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Inclusion Evaluation of the Slab by the Focused Ultrasonic Method

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Abstract

With modern steel manufacture capacity increasing, the demand for techniques of quick and accurate inclusion evaluation of the slab by large scale becomes urgent for the metallurgical technicians, especially the test carried out on the initial steel products. By these test results, the quality of further processed steel product can be forecasted. These techniques involve the investigation on inclusion’s size, distribution, kind, and quantity. At present, the ultrasonic method is a suitable means to meet this demand. In this paper, inclusions detection sensitivity by focused ultrasonic method on the slab specimen is discussed, and an ultrasonic method by which inclusion as small as 100μm in the slab specimen of 30mm thick can be efficiently tested is proposed by the help of the focused ultrasonic transducer whose working frequency is 7.5MHz. The test result is verified by mechanical dissection and microscope observation at last, the experiment result demonstrates that not only it is feasible to carry out inclusion detection directly on the slab specimen by ultrasonic method, but also the ultrasonic detection sensitivity can be much higher than commonly estimated degree.

Keywords: Ultrasonic; Inclusions; Slab; Sensitivity; Dissection

1 Introduction

Producing clean steel with uniform and tiny grain is a main means to improve the synthesize performance of the steel products. But it is difficult to control inclusions not appear in the slab, which will have the significant influence on the cleanness and quality of the steel products, so inclusions detection of the steel products is an important quality information feedback, in addition, it will be much more valuable if this detection is carried out at the very beginning of the steel making process[1].

Slab is the primary steel product, and its inclusion detection mainly involves search and analysis on the following aspects about inclusions, such as its distribution, size, sort, and amount. The task usually could be dealt with by the metallurgical method with microscope, by which inclusions in the steel can be inspected directly under even 1000 multiple amplification condition, but for the specimen of large size, a lot of metallurgical specimen need to be prepared, in addition, the inspection results will also be affected by person who carry out the inspection, so it is difficult to evaluate the cleanness state of the specimen objectively.

Compared with the metallurgical method, the ultrasonic method is more practical in the application of inclusions detection. In this paper, we described inclusions detection experiment carried out directly on the slab, and introduced the detection ability on inclusions under mentioned condition by the focused ultrasonic method.

2 Estimation of the detection sensitivity of the ultrasonic method

2.1 The analysis on the smallest defect can be detected by ultrasonic method

The ultrasonic test sensitivity has close relationship with the working frequency, in addition, the working frequency also determines the attenuation speed, stability, repeatability[2]. So for a given detection task, the chosen of the reasonable test frequency is very important for the result. The practical situation is that the test sensitivity is constrained by following factors:

1) The differences of the target defects;
2) The acoustics impedance difference between the target defect and the medium.
3) The diffraction of the specimen texture;
4) The difference between the practical frequency and the named frequency of the transducer.
5) The ultrasonic equipment’s responding capability to the faint scattered wave.

It is not only time-wasting, but also difficult to drawn any simple conclusions to consider above factors separately, so it might be feasible to treat all of the mentioned factors wholly base on the practical experience.

According to ultrasonic diffraction theory, when ultrasonic wave transmitted in the tested material encounters the obstacle, following physical effects will happen, including reflection, dispersion, and diffraction. And the smallest defect can be detected commonly is regarded as the half of the wavelength. Determination of the test sensitivity and choice of the test frequency base on the relationship between the size d (represents the utmost test sensitivity) of the test target and wavelength λ (indirectly represents the choice of the test frequency). Ultrasonic transmits in the medium by vibration, so it has the diffraction effect. When ultrasonic encounters an inclusion which has a comparable size with the ultrasonic wavelength in the medium, the diffraction effect will become distinct, and the shadow concept of the geometry acoustics will no longer applicable.

