Noncontact method applied to determine thickness of thin layer based on laser ultrasonic technique

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This paper describes a novel method to non-destructively determine the thickness of thin layer in a non-contact way. A model of wave interference was established based on the multireflection of shear wave in layered system. Furthermore, its expression of reflection coefficient phase was deduced to provide the principle of thickness measurement. A formed laser source by focusing a line on the layer surface was used to generate shear wave, while an electromagnetic acoustic testing (EMAT) sensor was proposed to receive the wave. An example of the method and experimental measurement for comparison is given for a thin steel sheet with the thickness of approximate 0·4 mm. The relative error between the present method and metallography method is less than 4%, which shows laser-EMAT technique is very suitable to non-destructive assess the thickness of the layer.

Keywords: Nondestructive testing, Laser ultrasonic, EMAT, Thin layer

Introduction

Thin layer systems are increasingly used to reduce and avoid degradation of engineering components in wide fields of industry. For instance, layers with special properties are extensively applied to corrosion protection, heat or electrical insulation, decorative purposes, or to enhance structural damping. The thickness of layer is directly related to its physical and mechanical properties.[1–3] Therefore, its evaluation is quite crucial in many industrial applications, especially in a non-destructive way.

A number of non-destructive testing (NDT) techniques are available for thickness measurement of various layers, such as impedance spectroscopy,[4] eddy current[5] and infrared thermograph.[6] Ultrasonic inspection technique is promising to evaluate thickness of layer systems as it offers a relatively inexpensive, mobile and potentially non-invasive technique.[7] Generally, the frequency of ultrasonic generated by piezoelectric technique (PZT) is less than 50 MHz, and the reflection echoes from the front and back surfaces of layer easily overlap in the time domain in this frequency range. Therefore, traditional ultrasonic technique that is based on the round trip time measurement method is not well suited for the thin layer because the time interval is not available directly. At present, there are two approaches to work out the above problem. Laser is introduced to effectively generate the high frequency ultrasonic (>100 MHz) in thin layer, for example, optical generation and detection has been one of the most successful method to assess the thin layer with the thickness in the order of 10^{-9} m in the laboratory.[8] Nevertheless, an optically reflective surface is required for efficient detection, which is a major drawback for on-line monitoring and detection on rough surfaces. Alternatively, combining traditional PZT with special signal processing technique, such as spectrum analysis,[9] wavelet analysis[10] and inverse algorithm,[11] can be also deal with the problem in a relatively low frequency range (<15 MHz). However, the application of PZT is severely limited by the physical coupling between sensors and material surface, which reduces testing efficiency. Thus, providing an approach used in practical application became a very important research direction in the field of NDT.

The objective of the study is to provide a novel method that is used to inspect thickness of thin layers in a non-contact way. First, the principle of assessing the layer thickness was shown in detail, which mainly based on combining techniques of laser-electromagnetic acoustic testing (EMAT) with reflection coefficient phase spectrum (RCPS) in a model of layered media. Then, some experiments were designed to verify the proposed method. At last, good agreement between the theoretical and measurement results demonstrated that the combination of a hybrid laser ultrasonic testing technique and RCPS is feasible to assess the thickness of thin layer.

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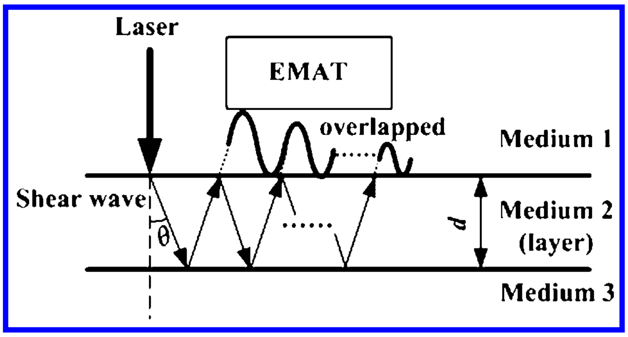


1 Model of shear wave propagating in three-layered medium

Principles

Directivity of shear wave generated by laser

Shear wave can be generated simultaneously when a pulsed laser irradiates on the surface of target material. Characteristics of shear wave are determined by various factors such as the size and shape of laser beam, elastic and thermal properties of target material and surface condition. The behaviour of the wave can be described by its directivity patterns. Theoretical analyses on the directivity patterns of shear wave generated by the line source have been carried out based on the equation (1)[12]

$$S(\theta)=\frac{k_2^4\cos\theta\cos 2\theta}{4k_2^3\sin^2\theta\cos\theta\left(k_2^2\sin^2\theta-k_1^2\right)^{1/2}-s_2^4\cos^2\theta} \quad (1)$$

where θ is the directivity angle, and the k_1 and k_2 are wavenumber of longitudinal and shear waves, respectively.

