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DESIGN NOTE

Ultrasonic imaging in molten magnesium

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Abstract

Processing magnesium (Mg) and its alloys in the molten state is often necessary for the refining and recycling, and for the casting to achieve the net shape forming. The containers to hold the molten Mg are commonly made of steel. There is a concern that the steel wall of the container will corrode from the inside, which might induce cracks resulting in dangerous and expensive spillage. In this note, development of ultrasonic techniques for imaging in molten Mg using clad steel buffer rods operated at 10 MHz is presented. The probing end of the buffer rod, having an ultrasonic lens, was immersed into molten Mg, 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, which simulates a surface defect on a plate, immersed in molten Mg has been successfully observed at 690 °C using the focused probe.

Keywords: ultrasound, clad buffer rod, imaging, molten magnesium, high temperature, ultrasonic lens

1. Introduction

Recently, the utilization of magnesium (Mg) alloys for structural applications in manufacturing, especially in the automobile industries, has been increased rapidly. This is mainly due to advantages of Mg alloys such as low weight and high strength-to-weight ratio compared with metals such as iron (Fe), aluminium (Al) and zinc (Zn), resulting in the improvement of the fuel efficiency and the environmental performance of the vehicles. Such features are also desirable to the electronic and telecommunication industries for portable devices such as laptop computers and cell phones. The containers to hold the molten Mg are commonly made of steel. There is a concern that the steel wall of the container will corrode from the inside, which might induce cracks resulting in dangerous and expensive spillage. Since the removal of molten Mg for inspection might be time consuming and costly, there is

a need to inspect and image the steel container inside the molten Mg. However, no ultrasonic imaging attempt has been reported to inspect defects in steel in molten Mg because it seems that no imaging probe and technique were available. The purpose of this investigation is then to develop ultrasonic probes and techniques to image a simulated defect on the surface of a steel plate immersed in molten Mg.

Ultrasonic probes used in the earlier studies involving molten metals were composed of ultrasonic transducers and buffer rods having no cladding [1–5]. The metals involved were mostly aluminium alloys. Due to the lack of cladding, the signal-to-noise ratio (SNR) of the ultrasonic signal in such non-clad buffer rods is 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 mainly because of mode conversion, diffraction, etc. Our previous works have demonstrated that the cladding improves ultrasonic guidance in the probe and increases the SNR [6–9]. The higher the SNR, the better the image.

Furthermore, recently we also used an ultrasonic lens to focus the ultrasonic energy for ultrasonic imaging in molten Zn [6] and molten Al [7]. In this study, we will use an

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Figure 1. Double-taper shape clad steel buffer rod; external view (a) and spherical concave ultrasonic lens fabricated at the probing end of the rod (b).

ultrasonic imaging experiment to evaluate the performance of the ultrasonic lens in molten Mg. It should be noted that ultrasonic wetting conditions, corrosion of the probe and ultrasonic attenuation in molten Mg are different from those in molten Zn and Al. The clad steel buffer rod used in this study may be a promising candidate for molten Mg process monitoring, since Mg and its alloys in the molten state are almost universally processed using iron or steel tools such as pipes, containers and moulds [10] due to the facts that no intermetallic phase can form between solid Fe and pure molten Mg and that the mutual solubility between them is low [11].

In this note, ultrasonic imaging in molten Mg using a clad steel buffer rod having an ultrasonic lens on the probing end of the rod is investigated in order to evaluate the capability of this steel rod as a probe to carry out ultrasonic imaging of a simulated defect in a steel plate immersed in molten Mg.

2. Imaging

It is understood that a buffer rod can be used as a probe to perform ultrasonic measurements in molten metals [1–9]. However, the well known problem in using a long buffer rod in the ultrasonic pulse-echo technique is the presence of spurious echoes, namely trailing echoes [12], 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, since they interfere with desired signals from an inspected object 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 [13]. In addition, cladding effectively works on not only reducing the trailing echo but also enhancing the ultrasonic guidance, which results in better SNR [8, 9]. In this section, the ultrasonic imaging in molten Mg is performed in the pulse-echo technique to evaluate the SNR and focusing ability of ultrasonic probes using a clad steel buffer rod with a double-taper shape in molten Mg.

2.1. Experimental set-up

Figure 1(a) shows a double-taper shape clad buffer rod, consisting of a mild steel core and a stainless steel (SS)

Table 1. Comparison of focusing ability of ultrasonic probe, shown in figure 1, in water at 23 °C and molten Mg at 690 °C. F , focal length; dr , lateral resolution; dz , focusing depth.

