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Application of Generalized Lamb Wave for Evaluation of Coating Layers

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Abstract This work is aimed to explore a possibility of using the generalized Lamb waves for nondestructive evaluation of the bonding quality of layered substrates. For this purpose, we prepared two sets of specimens with imperfect bonding at their interfaces; 1) TiN-coated specimens with various wear conditions, and 2) CVD diamond specimens with various cleaning conditions. A dispersion simulation performed for layered substrates with imperfect interfaces are carried out to get the characteristics of dispersion curves that can be used for bonding quality evaluation. Then the characteristics of dispersion curves of the fabricated specimens are experimentally determined by use of an ultrasonic backward radiation measurement technique. The results obtained in the present study show that the lowest velocity mode (Rayleigh-like) of the generalized Lamb waves are sensitively affected by the bonding quality. Therefore, the generalized Lamb waves can be applied for nondestructive evaluation of imperfect bonding quality in various layered substrates.

Keywords: Bonding Quality, Generalized Lamb Wave, TiN Coating, CVD Diamond Coating, Ultrasonic Backward Radiation

1. Introduction

Layered substrates can be found in a variety of industries due to their outstanding characteristics. One of the simplest examples is metal components covered by layers of paint on its surface for the purpose of corrosion prevention. The use of layers as a part of surface acoustic wave devices can be found in semiconductor industry. Layered substrates are also widely adopted for performance enhancement of heavy-duty machinery components. Examples of such application include the use of thin coating layers of titanium nitride (TiN), diamond-like carbon (DLC) or chemical vapor deposit (CVD) diamond due to their unique advantages of providing excellent wear resistance and low friction characteristics to the surface of substrates (Holmberg, et al., 2000).

The performance of layered substrate is critically dependent on the bonding conditions between layer and substrate. In addition, the surface properties of the layered substrates tend to gradually change due to exposures to severe environment for a long time (Celis et al., 1992). Therefore, it is necessary to evaluate the characteristics of such layers nondestructively.

Most of research on the bond quality of layered substrates was confined to two extremes: perfect bond and complete misbond. For example, many studies of the interface problems assumed intimate mechanical contact between the two surfaces that constitute the interface. However, this assumption only applies to the perfect bond. The results of these studies provide a range of possible variations, but give no details

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about the in-between cases. In reality, bond quality could exist in a wide spectrum. How to evaluate the imperfect substrates is, thus, a challenging area of study. Up to now, elastic surface waves have been adopted as one of the most promising tools for investigating such a phenomenon.

The elastic wave propagation in thin layers on a half space has been studied by many researchers. Farnell and Adler (1972) studied the effects of a thin solid layer in intimate mechanical contact with an infinite substrate. They examined the so called Rayleigh-like mode, or simply Rayleigh mode. The slope of the dispersion curve of this mode depends on the combination of materials. The lowest velocity mode (Rayleigh-like) of the generalized Lamb waves can be classified into three types depending on the dispersion behavior: loaded, intervened, stiffened cases. It is known that the dispersion curves are sensitively affected by the bonding quality (Kwon and Yoon, 1996). It has been recognized that the combination of materials can affect the phase velocity of the wave propagating on the surface of the specimen even in the perfect bond case. Adler et al. (1990) examined friction-welded aluminum steel bonds using dispersive guided modes. It was shown that depending on the bonding condition the experimental results scattered in quite a wide range bounded by dispersion curves of the two extreme bonding conditions. Ko et al. (1992) studied the imperfect layered substrate using meshed layered specimens. Experimental dispersion curves for various partial bonds were obtained. An attempt was made in their study to evaluate the interfacial properties of layered substrate with stiffness constants.

In the present work, nondestructive evaluation of the bonding quality is attempted for two sets of specimens with imperfect bonding quality in their interfaces; 1) TiN coating specimens with different wear conditions, and 2) CVD diamond specimens with different cleaning conditions. Specifically, the characteristic parameters of dispersion curves are experimentally determined by use of an ultrasonic backward radiation measurement technique (Kwon et al., 2000; Kwon et al., 2005). Then the possibility is explored for nondestructive evaluation of their bonding quality using the generalized Lamb waves that exist on layered substrates.

2. Experiments

2.1 Specimen Preparation

For the present study, TiN ceramic coated specimens and CVD diamond coated specimens were prepared. A set of TiN ceramic coated specimens was made of AISI 1045 steel (with the surface roughness of 0.027 m in Ra value) and austenitic 304 steel (with 0.022 m in Ra value) as the substrate materials. TiN ceramic coating layers of 1.0 m thickness were built on the substrates by an arc ion plating method. After a measurement for the virgin specimens, a contact load of 0.36 N was applied to the coated specimens made of AISI 1045 steel as the substrate using a ball-on-disc sliding tester with a slow sliding speed of 0.063 m/s (60 rpm). However, for the specimens made of austenitic 304 steel as the substrate, different amounts of sliding load was applied to produce severer degradation in the surface region of the specimens. AISI 52100 steel balls with a diameter of 10 mm were used for the sliding test.

