ULTRASONIC EVALUATION OF INTERFACIAL PROPERTIES IN LAYERED SUBSTRATE

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INTRODUCTION

Layered substrate is a very important type of material. The layer, such as the paint on metal, has been used widely for the purpose of corrosion prevention. The use of a layer as part of surface acoustic wave devices also has been found to have important applications in such high-tech environments as the semiconductor industry. The performance of layered substrate is critically dependent on the bonding conditions between layer and substrate.

Most of the 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 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.

BACKGROUND

The elastic wave propagation in thin layers on a half space has been studied by many researchers. Farnell and Adler [1] 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. In a stiffening situation, the initial slope of the dispersion curve is positive and the wave velocity increases as a function of frequency above the substrate Rayleigh velocity. In a loading situation, the initial slope of the dispersion curve is negative, and the wave velocity decreases as a function of frequency below the substrate Rayleigh velocity. In summary, 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.

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In a study of the imperfect layered substrate, Adler *et al.* [2] 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. In order to further examine bonding conditions, Ko *et al.* [3] studied the imperfect layered substrate using meshed layered specimens. By utilizing these specimens, experimental dispersion curves for various partial bonds were obtained. Based on these data, an attempt was made in this study to evaluate the interfacial properties of layered substrate with stiffness constants. Initially, this evaluation was done with an isotropic model because these data were taken in a plane of symmetry of the specimen. However, based on the fact that the specimen is anisotropic, the effect of anisotropy on the evaluation of the interfacial properties was further exploited. Results of this progress are discussed in two sections: imperfect interfaces and the effect of anisotropy. In the first section, the turning point in the dispersion curve and the application of this turning point in the evaluation of interfacial properties will be discussed. In the second section, the effect of anisotropy on this turning point will be addressed.

IMPERFECT INTERFACES

Calculated Dispersion Curves of Various Bond Qualities

The imperfect interface between a layer and a substrate is represented as an effective interface layer in the calculation of the dispersion relationship [2]. 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, or elastic constants, of this effective layer depend on the stiffness constants, and their relations are described in Equations 1 and 2:

$$v_l^i = [S_n d^i / \rho^i]^{1/2} \quad (1)$$

$$v_t^i = [S_t d^i / \rho^i]^{1/2} \quad (2)$$

where v_l^i and v_t^i 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 [4] for numerical calculation.

The Turning Point in the Dispersion Curve of the Lowest Order Mode

In order to focus on bond quality rather than material combination, both the layer and substrate studied were of the same material. Figure 1 shows five calculated dispersion curves of the lowest order mode of various bond qualities. The stiffness constants used in the calculation are listed in Table 1. 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 misbonded 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. 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 the 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. Of the dispersion curves plotted in Figure 1 the one closer to the perfect bond (curve 1) has higher phase velocity and frequency at the turning point. Moreover, the one closer to the complete misbond (curve 5) has lower phase velocity and frequency at the turning point. It is also noticed that the one closer to the perfect bond has higher stiffness constants, and the one closer to the complete misbond has lower stiffness constants. After a parametric study, the position of this turning point was found to increase monotonously with the stiffness constant.

Experimental Conditions

Both the layer and substrate components of the specimen are made of silicon single crystal. A meshed intervening layer technique [3] was used to prepare specimens with controlled interface conditions between layer and substrate. The direction of the normal of the bonding surface for each component was [111]. Before bonding, both components were aligned in the same orientation in the (111) plane. Figure 2 shows a schematic view of the experimental setup. The ultrasonic pulser/receiver used was Panametrics 5052PR, and the oscilloscope used was a 9400 LeCroy 125 MHz digital oscilloscope. The ultrasonic transducer used was a 5 MHz broad band transducer. The specimen was mounted on a fixture which consisted of two goniometers. The angle of incidence was controlled by one goniometer while the orientation, thus the direction of propagation, was controlled by another goniometer. A flat aluminum reflector was used in place of a second transducer.

The procedure of measurement was performed by rotating the incident angle goniometer to an angle beyond the critical angles, then adjusting the reflector so that the reflected waves could be bounced back to the transmitting transducer. In the study of bond quality, the orientation was fixed. In the study of the effect of anisotropy, on the other hand, the orientation was varied by adjusting the orientation goniometer. The signals of the reflected waves were averaged and stored in the digital oscilloscope. The frequency spectrum analysis was then applied on these averaged signals. The value of the minimum in the frequency spectrum was recorded. Both the orientation and the angle of incidence were also recorded.

