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A Study of the Couplant Effects on Contact Ultrasonic Testing

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Abstract The amplitude of a back-wall echo depends on the reflection coefficient of the interface between a transducer and a test material when using contact pulse-echo ultrasonic testing. A couplant is used to transmit ultrasonic energy across the interface, but has an influence on the amplitude of the pulse-echo signal. To investigate the couplant effect on pulse-echo ultrasonic testing, back-wall echoes are measured by using various couplants made of water and glycerine in a carbon and austenitic stainless steel specimens. The amplitude of the first back-wall echo and the apparent attenuation coefficient increases with the acoustic impedance of the couplant. The couplant having a higher value of the transmission coefficient is more effective for flaw detection. The reflection coefficient should be known in order to measure the attenuation coefficient of the test material.

Keywords: ultrasonics, contact method, couplant, glycerine, apparent attenuation coefficient

1. Introduction

The ultrasonic pulse echo technique has been widely used for detecting flaws in materials and for measuring ultrasonic velocity and attenuation coefficients which are the basis for evaluating elastic moduli, characterizing microstructure and assessing mechanical properties (Store, 1991). This technique uses a broad band transducer in contact with a test material at normal incidence, using such liquid couplants as water, glycerine, grease and so on, to make the ultrasonic energy efficiently transmit across the interface between the transducer and the test material. The couplant is appropriately selected by the testing conditions or environment, for example, water is not appropriate to the inspection of carbon steel due to corrosion, and viscous couplants may be required to inspect the inclined plate (Golis, 1992).

The couplant would form a layer between the transducer and a test material. This layer causes an error in the measurement of ultrasonic velocity and attenuation. A few studies on the couplant effect have been reported for the measurement of ultrasonic velocity by the pulse echo technique (Vincent, 1987). The phase and amplitude of the back-wall echoes is varied by the wavelength and thickness of the layer formed by the couplant and the wear plate of the transducer. Thus, this same error must be considered in ultrasonic velocity and attenuation coefficient measurements by contact ultrasonic testing. Although the couplant effect in ultrasonic velocity measurement has been considered, there are few studies on the couplant

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effect associated with ultrasonic attenuation measurement and flaw detection. In the present work, amplitude of the first back-wall-echo is investigated and the apparent attenuation coefficient of carbon and stainless steel by varying the characteristic acoustic impedance of water and glycerin couplants. The thickness of the couplant is controlled by using the aluminium foil spacers.

2. Theoretical Background

2.1. Reflection and Transmission of Plane Waves Normally Incident onto a Layer between Two Media

When a plane wave is normally incident onto a plane interface between two media, the wave is reflected and transmitted. The intensity of the reflected and transmitted wave is dependent on the intensity transmission and intensity reflection coefficient, T_I and R_I as follows (Kinsler et al., 1980)

$$T_1 = \frac{4Z_1Z_2}{(Z_1+Z_2)^2} \qquad \cdots\cdots\cdots(1)$$

$$R_1 = 1 - T_1 = \left(\frac{Z_1 - Z_2}{Z_1 + Z_2}\right)^2 \qquad \cdots\cdots\cdots(2)$$

where Z_1 is the characteristic acoustic impedance of the medium in which incident and reflected waves are travelling, and Z_2 is that of the medium in which the transmitted wave is travelling. In contact ultrasonic testing, eqns. (1) and (2) are generally used to obtain intensity reflection and transmission coefficients between a transducer and a test material. Since a thin layer is formed by using a couplant such as glycerine or grease between the transducer and the test material, the intensity reflection and transmission coefficients become different from eqns.(l) and (2) in real contact testing. As shown in Figure 1, when a layer of finite thickness is formed between two media, an ultrasonic wave normally incident onto the interface from medium 1 generates reflected waves and transmitted waves into the layer. The transmitted wave into the layer is reflected again at the rear interface and transmitted into medium 3. In this case, the intensity transmission coefficient, T_I is represented as follows:

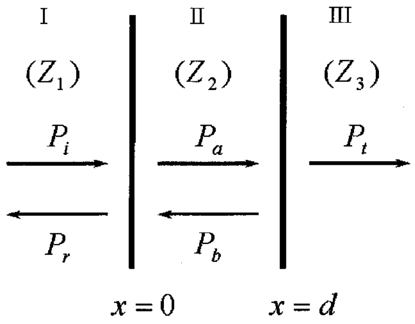

Fig. 1 Transmission and reflection of plane waves normally incident onto layer

$$T_1 = \frac{4}{2 + \left(\frac{Z_3}{Z_1} + \frac{Z_1}{Z_3}\right)\cos^2 k_2 d + \left(\frac{Z^2{}_3}{Z_1 Z_3} + \frac{Z_1 Z_3}{Z_2}\right)\sin^2 k_2 d} \qquad \cdots\cdots\cdots(3)$$

where Z_1, Z_2, Z_3 are the characteristic acoustic impedances of the three media, respectively, k_2 the wave number in the layer, and d the layer thickness. The intensity transmission coefficient depends on the ratio of the layer thickness to the ultrasonic wavelength, which results from the interference due to the multiple reflections at the two interfaces of the layer (Rose and Meyer 1974).

