as chemical analysis need to be performed to verify the phenomena.

Furthermore, the SS sample immersed in the molten Al, shown in Fig. 7(b), was no longer the same one, shown in Fig. 2, because of the corrosion. The images presented in Figs. 5(b) and 6 reflect the corrosion of the objects in the molten Al. Therefore, it is possible to inspect the objects and their corrosions inside molten Al using our probes. The steel buffer rod can sustain corrosion in molten Al for a short period of time. However, it is important and necessary to investigate the proper probe materials and/or coating materials on the probe, which have good ultrasonic coupling and sufficient corrosion resistance to molten Al.

III. Particle Detection

Cleanliness of molten Al is crucial for part manufacturing and recycling in Al processing; therefore, it is highly

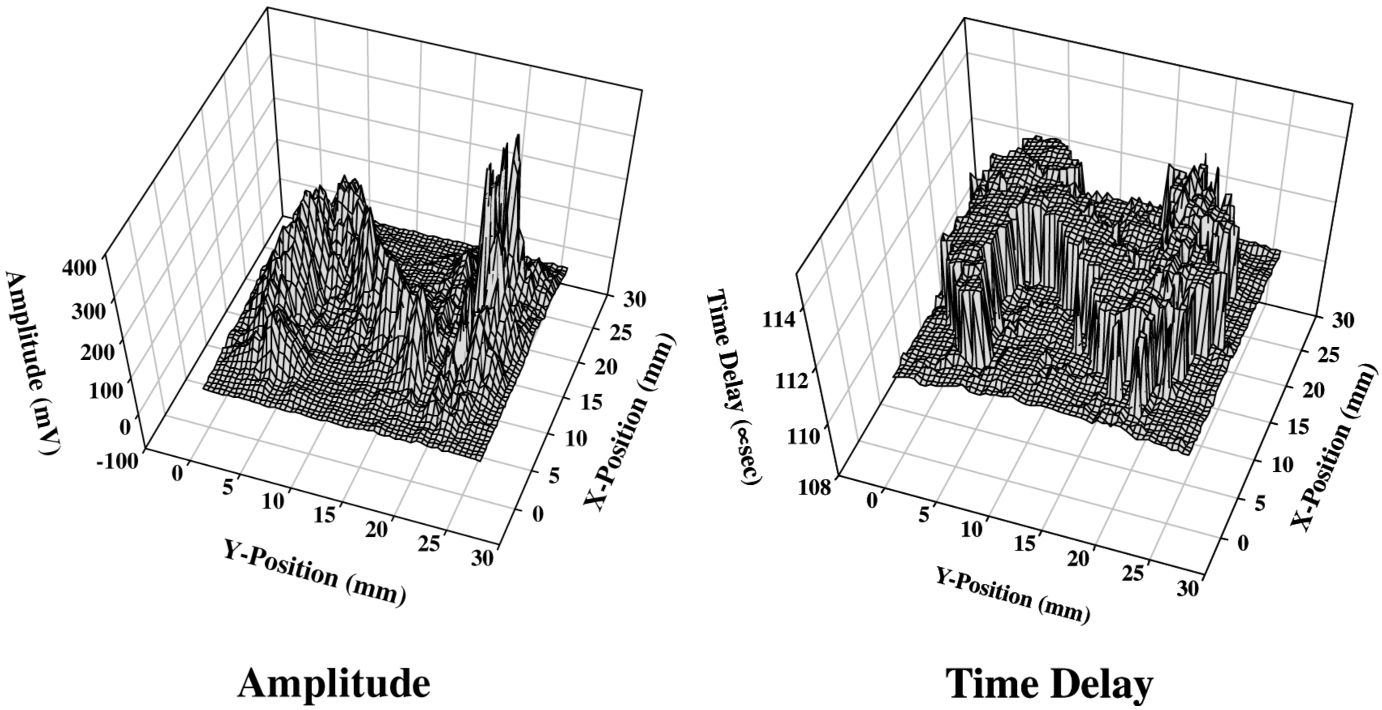

Fig. 6. Ultrasonic three-dimensional images of the character "N" obtained in molten Al at 780°C.

