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Nondestructive measurement of elastic modulus for thermally sprayed WC-Ni coatings based on acoustic wave mode conversion by small angle incidence

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A B S T R A C T

a nondestructive method for characterization of thermally sprayed coatings is developed using an ultrasonic small angle incidence scheme in coatings of four layers and three interfaces. Through wave mode conversion analysis, the longitudinal and the transverse waves at the interfaces are simultaneously derived at an incident angle of 4.1°. The ultrasonic reflection coefficient amplitude spectrum (URCAS) is used to determine the thickness and longitudinal wave velocity of specimens through a two-parameter inversion utilizing the cross-correlation algorithm. The elastic modulus and Poisson's ratio of coatings were calculated utilizing the inversion results and modified density. Ultrasonic experiments were carried out on four WC-Ni specimens sprayed using the high velocity oxygen fuel (HVOF) method at spray angles of 30°, 45°, 60°, and 90°. The thicknesses measured by the ultrasonic method were in good agreement with those observed by optical microscopy with less than 10% error. The porosities determined from cross-section SEM photographs were 4.67%, 1.76%, 0.92%, and 0.19%, respectively with increasing spray angle. The elastic moduli of the specimens measured by the ultrasonic method were in the range of 315 GPa–351 GPa, and the Poisson's ratios were during 0.221–0.245. Metallurgical analysis indicated that increasing the spray angle increases both the density and the bond strength between particles which leads to an enhancement of the elastic modulus of the coatings. The proposed ultrasonic method is valid for nondestructive characterization of the elastic modulus and Poisson's ratio of the coatings.

1. Introduction

Sintered WC-Co, WC-Ni cermets combine high modulus, high wear resistance, and adequate fracture toughness, making them the choice material for enhancing the wear resistance of various engineering components [1,2]. Compared with other spraying techniques, HVOF spraying results in less decomposition of the WC during the spraying process because of the higher velocities and lower temperatures experienced by the powder. Consequently, coatings with higher amount of retained WC and lower porosity are obtained [2]. However, Houdková et al. showed that the HVOF is not suitable for parts with complicated geometry, particularly components with small internal regions. The microstructure, thickness, and elasticity of coatings are dependent on the spray angle [3]. Tillmann and Chivavibul also indicated that variation of HOVF spray process (such as particle size, spray angle) will change the thickness, hardness, elasticity, and bond strength of coatings, which are closely related to the fracture toughness of the coatings [4,5]. Chicot et al. [6] showed that the interfacial fracture toughness K_{ca0} of WC coatings depended on the elastic modulus and indicated the K_{ca0} could be utilized to determine the adhesion toughness of coatings. Cheng et al. [7] pointed out that the elasticity of coatings can change during the spray process, which is relevant to the contact stress field, residual stress distribution, and debonding. Therefore, feasible and valid characterization of the elastic modulus is urgent for assisting comprehensive property optimization and quality control of coatings.

At present, there are two categories of techniques for characterizing the elastic modulus of coatings: static and dynamic methods. Static methods include the indentation method, tensile method, and bent-beam

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method. Dynamic methods include the resonance method and ultrasonic method. The indentation technique [8,9] utilizes a rigid indenter to load the coating. The elastic modulus is calculated from the load-displacement curve. The measurement error of this method is very large for characterization of multiphase or composite coatings and the influence of the substrate cannot be completely eliminated. In the tensile method [10,11], a piece of the coating is separated from the part and stretched in uniaxial tension. The elastic modulus of the coatings is calculated from the measured stress-strain curve. This is a destructive method. The bent-beam method [12,13] is carried out on a coating/substrate structure using a three- or four-point bent test. The elastic modulus is calculated from the load-displacement curve or load-curvature curve. The accuracy of this method is highly sensitive to the dimension of the coating and the substrate. The resonance method [9,14] utilizes the resonance frequency of specimen to determine the elastic modulus of the coatings. This method is only suitable for very thin coatings. In the ultrasonic method [4,11,15–17], the elastic modulus of the coating is calculated from the longitudinal wave velocity and shear wave velocity. This method is nondestructive, easy to operate, and has a wide range of application. Traditional ultrasonic bulk wave methods require adjustment of the incidence angle of the transducer or require multiple transducers to obtain the longitudinal wave velocity and shear wave velocity which increases the complexity of the measurement process. The surface acoustic wave (SAW) technique [4,15] can be used to calculate the elastic modulus of coatings. However, the Poisson's ratio of the coating must be known a-priori, thus the SAW method cannot be used for direct, quantitative measurement of the elastic modulus. Lima et al. [18] showed the measured E values in the cross-section direction of the WC-Co coatings were larger than the E values in the top-surface (in-plane) direction. The E values measured on the cross section via Knoop indentation techniques agreed well with those measured via laser-ultrasonic. The SAWs induced by laser-ultrasonic technique only propagates along the coating surface with a small penetration depth. Bescond et al. [19] simultaneously measured the thickness, elastic moduli and density of thermal sprayed WC-Co coatings utilizing SAW combined with surface skimming longitudinal wave excited by laser-ultrasonic. This method needs a complex optical interferometer system and the obtained elastic properties are along the coating surface direction.