Reflection coefficient of shear wave in thin layer

Shear wave propagating in a system of thin layer system at incidence with a certain degree was analysed in this work (Fig. 1). Actually, the received echoes overlap in time domain and interfere, which produce frequency dependent reflection coefficients for waves travelling through the layer. The general solution for the complex reflection coefficient of acoustic pressure to the layer in Fig. 1 was given by Brekhovskikh[13] as

$$R=\frac{(Z_1+Z_2)(Z_2-Z_3)\exp(-ik_2d\cos\theta)+(Z_1-Z_2)(Z_2+Z_3)\exp(ik_2d\cos\theta)}{(Z_1+Z_2)(Z_2+Z_3)\exp(-ik_2d\cos\theta)+(Z_1-Z_2)(Z_2-Z_3)\exp(ik_2d\cos\theta)} \quad (2)$$

where d is the thickness of medium 2 (layer), k_2 is the wave number, the frequency independent Z for each medium is given by the product of the density and the velocity c, and the subscripts '1', '2' and '3' refer to medium 1, medium 2 and medium 3, respectively.

Thickness measurement of thin layer

For the case of attenuating medium, k_2 is a complex number with the general form

$$k_2=2\pi f/c_2+i\alpha(f) \quad (3)$$

where *(f)* is the frequency dependent for attenuation coefficient in the layer.

Then, the expression of RCPS (*f*) can be deduced as

$$\phi(f)=\frac{4Z_2Z_3(Z_1{}^2-Z_2{}^2)\exp(-2\alpha d\cos\theta)\sin(4\pi fd\cos\theta/c_2)}{(Z_2{}^2-Z_3{}^2)\left[(Z_1+Z_2)^2+(Z_1-Z_2)^2\exp(-4\alpha d\cos\theta)\right]+2(Z_1{}^2-Z_2{}^2)(Z_2{}^2+Z_3{}^2)\exp(-2\alpha d\cos\theta)\cos(4\pi fd\cos\theta/c_2)} \quad (4)$$

Clearly, equation (4) is periodic with period . A series of zero values occur when=n (n=1, 2, 3…), that is when

$$f_\mathrm{n}=\frac{nc_2}{4d\cos\theta} \quad (5)$$

where f_n is the harmonic frequency. Knowing the velocity in the layer, equation (5) can be used to measure the layer thickness from experimental data and vice versa.

