A study on the inclusion sizing using immersion ultrasonic C-scan imaging

D Chen¹, H F Xiao¹*, M Li¹, J W Xu¹
¹Collaborative Innovation Center of Steel Technology, University of Science and Technology Beijing, Beijing 100083, PR China

E-mail: huifangxiao@ustb.edu.cn

Abstract: Inclusion sizing, especially for large inclusions greater than 30μm provides important reference for metallurgical process control and fatigue life assessment of steel. Ultrasonic non-destructive testing (NDT) shows great advantages in detecting infrequently occurred large inclusions than eddy current, magnetic particle, microscopic or macroscopic examination procedures. In this paper, the performance of inclusion sizing by immersion ultrasonic C-scan imaging is studied numerically. A two-dimensional model that consists of spherically focused transducer, water couplant and steel with embedded inclusion is established and solved numerically by the finite element method. The signal intensity distributions of inclusion with different sizes are acquired and the effects of inclusion type, shape, orientation on signal intensity distribution are analysed. The results show that the 6dB-drop threshold has the smallest relative error compared with the 12dB-drop threshold and the full-drop threshold, which is better for determining inclusion size larger than 100μm. Experiment is also performed to validate the simulated results.

Key words: Ultrasonic testing; inclusion size; signal intensity distribution; numerical solution

1. Introduction

Non-metallic inclusion has a serious impact on the strength, fracture toughness, plasticity and fatigue life of steel. Analyzing and evaluating inclusion’s type, shape and size will be helpful to improve steel cleanliness[1]. Inclusions size is one of the most important index for evaluating steel cleanliness, which is closely related to the metallurgy technology[2].

The most commonly used methods for inclusion testing are Metallographical Microscope Observation (MMO), Scanning Electron Microscopy (SEM) and Electrolysis. These methods, however, have their own drawbacks on material destruction, sample preparation and time consumption that limit its application in industrial site[3]. Ultrasonic testing has strong penetration, high resolution and detection efficiency, which is very suitable for inclusion detection, especially for the large inclusions that occurred infrequently[4]. Currently, inclusion sizing mainly depends on the signal intensity at a particular position or the signal intensity distribution of C-scan image. The signal intensity is not only associated with the inclusion size, but also related to the inclusion type, shape and orientation[5]. The C-scan image can be used to depict inclusion size visually by signal intensity

* Corresponding author Tel: +86 010 62334255; fax: +86 010 62334255
distribution, but which resolution is limited for the inclusion size of tens of microns, even if the ultrasonic frequency is up to 100MHz.

In this paper, a two-dimensional model that consists of spherically focused transducer, water couplant and steel with embedded inclusion is established, which aims to acquire the signal intensity distribution of inclusions with sizes ranging from 30μm to 200μm. The influence of inclusion type, shape and orientation on signal intensity distribution is analyzed and the relative error of inclusion size under 6dB-drop, 12dB-drop and full-drop thresholds are discussed, which provide guidance for the inclusion sizing by ultrasonic C-scan imaging.

2. Model description

The two-dimensional model that was used to acquire signal intensity distribution is illustrated in figure 1, where $R$ is the radius of piezoelectric element, $F$ is the focal length in water, $h$ is water thickness, $d$ is the inclusion depth, $H$ and $D$ is the thickness and width of steel plate.

![Model diagram](image)

Figure 1. Model diagram.

Assuming inclusion and steel are homogeneous and isotropic, wave equation and equilibrium differential equation are expressed as:

$$\frac{1}{\rho c^2} \frac{\partial^2 p}{\partial t^2} + \nabla \cdot \left( -\frac{1}{\rho} \nabla p \right) = 0$$

(1)

and

$$\rho \frac{\partial^2 u}{\partial t^2} - \nabla \cdot \sigma = F_b \cdot \nu$$

(2)

where $P_t$ is the total pressure, $F_b$ is the body force on object, $\rho$ and $c$ are the material density and longitudinal wave velocity, $u$ is the particle vibrational displacement and $\nu$ is the Poisson ratio. According to the O’Neil principle, the sound wave radiated from transducer surface has identical normal vector. The pressure on the surface of acoustic lens is expressed as:

$$P_t = \left\{ \begin{array}{ll}
P_0 \sin 2\pi ft \times 0.5 - 0.5 \cos 2\pi ft / 3, & 0 < t < 3T \\
0, & t \geq 3T \\
\end{array} \right.$$  

(3)

where $f$ and $T$ are the frequency and cycle of pulse wave whose duration is three cycles. Figure 2(a) and figure 2(b) show the transducer responses in time domain and frequency domain, respectively. The pulse duration is 30ns and the -6dB bandwidth is 60MHz.
In the water-steel interface the boundary function is controlled by:

\[ n \cdot \left( \frac{1}{\rho} \Delta p_i \right) = -n \cdot u_n \]

(4)

In order to eliminate sound wave reflection on both sides of steel plate, the low-reflection boundary is applied and controlled by the function of:

\[ \sigma \cdot n = -\rho c_p \left( \frac{\partial u}{\partial t} \cdot n \right) n - \rho c_s \left( \frac{\partial u}{\partial t} \cdot \tau \right) \tau \]

(5)

where \( \sigma \) is stress, \( n \) and \( \tau \) are the normal and tangential unit vector, \( c_p \) and \( c_s \) are the velocity of longitudinal wave and transverse wave.