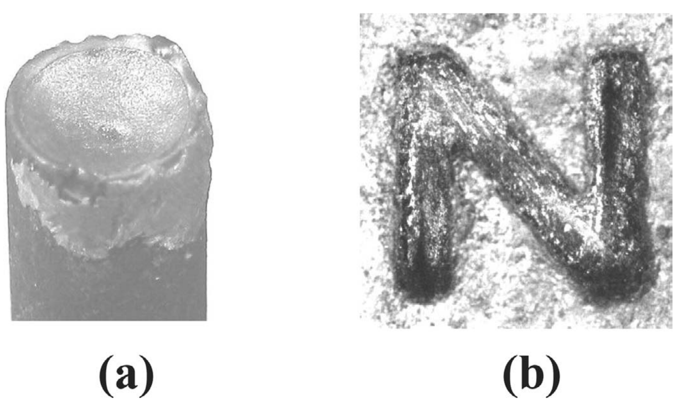

Fig. 7. Photographs of corrosions of the ultrasonic lens (a) and the character "N" engraved on stainless steel (b), immersed in molten Al for 6 hours during experiments.

desirable to monitor and control quality of molten metals and melting processes as mentioned in Section I. One of our goals for this study is to establish quantitative evaluation of metal cleanliness in the molten metal pool for continuous sand- and die-casting. The particle size of inclusions may be less than 1 μm to more than 100 μm. In this section, preliminary experimental results for the detection of particles in molten Al and the evaluation of molten metal cleanliness are presented.

In our previous work [13], we successfully detected particles in molten Zn at 600°C using a focused probe in the pulse-echo mode. The focused probe can provide high spatial resolution, which might allow us to detect smaller particles. However, there are some limitations, such as inspection volume. Although the spatial resolution is crucial for the image quality as mentioned in Section II, we would like to investigate the role of the SNR of the ultrasonic probing system in the detection of the small inclusions in molten Al. One way to enhance SNR is to improve the performance of the probe itself; another is to change the sensing configurations.

A. Experimental Results

Fig. 8 shows a schematic view of a configuration for particle detection in pitch-catch mode using two clad buffer rods with flat probing ends. One probe transmits the plane ultrasonic waves and another one receives the signals scattered by the particles in the molten metals. Clad buffer rods were used here due to the fact that they have a higher SNR than the nonclad one [14]–[16]. Two sensing configurations—namely, the above mentioned pitch-catch mode and the pulse-echo mode—were studied here. In the pulse-echo mode, only one probe is used to serve as both the transmitter and the receiver of the ultrasound. In the experiments, the buffer rods having flat probing ends with almost the same dimensions in length and diameter as the one shown in Fig. 1(a) were used. The Al contained in a SS crucible was heated by the same furnace as shown in Fig. 3. The Ar gas was supplied above the surface of the molten Al to avoid oxidation of the Al as Al oxide is considered a major impurity. Silicon carbide (SiC) particles, with a size range of 30 to 60 μm, were suspended into molten Al as inclusions after the Al completely melted. The molten Al was well stirred manually to distribute the particles uniformly and to prevent clusters of the particles from forming in the molten Al before acquiring signals, although a few signals from the particles were already observed without stirring due to convection of molten Al.