If the layer thickness is very thin compared with wavelength, i.e $k_2 d \ll 1$, then $\cos k_2 d \approx 1$, $\sin k_2 d \approx k_2 d$ and also if the acoustic impedance of the layer is smaller than that of media 1, 3, i.e. $Z_2 < Z_1, Z_3$, then eqn.(3) simplifies to

$$T_1 \cong \frac{4}{A + B\left(\frac{k_2 d}{Z_2}\right)^2} \qquad \cdots\cdots\cdots(4)$$

where A and B are constant given by the following.

$$A = \frac{2Z_1Z_3 + Z^2_1 + Z^2_3}{Z_1Z_3}$$

$$B = Z_1Z_3$$

When the ultrasonic testing is performed by using a normal beam longitudinal mode transducer which is directly in contact with the surface of the test material using such couplants as glycerine or grease, the couplant forms a very thin layer much smaller than the wavelength and its characteristic acoustic impedance is smaller than those of the transducer and the test material. Since the acoustic impedances of the transducer and test materials are fixed in the ultrasonic test, the intensity of the transmitted wave is influenced by the wavelength of the transducer, the thickness, and the characteristic acoustic impedance of the couplant being used. Eqn. (4) shows that the smaller the thickness of the layer, the stronger will be the intensity of a transmitted wave.

2.2. Couplant Effect on the Back-wall Echoes and Attenuation Coefficient

The amplitude of an ultrasonic wave decreases as the propagating distance increases. The amplitude of an ultrasonic wave that has propagated a distance of χ is represented as

$$V(x) = V_0 e^{-\alpha x} \qquad \cdots\cdots\cdots (5)$$

where, α is the attenuation coefficient of the material.

To measure the attenuation coefficient of the material, the amplitudes of the back wall echoes reflected from the bottom surface of a specimen are compared. As shown in Fig. 2, the wave incident onto a front surface of a specimen is reflected at the bottom of the specimen in contact with air, and the reflected wave returns back to the transducer, and some of it reflects again at the boundary between the transducer and test material and then propagates into the specimen. Thus the back-wall echoes will appear on a CRT screen of ultrasonic testing equipment and the amplitude of those echoes will gradually decrease as transit time corresponding to the propagating distance increases. If the back-wall echoes are measured by the contact pulse-echo method in a specimen of thickness *h*, the amplitude of the back-wall echoes would be influenced by the thin couplant layer, as referred to in the preceding equation as well as the material attenuation. Since the intensity, *I*, is related to the amplitude, *V*, as, $I \propto V^2$, the intensities of the first and second back-wall echoes can be represented as follows,

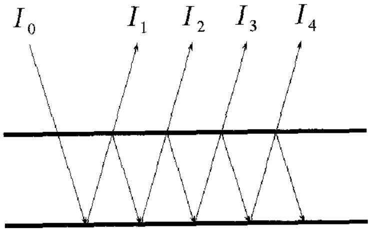

Fig. 2 Back-wall echoes from a plate

$$\begin{aligned} I_1 &= I_0 T^2_I e^{-4\alpha h} \\ I_2 &= I_0 T^2_I R_I e^{-8\alpha h} \end{aligned} \qquad \cdots\cdots\cdots\cdots (6)$$

where, T_I and R_I are the intensity transmission and reflection coefficients in eqns. (1) and (2). We assumed that the intensity reflection coefficient at the interface between specimen and air is 1, and neglected the diffraction effect and attenuation in the layer formed by the couplant.