Experimental

Testing system

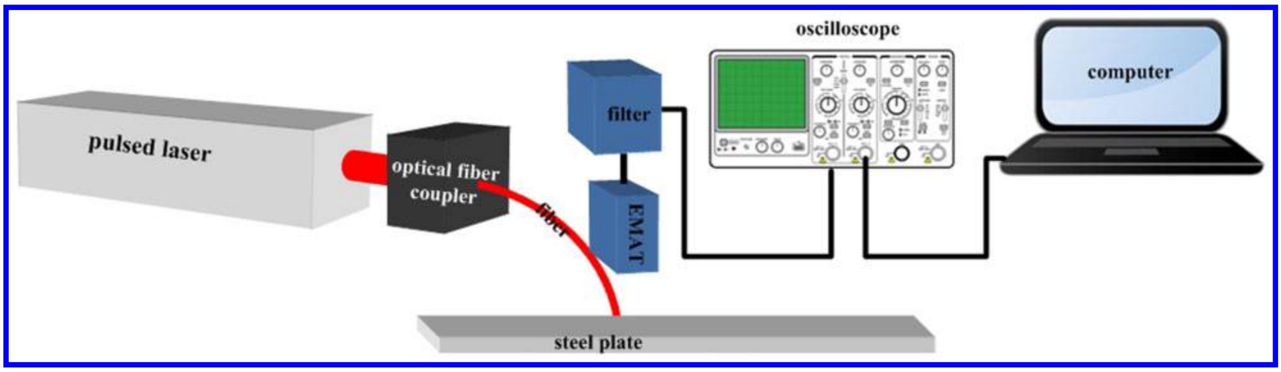
The experimental set-up is shown below in the schematic diagram of Fig. 2. In this work, a Q-switch pulsed Nd : YAG laser with a wavelength of 1064 nm, a pulse width of 10 ns, a repeat rate of 20 Hz, a maximum energy of 200 mJ and a beam diameter of approximately 10 mm is used to generate the shear wave in the layer. Focusing the laser pulse with a plano-convex lens, a laser line source about 10 × 0·2 mm was obtained, which is helpful to generate shear wave with the concentrated directivity. The angle of the resulting shear wave is dependent on the material properties of the sample, which was discussed in the section on 'Directivity of shear wave generated by laser'. The EMAT that can be used on unprepared surface of the materials is used to receive the signal of shear wave. Design EMAT coil with butterfly structure allows the loop noise to be eliminated as much as possible.[14] An analogue filter with bandwidth of 0·5–4 MHz is designed to reduce the surrounding noise. Then, average process with 8 times is carried out by an oscilloscope for all the experiments, in order to make a further improvement of the signal to noise ratio. After that, data collection of signals is completed by the computer.

Samples

Experiments performed on two types of samples are described in this paper. The 304 stainless steel sample with size of 124 × 58 mm was employed to test the directivity pattern of shear wave generated by the line laser source. Thin sheet of 304 stainless steel with size of 500 × 300 × 0·4 mm, attached on the substrate of polyvinyl chloride plastics, were selected to evaluate the capability of laser-EMAT testing thickness.

Signal processing

Reference signal and multi-reflection signals are necessary to obtain RCPS of thin layer. In the present work, a signal from a semi-cylinder 304 stainless steel sample received by EMAT is regarded as the reference signal. The RCPS can be therefore obtained by using the following procedure. Both the two signals above were collected respectively. After that, data of each waveform were padded with zeros to allow a resolution of 5 kHz between 0 and 5 MHz. Next, to get the corresponding

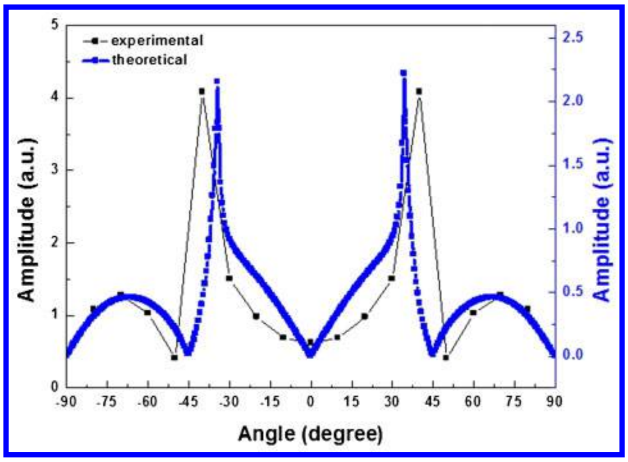


2 Schematic diagram of laser-EMAT testing system

frequency domain data of the above signals, fast Fourier transform (FFT) with a Hanning function were carried out by the Origin 8·0 software. Then, the experimental RCPS can be obtained from equation (6)

$$\phi(f)=\arctan\frac{\mathrm{Im}[S(f)]\cdot\mathrm{Re}[S_r(f)]-\mathrm{Re}[S(f)]\cdot\mathrm{Im}[S_r(f)]}{\mathrm{Re}[S(f)]\cdot\mathrm{Re}[S_r(f)]+\mathrm{Im}[S(f)]\cdot\mathrm{Im}[S_r(f)]} \quad (6)$$

where $S(f)$ and $S_r(f)$ are the complex spectrum of the signal reflected from the studied layer and semi-cylinder 304 stainless steel sample, respectively; Im and Re represent the real part and imaginary part of complex spectrum, respectively.