	In water at 23 °C	In molten Mg at 690 °C
F (mm)	8.5	25.7
dr (mm)	0.11	0.92
dz (mm)	0.53	14.4

cladding, used in the experiment. One end of the rod has a spherical concave ultrasonic lens, as shown in figure 1(b), to focus ultrasonic energy in molten metals, and the other end has a flat surface to which an ultrasonic transducer (UT) is attached. The taper angle was 2°, and the radius of curvature and the aperture diameter of the lens were 6.35 and 11.5 mm, respectively. The thickness of the cladding was 1 mm. The detailed design of the rods such as taper angle and the rod evaluation have been presented in the literature [8, 9, 14]. A commercially available 10 MHz longitudinal UT (model A127S, Panametrics, Waltham, MA, USA), which radiates and receives pulsed ultrasound with a pulser–receiver, was attached to the UT end of the rod with an air-cooling system. The ultrasonic signals were recorded using a data acquisition board with a resolution of 12 bits and a sampling rate of 100 MHz. The basic set-up was almost the same as in our previous works in molten Zn [6] and molten Al [7].

The character ‘N’ was engraved on the SS plate (S304). This simulates a defect on a steel plate. The area of the character was 20 mm square, and the line thickness and depth of the character were 4 and 5 mm, respectively. The character sample was fixed on the bottom of an SS crucible containing molten Mg. The temperature of the molten Mg was measured by a thermocouple. CO₂ gas containing 1% sulfur hexafluoride (hereafter referred to as SF₆ gas) was continuously supplied as a protective gas over the Mg, which created a protective film on the melt surface, in order to prevent oxidation and burning of molten Mg [15] since molten Mg is reactive with oxygen and ignites in the atmosphere [10, 16].

Here, we evaluate the focusing ability of ultrasound using this probe numerically at an ultrasonic frequency, f , of 10 MHz in order to estimate spatial resolution for imaging in molten Mg with comparison of that in water, since water is one of the ideal couplants in ultrasonic measurements. It is predicted that the image in water represents the best possible result that we could obtain in molten Mg. The lateral resolution, dr , and focusing depth, dz , are approximately calculated using the following equations [17]:

$$dr \approx 1.02\lambda(F/D) \quad (1)$$

$$dz \approx 7.1\lambda(F/D)^2, \quad (2)$$

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 $\lambda = v_{\text{liquid}}/f$ and $F = R/(1 - v_{\text{liquid}}/v_{\text{steel}})$, respectively, where v is longitudinal wave velocity and R is a curvature radius of the lens. The calculated values of F , dr and dz are summarized in table 1. The values of v_{liquid} for molten Mg and v_{steel} at 690 °C are 4043 m s^{−1} [18] and 5368 m s^{−1} [19], respectively, and the values of v_{liquid} for water and v_{steel} at 23 °C are 1491 m s^{−1} [20] and 5923 m s^{−1} [19],

Figure 2. Reflected signals from the rod and the sample in water at room temperature (a) and in molten Mg at 690 °C (b).

respectively. F in molten Mg is three times as long as in water with the presented probe. It is predicted that because the ratio of the velocity of the steel over that of the liquid ($v_{\text{steel}}/v_{\text{liquid}}$) is only 1.3 for molten Mg while it is 4.0 for water, spherical aberration [21] is large for this imaging lens configuration and causes the resolution to be poorer in molten Mg than in water. The dr estimated in molten Mg is about eight times as large as in water with the presented probe.

2.2. Experiments and results

The experiment was firstly carried out in water, then that in molten Mg (purity 99.80%) was conducted using the same probe and sample. Figures 2(a) and (b) show observed ultrasonic signals in water at room temperature and in the molten Mg at 690 °C, respectively. The focal position was set on the top surface of the sample. The signals from the top surface (indicated by 'Top' in figure 2(a)) were the echoes reflected from the non-engraved area of the SS plate and those from the bottom surface (indicated by 'Bottom') were from the engraved area of the character 'N' (see the inset in figure 2(a)). The first round trip echo of the longitudinal wave in the rod, indicated by L^1 , in the molten Mg was about 3 μs larger than that in water due to the significant increase in temperature of the buffer rod in the molten Mg. 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 owing to the taper shape and cladding of the rod. Therefore, the desired echoes for imaging purposes, as indicated by 'Top' or 'Bottom' in figure 2, were observed with the sufficient SNR both in water and molten Mg. The

SNRs obtained for the top and bottom echoes in water were 36 and 15 dB, respectively, and those in the molten Mg were 30 and 19 dB. Such SNRs are sufficient for performing ultrasonic imaging.

Figures 3(a) and (b) show the ultrasonic images obtained in water and in the molten Mg, respectively. It took about 30 min for a 25 mm by 25 mm area scan with a scan step of 500 μm in our experimental conditions. The upper and lower figures were constructed from the amplitude and time delay of the echoes, respectively. In the case of water (figure 3(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 Mg (figure 3(b)), although the quality of the images is poorer than that in water because of larger lateral resolution as predicted, we can recognize the character 'N' in both images. It should be noted that for the time delay images (lower figure) the time delay of the largest echoes from the sample surface was used, while for the amplitude image (upper figure) only the echoes from the bottom surface (engraved area) were used, since the amplitudes of the echoes in the molten Mg were not stable as can be seen in figure 3(b), and an amplitude image obtained using both signals from the top and bottom echoes did not have better quality than the one shown in figure 3(b).