In contact ultrasonic testing, the attenuation coefficient is generally obtained by the ratio of the amplitudes of the first back-wall echo to that of the second back-wall echo. It is called the apparent attenuation coefficient, which is presented in ASTM E 664-78 as follows,

$$\alpha' = 20\frac{1}{2h}\log\frac{V_1}{V_2} \text{ (dB/m)} \qquad \cdots\cdots\cdots\cdots (7)$$

in which the couplant effect is neglected. Because the thin layer is formed by the viscous couplant on the rough surface of the specimen in the contact ultrasonic test, the amplitude of the back-wall echo is influenced by the transmission and the reflection coefficients as represented in eqn. (6). Birks et al. (1991) proposed that the attenuation coefficient should be revised as follows:

$$\alpha = 20\frac{1}{2h}\log\frac{\sqrt{R_1}\,V_1}{V_2} \text{ (dB/m)} \qquad \cdots\cdots\cdots(8)$$

By substituting eqn. (8) into eqn. (7), the apparent attenuation coefficient is related to the real attenuation coefficient of the material as follows:

$$\alpha' = \alpha - \frac{5}{h}\log R_I \text{ (dB/m)} \qquad \cdots\cdots\cdots(9)$$

Since the intensity reflection coefficient is less than 1, $\log R_I$ is negative. Therefore, the apparent attenuation coefficient is larger than the real attenuation coefficient of the material.

3. Experiment

In the contact pulse-echo ultrasonic test using the normal beam longitudinal mode transducer, 11 kinds of couplants made of water and glycerine were prepared for an investigation of the couplant effects. The densities and ultrasonic velocities of the couplants used were measured and the characteristic acoustic impedances of those were calculated along with the measured densities and ultrasonic velocities. They are listed in Table 1. The longitudinal wave velocities measured by the pulse-echo overlap method are 5,960 m/s for carbon steel and 5,600 m/s for stainless steel. The measurement of the pulse-echo signals in the test materials were performed with a normal beam longitudinal mode transducer of diameter 12.7 mm and center frequency 5 MHz (Ultran WC 50-5). The transducer was in direct contact with the surface of the test material using the prepared couplants. An ultrasonic pulse generator and receiver (JSR PR-35) was used to excite the transducer and to receive the pulse echo signals. The measured signal was then sent to a digital oscilloscope (Lecroy 9410) set up to display 4 back-wall echoes on the CRT screen. As the thickness of the couplant can vary due to its viscosity, we fixed the thickness a constant value by placing an aluminium foil (thickness 16 μm) between the test material and the transducer.

Table 1 Couplants and their acoustic impedance

couplant	Water: glycerine	density (kg/m^3)	velocity (m/s)	impedance (x 10^6kg/m^{2}s)
C1	10:0	998	1490	1.49
C2	9: 1	1018	1533	1.56
C3	8: 2	1039	1586	1.65
C4	7: 3	1065	1637	1.74
C5	6: 4	1089	1685	1.84
C6	5: 5	1113	1739	1.94
C7	4: 6	1141	1790	2.04
C8	3: 7	1173	1836	2.15
C9	2: 8	1195	1863	2.23
C10	1: 9	1224	1895	2.32
C11	0:10	1260	1920	2.42

4. Results and Discussion

Figures 3 and 4 show the back-wall echoes on the CRT screen of an ultrasonic flaw detector using pure water and glycerine couplants for the carbon steel experiment. In order to keep the first back-wall echo at 80% of full screen, pure water couplant required 5 dB higher gain compared to the case of the glycerine couplant. In addition, the decreasing rate of the back-wall echoes was different compared with each other and the second back-wall echo since using glycerine decreases more rapidly than that using water. The amplitudes of the first echo in the carbon steel and stainless steel versus the impedance of the couplants is shown in Figure 5. The amplitudes of the first echo using pure glycerine is about three times as large as that of using pure water. This means that the amplitude and decreasing rate of the back-wall echoes are influenced by the couplant. As represented by eqn. (6), the intensity of the first echo increases with the transmission coefficient, and that of the second echo and other consecutive echoes decrease as the transmission coefficient increases. The intensity transmission coefficient increases with the characteristic acoustic impedance of the couplant as represented in eqn. (4). The amplitude of the first back-wall echo in the carbon steel is larger than that in the stainless steel, because the attenuation coefficient of stainless steel is larger than that of carbon steel.