3. The signal intensity distribution of inclusions with different sizes

The signal intensity distribution of inclusion with sizes ranged from 30μm to 200μm is acquired. The center frequency and focal length of the transducer are 50MHz and 8mm, respectively. Figure 3 shows the signal intensity distribution of inclusions whose shape is ellipse and their type is Al₂O₃. The horizontal axis is the relative position \( r \) between transducer and inclusion as shown in figure 1, and the vertical axis is the maximum echo amplitude that represents the signal intensity. With the increase of inclusion size, the signal intensity distribution becomes wider gradually. Figure 4 shows the relative errors of inclusion size by the 6dB-drop, 12dB-drop and full-drop thresholds. Comparing with the other two cases, the 6dB-drop threshold has the smallest relative error for each size of inclusion. Meanwhile, the relative error of inclusion size larger than 100μm is less than 15% by the 6dB-drop threshold.

Figure 2. Characteristics of pressure (a) time domain (b) frequency domain.

Figure 3. Signal intensity distribution of different inclusion sizes.

Figure 4. Relative error variation of different inclusion sizes.
4. Other factors on signal intensity distribution
For the inclusion sizing by ultrasonic C-scan imaging, the inclusion type, shape and orientation can affect signal intensity distribution, which are discussed in the following sections.

4.1. Inclusion type
Two typical types of inclusions Al₂O₃ and MnS are selected to analyse the influence of inclusion type on signal intensity distribution. The material properties of steel and inclusions are listed in table 1.

| Material | Density (kg/m³) | Poisson ratio | Young’s modulus (GPa) | Sound velocity (m/s) | Acoustic impedance (MRayl) |
|----------|-----------------|---------------|------------------------|----------------------|--------------------------|
| Steel    | 7890            | 0.27          | 209                    | 5753                 | 45.39                    |
| Al₂O₃    | 3960            | 0.23          | 375                    | 10478                | 41.49                    |
| MnS      | 4057            | 0.30          | 138                    | 6767                 | 27.45                    |

The inclusion shape is ellipse and its macro axis and minor axis are 50μm and 20μm, respectively. As shown in figure 5, the signal intensity of MnS is larger than that of Al₂O₃ at the same position. According to the Snell’s law, the signal intensity is proportional to the difference of acoustic impedance. As shown in table 1, the difference of acoustic impedance between MnS and steel is 17.86 MRayl, which is larger than that of Al₂O₃ and steel (3.9 MRayl). It means that the image contrast of MnS is higher than that of Al₂O₃, which make it possible to distinguish inclusion type by the contrast of C-scan image under the same test parameters.

![Figure 5. Signal intensity distribution of different inclusion types.](image)

4.2. Inclusion shape
The MnS inclusion with ovality of 1:1, 5:2 and 25:3 are selected to analyze the influence of inclusion shape on signal intensity distribution. As shown in figure 6, the inclusion with ovality of 2:5 has the highest signal intensity in each position and the inclusion with ovality of 25:3 has the lowest signal intensity. When the inclusion’s ovality is 25:3, its minor axis is 12μm, which is much less than the wavelength (120μm). According to the reflection law in thin-layer media[6], the sound pressure reflectivity is proportional to the inclusion’s thickness. This result, from a certain extent, explains the reason why the MnS inclusion is difficult to be detected in the rolled steel.
4.3. *Inclusion orientation*

The inclusion orientation is defined as the angle between macro axis of inclusion and incident direction of ultrasonic wave. Figure 7 shows the signal intensity distribution of Al₂O₃ inclusion with orientation of 45° and 90°. The inclusion’s ovality is 5:2 and its macro axis is 100μm. As shown in figure 7, the signal intensity of inclusion with 45° orientation is much lower than that of inclusion with 90° orientation. The signal intensity distribution of inclusion with 45° orientation has two peaks, i.e. position 1 and 2 in figure 7. Figure 8 illustrates the relative position between transducer and inclusion. Along the moving direction, when the transducer is located in position 1, the scattering cross section of incident wave reached to the maximum and the top-surface of inclusion is located in the focal region, which leads to the signal intensity maximized. While, with transducer further moving the scattering cross section is invariant but deviate from the focal region, which leads to the signal intensity decreased. In the position 2 the top surface of inclusion is vertical to the incident wave, which leads to the signal intensity increased again.

Figure 6. Signal intensity distribution of different inclusion shapes.

Figure 7. Signal intensity distribution of different inclusion orientations.

Figure 8. Schematic of transducer position

5. *Experiment validation*

The Acoustic Scanning Microscope SAM 300 is used to verify the accuracy of simulated results. The tested sample is interstitial steel (IF steel) that passed through cold-rolling. Table 2 lists the experimental parameters of C-scan imaging, which result is showed in figure 9. By cutting, grinding and polishing, the maximum cross-section of inclusion that exposed to the specimen’s surface is 54μm in figure 10. The signal intensity distribution of this inclusion is compared with the grey value curve signed in figure 9 with dot-dash line. As shown in figure 11, the simulated result is consistent well with the experimental result, which proves the correctness of our model.

Table 2. Experimental parameters.
### Conclusions

In this paper, the signal intensity distributions of inclusions with sizes ranged from 30\(\mu\)m to 200\(\mu\)m are acquired by the two-dimensional model that consists of spherically focused transducer, water couplant and steel with embedded inclusion. By comparing with the 12dB-drop threshold and the full-drop threshold the 6dB-drop threshold has the smallest relative error on inclusion sizing. For the same size and shape, the signal intensity of MnS is higher than that of Al\(_2\)O\(_3\), which makes it possible to determine inclusion type by the contrast of C-scan image under same test parameters. The inclusion shape and orientation have serious impacts on signal intensity distribution, which make it more difficult to evaluate inclusion size.

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