There are three kinds of phenomena:

- While the size of inclusions is larger than the wavelength, geometry acoustics theory is applicable. The max energy intensity reflected by inclusions only appeared in the opposite direction of the incident ultrasonic, and there will be a shadow behind inclusions.
- While the size of inclusions is comparable with the wavelength, dispersion dominates the energy spreading, there are several maximum values in different directions, not the same with the opposite direction of the incident ultrasonic.
- While the size of inclusions is smaller than the wavelength, whatever the shape or its size, it always scatters energy to different direction, including the opposite direction of the incident ultrasonic, and the amplitude of the scattered energy might be very low compared with the incident energy.

An experience formula curve (figure 1)imitated by computer based on the experiment carried out on FBH (flat bottom hole) of the different diameters demonstrates that the smallest defect can be detected maybe smaller than the half of the ultrasonic wavelength[3-4]. Figure 1 illustrates the ultrasonic experiments on 0.5mm bottom hole drilled in the bottom side of the normalized Ni-Cr-Mo alloy steel specimen with B4S and B2S transducers, the named test frequency of B4S transducer is 4MHz (the practical test frequency is 3.8MHz), and the named test frequency of B2S transducer is 2MHz (the practical test frequency is 1.98MHz). Horizontal scale represents FBH diameter and wavelength ratio (d/λ), vertical scale is decibel, represents responding amplitude of the FBH echo. The hardness of the specimen is 260Hd after treatment, and there is no interference from grain. Standard KrautkramerUSIP11 equipment was used, and ultrasonic transmit speed in the specimen is 5998m/s, the corresponding wavelengths are 1.57mm and 3.03mm separately.

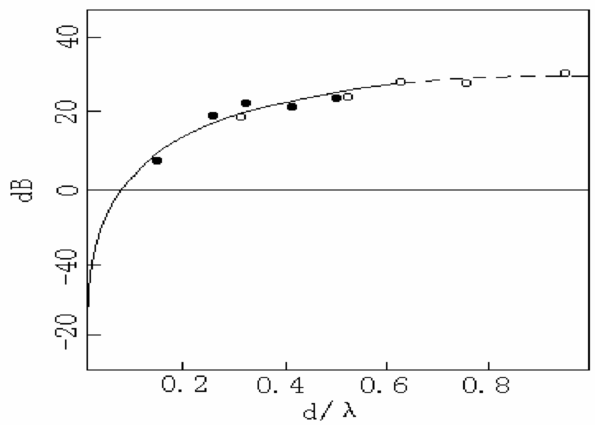


Figure 1 The relationship between echo amplitude and d/λ based on the detection experiment on 0.5mm bottom hole drilled in the bottom side of the normalized Ni-Cr-Mo alloy steel specimen by B4S and B2S transducers (• 2MHz, ° 4MHz)

Test result show that on the 0.5mm FBH, 70mm+10dB reflected wave can be measured, this reveals that the practical defect can be detected might be smaller than λ/2, a rough estimation about the utmost test sensitivity. The test data shown following regulation:

$$dB=-50/3[(d/\lambda)^2-(d/\lambda)]+42lg(d/\lambda)+127/3$$

The 2mm amplitude reflection on the CRT indicates the equivalent decibel value is,

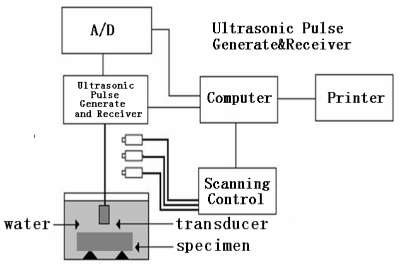
$$20\lg\frac{2}{70}=-30.8dB$$

the corresponding d/λ value is 0.018, and the test sensitivity can be as small as 0.05mm, that is the least signal amplitude can be read out on the oscillograph while there exists interference from grain and other scattering factors.

3 The experiment configuration used for inclusions detection

3.1 The ultrasonic system configuration used for inclusions detection

The specimen is taken directly from the cast slab with thickness of 30mm, and its surface roughness is grinded to be about 1.6μm. The ultrasonic C-scan system configuration used for inclusions detection is illustrated in figure 2(a), the focal ultrasonic transducer's working frequency is 7.5MHz (Panametrics, V320, 13mm diameter), its focal length is 120mm, focal diameter is 1.88mm, and focal is 106.2mm, the ultrasonic pulse and reflected signal are generated and collected by integration card (Physical Acoustics Corp, AD-IPR-1210).



