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Detection and Harmonic Imaging of Inclusions in Continuously-Casted Steel Plates

高調波による連続鋳造鋼中介在物の検出

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1. Introduction

Nonmetallic inclusions in continuously casted steel plates are often formed at the boundary between coarse columnar dendrites and spherical grains. If we could detect nondestructively such inclusions before rolling of the steel slabs, we could produce cleaner steel. For thin steel plates of fine grains, the detection of inclusions is possible with focused ultrasonic transducers[1, 2)].

Ultrasonic detection and imaging of such inclusions in coarse grain steel are, however, difficult by the conventional pulse-echo technique based on the acoustic impedance mismatch at the interface between steel and inclusion. The main reason is strong scattering at the grain boundaries of the dendrites.

Nonlinear ultrasonic technique[3)] evaluating waveform distortion as higher harmonics has been developed. At the contact interface[4)], strong higher harmonics are often excited and easily detected. The inclusion/steel interface shows high stiffness in compressive phase, but no stiffness in tensile phase. In this study, we demonstrate the effectiveness of nonlinear ultrasonic technique for detection of nonmetallic inclusions under coarse columnar dendrites.

2. Nonlinear response at inclusion/steel interface

The stress-strain relation of nonlinear elastic continuum is modeled as shown in Fig. 1(a). Sound velocity is proportional to $(E/\rho)^{1/2}$, therefore the velocity in compressive phase is higher than one in the tensile phase. This results in the waveform distortion shown by solid curve in Fig. 1(b), when a sinusoidal tone-burst wave is transmitted. In frequency domain, higher harmonics are excited in addition to the fundamental frequency component.

The inclusion/steel interfaces would have nm gaps, therefore, significant nonlinear response shown in Fig 2(b) and(c) will be expected when tone-burst wave of larger amplitude than the gaps is transmitted. Except for the inclusions, steel shows

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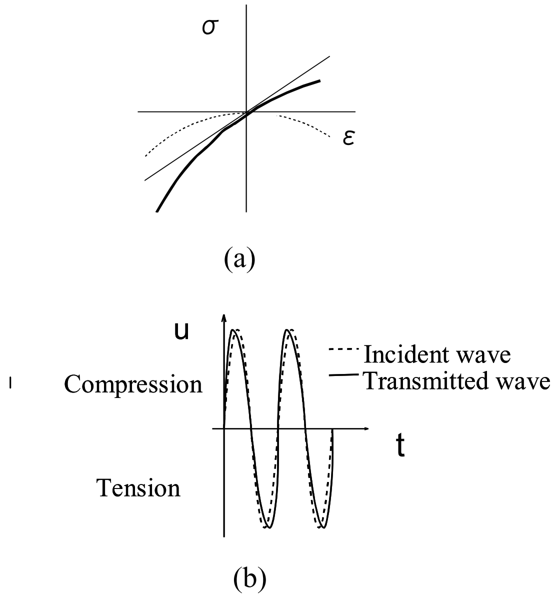

Fig. 1. Nonlinear stress-strain response of nonlinear elastic continuum (a) and waveform distortion (b).

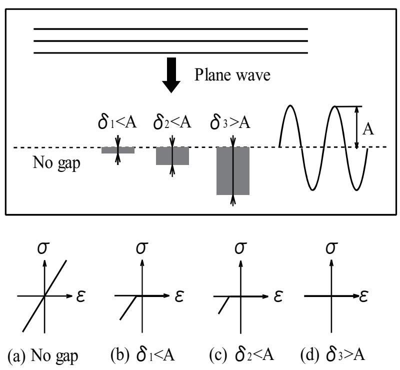

Fig. 2. A model of nonlinear stress-strain response at inclusion/steel interface of nm gaps.

the linear response shown in Fig. 2(a), thus overall response is similar to Fig. 1(a). At the inclusion/steel interface, the area in which the gap is smaller than the incident wave amplitude is quite small. Moreover, only a small fraction of the area has favorite orientation to the incident ultrasonic beam. Even so, we can detect higher harmonics with the state-of- art measurement instruments.

3. Sample and experimental apparatus

The sample tested is a steel plate of 200×200×60mm cut out from a continuously casted thick steel plate. The sample was immersed in a water bath.

A focused transducer of which diameter, focal length and frequency are 75mm, 200mm and 2MHz was used for transmission, and a hydrophone of 1-10MHz in band width was inserted in the center of the focused transducer for reception of harmonics.

A tone-burst wave of 1.6MHz and 5 cycles was normally transmitted by RITEC SNAP-5000 for the steel sample and the 2nd harmonic was extracted with a band-pass filter. The harmonic amplitude was imaged with the Sonix Flexscan software.

4. Harmonic images of inclusions

Typical harmonic images of inclusions are shown in Fig. 3. There are many white dots, however, only points A, B and C are supposed to be inclusion. The received waveform and the normalized spectrum at the point A are shown in Figs. 4 and 5, respectively. In Fig. 4, the wave packet around 120μs is the backscattered signal from the inclusion. The signal before 115μs is reverberation of the surface reflection. The normalized spectrum of the wave packet from the inclusion is shown in Fig. 5, where 3.2MHz (the 2nd harmonic) component is prevailing due to 40dB amplification by the band-pass filter.

5. Confirmation of inclusions by X-ray

By the nonlinear ultrasonic measurement, the location of inclusions were supposed, therefore, the 6mm thick sample including the inclusions was cut from the steel plate for X-ray radiography.

The inclusions at the points A and B were confirmed by the X-ray testing, but no indication was at the point C. At another point, one inclusion was detected.

6. Conclusions

The effectiveness of nonlinear ultrasonic imaging has been demonstrated for detection of nonmetallic inclusion in continuously casted steel plate with columnar coarse dendrites. In this study, only 2nd harmonic is utilized.

As pointed by Solodov[3], strong higher harmonics are excited at contact interfaces, therefore, we could make use of 3rd and 4th harmonics for further nonlinear study of contact interfaces. Several examples of higher harmonic imaging on defects and damage in engineering materials are shown in the reference [5].

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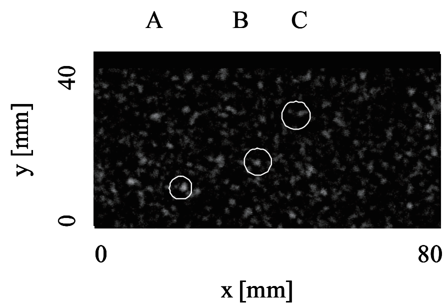

Fig. 3. Harmonic images of inclusions.

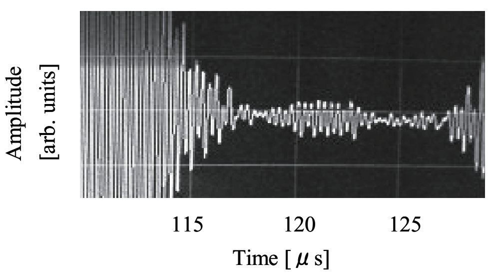

Fig. 4. Received waveform at point A.

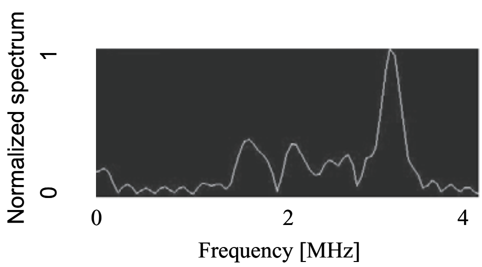

Fig. 5. Normalized spectrum of the gated signal.