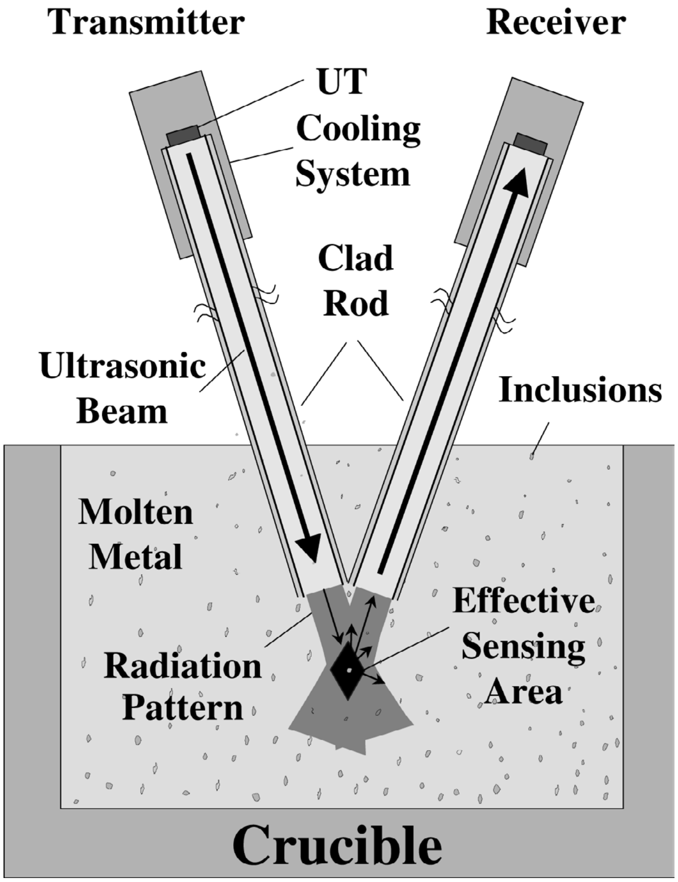

Fig. 8. Schematic view of the inclusion detection configuration in molten metals in pitch-catch mode using two clad buffer rods with flat probing end for plane waves.

The results obtained in the pitch-catch mode are shown in Fig. 9(a). The temperature of the molten Al was 780°C. The length of the rod for the transmitter was 264 mm, and that for the receiver was 272 mm so the time delay in the rods was estimated to be 90 μs. Signals were recorded every 2 ms with a time window of 20 μs covering the whole sensing area in which desired signals were reflected from the particles. However, only the frames at an interval of 40 ms with a time window of 6 μs are shown in Fig. 9. The echoes from the particles appeared in the time-delay range from 96 to 110 μs with our experimental condition. The time-delay range of the echoes appearing depends on the volume and position of the sensing area of the probes and ultrasonic velocity in molten Al. The backscattered ultrasonic signals from particles were observed when the particles passed through the sensing area as shown in Fig. 8. Movements of the individual particles were clearly visible due to our special carefulness to suspend the particles without clusters into molten Al. It should be noted that we also have detected echoes reflected from polyvinyl chloride (PVC) particles with an average diameter of 30 μm in water with the same configurations in which the diameter of the probing ends was 14 mm. Because PVC particles are known to disperse well in water, it is our conclusion that the spatial resolution is not the main limiting factor for particle detection. In the case of actual industrial conditions and environments for molten Al processes, it is necessary to verify that particles are not clustered and signals are not caused by other inclusions, such as Al oxide created by reaction of molten Al with air.

The results obtained in the pulse-echo mode using one probe are shown in Fig. 9(b). The temperature was 770°C, and the length of the rod was 280 mm. The echo L^1 from the probing end and a spurious echo, which might be the first trailing echo, were observed at the time delay of 97 μs and 101 μs, respectively [these echoes are not shown in Fig. 9(b)]. Therefore, the SNR of the echoes from the particles was poor in the time-delay range before 101 μs. However, by selecting the proper sensing area in the time-delay range after 101 μs, we could observe the echoes from the particles and their movements in the pulse-echo mode with sufficient SNR as shown in Fig. 9(b) as well as in the pitch-catch mode.

B. Discussion

Here, we compare the two sensing configurations. In the pitch-catch mode, one can have high dynamic range due to the high SNR and control the effective sensing area by adjusting the distance and angle between two buffer rods. However, careful alignment of the rods is required. However, alignment is not necessary in the pulse-echo mode; but, one has to consider at least the existence of the echo L^1 from the probing end and the first trailing echo in our experimental condition. These echoes form a blind zone in the ultrasonic sensing area. This means that, when signals from inclusions appear in these time windows (intervals), they will not be observed due to the insufficient SNR. However, a sufficient SNR could be obtained by selecting the proper time window in the pulse-echo mode.