Six CVD diamond coated specimens were prepared. Polycrystalline silicon with the thickness of 5 mm was used as the substrate, and the diamond film was deposited on the substrate by a microwave CVD technique by irradiating 2.45 GHz microwave with 1 kW power onto the surface of substrate in 98% H_2+2% CH_4 gas. The specimens were coated on one side with diamond films to different thickness. Before coating, the side of the specimen to be coated was mechanically polished with sand papers with different mesh grades to deliberately produce various surface conditions between the diamond coating layer and the silicon substrate. Table 1 summarizes the preparation conditions of the fabricated specimens. Here it is also worthwhile to mention that the "well cleaned" specimens are expected to have higher interfacial bonding strength between the diamond film and the substrate, while "not cleaned" poor bonding quality (Abe et al., 2004). "Oxidized" means that the specimens were oxidized during fabrication.

2.2 Ultrasonic Backward Radiation Measurement

When ultrasound is incident to a specimen at a certain angle near the Rayleigh angle, surface wave is generated by mode conversion and propagates along the surface of the specimen. In pulse-echo measurement of ultrasonic backscattering, one can capture three responses including: 1) direct scattering at the incident position, 2) leak of the surface wave propagating backward due to microstructures and 3) leak of the surface wave reflected at the specimen edge. In the present work, we adopted the direct backward radiation method in order to evaluate the layers in specimens treated under different conditions.

In the measurement of ultrasonic backward radiation in an immersion setup, one can obtain a plot of the peak amplitude (of the ultrasonic backward radiation signal captured at a certain incident angle which is corresponding to near the Rayleigh angle) variation according to the angle of incidence, which is known as the "ultrasonic backward radiation profile" (Kwon et al., 2000). From the backward radiation profile, one can extract three parameters that have been widely adopted in many previous works for the evaluation of materials with subsurface gradients. They are 1) the "peak amplitude" which is maximum amplitude of the profile, 2) the "peak angle" which is the incident angle where the peak amplitude locates, and 3) the "profile width" which is usually defines as the width of the profile where the amplitude is dropped by 6 dB compared to the peak amplitude. In fact, the peak amplitude is related to the scattering sources existed in the wave propagating path, the peak angle to the Rayleigh surface wave velocity, and the profile width to the wave dispersion.

For the measurement of ultrasonic backward radiation, a broadband ultrasonic transducer with the center frequency of 30 MHz was used to interrogate the specimen immersed in water at different angles of incidence. Fig. 1 shows a schematic diagram of the automated measurement system. This system has the capability of changing the angle of incidence automatically by a computer control system, and can store the ultrasonic backward radiation signal at every incident angle. The accuracies in rotating angle and translation are 0.01° degree and 0.05 mm, respectively.

Table 1 CVD diamond specimen conditions

No.	Mesh No.	Cleaning	Coating thickness	Remark
1	#180	Not cleaned	2.28μm	not oxidized
2	#180	Well cleaned	2.28μm	not oxidized
3	#800	Not cleaned	4.88μm	not oxidized
4	#800	Well cleaned	4.38μm	not oxidized
5	#180	Not cleaned	1.30μm	Oxidized
6	#180	Well cleaned	1.38μm	Oxidized

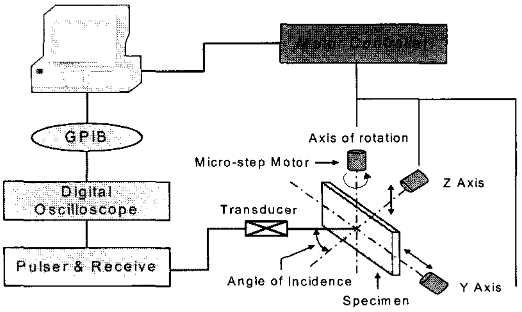


Fig. 1 Schematic diagram of the experimental setup

3. Effective Interface Layer

The imperfect interface between a layer and a substrate is represented as an effective interface layer for the purpose of predicting dispersion relationship (Baik and Thompson, 1984; Fraisse et al., 1992). The thickness of this effective layer is much smaller than the wavelength of the ultrasonic wave used, and the density of this effective layer is much smaller than those of the layer and the substrate. The wave velocities of this effective layer on the stiffness constants and their relations are described in equations 1 and 2:

$$v_i^l = [S_n d_i/\rho_i]^{1/2} \tag{1}$$

$$v_i^t = [S_t d_i/\rho_i]^{1/2} \tag{2}$$

where v_i^l and v_i^t are the longitudinal and shear wave velocities of the effective interface layer respectively; d_i is the thickness of the effective interface layer; ρ_i is the density of the effective interface layer; and S_n and S_t are the normal and transverse interfacial stiffness constants respectively. This effective interface layer was incorporated into a multiple layered model (Brekhovskikh, 1980) for numerical calculation.

