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Stress evaluation of laser cladding coating with critically refracted longitudinal wave based on cross correlation function

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ABSTRACT

Research on stress evaluation of laser cladding coating with critically refracted longitudinal wave was introduced in this paper. Two critically refracted longitudinal wave transducers with 5 MHz frequency, spacing between which was constant, were employed as signal emitter and receiver. Based on acoustoelastic equation deduction, relationship between the difference in time of flight and tensile stress is obtained. Combing with cross correlation theory, the difference in time of flight between stressed and unstressed critically refracted longitudinal signals was calculated. Results show that stress evaluation is affected by layer interface and anisotropic microstructure of laser cladding coating, precision of stress evaluation of laser cladding coating increases as step length increases until it attains one cycle. In addition, influence of waveform distortion caused by microstructure of laser cladding coating on stress evaluation is discussed. At last, verification test is carried out and the experimental result is well consistent with theoretical result.

1. Introduction

Because of high energy density, laser cladding technology has been applied widely in surface engineering and repairment fields [1–3]. Stress including applied stress or residual stress is important for properties of laser cladding coating, it is also an important factor for premature failure of laser cladding coating. Therefore, the attention of researcher is attracted by stress evaluation method including diffraction, hole-drilling, ultrasonic, magnetic and so on [4–7]. Compared with these methods, it can be known that ultrasonic method is more convenient to evaluate stress, and there are also other distinct advantages such as on-line, free of radiation and cheap instruments.

The ultrasonic acoustoelastic theory for stress evaluation states that relationship between stress and propagation velocity of ultrasonic wave is strictly linear. It is well known that some kinds of failure in components or remaining life of structural parts is affected by internal stress. At present, longitudinal wave is usually used to evaluate internal stress along length or thickness direction of material. Because of more sensitive acoustoelastic effect, aluminum alloy and polymethylmethacrylate material [8–10] have been studied a lot and many achievements have been gained. While most of mechanical equipments used in industry field are made of steel material, therefore research on stress evaluation of steel material is on the agenda.

So far, the studies on stress evaluation of steel material with critically refracted longitudinal wave had been carried out gradually, it can be divided into theoretical investigation and experimental investigation. Based on acoustoelastic effect, the complete tensorial description of acoustoelastic theory had been deduced by Hughes and Kelly [11]. Belahcene and Lu [12] discussed the distribution of residual stress in S355 steel butt-welded plate. Javadi and Najafabadi [13] analyzed the influence of longitudinal wave frequency on welding residual stress evaluation of dissimilar steel butt-welded plate (304 stainless steel and A106 carbon steel), and the result was compared with result of finite element simulation. Bray and Tang [14] analyzed the subsurface stress evaluation of steel plate with critically refracted longitudinal wave. Although lots of achievements on stress evaluation of steel materials with critically refracted longitudinal wave had been obtained, few public reports was found on stress evaluation of laser cladding iron based coating because of complicated microstructure compared with that of steel materials.

In this paper, stress of laser cladding Fe314 alloy coating is evaluated with critically refracted longitudinal wave. In order to evaluate stress of laser cladding Fe314 alloy coating, optimized acoustoelastic formula of critically refracted longitudinal wave

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and normalized cross correlation coefficient function are deduced. By using two critically refracted longitudinal wave transducers, propagation velocity of critically refracted longitudinal wave is substituted by variation in propagation time of critically refracted longitudinal wave through the same spacing. At last, the acoustoelastic constant of laser cladding Fe314 alloy coating is got combing with calibration test and its main influence factors are discussed.

2. Experiment material and system

2.1. Sample material

With lapping and piling up procedure, Fe314 alloy powder is melted on surface of 45 steel with laser and laser cladding Fe314 alloy coating is obtained. The main composition of Fe314 alloy powder is as follows: 0.15%C, 15.0%Cr, 10.0%Ni and 1.0%B. Under standard of metallic materials static tensile testing at room temperature, laser cladding coating sample, thickness of which is 3.0 mm, is machined. The mechanical property is 705 MPa for yield limit.

2.2. Experimental system

The experimental system that is used to evaluate residual stress of laser cladding coating with critically refracted longitudinal wave is illustrated in Fig. 1.