Because the movements of the particles were random in molten Al, it is difficult to determine the size and number of the particles from the signals obtained in these experiments. However, we believe that they could be determined by controlling the particle movements and speed using a tube and a molten metal pump. Further study for the procedure and system for quantitative evaluation of molten metal cleanliness by sizing and counting the inclusions was presented elsewhere [28].

From the signals obtained in this experiment, the relative cleanliness of the molten Al is investigated. We have chosen the pitch-catch mode because it has a higher SNR in the wider time window than the pulse-echo mode. After the SiC particles were added, the molten Al was stirred manually only before acquiring the signals. The bar graph shown in Fig. 10 presents the variation of the total power of the detected signals with respect to the measurement time. The total power was obtained by summation of the power of the detected signals appearing in the time-delay ranges from 96 to 110 μs during 5-second acquisition periods in each 20 seconds. The temperature range was between 712 and 716°C during the entire experiments. Just after stirring the molten Al, the detected power was a maximum as

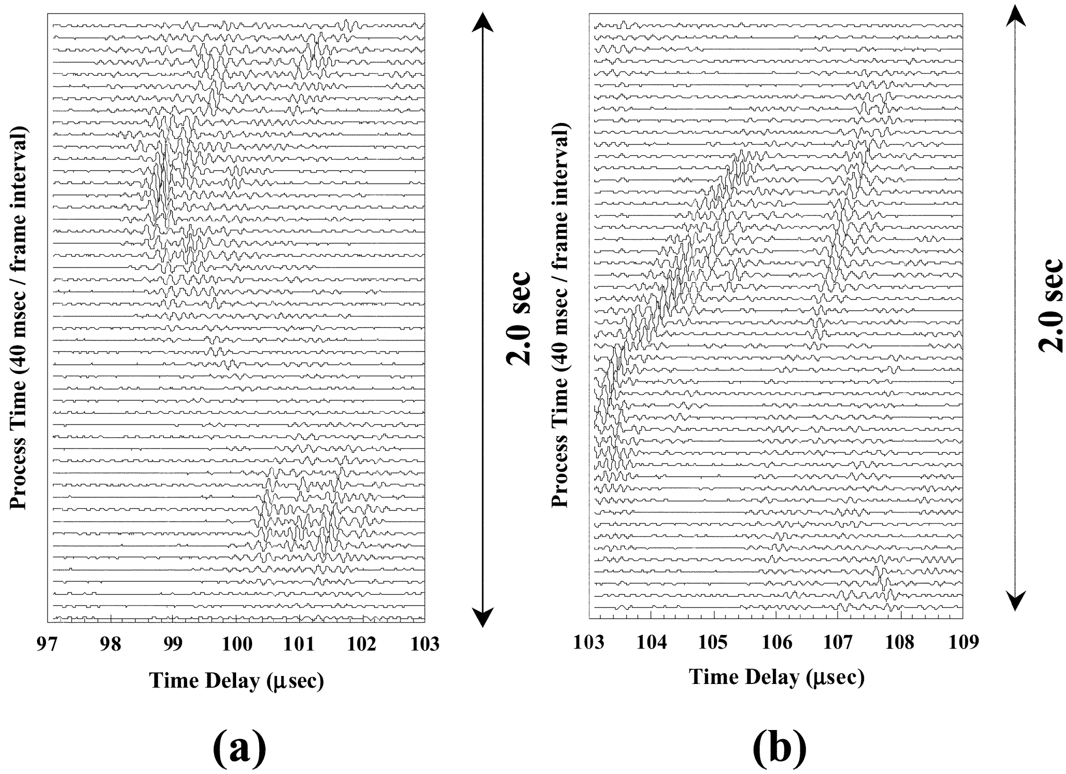

Fig. 9. Detected backscattered signals from inclusions suspended in molten Al in pitch-catch mode (a) and in pulse-echo mode (b).