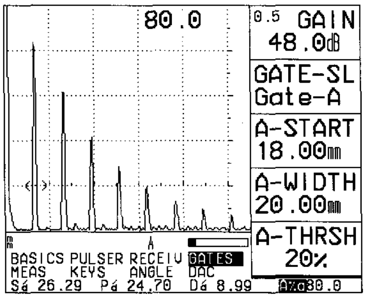
80.0
0.5 GAIN 48.0dB
GATE-SL Gate-A
A-START 18.00mm
A-WIDTH 20.00mm
A-THRSH 20%
Sá 26.29 Pá 24.70 Dá 8.99

Fig. 3 Back-wall echoes using water couplant for carbon steel

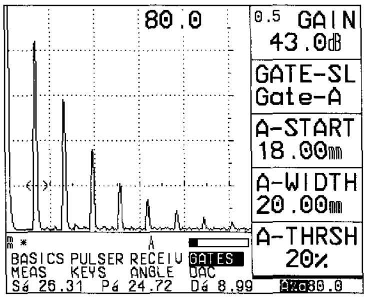
80.0
0.5 GAIN 43.0dB
GATE-SL Gate-A
A-START 18.00mm
A-WIDTH 20.00mm
A-THRSH 20%
Sá 26.31 Pá 24.72 Dá 8.99

Fig. 4 Back-wall echoes using glycerine couplant for carbon steel

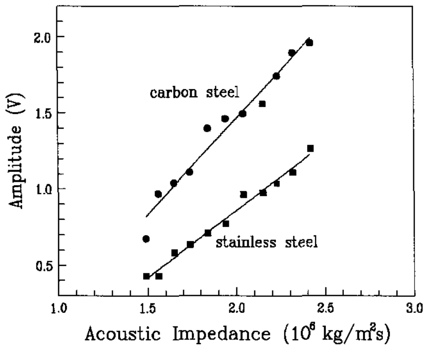

Fig. 5 Amplitude of the 1st back-wall echo versus the acoustic impedance of the couplants

The apparent attenuation coefficient, α', obtained from the amplitude variation of the back-wall echoes versus the characteristic acoustic impedance of the couplants is shown in Figure 6. The apparent attenuation coefficient is increased with acoustic impedance of the couplant and those using pure glycerine are about two times as large as that of using pure water. As represented in eqn. (9), the apparent attenuation coefficient is influenced by the intensity reflection coefficient at the boundary of the transducer and the test material.

Eqn. (9) implies that the couplant effects on the apparent attenuation could be corrected and the real attenuation coefficients could be calculated. The calculated values of real attenuation are not dependent on the acoustic impedance of the couplant as shown in Figure 7. Therefore , the real attenuation of stainless steel and carbon steel could be determined as 40.0 dB/m and 8.5 dB/m, respectively.

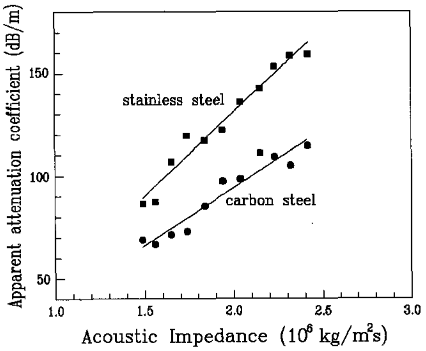

Fig. 6 Apparent attenuation coefficients versus the acoustic impedance of the couplants

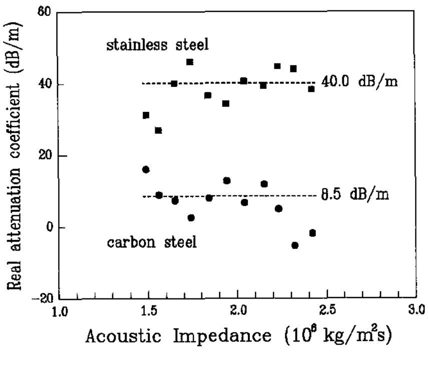

Fig. 7 Real attenuation coefficients versus the acoustic impedance of the couplants

Since the intensity reflection and the transmission coefficients have a complementary relation, the increasing intensity transmission coefficient caus es the amplitude of the first back-wall echo and the apparent attenuation coefficient to increase. To have improved flaw detection, the amplitude of the first back-wall echo should be large, which is caused by increasing the transmission coefficient, but on the other hand the error of the attenuation coefficient increase with the transmission coefficient.

5. Conclusion

The back-wall echoes in carbon and stainless steel are measured by using the various couplants made of water and glycerine. The amplitudes of the first back-wall echo and the apparent attenuation coefficients increased with the characteristic acoustic impedance of the couplants. The amplitude of the first echo and the apparent attenuation coefficient measured by using pure glycerine was about three and two times, respectively, as large as that of using pure water. The larger the transmission coefficient at the boundary formed between transducer and test material, the higher the sensitivity becomes for flaw detection in normal beam contact ultrasonic testing. Since the apparent attenuation coefficient is influenced by the reflection coefficient at the boundary between the transducer and the test material in the contact ultrasonic test, the real attenuation coefficient should be corrected.

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