(a) Experiment setup

(b) The machine used for the dissection analysis

Fig 2. The experiment configuration for inclusions detection and the method used for the dissection analysis

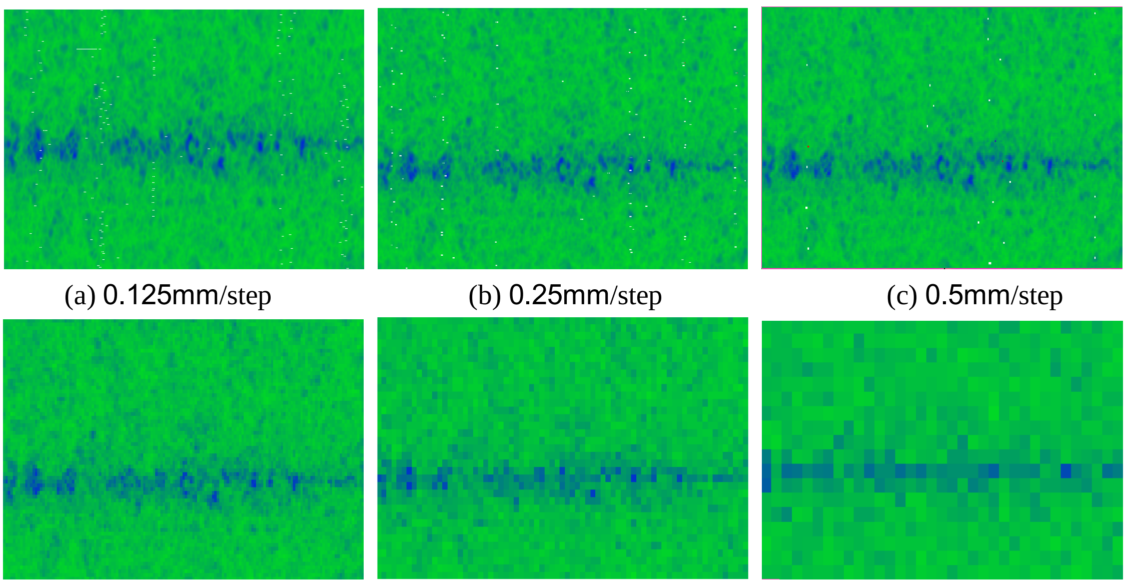
3.2 The dissection verification method of the detected inclusion

In our work, the grinding machine is used to finish the verification tasks (figure 2(b)). After the position where inclusions has been detected by the ultrasonic is marked, we dissected the specimen stratum by stratum (200μm per stratum), until inclusions was found. Inclusions found by dissection method was observed and taken picture by the handy metallurgical microscope. After the dissection work, all of the stratums in which inclusions appeared were piled up and inclusions spread projection map on the detected surface was formed. By comparing the practical dissection projection map and the projection map formed by ultrasonic scanning, the optimal detection sensitivity on the steel slab specimen under taken experimental condition can be estimated.

