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Characterizing Non-Metallic Inclusions in Steel by Ultrasonic Spectrum

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Summary

Ultrasonic characterization of non-metallic inclusions in steel can be largely categorized into two aspects, i.e., time-domain and frequency-domain characterizations. In general, characterization parameters in time domain are insensitive to the type, location, and size of non-metallic inclusions; meanwhile, traditional frequency-domain characterization parameters cannot represent the features of inclusions generally and accurately due to that they are calculated by several key points on spectrum curve. Therefore, critical spectrum parameters calculated by all points on spectrum curve are put forward to characterize the depth and size of non-metallic inclusion, including spectrum energy, waveform factor and kurtosis coefficient. Simulations and experiments of Al_2O_3 inclusions in galvanized sheet were carried out by 50 MHz immersion spot focusing ultrasonic transducer in pulse-echo mode to testify the validity of the proposed parameters. The depths of inclusions were 0.45–0.95 mm in simulation, while the sizes were 0.03–0.20 mm. Results of both methods indicate that the three new parameters all have specific relationships with the depth and size of non-metallic inclusions, and they are more sensitive to the change of the size. Furthermore, the qualitative characterization of the depth and size of non-metallic inclusion can be achieved by the new parameters. Especially, the quantitative characterization of inclusion depth is tentatively in reach.

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1. Introduction

Non-metallic inclusions are inevitably lead into iron and steel materials in the smelting process. As one of the defects of steel, non-metallic inclusions not only damage the continuity and compactness of steel, but also greatly affect the mechanical properties of steel. Especially, non-metallic inclusions larger than 50 μm would cause serious damages to materials [1]. The larger the size of non-metallic inclusion is, the greater the probability of crack initiation is, and the worse the toughness of steel plate is. Meanwhile, the large non-metallic inclusion always exists independently. Therefore, it's necessary to detect a single large non-metallic inclusion in steel. Traditional detecting methods such as metallographic method, extraction method, and electrolysis method, are destructive and irrecoverable to the specimen [2, 3]. Ultrasonic testing, as the most widely used non-destructive testing technology, has plenty of advantages such as no specimen damage induced, high efficiency with low cost, wide range of detectable objects and healthy operating environment, etc [3, 4].

Ultrasonic characterization of in steel can be divided into two categories: time-domain and frequency-domain techniques. In time domain, the main characterization parameters are sound velocity and attenuation coefficient. The sound velocity is not only related to the density, elastic modulus and Poisson ratio of the materials, but also has a close relationship with the grain size and hardness of materials [5, 6, 7]. Moreover, Reference [8] pointed out that the content of ferrite influenced the sound velocity of 2205 duplex stainless steel as well. The attenuation coefficient was proved to increase with the growth of grain size [8, 9], and also to be associated with the hardness of materials [7, 10]. To sum up, the time-domain parameters are largely dependent on the material properties. On account of various types and shapes, micro size and random orientation of non-metallic inclusions, it's impossible to characterize them by the tiny diversity in ultrasonic waveform. Furthermore, Reference [11] indicated that precisely measuring the inclusion depth through time of flight method was difficult in reality because of the difficulty in correction of sound velocity. On the one hand, the ultrasonic signal was prone to the influence of random noise, enhancing difficulty in measurement of time history of ultrasound. On the other hand, the non-parallelism of the specimen surface also lead to errors in thickness measurement.

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In contrast, the information in frequency domain is quite rich; the influence of random noise on the spectrum is also suppressed significantly. Thus, the spectrum parameters have better abilities to characterize the non-metallic inclusions. The most common parameters in frequency domain are peak value, peak frequency, bandwidth and center frequency, etc. Reference [12] reported that the area defect and the volume defect could be accurately distinguished by peak frequency, the amplitude of the defect wave spectrum curve and the shape characteristic values constructed by the normalized spectrum. In [13], Dong *et al.* carried out two-dimensional simulations for three types of non-metallic inclusions in steel, including marble inclusion, glass inclusion and no inclusion. Analyzing the spectrum curve of bottom wave, they found out that the critical parameters of samples within inclusions such as peak frequency, center frequency, bandwidth, half width, and peak value were reduced compared with the parameters of the sample without inclusion. In addition, it showed that different inclusions had different sensitive frequencies. In [14], Li *et al.* characterized the grain size of the solid solution in 304 stainless steel by ultrasonic testing, showing that the peak frequency significantly reduced while the peak value increased as the grain size increased. Reference [15] simulated the Al_2O_3 inclusions at different depths in steel, showing that the spectrum features of both surface wave and bottom wave changed with the increase of inclusion depth.

Despite of all this, traditional characterization parameters in frequency domain only exploit the information of a few key points on the spectrum curve, such as the peak point and the 6-dB endpoints of the amplitude decrease, which only reflect several fundamental frequency components of the ultrasonic echo. As a result, they may be insensitive to characterize the change of inclusion depth and size. Therefore, new spectrum parameters which are more comprehensive and reliable are in need.

To solve the problem, the spectrum energy, waveform factor and kurtosis coefficient are put forward. The spectrum energy is the envelope area of the spectrum curve. The envelope of the spectrum curve not only further reduces the effect of noise, but also reflects the energy of the whole spectrum. In [11, 16], the attenuation coefficient and a support vector regression model, which were both based on the spectrum energy, were testified to outperform the sound velocity and traditional attenuation coefficient in predicting grain size, where the average relative errors of the two new methods were confirmed to be less than 15% and 5.65%, respectively. In addition, the waveform factor and the kurtosis coefficient further represent the energy distribution and concentration conditions in the frequency domain.