In this study, a novel non-destructive ultrasonic technique for determining the thickness, Poisson's ratio, and elastic modulus of thermally sprayed WC-Ni coatings is proposed based on wave mode conversion by small angle incidence. Unlike other ultrasonic techniques, the present technique utilizes a single immersion-focusing transducer. A cross-correlation algorithm based on the ultrasonic reflection coefficient amplitude spectrum (URCAS) is used to determine the thickness, longitudinal wave velocity, and shear wave velocity of WC-Ni coatings. The elastic modulus and Poisson's ratio are obtained from these two velocities. The ultrasonic experiments are implemented on four WC-Ni specimens to verify the feasibility and validity of the proposed ultrasonic technique.

2. Theory

For a longitudinal or shear wave incident on a material interface, continuity conditions on the particle velocity and stress at the interface give the reflection factor equations [20]:

$$\begin{bmatrix} -\cos\alpha_l & \sin\alpha_t & -\cos\beta_l & \sin\beta_t \\ -\sin\alpha_l & -\cos\alpha_t & \sin\beta_l & \cos\beta_t \\ -k_{l1}(\lambda_1+2\mu_1)\cos 2\alpha_l & k_{t1}\mu_1\sin 2\alpha_t & k_{l2}(\lambda_2+2\mu_2)\cos 2\beta_t & -k_{t2}\mu_2\sin 2\beta_t \\ -k_{l1}\mu_1\sin 2\alpha_l & -k_{t1}\mu_1\cos 2\alpha_t & -k_{l2}\mu_2\sin 2\beta_l & -k_{t2}\mu_2\cos 2\beta_t \end{bmatrix} \begin{bmatrix} R_l \\ R_t \\ T_l \\ T_t \end{bmatrix} = a \tag{1}$$

where a is a 4×1 matrix. The reflection and transmission coefficients, R_l, R_t and T_l, T_t are functions of the density ρ and the wave velocity V of the media. α_l and α_s are the reflection angles of a longitudinal or shear wave, respectively. β_l and β_s are the transmission angles of a longitudinal or shear wave, respectively. For longitudinal or shear wave incidence, a in Eq. (1) takes the form, respectively,

$$a = [-\cos\alpha_l \quad \sin\alpha_l \quad k_{l1}(\lambda_1+2\mu_1)\cos 2\alpha_l \quad -k_{l1}\mu_1\sin 2\alpha_l]' \tag{2}$$

$$a = [\sin\alpha_t \quad \cos\alpha_t \quad -k_{t1}\mu_1\sin 2\alpha_t \quad -k_{t1}\mu_1\cos 2\alpha_t]' \tag{3}$$

If the longitudinal, shear wave velocity and density of the media at the interface are known, the reflection coefficient of the longitudinal wave R_l, the reflection coefficient of the transverse wave R_t, the transmission coefficient of the longitudinal wave T_l, and transmission coefficient of the transverse wave T_t can be calculated based on Eqs. (1)–(3). If the incidence of the longitudinal or shear wave is controlled in a small angle, the signals received at the transducer are dominated by the reflected longitudinal and transverse waves from the front and back surfaces of the coatings. Because the wave propagates to the coating with a small incidence angle, the URCAS technique [21,22] was utilized to obtain the property (velocity, thickness) of WC-Ni coatings,

$$|R(f;d,V)| = \left[\frac{(R_{sc}+R_{cw}\exp(-2\varepsilon d))^2 - 4R_{sc}R_{cw}\exp(-2\varepsilon d)\sin^2(2\pi f d/V)}{(1+R_{sc}R_{cw}\exp(-2\varepsilon d))^2 - 4R_{sc}R_{cw}\exp(-2\varepsilon d)\sin^2(2\pi f d/V)}\right]^{1/2} \tag{4}$$

where the subscripts s, c, and w represent steel (substrate), WC-Ni coating, and water (couplant), respectively. The density ρ and wave velocity V of the water and steel are known. The density ρ of the WC-Ni coating can be determined by the Archimedes principle [3]. Therefore, the URCAS is an implicit function of the frequency f, thickness d, and wave velocity V, expressed as $|R(f;\ d,\ V)|$. The Newton least square method [23] and cross-correlation algorithm [24] have been widely used to resolve the implicit function. In signal processing, cross-correlation algorithm is a measure of similarity of two series as a function of the lag of one relative to the other and is independent of the average of each series, which is more suitable for resolving the function of URCAS. In order to determine the velocity V and thickness d simultaneously, a two-parameter inversion based on the cross-correlation algorithm is employed, as shown in Eq. (5):