4 The C-scan imaging test on inclusions in the slab specimen

4.1 Inclusion C-scan imaging detection results on the slab specimen

By ultrasonic C-scan method, the projection map is affected by the mechanical moving step, transducer's transverse distinguish ability, experimental setup, and so on. Our experiment is carried out while system gain is at 40 dB, and transducer's working frequency is 7.5MHz, focal length is 120mm. The following scanning steps, 0.125mm, 0.25mm, 0.5mm, 1mm, 2mm, and 4mm are taken to scan the 30mm thick specimen's same area (120mm×60mm) where inclusions were detected. Figure 3 shows the scanning results corresponding to above steps. It is obvious that the macro spreading configurations of the inner inclusions are almost same while the scanning steps are 0.125mm, 0.25mm, 0.5mm, 1mm, the projection maps can clearly illustrate the shape of the inner inclusion. The distinguish ability of 4mm scanning step is the poorest among used scanning steps. From above results, the efficient experimental configuration ought to consider the matching between transducer's transverse distinguishing ability and the mechanical scanning step, if transducer's transverse distinguishing ability is larger than the mechanical scanning step, the same inclusion within the specimen will be repeatedly imaged and juxtaposed at the optimal sensitivity, and if the mechanical scanning step is larger than transducer's transverse distinguishing ability, some part of the specimen will not be imaged at the expected sensitivity.



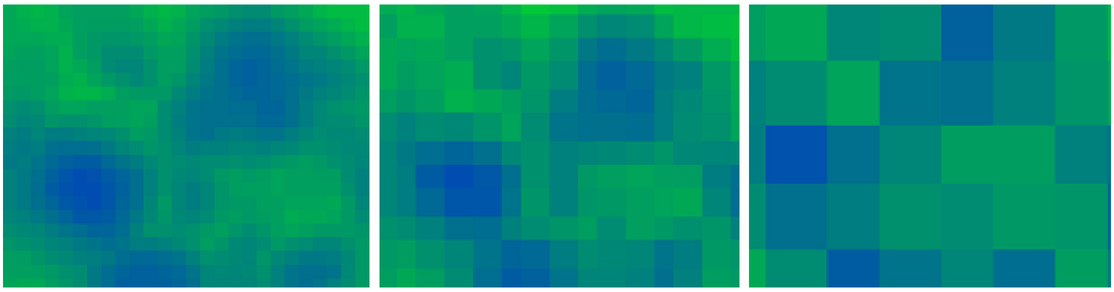
(a) 0.125mm/step (b) 0.25mm/step (c) 0.5mm/step

(d) 1mm/step (e) 2mm/step (f) 4mm/step

Fig 3. The C-scan results on the same area where inclusions were detected with different scanning steps

4.2 Transverse distinguishing ability analysis

Figure 4 shows the detailed effect of the same region within the above scanned specimen, the corresponding scanning steps are 0.25mm, 0.5mm, 1mm respectively. It can be drawn that the details from the map of 0.25mm scanning step demonstrate that the mechanical scanning step is smaller than transducer's transverse distinguishing ability, and the details from the map of 1.0mm scanning step divulge that the mechanical scanning step is larger than transducer's transverse distinguishing ability. And the details from the map of 0.5mm scanning step reflect a appropriate matching between the mechanical scanning step and transducer's transverse distinguishing ability. So it is obvious that under above detection condition, transducer's transverse distinguishing ability is about 0.5mm at the stratum depth inclusions located. And under above experiment configuration with the 0.5mm scanning step, inclusions larger than the system's sensitivity will not be overlooked, but it will not be so while the scanning step is set larger than 0.5mm.



(a) 0.25mm/step (b) 0.5mm/step (c) 1mm/step

Fig 4. The detailed images of the same region within the scanned specimen of different scanning step.

4.3 Inclusions dissection experiment results

To detect inclusions in the slab specimen using focal ultrasonic transducer, the detection effect will be affected by following factors, such as specimen state, specimen texture, inclusion morphology, transducer technique parameters, test conditions, and so on. So it will is difficult to give an accurate theoretic estimation on the detection result. By the help of the grinding machine, the specimen in which inclusions were detected was dissected stratum by stratum.

Before the dissection verification experiment, the location where inclusions was found was marked, then the specimen was grinded to estimated depth, at last, the specimen was grinded by the grinding machine 0.2mm per stratum and observed and recorded by the microscope by turns.