Here, the longitudinal wave velocity in the molten Mg is experimentally estimated. An average value of time delay difference, ΔT , between the echoes from the top and bottom of the character 'N' was obtained to be 2.476 μs from the data used for the time delay image shown in figure 3(b). In addition, the average depth, H , of the character 'N' was obtained to be 5.00 mm using the values of depth measured at seven different points by a micrometer with a resolution of 10 μm . Therefore, the longitudinal wave velocity, v , is calculated to be 4039 m s^{-1} in the molten Mg at 690 °C by the equation $v = 2H/\Delta T$, which has good agreement with the literature value of 4043 m s^{-1} [18] described in section 2.1. This means that the time delay image represents the information of the shape variation of the object in the melt along ultrasonic beam axis, which is vertical (melt depth) direction in the presented experiment. The amplitude variation in the amplitude image shown in figure 3(b) is further discussed later.

2.3. Discussion

One of the reasons for the poorer quality of the image in the molten Mg shown in figure 3(b) is the larger lateral resolution in the molten Mg than in water as discussed in section 2.1. Higher frequencies and rod materials, such as ceramics, having larger longitudinal velocity can improve the quality of the image due to better spatial resolution according to equation (1). However, it should be taken into account that higher frequencies have greater ultrasonic attenuation and that ceramics have poor thermal shock resistance and are corroded by molten Mg.

It is obvious from figure 3(b) 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. As mentioned previously, there was a protective film, consisting of MgO and MgF_2 , having a thickness of less than 1 μm on the surface of the molten Mg due to SF_6 gas [22]. In addition, it should be considered that MgO particles were probably created by the oxidation of the molten Mg since a part of the protective film

Figure 3. Ultrasonic images of character 'N' obtained in water at room temperature (a) and in molten Mg at 690 °C (b) using the amplitude and time delay of signals reflected from the sample surface.

was momentarily torn due to the scanning of the buffer rod in the molten Mg. Such films and particles could be drifting in the molten Mg and partially blocking the ultrasound propagation in the molten Mg, which made the detected ultrasonic signals unstable. They might also deposit on the sample and/or lens surfaces. In addition, the sample and lens surfaces may have been corroded in the molten Mg at high temperature, which is discussed as follows.

After about 4 h immersion of the probing end of the rod and character sample in the molten Mg at a temperature of around 690 °C for the experiment, the molten Mg was removed from the crucible. Then, the probing end and the sample surface were investigated by visual inspection. No significant corruptions on either of them were observed. The edges and corners of the sample were as sharp as before the experiment. It was reported that several microns of roughness would be induced on the surface of the mild steel immersed in molten Mg due to the dissolution of iron (Fe) [23]. However, the effect of such roughness of the lens surface on the image quality could be negligible at the presented frequency of 10 MHz, since the roughness is much smaller than the longitudinal wavelengths of about 500 μm in mild steel and of 400 μm in molten Mg at 690 °C.

In addition, it was also reported that aluminium (Al) and silicon (Si) present as impurities in molten Mg could combine with Fe to form a thin layer, having a thickness of several microns, of an $\alpha\text{-Fe(Al, Si)}$ and/or $\text{Fe}_2(\text{Al, Mg})\text{C}$ on the surface of mild steel [23]. The effect of such layers on ultrasound transmission at the interface between the probing end and molten Mg and on the focusing capability of the lens

needs to be investigated if the above-mentioned impurities exist in molten Mg. However, it should be noted that in our previous work [9] we did not notice any physical degradation of the performance of the clad steel rod for the 330 h operation in the molten Mg in an industrial environment. Therefore, the focused clad steel buffer rod could be applicable to inspect the object and its condition in molten Mg for a sufficient period of time. Further investigation is necessary to improve the quality of the image in order to apply this ultrasonic technique to solve industrial problems.

3. Conclusions

This note has demonstrated the capability of ultrasonic imaging in molten Mg using clad buffer rods operated at 10 MHz. Ultrasonic imaging of the object immersed in the molten Mg was attempted using the double-taper shape focused clad steel buffer rod. The image of a character 'N', engraved on a stainless steel plate, which simulated a surface defect on a steel plate immersed in the molten Mg was clearly observed at 690 °C in the pulse-echo mode due to the high SNR of the clad buffer rod. The SNR of 30 dB was obtained for the desired echo from the sample surface at focal position in the molten Mg. It was verified that our probe could inspect the objects and its conditions, and sustain for a sufficient period of time in the molten Mg.

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