In this work, the relationship between the three new frequency-domain parameters with the depth and size of non-metallic inclusion was discussed through simulations and experiments. The experimental material was galvanized sheet in which the main inclusions were Al_2O_3 inclusions. Simulation results show that the new parameters

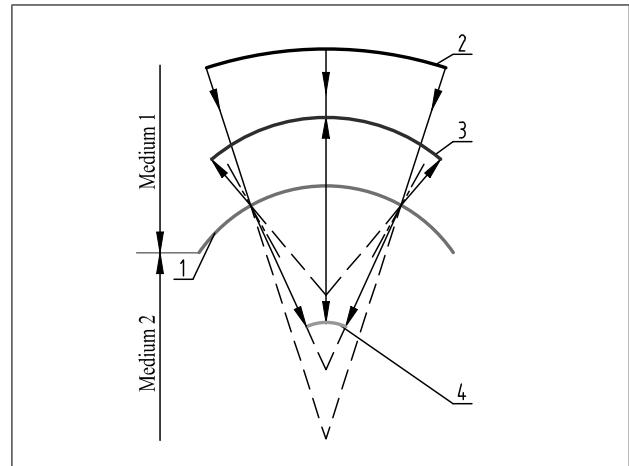


Figure 1. (Colour online) Propagation of ultrasonic at heterogeneous interface. 1 - The heterogeneous interface. 2 - The incident wave. 3 - The reflection wave. 4 - The refraction wave.

played a more critical role in accurately characterizing the non-metallic inclusions, especially in size identification. Finally, the validity of the new parameters was verified by experiments of galvanized sheet.

2. Theory foundation of ultrasonic testing

Ultrasound belongs to the mechanical wave whose frequency is greater than 20 kHz. It can be divided into shear wave, compressional wave, surface wave and plate wave. Due to the fact that the fluid can't sustain shear force, only compressional wave is considered while using water immersion method.

According to the Huygens Principle, the ultrasonic wave in isotropic homogeneous medium propagates along a straight line. However, once there are different phases in medium, such as inclusions, cracks, bubbles and shrinkage holes in steel, the reflection and refraction phenomena will occur at the heterogeneous interface, as can be seen in Figure 1.

The ultrasonic energy distribution at heterogeneous interface depends on the acoustic impedance of the mediums on both sides. Supposing the ultrasound propagates vertically from medium 1 to medium 2, the reflectivity and transmissivity of sound pressure are

$$r = \frac{P_r}{P_0} = \frac{Z_2 - Z_1}{Z_1 + Z_2}, \quad (1)$$

$$t = \frac{P_t}{P_0} = \frac{2Z_2}{Z_1 + Z_2}, \quad (2)$$

where r and t are reflectivity and transmissivity of sound pressure relatively, P_0 is incident sound pressure, P_r and P_t are reflected and transmitted sound pressure relatively, and Z refers to the acoustic impedance. It should be noted that the negative reflectivity of sound pressure indicates that the reflection wave has opposite phase with the incident wave. The formulae point out that if the acoustic impedances of both sides of the heterogeneous interface

are similar, i.e. $Z_2 \approx Z_1$, nine tenths of ultrasonic energy will spread through the interface, and the reflected sound pressure will be hardly any; however, if the ultrasound propagates from solid into air, i.e. $Z_2 \approx 0$ and Z_1 is large, the ultrasonic wave will almost completely reflect back and hardly transmit through the interface, the phases of reflection wave and incident wave will be opposite as well.

In summary, the essence of ultrasonic testing is the influence of the different acoustic impedances between the two sides of heterogeneous interface on phenomena of reflection and refraction of ultrasound. In the existing studies and applications of ultrasonic testing, the pulse-echo method is widely used because of its ability to obtain the position of heterogeneous interface by the echo time. Defect echo, i.e. reflection wave from defect, not only indicates how different the acoustic impedances of the adjacent phases are, but also contains depth, size, or other information of defect. Therefore, it's necessary to search effective parameters of defect echo to characterize the defects in materials.

3. Characterization parameters of ultrasonic spectrum

In this work, the defect echo refers to the inclusion echo, which is caused by non-metallic inclusions in steel. The inclusion echo will be extracted by a suitable time gate with the negative peak as the center. Then, the spectrum of inclusion echo can be obtained by Fourier transformation. The detailed explanation of the time gate can be found in Section 4.3.

The spectrum energy of the inclusion echo is defined as the envelope area of the ultrasonic spectrum of the inclusion echo. Although the frequency components of any real continuous signal can be obtained by the Fourier transformation, the corresponding energy amount of the frequency components cannot fully represent the characteristics of an ultrasonic signal.

However, the envelope of the ultrasonic spectrum can represent the energy distribution of the ultrasonic signal in frequency domain. Therefore, the Hilbert transformation is used to obtain the envelope curve. According to [17], a complex signal can be constructed by the Hilbert transformation based on the inclusion echo as

$$q(t) = x(t) + j\tilde{x}(t), \quad (3)$$

where $x(t)$ is the inclusion echo, and $\tilde{x}(t)$ is its Hilbert transformation. Then, the envelope of the inclusion echo can be expressed as the module of the complex signal, written as

$$|q(t)| = \sqrt{x^2(t) + \tilde{x}^2(t)}. \quad (4)$$

Similarly, the envelope of the ultrasonic spectrum is

$$|Q(f)| = \sqrt{X^2(f) + \tilde{X}^2(f)}, \quad (5)$$

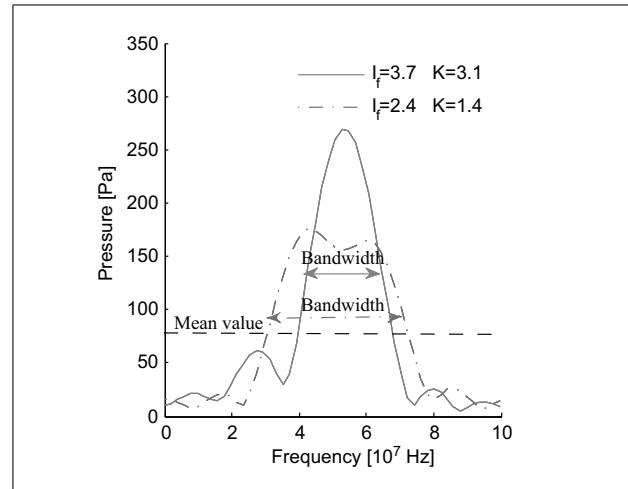


Figure 2. (Colour online) Spectrums of different inclusions.