The electronic instrument is Panametircs 5800PR pulser-receiver, which is used to excite and receive critically refracted longitudinal wave. The critically refracted longitudinal signals are stored by the Tektronix TDS3034B digital oscilloscope. Based on longitudinal wave refraction method, the incidence angle of longitudinal wave is determined, and the critically refracted longitudinal wave transducers have one transmitting transducer and one receiving transducer, central frequency of which is 5 MHz. To improve accuracy of stress evaluation, transmitting transducer and receiving transducer, spacing between which is determined by attenuation test of critically refracted longitudinal wave propagating in laser cladding coating. The calibration test is carried out with MTS810 servo hydraulic testing machine.

2.3. Theory of stress evaluation with critically refracted longitudinal wave

Under defining orthogonal coordinate axis (1,2,3) of material, the complete tensorial description of acoustoelastic theory deduced by Hughes and Kelly [11] is described in terms of the velocity shift [11] in the following form

$$\frac{V_L(\theta)-V_L^0}{V_L^0}=\frac{K_1+K_2}{2}(\sigma_{11}+\sigma_{22})+\frac{K_1-K_2}{2}(\sigma_{11}-\sigma_{22})\cos(2\theta) \tag{1}$$

where θ is angle between propagation direction of critically refracted longitudinal wave and 1 axis, V_L^0 is propagation velocity of critically refracted longitudinal wave in unstressed material, $V_L(\theta)$ is propagation velocity of critically refracted longitudinal wave along θ direction in stressed material, K_i is acoustoelastic constant, σ_{ij} is principal stress ($i = 1,2,3$; $j = 1,2,3$).

So when only one direction stress is measured (for instance direction 1), Eq. (1) can be written as follows

$$\frac{V_1-V_L^0}{V_L^0}=K_1\sigma_{11}+K_2\sigma_{22} \tag{2}$$

The result of $K_1 >> K_2$ has been confirmed by Thompson [15], therefore Eq. (2) can be simplified as

$$\frac{V_1-V_L^0}{V_L^0}=K_1\sigma_{11} \tag{3}$$

From Eq. (3), the difference in time of flight between critically refracted longitudinal signals propagating through a certain distance can be written as

$$\Delta t=t_0K_1\sigma_{11}=K\sigma_{11} \tag{4}$$

where Δt is the difference in time of flight, t_0 is the propagation time of critically refracted longitudinal wave in unstressed material, K is defined as nominal acoustoelastic constant that can be obtained with calibration test.

2.4. Cross correlation theory

Different propagation velocities of critically refracted longitudinal wave correspond to different stresses, while the difference in propagation velocity is not obvious. Generally, the variation in propagation velocity of ultrasonic wave caused by stress change of 100 MPa is about 0.1% in aluminum materials, so accuracy of propagation velocity measurement is important for stress evaluation. In order to reduce the error in stress evaluation, the propagation velocity is substituted by the difference in time of flight between ultrasonic signals, and it can be determined with cross correlation function [16–18].

Under normalization processing, cross correlation coefficient of two different digital signals is defined as

$$\rho_{xy}=\frac{\sum x(i)\cdot y(i)-\sum x(i)\cdot\sum y(i)/n}{\sqrt{[\sum x^2(i)-(\sum x(i))^2/n]}\cdot\sqrt{[\sum y^2(i)-(\sum y(i))^2/n]}}\quad(i=1,2,3\ldots n) \tag{5}$$

where $x(i)$, $y(i)$ are two digital signals, n is defined as step length in this paper.

The starting time of initial critically refracted longitudinal signal is always the same, so the time delay between receipt signals is equivalent to the difference in time of flight between signals. Defining the first zero crossing point as the start point, step length

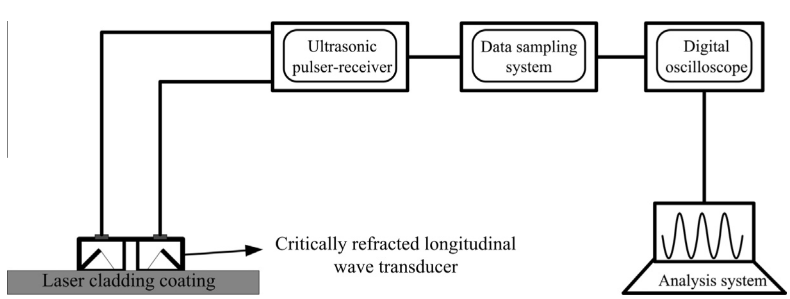

Fig. 1. The experimental system of stress evaluation.