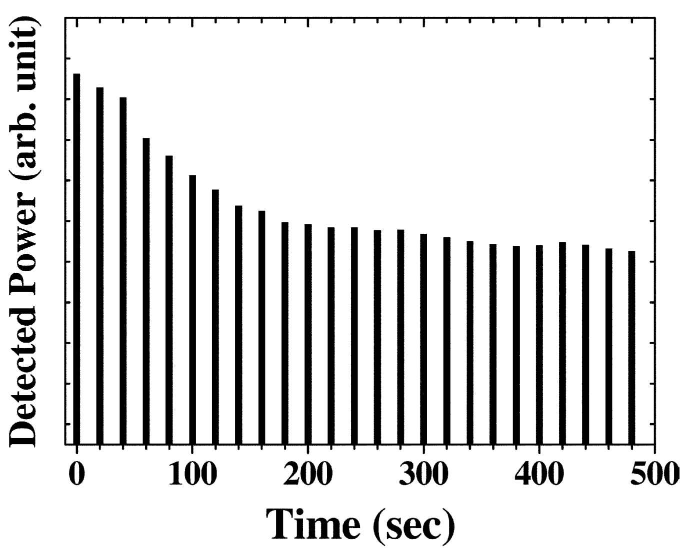

Fig. 10. Variation of total power of the detected signals in molten Al at 715°C with respect to measurement time after stirring molten Al in pitch-catch mode.

the SiC particles were distributed uniformly in molten Al, and many particles passed through the sensing area. However, the detected power gradually decreased because the particles that were heavier than molten Al precipitated to the bottom of the crucible, and less and smaller particles passed through the sensing area. After 200 seconds, the total power became almost constant because a fixed number of particles were floating due to circulation of molten Al by convection. The result, shown in Fig. 10, indicates that relative cleanliness with respect to depth of molten Al can be evaluated by moving the probes along the thickness direction of the molten Al, because dirty melts scatter back more ultrasound than clean melts.

IV. Wetting Evaluation and Temperature Sensing

It is known that alumina has a strong corrosion resistance and little wettability to molten Al [29], [30]. Commonly, a contact-angle method is used to evaluate the wettability between a liquid and a solid [31]. Our interest here is to use an ultrasonic technique as an alternative method to study the wetting behavior at the interface between molten Al and alumina at elevated temperatures, which is related to corrosion resistance. A poorer ultrasonic coupling means a poorer wetting, which gives a higher corrosion resistance. If the wetting exists, we may use an alumina rod as an ultrasonic buffer rod in molten Al because the ultrasound can be propagated from the alumina into the molten Al. Conversely, the alumina buffer rod may be used as a temperature sensor [32], [33] due to the fact that ultrasonic velocity in alumina is temperature dependent [34].

In the experiments, an alumina rod (Purity: 99.8%, Coors Tek, Golden, CO) with a uniform diameter of 20 mm and a length of 152 mm without cladding was used in the pulse-echo mode. A 10 MHz UT was attached to the UT end of the rod. An air-cooling tube made of SS was set

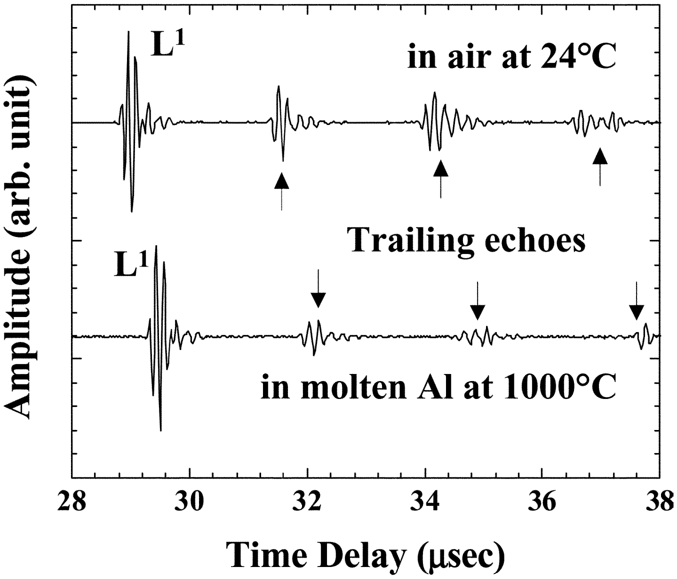

Fig. 11. Observed signals in alumina rod in air at 24°C (upper line) and in molten Al at 1000°C (lower line). Arrows show trailing echoes.