where $X(f)$ and $\tilde{X}(f)$ are spectrums of $x(t)$ and $\tilde{x}(t)$, respectively. At last, the spectrum energy of inclusion echo E is calculated by

$$E = \int_{f_1}^{f_2} \sqrt{X^2(f) + \tilde{X}^2(f)} df. \quad (6)$$

Because of equalization transformation, the spectrum energy is the same with the time-domain energy of inclusion echo. According to formula (1), the spectrum energy indicates the difference of acoustic impedance between the inclusions and the steel material.

The formula for the waveform factor I_f and kurtosis coefficient K of spectrum of the inclusion echo can be given by

$$I_f = A_p / \bar{A} \quad (7)$$

and

$$K = \frac{1}{N} \sum_{i=1}^N \left(\frac{X_i(f) - \bar{A}}{\sigma} \right)^4, \quad (8)$$

where A_p , $\bar{A}$ and σ refer to peak value, mean value and standard deviation of spectrum curve of the inclusion echo, respectively, $X_i(f)$ is the amplitude of each point on the spectrum curve, and N denotes the number of sampling points. Formula (5) shows that a large waveform factor means the peak value is much higher than the mean value; therefore, the spectrum curve would exhibit a greater peak at the peak frequency and a narrower bandwidth. The formula (6) indicates that a large kurtosis coefficient signifies the differences between the mean value and the amplitude of each point on the spectrum curve is much bigger than the standard deviation. Consequently, the greater the kurtosis coefficient is, the steeper the spectrum curve is, and the more concentrated the spectrum energy is at the peak value.

The relationships between waveform factor and kurtosis coefficient with the shape of the spectrum curve are shown in Figure 2. The two spectrum curves belong to two Al_2O_3 inclusions in different size, having the same mean value

of 73.57 Pa and similar standard deviation of 84.63 Pa and 66.28 Pa, respectively. According to formulae (5) and (6), the waveform factor and kurtosis coefficient of the solid line are larger than those of the dotted line. As predicted, the peak of the solid line is visibly bigger, the bandwidth of the solid line is obviously smaller, and the spectrum energy of the solid line is more concentrative near the peak frequency than the respective parameters of the dotted line. In summary, both the waveform factor and the kurtosis coefficient reflect the distribution of spectrum energy in frequency domain. The more concentrative the spectrum energy is, the larger the waveform factor and kurtosis coefficient will be.

4. Numerical simulation of non-metallic inclusions

In order to testify the validity of the proposed spectrum characterization parameters and find out their relations to the depth and size of non-metallic inclusion, simulated ultrasonic testing of Al_2O_3 inclusion was operated by COMSOL Multiphysics software. The transducer was 50 MHz water immersion focusing probe, working in pulse-echo mode.

4.1. Introduction to the inclusion

Al_2O_3 inclusions are one of the common non-metallic inclusions in steel [18], usually produced in the deoxidation process. According to the Chinese national standard of content determination of non-metallic inclusions in the rolled materials [19], Al_2O_3 inclusions belong to the B-type inclusions. Most of them can keep the shape the same in the rolling process. And they are also apt to array along the rolling direction.

4.2. Establishment of simulation model

According to the Chinese national standard [19], most of B type inclusions have none deformation in the rolling process. As we known, the shape of inclusion in the casting state is sphere because of the surface tension. On this base, the shape of Al_2O_3 inclusion in simulation can be assumed to be a sphere with spatial symmetry. According to the Huygens Principle, the wavefront of ultrasound is spherical, also having spatial symmetry. Therefore, it is available to simplify the simulated spatial model to a 2D model. In addition, the computation time reduces greatly.

The simulation model was established in the X-Z plane, as shown in Figure 3. The total size of the model was $2\text{ mm} \times 2\text{ mm}$. The X axis was perpendicular to the propagation direction of ultrasound, while the Z axis was parallel to the propagation direction of ultrasound. The focused ultrasonic wave beamed from the arc of the water layer and transmitted into the steel, and then secondary focused on the center of the Al_2O_3 inclusion. The simulated variables were depth H and diameter D of Al_2O_3 inclusion. The depth was noted to be the distance from the upper surface of the inclusion to the surface of the specimen.

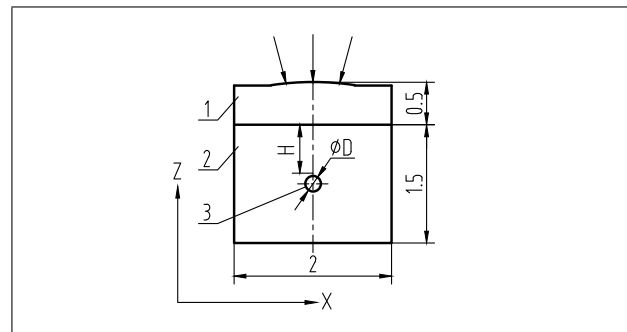


Figure 3. Simulation model. 1 - Water layer, 2 - Steel matrix, 3 - Inclusion.