3 Theoretical and experimental results of shear wave directivity in 304 stainless steel

Results and discussion

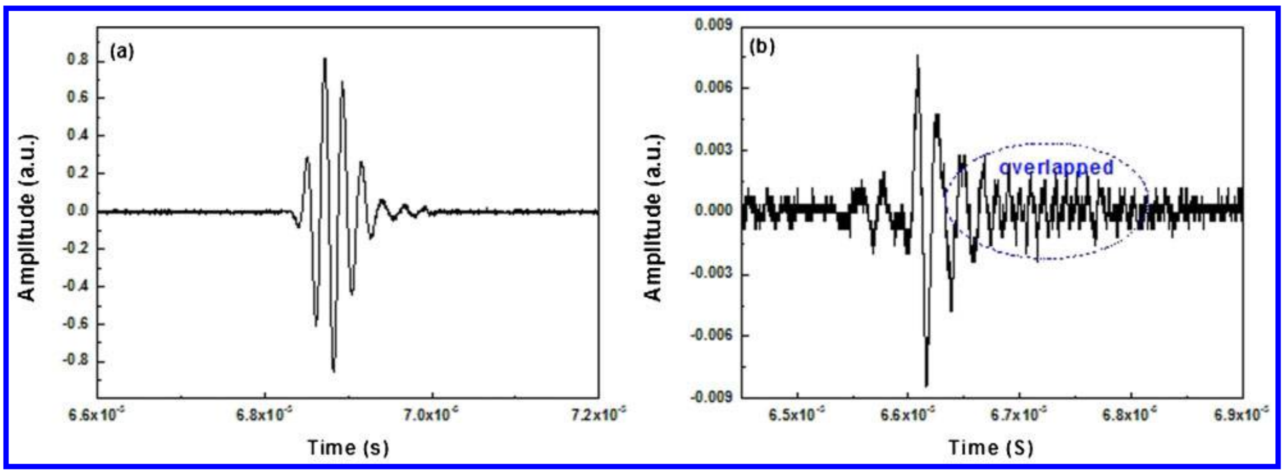
Directivity pattern of shear wave

The experimental arrangement placed the laser and EMAT sensor on the opposite sides in order to determine the directivity pattern of shear wave. The interval angel of the two adjacent testing points was 10 degree. The directivity pattern in the 304 stainless steel for a line source is shown in Fig. 3. It was found that the experimental result agreed with the theoretical one as a whole. Meanwhile, there was clear difference for the maximum and minimum between the two curves. This is because the EMAT actually covers a certain area rather than a line, which is the main reason leading to the error. The result is helpful to determine the separation between laser beam and EMAT sensor and identify the location of internal defect.

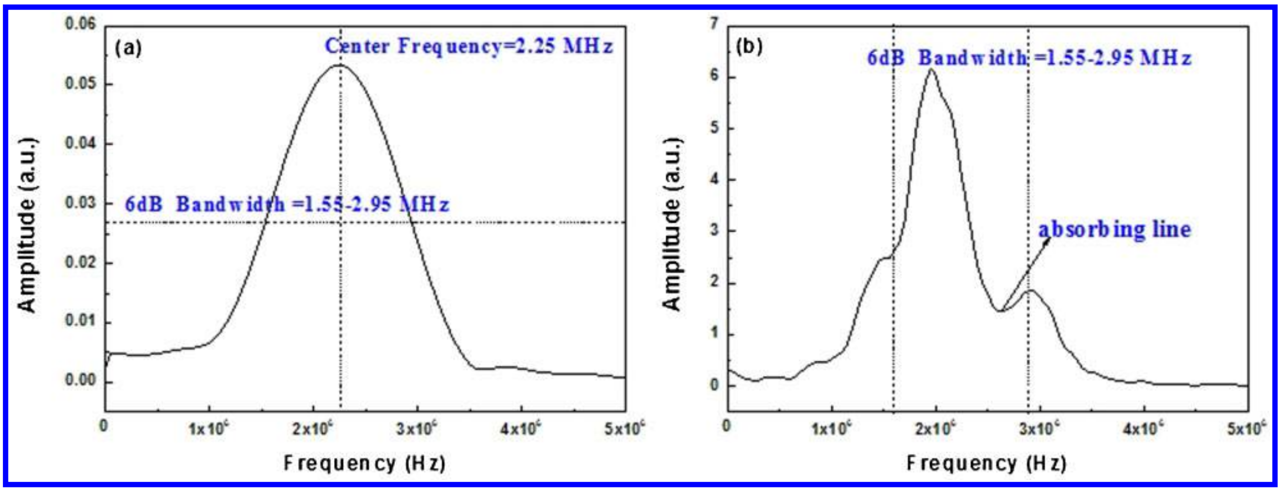
RCPS

Reference signal in the 304 stainless steel and reflection signal in the thin sheet of 304 stainless steel are necessary to obtain the RCPS. The typical signals are shown in Fig. 4*a*, which was clearly observed that echoes from the front and back surfaces of the layer overlapped in Fig. 4*b*.