The dissection results demonstrate that within certain depth range where inclusions were detected by ultrasonic method, the corresponding inclusions randomly distributed can be found, within them the smallest size is about 0.1mm. Figure 5 shows 9 morphological pictures of the dissected inclusions within a stratum. For the sake of mechanical grinding, a lot of inclusions have been brushed off, and as a result, the tiny cracks are formed in the base materials, this demonstrates that inclusions are baleful kind. The dissection results demonstrate that under appropriate test setup, by using focal ultrasonic transducer of 7.5MHz detection frequency, the detection target which is much smaller than the half size of the transmission wavelength can be detected, and base on the normal NDT estimation, this detection target size only can be detected by taking use the transducer whose detection frequency is around 30MHz.

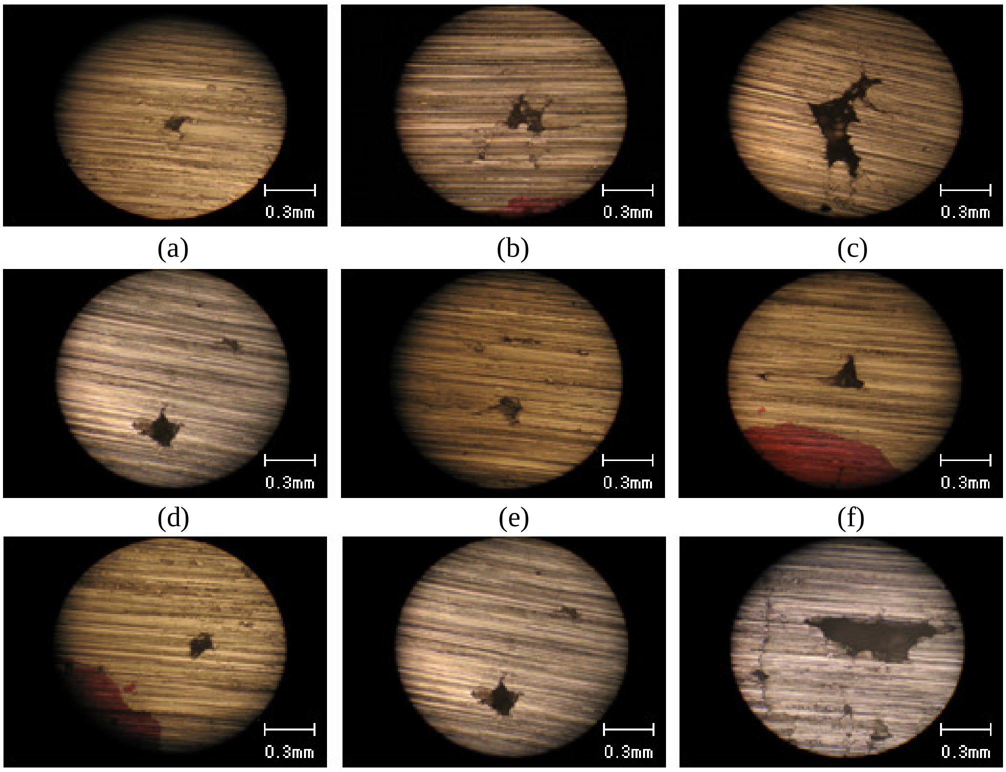


Fig 5. The morphology of 9 dissected inclusions after slab specimen was dissected by grinding machine.

5 Conclusion

(1) In this paper, we described inclusion detection experiment carried out directly on the steel slab specimen, the test results were verified by the corresponding dissection experiment, the experiment results demonstrate that the method is feasible for the detection and evaluation on inclusions in the slab specimen.

(2) Under choosing detection conditions, for the aim of making the detection work efficient, the scanning step needs to match with the transducer's transversal distinguish ability. By the ultrasonic and dissection experiments, we found that under test condition taken in this paper, inclusions as small as 0.1mm can be detected in the 30mm thick steel slab specimen, while the transducer's transversal distinguish ability is about 0.5mm.

(3) By taking focused ultrasonic transducer, the detection system's sensitivity can be improved evidently, much higher than normal NDT theory estimated degree, $\lambda/2$. The 7.5MHz focused transducer taken used in the experiment can detect the small target normally with only 30MHz or higher working frequency of unfocused transducer can do.

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