Table I. Acoustic parameters of media. ρ : Density, kg/m^3 , E : Young's modulus, GPa, σ : Poisson ratio.

Medium	ρ	E	σ
Water (coupling agent)	1000	—	—
Steel (matrix)	7805	208.2	0.291
Al_2O_3 (inclusion)	3960	375	0.230

Table II. Parameters of ultrasonic probe.

Center frequency:	50 MHz
Working mode:	Pulse-echo type
Focal length:	10 mm
Diameter of wafer:	3 mm
Sensitivity:	$10\text{ }\mu\text{m}$
Diameter of focal region:	$100\text{ }\mu\text{m}$
Length of focal region:	$330\text{ }\mu\text{m}$
Length of blind area:	$380\text{ }\mu\text{m}$

The left and right boundaries of the simulation model were set as absorption boundaries to simulate the infinite area. At the same time, the top and bottom boundaries were free boundaries to imitate the actual interfaces.

The meshing grid was triangular element. Considering the convergence of simulation solution and computation time, the maximum cell sizes were set to be 1/4 of the ultrasonic wavelength in mediums, and the time step was 1/25 of the period of highest frequency of interest. As shown in Figure 4b, the highest frequency of interest is 50 MHz. Moreover, the default minimum cell size in the software was $0.6\text{ }\mu\text{m}$. In detail, the characteristic spatial sizes were $0.6\text{--}7.4\text{ }\mu\text{m}$ in water and $0.6\text{--}29.9\text{ }\mu\text{m}$ in steel and inclusion, respectively; the temporal step was 0.8 ns. The acoustic parameters of media [20] are elaborated in Table I.

The probe simulated was 50 MHz spot focusing probe, and its parameters are illustrated in Table II. The loading signal was a 3-cycle (60 ns) sinusoidal pulse modulated by Hanning window with a center frequency of 50 MHz, as shown in Figure 4. For the reason that water can't bear shear stress, only longitudinal wave was studied.

When we discuss the influence of inclusion depth on the spectrum parameters, the depth H of the Al_2O_3 inclusion increased from 0.45 mm to 0.95 mm by step of 0.1 mm,

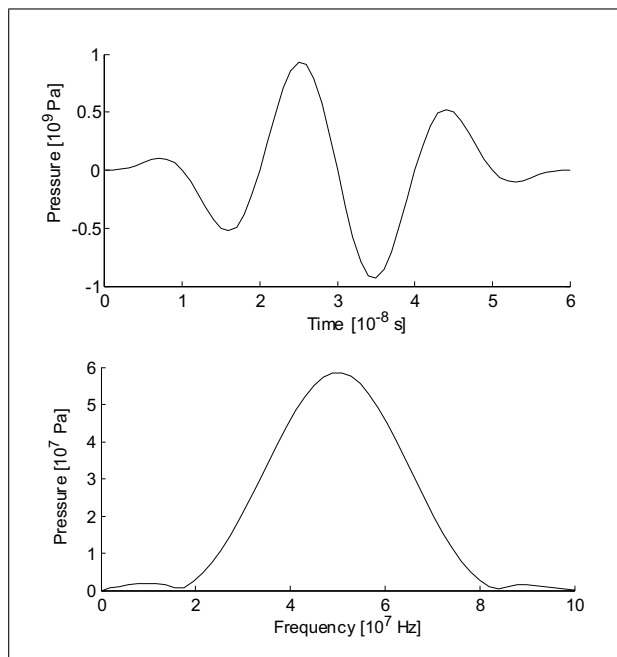


Figure 4. Top: Time-domain waveform of loading signal. Bottom: Frequency-domain spectrum of loading signal.

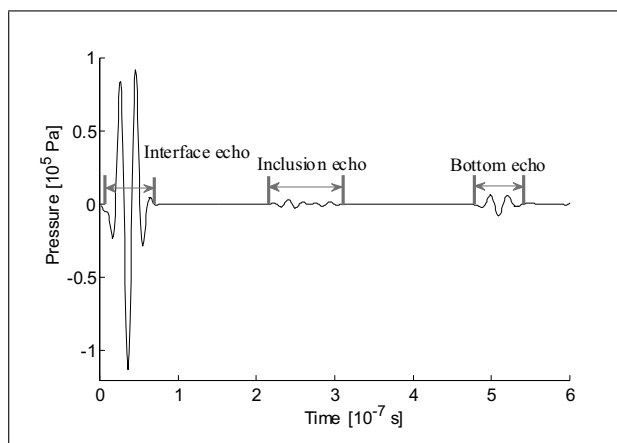


Figure 5. (Colour online) Simulated ultrasonic signal.

and the diameter D remained 0.1 mm. In this case, the range of inclusion depth was about 1.5 times the length of focal region of the ultrasonic probe.

As for the influence of inclusion size on the spectrum parameters, the diameter D of the Al_2O_3 inclusion increased from 0.05 mm to 0.20 mm by step of 0.03 mm, while the depth H remained 0.7 mm. Thus the range of inclusion diameter equaled 1.5 times the diameter of focal region of the ultrasonic probe as well.

4.3. Analysis of simulation results

The simulated ultrasonic signal is shown in Figure 5. The echoes appearing in the figure are interface echo, inclusion echo, and bottom echo, respectively.

The inclusion echo regarded the negative peak of inclusion waveform as the center and was intercepted within 60 ns. Then, the Fourier transformation was operated on

the inclusion echo. It should be noted that the time gate of inclusion echo equals the pulse time of simulated loading signal, and is 3 times the cycle of center frequency of ultrasonic probe.

The characterization parameters of ultrasonic spectrum are shown in Table III. The bars in Table III represent the simulation results of the spectrum parameters, and the lines are the fitted curves of the simulation results.