Table 1. 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

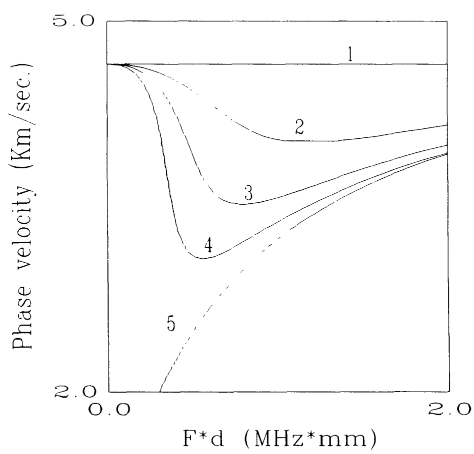

Figure 1 Calculated dispersion curves of the lowest order mode on layered substrates of various bond qualities. Their stiffness constants of are listed in Table 1.

The phase velocity of the waves was calculated based on the angle of incidence using Snell's Law. Therefore, the dispersion curve at various orientations was constructed by using the data of phase velocity and frequency minimum.

Figure 3 shows typical spectra of an imperfect layered substrate. These spectra were all taken along the $[11\bar{2}]$ direction. Unlike the layer substrates of the extreme cases that either have one or no minimum in spectrum, the partially bonded layered substrate has two minima in spectrum within a range of angles of incidence. It is noticed that the separation of these two minima decreases as the angle of incidence increases. At a certain angle of incidence, there is only one minimum in the spectrum. Furthermore, beyond this angle, there is no minimum in the spectrum.

The calculated curves as well as the experimental curves from three types of bonding conditions are shown in Figure 4. Figure 4a shows a dispersion curve of a completely

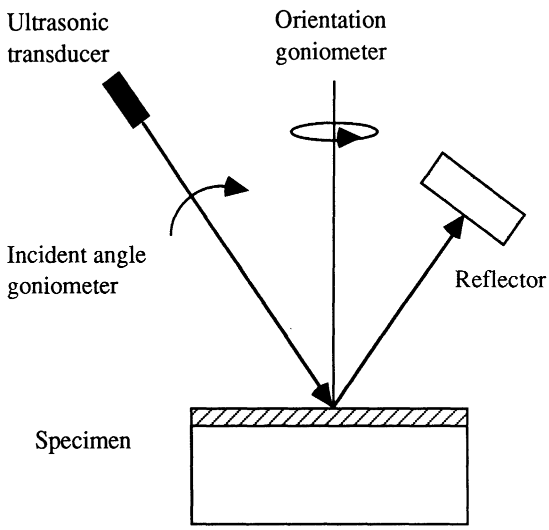

Figure 2 A schematic view of experimental setup for measuring the interfacial properties in an imperfect anisotropic layered substrate.

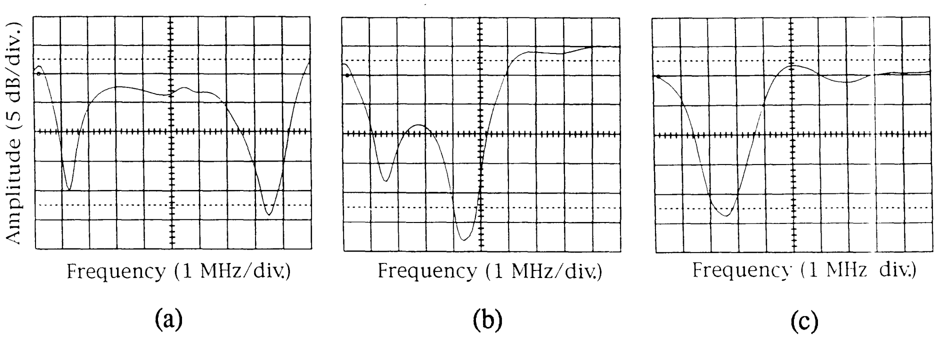

Figure 3 Typical spectra from an imperfect layered substrate at three angles of incidence: (a) 21^0 (b) 23.5^0 and (c) 25^0. Note that the separation between two minima decreases from (a) to (b), but only one minimum can be observed in (c).