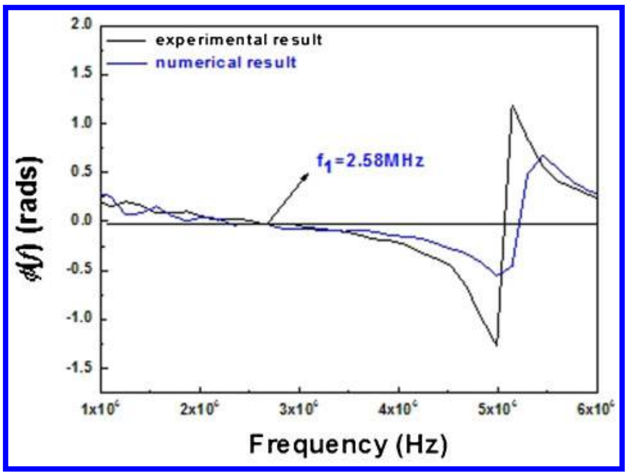
Corresponding FFT results are presented in Fig. 5, and the 6 dB broadband is in the range of 1·55–2·95 MHz in Fig. 5*a*. There is an obvious absorption



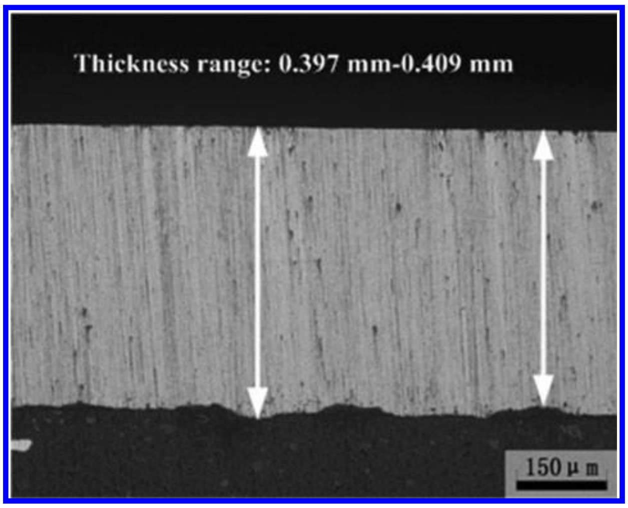
4 Shear waves in 304 stainless steel: *a* reference signal; *b* reflection signal in thin sheet



5 Results (FFT) of shear waves: *a* reference signal; *b* reflection signal in thin sheet



6 Result (RCPS) of steel sheet



7 Metallography result of steel sheet

line at 2·5 MHz approximately due to the interference of multiple echoes in Fig. 5*b*.

Furthermore, the experimental RCPS in company with the theoretical one was obtained according to the principle in the section on 'Signal processing' and on 'Thickness measurement of thin layer', respectively (Fig. 6). Then, f_n=2·48 MHz is obtained in the broadband. When the velocity of shear wave is selected as 3300 m s^{-1} in this work, and the value 0·405 mm of the sheet thickness can be calculated according to the equation (5). Then, the thickness was measured metallography in order to assess the validity of by ultrasonic method (Fig. 7). The relative error between the two methods is less than 4%.

Conclusion

A non-contact NDT method is provided to assess the property of layered system in the present work. Laser-EMAT technique is introduced to determine the layer thickness based on the combination of wave interference model and spectrum analysis. Experimental verification was performed on the 304 stainless steel sheet. The relative error in the measurement of the thickness was found to be less than 4%, which satisfies the requirement of accuracy in the practical application. Also, the method is feasible to determine velocity and attenuation coefficient and so forth.

Acknowledgments

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