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A model of blind zone for in situ monitoring the solid/liquid interface using ultrasonic wave

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ABSTRACT

To in situ monitor a solid/liquid interface to control metal qualities, the paper analysis blind models of the ultrasonic propagation in the solidifying molten metal with a solid/liquid interface in the Bridgman type furnace, and a mathematical calculation model of blind zone with different source locations and surface concavities is built. The study points out that the blind zone I is caused by ray bending in the interface edge, and the blind zone II is caused by totally reflection which is related with initial ray angle, critical refraction angle of solid/liquid media. A serial of simulation experiments are operated on the base of the model, and numerical computation results coincide with model calculated results very well. Therefore, receiver should locate beyond these blind zones in the right boundary to obtain time of flight data which is used to reconstruct the solid/liquid interface.

1. Introduction

Metal properties are strongly dependent upon microstructures produced during the metal solidification, and the solidified metal must suffer heat treatment to alter structures when microstructures are not ideal, therefore, solidification is an important link to obtain wanted metal properties. It is commonly held that the interface between the solid and liquid phase during unidirectional solidification affects metal qualities [1–4], thus, considerable attention is attracted by in situ observation of molten metal and real-time reconstruction of solid/liquid interface in the Bridgman type furnace using ultrasonic wave due to its nondestructive examination [5–8].

Currently, two ultrasonic approaches are commonly applied to monitor a solid/liquid interface [9,10]. A pulse-echo method was investigated by Parker [11], its principle is wave reflection in the solid/liquid interface, and the interface position can be located based on the time of pulse-echo and the wave velocity in the liquid metal. Early research reported that the interface position in both freezing and melting of 99.9 Sn could be easily detected to ±1 mm by sharp echoes, Carter and Lam [12] would able to locate the interface of germanium within 0.3 mm. Moreover, this technique is being developed for high-temperature applications, Ihara and Burhan [6,7] used pulse-echo method to in situ observe solid/liquid interface of aluminum and aluminum alloy in the temperature up to 800 °C, they successfully monitored a clear reflected echo form a solid/liquid interface during heating and cooling. Although, pulse-echo method was able to locate the interface position and was still attractive, little information of interfacial curvature was involved.

The other alternative approach is time-of-flight (TOF) method [9], this method is sought to measure the TOF of ultrasonic wave signal propagated through a solid/liquid interface by ultrasonic sensors, and mathematical reconstruction methods, such as a nonlinear least-squares, were used to reconstruct the interface location and shape combined with wave velocities and TOF data [13–16]. Wadley et al. used a laser source and a heterodyne laser interferometer as a receiver, and they pictured TOF with different interface shapes and reconstructed solid/liquid interfaces in two dimensional and three dimensional perspectives, reconstructed interfaces coincided with actual interfaces well [17–20]. In two dimensional wave propagation process, it is reported that the blind zone or dark zone where ultrasonic wave does not propagate existed because of wave totally reflection [18,19]. In the dark zone, a problem that the receiver does not detect any signal of TOF would affect surface reconstruction, therefore, it was significant to find out those blind zones to ensure that the receiver located beyond blind zones. However, little attention was focused on blind zone that was a key to reconstruct the solid/liquid surface.

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This paper is sought to model a blind zone of ultrasonic wave when it propagates through a solidifying molten metal, and find out relationships among blind zone, shape of the surface and location of ultrasonic source, then, minimize blind zone effect to realize real-time monitor solid/liquid interface to carry out closed loop feedback control of metal qualities. In the first part, the paper mainly discusses the mathematical model of blind zone with different surface shapes and source positions; the second part, the paper simulates all models above mentioned and compares results with mathematical models; the last part, the paper summaries results of mathematical model and simulation, and proposes better approaches to real-time monitor solid/liquid interface.

2. Mathematical models

Currently, Bridgman-type technology is the main method to research metal unidirectional solidification and blind zone appears only in the concave interface that molten liquid is above and solidified metal is blow according to Queheillalt and Wadley [16,17], therefore, we design a cylindrical sample shown in Fig. 1.

The ultrasonic source, which can be moved along the y axis, locates in the left outer boundary and the receiver arrays in opponent boundary. An ultrasonic ray emanated from the source meets the interface at a point, and refracts to another medium, the ray will bent by Snell's law due to different velocities of ray in two mediums, and then reaches the right boundary where the receiver can detects this signal [18]. Simultaneously, there would be an area where the bent ray cannot travel through and the receiver cannot detect any signal, this area is the blind zone that we aim to find out.