Analysis of Table III in the vertical direction shows that the peak increases distinctly with the depth and size of Al_2O_3 inclusion enlarged. However, the bandwidth nearly remains unchanged as the inclusion depth increases, and shows indistinctive decrease with the growth of inclusion size. Meanwhile, the decrease of center frequency related to the inclusion depth is not very obvious either, and the change of center frequency is even messy with the rise of inclusion size. Therefore, accurate characterization of inclusions is impossible by the three traditional spectrum parameters. As for the new spectrum parameters put forward in this work, it can be found that:

1. the spectrum energy has significant developments along with the growth of both depth and size of inclusion;
2. the waveform factor is more likely to rises up at first and then remains unchanged as the inclusion depth increases, and it develops gently along with the increase of inclusion size;
3. the kurtosis coefficient almost keeps invariant with the rise of inclusion depth but obviously grows up as the inclusion size increases.

In view of the above, the spectrum energy, the waveform factor and the kurtosis coefficient play a more critical role in accurately characterizing the non-metallic inclusion's depth and size.

Furthermore, the comparison of the representational capacity of the new spectrum parameters in horizontal direction says that the slopes of the fitted curves related to the inclusion size is bigger than the slopes related to the inclusion depth. Consequently, it's more sensitive to indicate the change of inclusion size by spectrum energy, waveform factor and kurtosis coefficient.

5. Ultrasonic experiments of non-metallic inclusions

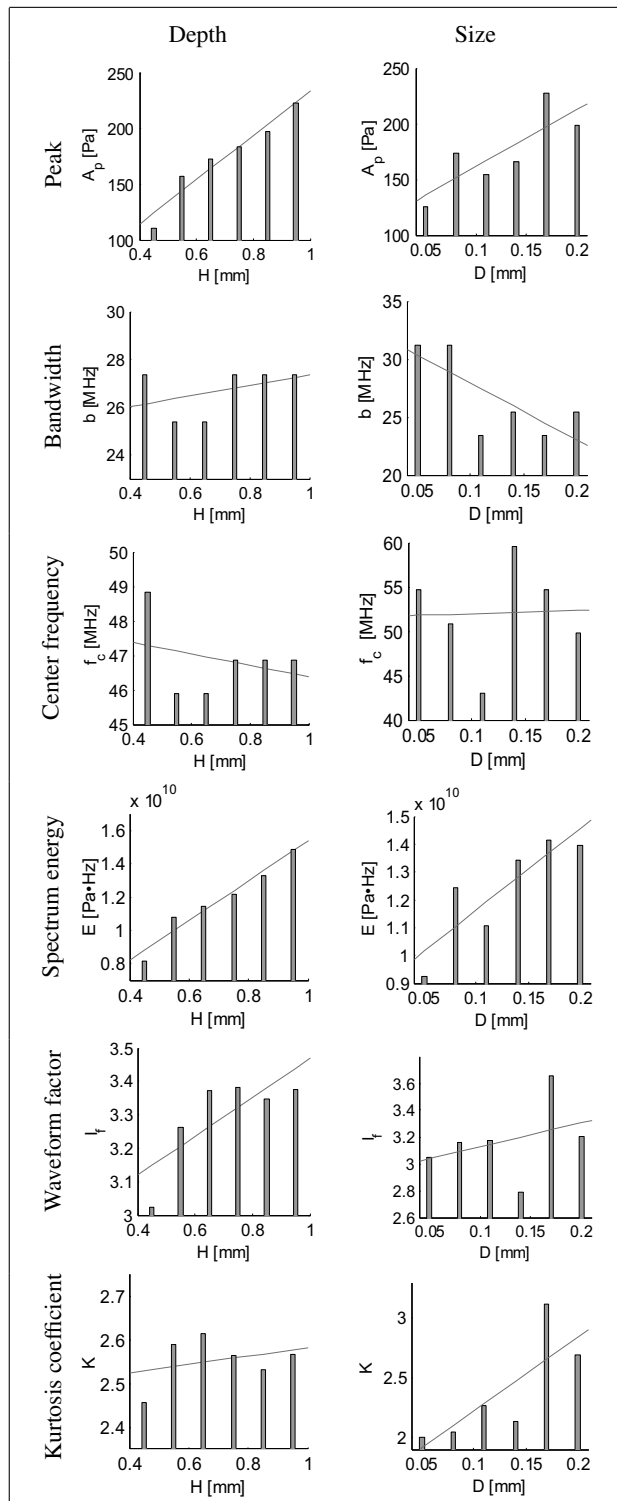
The ultrasonic experiments of galvanized sheet have been operated to further verify the reliability of the proposed spectrum parameters in characterizing the depth and size of non-metallic inclusions.

5.1. Introduction to the equipment and material

The testing equipment was the German PVA scanning acoustic microscope. To ensure the same experimental condition, the ultrasonic probe was 50 MHz immersion spot focusing probe, operating in pulse-echo mode. The parameters of the probe are shown in Table II.

The material was galvanized sheet, in which Al_2O_3 was the main non-metallic inclusion. Two samples with size of 10 mm × 10 mm × 1.5 mm were prepared.

Table III. (Colour online) Simulation results of effects of Al_2O_3 inclusion's depth and size on spectrum parameters.