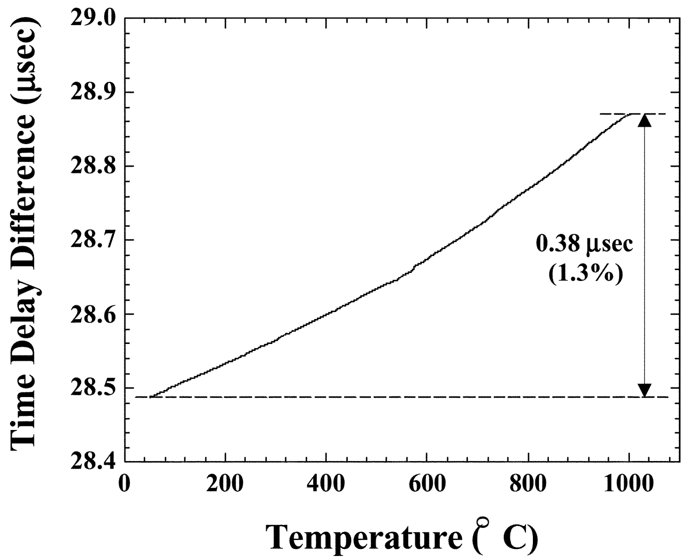

Fig. 12. Time-delay difference between the echoes L^1 and L^2 reflected from the alumina rod as a function of temperature measured by thermocouple.

outside of the rod as it was with the steel rods used in Sections II and III.

A. Experimental Results

The probing end of the alumina rod and the Al first were heated side by side from room temperature up to 1000°C in order to avoid thermal shock for the alumina rod. Then the probing end of the alumina rod was immersed into molten Al to a depth of 5 mm. Signals, including the first and second round trip echoes (L^1 and L^2, respectively) in the rod, were recorded every 5 seconds during cooling. Temperature of the molten Al was measured simultaneously by a thermocouple in contact with the side surface of the rod. The tip of the thermocouple was flush with the probing end surface of the rod. The cooling rate was about 200°C/hour. Fig. 11 shows the measured echo L^1 and a few trailing echoes induced in the rod in air at 24°C (upper line) and in molten Al at 1000°C (lower line). The echo L^2 is not presented in Fig. 11. The time delay of the echo L^1 measured in molten Al at 1000°C was 400 ns greater than that in air at 24°C. This is because of the smaller longitudinal velocity in the alumina rod and the longer propagation distance due to thermal expansion of the rod at the higher temperature [34].

As seen in Fig. 11, the waveform and amplitude of both L^1 echoes at 24°C and 1000°C were almost identical. This means that the ultrasonic energy was totally reflected at the probing end of the rod and not transmitted into the molten Al, even though the alumina has almost the same acoustic impedance as steel for longitudinal waves. Therefore, it is confirmed that, because no visible ultrasonic coupling existed between the alumina rod and molten Al, no wetting existed at this interface. Hence, alumina is a good corrosion-resistant material for molten Al, but it is not a proper material for use in probes for the ultrasonic imaging and particle detection in molten Al. In addition, the ultrasonic coupling coefficient at a solid material/molten metal interface could be used to evaluate the degree of wetting at this interface because a poorer ultrasonic coupling means a poorer wetting at the interface. Further studies will be carried out in the future.