In order to focus our discussion on the analysis of a bond quality effect rather than the effects of material combination, let us assume that both the layer and the substrate of a layered substrate under investigation are composed of the same material. Fig. 2 shows five calculated dispersion curves of the lowest order mode of various bond qualities for such a hypothetical plate. The stiffness constants which are obtained from experimental values and a qusi-static model for imperfect interface (Baik and Thompson 1984) used in the calculation are listed in Table 2. The perfectly bonded layered substrate has infinite normal and transverse stiffness constants, and the shape of the dispersion curve is a flat line (i.e., the phase velocity is not dependent on the frequency). The completely disbonded layered substrate, on the other hand, has zero normal and transverse stiffness constants. The phase velocity in the latter case increases as a function of frequency and approaches a constant velocity in the high frequency region.

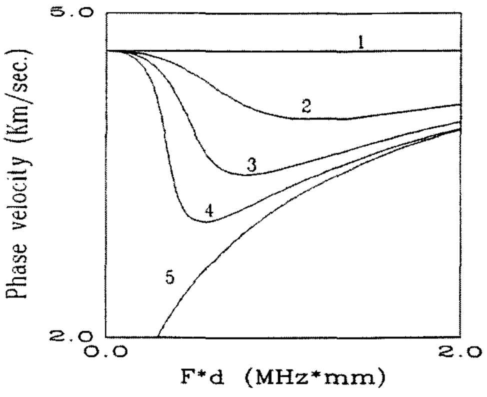


Fig. 2 Calculate dispersion curves of the lowest order mode on layered substrates of various bond qualities. Their stiffness constants of are listed in Table 2.

Table 2 Boundary stiffness constants for various bonds (unit: 10^{14}N/m^3)

	Normal	Transverse
1. Perfect bond	∞	∞
2. "Strong" bond	3.70	2.90
3. "Medium" bond	1.22	0.96
4. "Weak" bond	0.55	0.43
5. Complete misbond	0	0

The partially bonded layered substrates are in between these two extreme cases, and their stiffness constants are finite. The dispersion curve of the partially bonded layered substrate shows a turning point where the phase velocity reaches a minimum. It is noteworthy that the most sensitive frequency in the inspection of layered substrate is around the turning point. Since in the very low frequency region the layer has negligible effect on the surface wave propagation, the sensitivity to bond quality is low. In the very high frequency region, on the other hand, the wave is confined to the top surface area of the layer, and the sensitivity to bond quality is also low. However, around the turning point which is in between these extreme frequencies, the sensitivity to bond quality is much higher. The position of the turning point is related to the bond quality and increase monotonously with the stiffness constant.

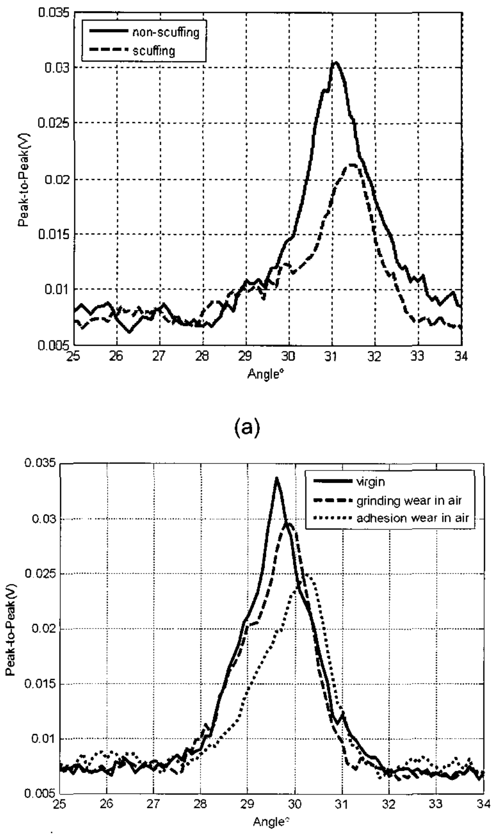
4. Results and Discussion

4.1 TiN Coated Specimen

Since there is sudden increase of friction upon scuffing (Ludema, 1996), it is important to recognize the onset of scuffing for the reliable use of machinery components rotating at high speeds under lubricated condition. Therefore, in the present study, we have prepared two sets of specimens; "scuffed" specimen and "non-scuffed" specimen. The scuffed specimen was prepared by applying the vertical load of 30 N while the specimen was rotating at 60 rpm until the onset of scuffed. However, it was possible to find substantial area not failed on the surface of specimen with scuffed. For the "non-scuffed" specimen, the sliding test was carried out by applying the vertical load of 25 N during the rotation of the specimen at the same speed not to fail on any surface area.