Actually, the ultrasonic detecting can't obtain the type of inclusion. Meanwhile, different inclusions result in different values of characterization parameters [12]. Therefore, it's necessary to ensure the tested defects were Al_2O_3 inclusions. The SEM-EDS results of one of the inclusions in the galvanized sheet are shown in Figure 6. As can be seen, the equivalent diameter of the inclusion in the fol-

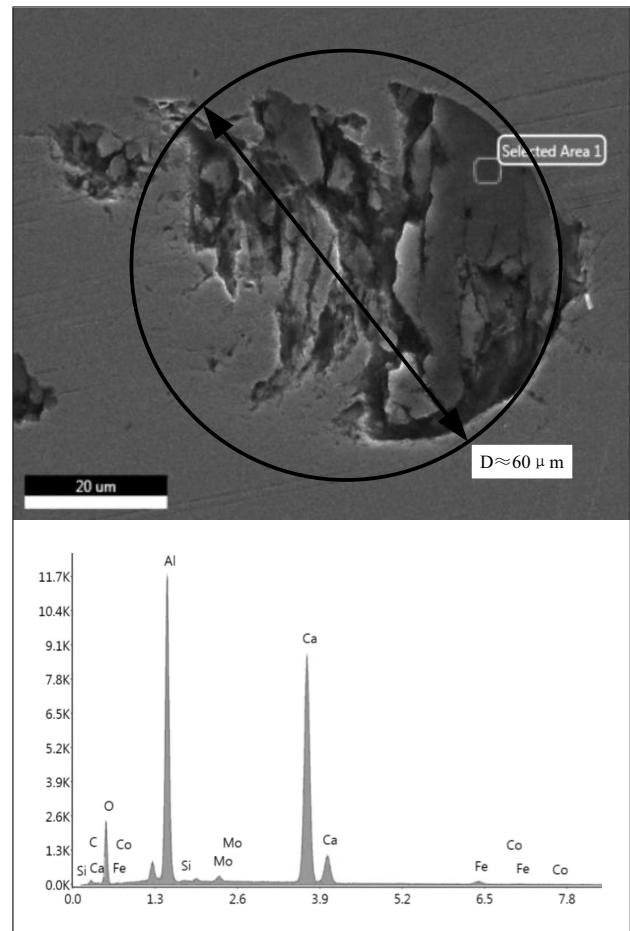


Figure 6. (Colour online) Top: micro morphology of an inclusion by SEM. Bottom: chemical compositions of the inclusion through EDS.

lowing picture is about 60 μm , and the compositions of the inclusion are CaO and Al_2O_3 .

5.2. Adjustment of detection parameters

In fact, the specific location of an inclusion in steel was unknown in the beginning. Therefore, it was necessary to sweep the sample roughly at first to determine the approximate location of inclusion. After that, scan the inclusions subtly to obtain their sizes. In the subtle scan procedure, considering that the energy of the focal region of an ultrasonic probe is the most concentrative, the ultrasound focused on the inclusions to gain the inclusion echo with highest amplitude. The detection parameters of ultrasonic testing are shown in Table IV.

5.3. Analysis of ultrasonic detection results

There were three inclusions detected out of each sample. The diameters of inclusions were all larger than 50 μm and their depths ranged from 0.4 mm to 1.1 mm, as shown in Figure 7. It should be noted that the equivalent diameter of the inclusion was the average length of the major and minor axes of the inclusion, as shown in Figure 6a, and the boundary of the inclusion was calculated by 6-dB descent

Table IV. Detection parameters of ultrasonic testing. f_s : Sampling frequency.

Frequency of probe	Focusing depth	Gain
50 MHz	0.5 mm, 0.6 mm, 0.7 mm, 0.8 mm, 0.9 mm, 1.0 mm	9 dB
Scanning accuracy	Scanning range	f_s
Rough scan: 80 μm Subtle scan: 6.4 μm	Rough scan: 10 mm $\times$ 10 mm Subtle scan: 0.8 mm $\times$ 0.8 mm	5 GHz

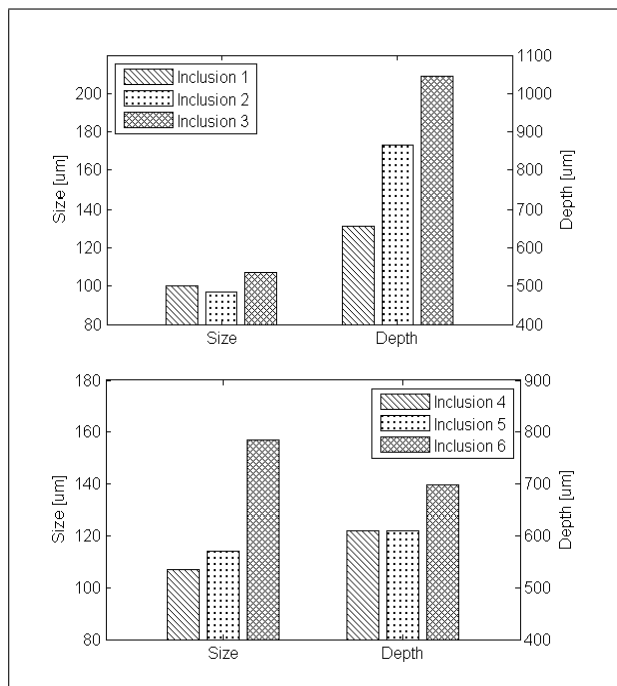


Figure 7. Top: depths and sizes of inclusions in sample 1. Bottom: depths and sizes of inclusions in sample 2. Figure 8 shows the time-domain ultrasonic signals of the six inclusions and the spectrum curves of inclusion echoes.

method in ultrasonic C-scanning image. Furthermore, the inclusion depths were measured by the relative travel distance of ultrasonic transducer when the time-domain peak value of the interface echo and inclusion echo were largest respectively.