Previous research reported that the concave interface is a spherical cap and the center of the curvature on the y axis [17]. Define the sample cylinder radius R and interface concavity h, the interface radius R_s is given by

$$R_s = \frac{R^2 + h^2}{2h} \tag{1}$$

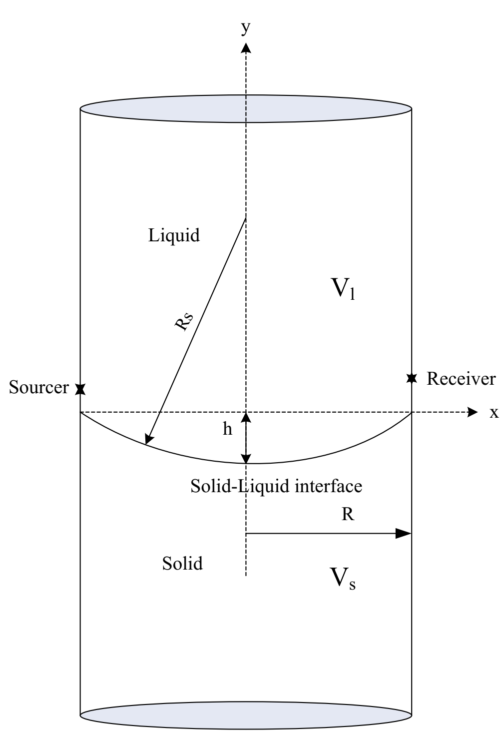

Fig. 1. A simple model for experiment research.

Location of the ultrasonic source directly affects the velocity of initial ray and refraction at the interface, the blind zone would be different [21,22].

2.1. Source in the liquid

If the source point S locates in the liquid metal above the curvature, a part of rays emanated from the source would directly transmit to the right boundary, and the other rays are bent by the interface shown as Fig. 2 [23]. To simple the mathematical model, we define the center of the curvature to be on the top boundary and set a coordinate system.

In the figure, ray path L_4 bends in the interface edge caused by the interface using Snell's law, therefore, the first blind zone I can be gotten. As the velocity of the ray in the solid exceeds that in the liquid, a critical incident angle, whose refraction angle is $\pi/2$, would appears during the ray propagation, and any ray's incident angle is greater than the critical angle, the ray would be totally reflected and cannot propagate into the liquid, then there would be a zone where no signal travels. To solve the blind zone, it is important to find out the critical incident angle and the ray incident angle. According to Snell's law, the critical incident angle can be obtained by

$$\beta = \sin^{-1}(v_l/v_s) \tag{2}$$

where v_l is the velocity of ray in the liquid and v_s is the velocity in the solid.

By geometrical relation, angle θ_1, θ_2 and θ_3 can be given by

$$\theta_1 = \tan^{-1}\frac{R}{R_s - h}, \quad \theta_2 = \tan^{-1}\frac{2R}{h_1} - \tan^{-1}\frac{R}{R_s - h}, \quad \theta_3 = \tan^{-1}\frac{2R}{h_1} \tag{3}$$

An arbitrary ray path L_3 transmitted by the source point $S(-R, h_1)$ intersects the interface at a point $A(x_1, y_1)$ with an angle θ respect to the interface normal, and only when the incident angle $\theta \leqslant \beta$, ray would be refracted at the interface and then propagate in the solid, whereas, ray would be totally reflected. We find that when the ray path is tangential to the straight line L and intersects the circle at a point $B(x_2, y_2)$, the incident angle θ_4 between the ray path L_2 and normal line l_2 is the largest, and the incident angle along the circle $\overset{\frown}{CB}$ is becoming larger and along the circle $\overset{\frown}{BD}$ is smaller. The largest incident angle θ_4 is given by

$$\theta_4 = \sin^{-1}\left(\sqrt{(R_s - h - h_1)^2 + R^2}/R_s\right) \tag{4}$$

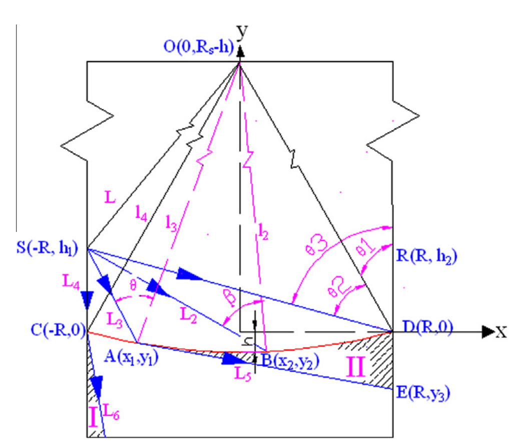

Fig. 2. Diagrammatic sketch of ray path with a concave interface.