B. Discussion

It was verified, by visual inspection, that little corrosion of the alumina rod immersed into molten Al was observed after 5 hours. In addition, the time delay of the echoes in the rod, shown in Fig. 11, was temperature dependent. Therefore, it is of our interest to investigate a method for measuring the temperature of the molten Al by using variations of the ultrasonic velocity or the time delay in an alumina rod immersed in molten Al. The signal reflected from the probing end of the rod was stable and had almost no deformation of the waveform in the temperature range from room temperature to 1000°C as shown in Fig. 11. This proves that there was no ultrasonic coupling between the alumina rod and molten Al.

Fig. 12 presents the variation of the time-delay difference between the echoes L^1 and L^2 at different temperatures obtained by a cross-correlation method. The time-delay difference increased monotonically with respect to the temperature measured. The maximum change of the time-delay difference was 1.3% for a temperature variation of 950°C. The changing ratio of the time-delay difference with respect to the temperature was 0.49 ns/°C at the molten state of Al (614–1000°C) under our experimental condition. Because a large temperature gradient inside the alumina rod existed, it is difficult to predict the absolute temperature of molten Al numerically from the measured time delay. However, the relative temperature changes could be monitored using a calibration curve between the temperature and the time delay difference shown in Fig. 12. Therefore, the alumina rod could be used as an excellent temperature sensor material in molten Al under 1000°C.

V. Conclusions

This paper demonstrated the capability of ultrasonic techniques for imaging and measurements in molten Al using the buffer rod operated at 10 MHz. Ultrasonic imaging of the object immersed in the molten Al was attempted using the clad steel buffer rod having an ultrasonic lens at the probing end. The image of a character "N", engraved on a stainless steel plate, and its corrosion in molten Al were observed at 780°C in the pulse-echo mode due to the high SNR of the rod. The SNR of more than 33 dB was obtained for the desired echo from the sample surface at the focal position in molten Al. It was verified that our probe could inspect the objects inside the molten Al.

The backscattered ultrasonic signals from the SiC particles, with an average diameter of 50 μm, suspended in molten Al were successfully observed at 780°C both in the pitch-catch and the pulse-echo modes using nonfocused, clad steel buffer rods. Movements of individual particles were clearly visible. High SNR leads to high dynamic ranges of detectability of inclusions. For optimal image quality, the spatial resolution of the focused probe was crucial, and the high SNR of the nonfocused probe was the prime factor responsible for the inclusion detection sensitivity using backscattered ultrasonic signals. The relative cleanliness evaluation of the molten Al was demonstrated in the pitch-catch mode at 715°C. The development of the quantitative evaluation of the metal cleanliness by measuring the size and counting the number of inclusions was presented elsewhere [28]. Although the results shown here were obtained at temperatures higher than 700°C, it should be noted that the signals from the particles were observed at temperatures even less than 700°C. However, the amplitude of the detected signals was larger at higher temperature because of less attenuation of ultrasound in molten Al due to lower viscosity and better ultrasonic coupling between the steel rod and the molten Al.

A poorer ultrasonic coupling at the interface between a solid material and a molten metal means a poorer wetting at this interface, which gives a higher corrosion resistance of the solid. Hence, the ultrasonic coupling coefficient at a solid material/molten metal interface can be used to evaluate the degree of wetting at this interface. Our experimental results showed that, because there was no ultrasonic coupling at the interface between the alumina rod and molten Al up to 1000°C, no wetting existed at such an interface. In addition, little corrosion of the alumina rod was inspected visually after the experiment. Therefore, the ultrasonic technique is an alternative method to prove that alumina has high corrosion resistance toward molten Al. Because of this and ultrasonic velocity in alumina is temperature dependent, alumina rod then was proved to be able to be used as in-line ultrasonic temperature sensor material under 1000°C.

The probe material concerns for long-term immersion in molten Al still remain to be investigated for imaging and particle detection. It is necessary to consider the rod and/or coating materials that have high-corrosion resistance as well as good ultrasonic coupling to molten Al. In addition, it is important for industrial applications to investigate optimum design of the rod in order to enhance their performance. Such factors as SNR, signal strength, and the ability to reduce the rod fabrication cost [35] need to be considered because a high SNR can make many practical ultrasonic applications feasible.

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