It's easily seen from Figure 5 and Figure 8 that the form and period of the interface echo are different in simulations and experiments. Actually, the diversity was caused by three main aspects. Firstly, the loading signal in simulation transmitted directly into water; but the ultrasound in reality had refracted through the acoustic lens in the transducer, resulting in energy attenuation in frequency bands before the ultrasound transmitted into the water. Secondly, the mediums in simulation were isotropic and homogeneous, thus the ultrasound spread along a straight line; however, the real materials were anisotropic, consequently the scattering phenomenon was unavoidable. Thirdly, ir-

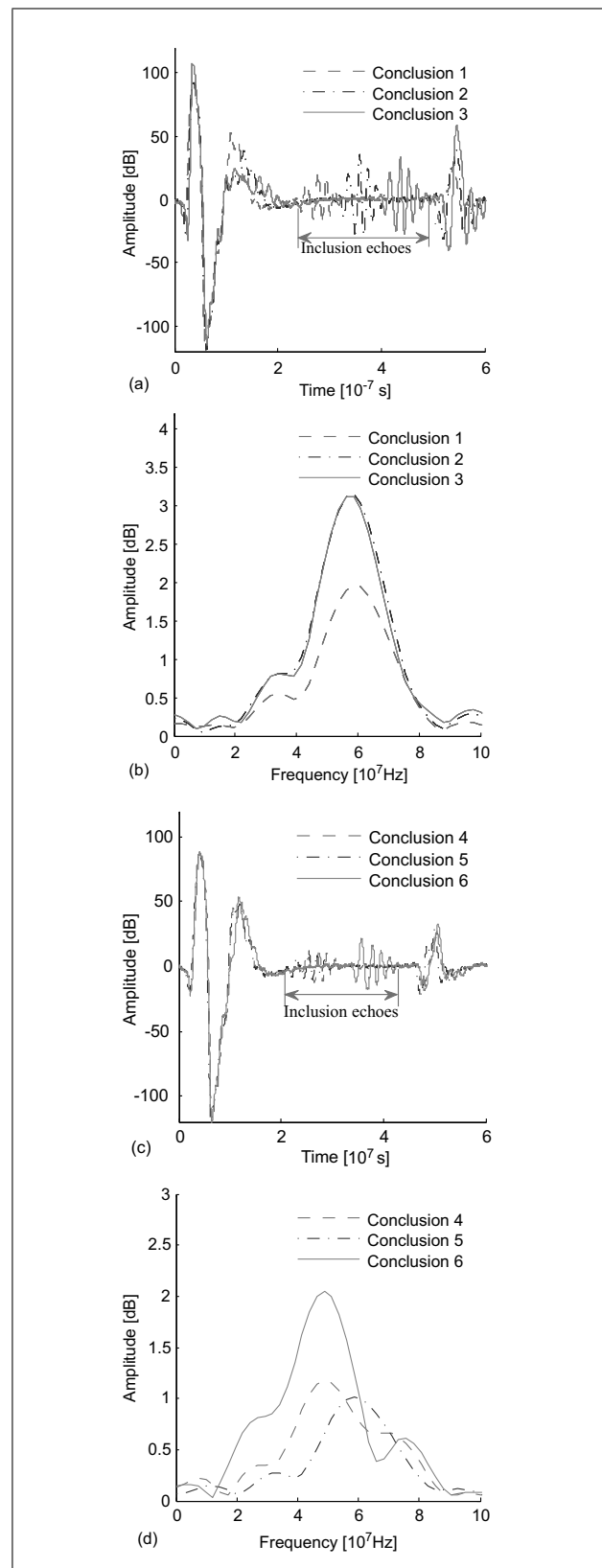


Figure 8. (Colour online) (a): time-domain ultrasonic signals of inclusions in sample 1. (b): spectrums of inclusion echoes in sample 1. (c): time-domain ultrasonic signals of inclusions in sample 2. (d): spectrums of inclusion echoes in sample 2.

regular surface of sample and non-ideal spherical shape of inclusion in experiments aggravated the scattering phe-

nomenon. Therefore, the waveform of interface echo is different between the simulated signal and the experimental signal. However, in terms of simulation, the propagation of ultrasound, as well as the properties of steel and inclusion was the same in the models; thus the interface echoes could be regarded as a constant in simulation. It is the same in experiments.

Figure 7 and Figure 8 indicate that:

1. the three inclusions in sample 1 are almost the same in size but different in depth; therefore, the time histories of inclusion echoes are different but the spectrum curves of inclusion echoes are similar, as can be seen in Figure 8a and (8);
2. the three inclusions in sample 2 almost equal in depth but diverse in size; consequently, as shown in Figure 8c and 8d, the time-domain ultrasonic signals are nearly similar but the differences among the spectrum curves of inclusion echoes are significant.

The experimental results of relationships between the inclusion depth or size and spectrum parameters are shown in Table V. The bars in Table V represent the experimental results of the spectrum parameters, and the lines are the fitted curves of the experimental results.