Fig. 3(a) shows the ultrasonic backward radiation profiles measured from the scuffed and the non-scuffed specimens. It can be recognized form the figure that the peak angle of the scuffed specimen was larger than that of the non-scuffed specimen, which means that the Rayleigh velocity in the scuffed specimen was lower than that of the non-scuffed one. Based on the above discussion on dispersion curves of layered substrates, it can be considered that 1) the effective layer produced in the scuffed specimen had less stiffness compared to the non-scuffed specimen, and 2) the bonding quality of the scuffed specimen is more degraded than the non-scuffed specimen.

Fig. 3(b) shows the ultrasonic backward radiation profiles measured from the specimens that have experienced up to three different wearing stages; virgin (no wear), grinding wear



(a)

(b)

Fig. 3 Comparison of backward radiation profiles at 30MHz: (a) in scuffing effect (b) in different wear condition and abrasive wear. As can be noticed in the figure, as the wear process continued the peak amplitude decreased while peak angle increased. The decrease of the profile peak corresponds to smoothening of the specimen surface, which happened when the wear stages changed from the virgin to the adhesive wear through the grinding wear. The increase of the peak angle implies the decrease of the Rayleigh velocity, possibly caused by the softening of the specimen surface and the degradation of bonding quality of the specimen due to wear. This behavior agrees with what was observed for scuffed specimen as shown in Fig. 3(a).

4.2 CVD Diamond Coated Specimen

Fig. 4 shows the time gated backward radiation profiles measured (by use of the time trace angular scanning method (Song et al., 2006) from six CVD diamond coated specimens with different fabrication conditions. As presented in Table 1, odd numbered specimens (1, 3, 5) were "not-cleaned" during the cleaning process for removing nano-sized CVD diamond seeds before deposition, while the even numbered specimens (2, 4, 6) were "well cleaned". It has been expected that the cleaning would have a positive effect in enhancing the bonding quality between the CVD diamond layer and the substrate. As shown in this figure, the peak angles of the not-cleaned specimens were higher than those of the cleaned specimens. In addition, the peak angles of the oxidized specimens (5, 6) which underwent more severe degradation were much higher than those of not-oxidized group. This behavior also agrees very well with the results observed in the TiN coated wear specimens discussed above. In fact, this observation implies the fact that cleaning is effective for improving the bonding quality of the CVD diamond coating layers.

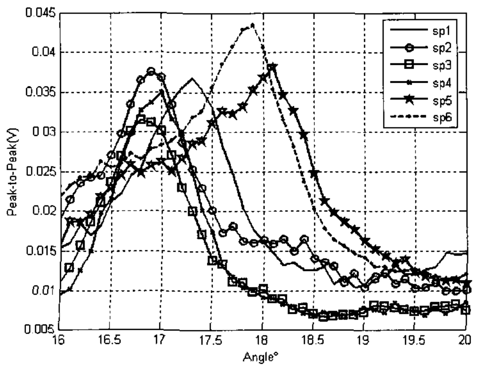


Fig. 4 Comparison of the gated backward radiation profile of CVD diamond specimens

5. Summary

In the present study, nondestructive evaluation of the imperfect bonding quality of layered substrates has been attempted using the generalized Lamb waves. The dispersion simulation performed in the present work showed that the dispersion curves of layered substrates with imperfect interfaces are in a form of concave curves with a null in the middle, and the null's depth and location vary with the stiffness constants of the effective interface layer. Therefore, the lowest velocity mode (Rayleigh-like) of the generalized Lamb waves has been interrogated for the evaluation of the bonding quality.

In order to explore such a possibility we have prepared two sets of specimens with imperfect bonding quality in their interfaces; 1) TiN coated specimens with different wear conditions, and 2) CVD diamond specimens with different cleaning conditions. Then the characteristic parameters of dispersion curves are experimentally determined by use of an ultrasonic backward radiation measurement technique. Lower velocities of Rayleigh like waves have been observed from the specimens with poorer bonding quality. Therefore, the results obtained in this study demonstrate that the Rayleigh-like modes of the generalized Lamb waves have a sufficient sensitivity to the bonding quality and can be successfully applied for the nondestructive evaluation of the bonding quality.

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