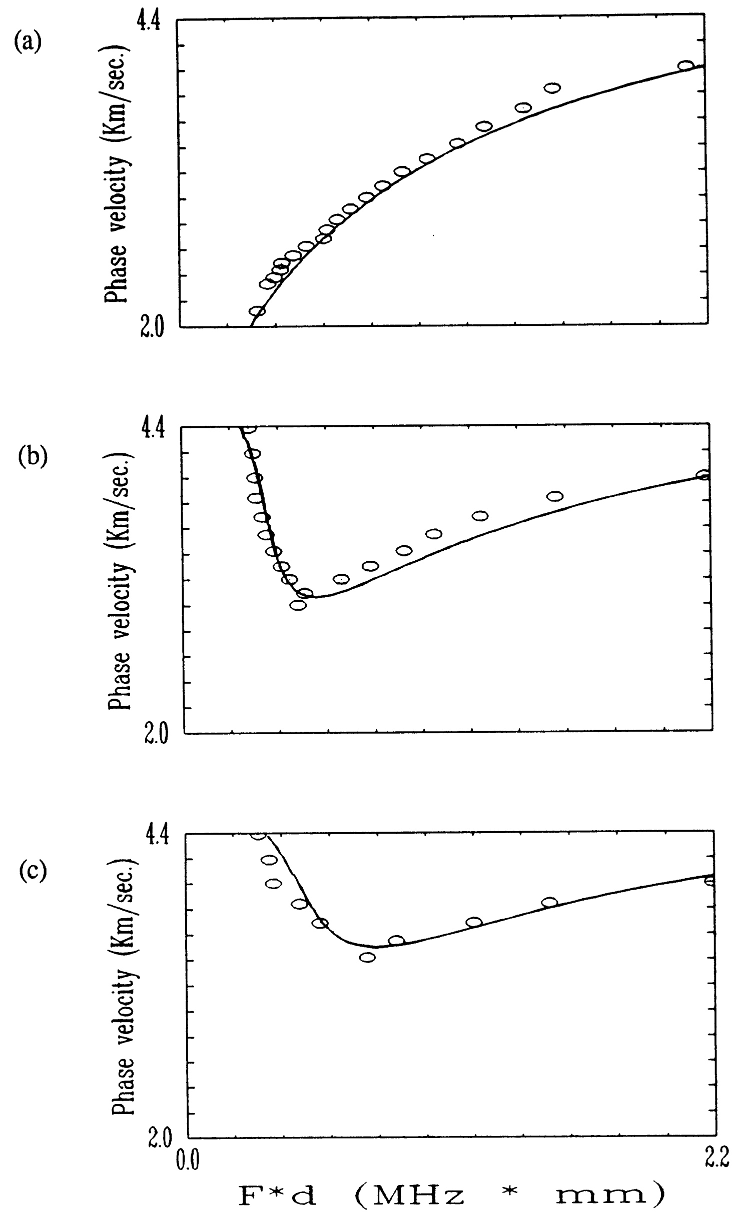

Figure 4 Calculated (—) and measured (O) dispersion curves of the lowest order mode at various bonding conditions: (a) complete misbond, S_n=S_t=0; (b) 'weak' partial bond, S_n=5.5x10^{13}, S_t=4.35x10^{13}; (c) 'medium' partial bond, S_n=1.22x10^{14}, S_t=9.6x10^{13} (Unit: N/m^3).

misbonded layered substrate in which both the stiffness constants were zeros. Figures 4b and 4c show dispersion curves of a 'weak' and a 'medium' layered substrate respectively. The significance of these comparisons suggests that the bonding condition of an imperfect layered substrate can be assessed by utilizing the turning point in the lowest order mode of the generalized Lamb wave.

Calculated Dispersion Curves of Various Orientations

In this section, results of the effect of anisotropy on the evaluation of imperfect interface in layered substrates are discussed. A schematic view of the direction of wave propagation in an imperfect anisotropic layered substrate is shown in Figure 5a. Both the layer and substrate are in the same orientation. In the numerical calculation, the effective interface layer was incorporated into an anisotropic multiple layer model [5]. Figure 5b shows the calculated results of the dispersion curves from an imperfect layered substrate. For the sake of simplicity, only three curves are displayed. The curve at 0^0 orientation, or $[11\bar{2}]$, is the lower bound of the dispersion curves at any orientation in (111) plane, and the curve at 30^0 orientation is the upper bound. The curves at other orientations lie in between these two bounds such as the one at 15^0 orientation. From these three curves, it can be seen that the shapes of the curves remained similar to one another regardless of orientation. At the extreme frequencies, some differences are noticed. In the low frequency region, the curves reach different phase velocities, and these velocities correspond to the Rayleigh velocity of the substrate at various orientations. In the high frequency region, on the other hand, the curves reach the Rayleigh velocity of the layer. Around the turning point, the variation with orientation was minimal. It is noticed that there is a periodic variation of velocity with orientation at the turning point, and the range of this variation is less than 2% of the phase velocity. It is noteworthy that there is insignificant variation in frequency regardless of orientation at the turning point.