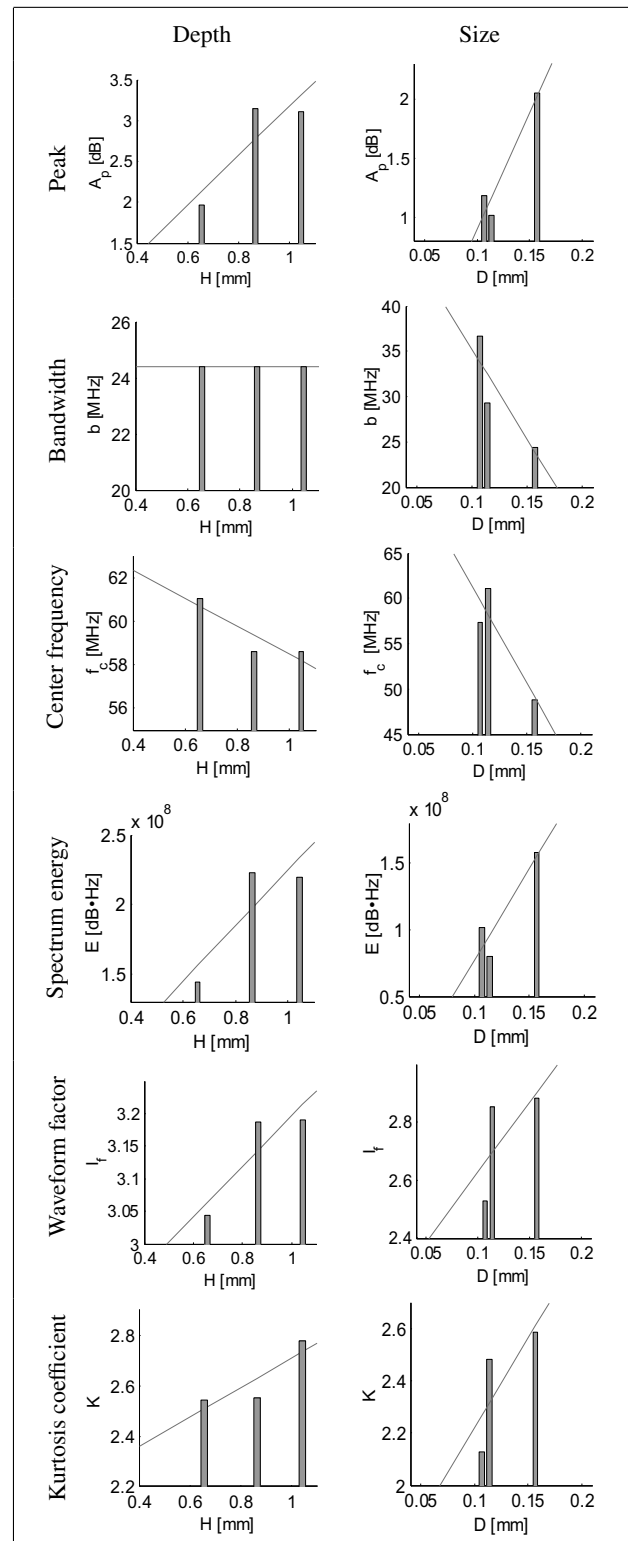
From Table V, the trends of the traditional spectrum parameters along with the change of inclusion depth and size are as follows: when the inclusion depth is enlarged, the peak increases while the bandwidth is unchanged, but the center frequency decreases; when the inclusion size is enlarged, the peak grows up, but the bandwidth and the center frequency reduce. As for the new spectrum parameters put forward in this work, it can be seen that all the spectrum parameters are positively correlated to the inclusion depth and size. Besides, the slopes of the fitted curves also indicate the sensitivity of the new spectrum parameters in characterization of inclusion size.

6. Discussion

Comparisons of Table III and Table V demonstrate that the experimental results of the three new spectrum parameters are in good agreement with the simulation results. The spectrum energy in both simulations and experiments significantly increases with the growths of both inclusion depth and size. The waveform factor and kurtosis coefficient are positively correlated to the inclusion size in simulations and experiments, too.

However, it seems that the simulated trends of the waveform factor and kurtosis coefficient related to the inclusion depth differ from the experimental results. As expressed in simulation, when the inclusion depth are enlarged, the waveform factor is more likely to rises up at first and then remains unchanged, while the kurtosis coefficient almost keeps invariant. But the two spectrum parameters both increase in the experiments. Further observation of the experimental results shows that the waveform factor of the shallowest inclusion in sample 1 is much less than the waveform factors of the other inclusions. Meanwhile, the kurtosis coefficients of the three inclusions in sample 1

Table V. (Colour online) Experimental results of effects of Al_2O_3 inclusion depth and size on spectrum parameters.



are very close. Therefore, the experimental results actually agree with the simulation results. As the results of simulations and experiments indicate, only the peak in the studied traditional spectrum parameters has stable and visible relationships with the change of inclusion depth and size; nevertheless, the peak is unable to distinguish the variable

is either depth or size. Fortunately, the three spectrum parameters put forward in this work covered the shortage. Firstly, the qualitative characterization of changes of inclusion depth and size can be achieved by the spectrum energy, which is positively correlated with the inclusion depth and size. Secondly, the type of variable can be further distinguished by the waveform factor and kurtosis coefficient on the base that the influences of inclusion depth or size on the two parameters differ from each other. Especially, the waveform factor, which rises up and then remains as the inclusion depth increases, may quantitatively characterize the change of inclusion depth. Consequently, the spectrum energy, the waveform factor and the kurtosis coefficient of spectrum curve of inclusion echo can develop a reliable prediction of inclusion depth and size.

7. Conclusions

The present work has put forward three spectrum parameters to characterize the depth and size of non-metallic inclusion in steel, including spectrum energy, waveform factor and kurtosis coefficient. The new spectrum parameters calculated by all frequency components are more comprehensive and reliable in characterization than traditional spectrum parameters, such as peak, bandwidth and center frequency. Results of both simulations and experiments validate specific relationships between the three new spectrum parameters with the depth and size of non-metallic inclusions, which are as following: the spectrum energy increase significantly along with the growth of inclusion depth and size; the waveform factor rises up firstly and then remains unchanged with the inclusion depth enlarged, and grows up gently with the inclusion size enlarged; the kurtosis coefficient almost holds on as the inclusion depth increase but rises up as the inclusion size increase. Especially, the characterization capacity of the proposed spectrum parameters is more sensitive in representing the inclusion size. In view of this, the new spectrum parameters can not only achieve the qualitative characterization of the inclusion depth and size, but also successfully distinguish the change of inclusion depth with size. Furthermore, the quantitative characterization of inclusion is tentatively in reach as well.

Acknowledgement

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