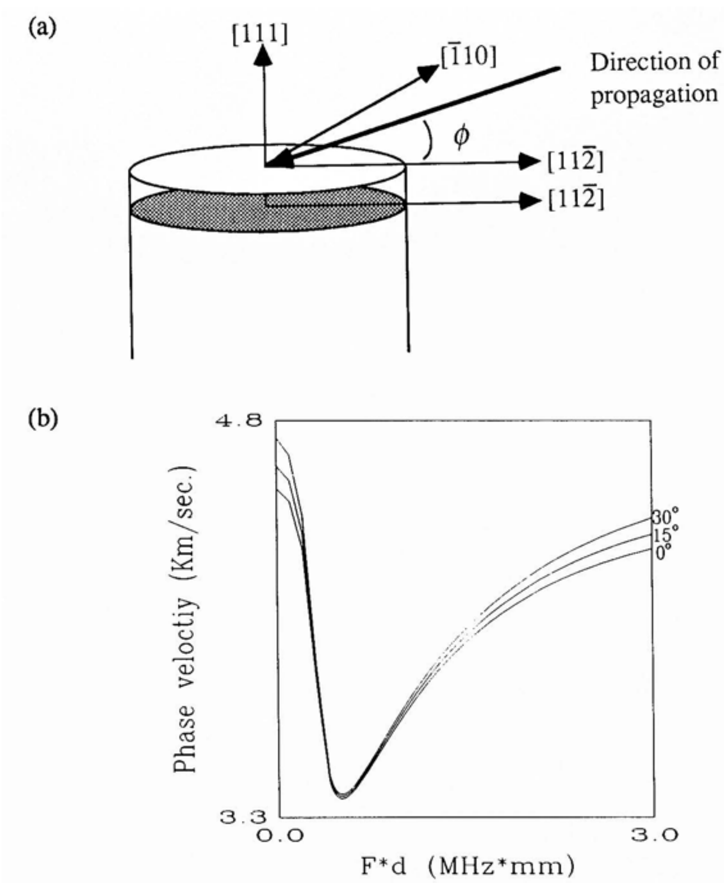

Figure 5 (a) A schematic view of an imperfect anisotropic layered and the direction of propagation. (b) The calculated results of the dispersion curves at three orientations.

Experimental Results and Discussion

The variations of F*d (Frequency*thickness) with orientation for the completely misbonded layered substrate is shown in Figure 6a. At 23^0 angle of incidence, the frequency spectrum minimum occurred at high F*d, and the variation was significant. At 29^0, the variation with orientation was not significant at all. There were one and a half periods in the range of 90^0 (from $[\bar{1}10]$ to $[11\bar{2}]$). In other words, the period was 60^0. This period was the same as that in the slowness curve of the silicon substrate in (111) plane. Figure 6b shows the variations of F*d with orientation for the partially bonded layered substrate. At 23^0, there are two frequency minima. The variation of the frequency minimum at higher F*d was more significant than that at lower F*d. As the angle of incidence increases, these two minima become closer to each other. At 28^0, there is only one minimum and the variation with orientation is not significant.

Figure 7a shows the dispersion curve for the completely misbonded layered substrate. The asterisk represents the measured data and the solid line represents the calculated results. The measured data were taken at every ten degrees, but for the sake of simplicity the calculated results were only taken from two extreme cases (i.e., at orientations equal to 0^0 and 30^0). The calculated results agreed well with the measured data. It was also noticed that in the low F*d region (i.e., less than 1.0 MHz*mm), the variation of the data with orientation was very small. As the F*d increased, the variation of data with orientation became increasingly significant. Figure 7b shows the dispersion curve for the partially bonded layered substrate. The experimental data agreed reasonably well with the calculated results. Large variation in data was noticed at both the high and low ends of F*d. What is more important is that the position of the minimum (i.e., F*d = 0.5 MHz*mm) of the dispersion curve is not affected significantly by orientation.

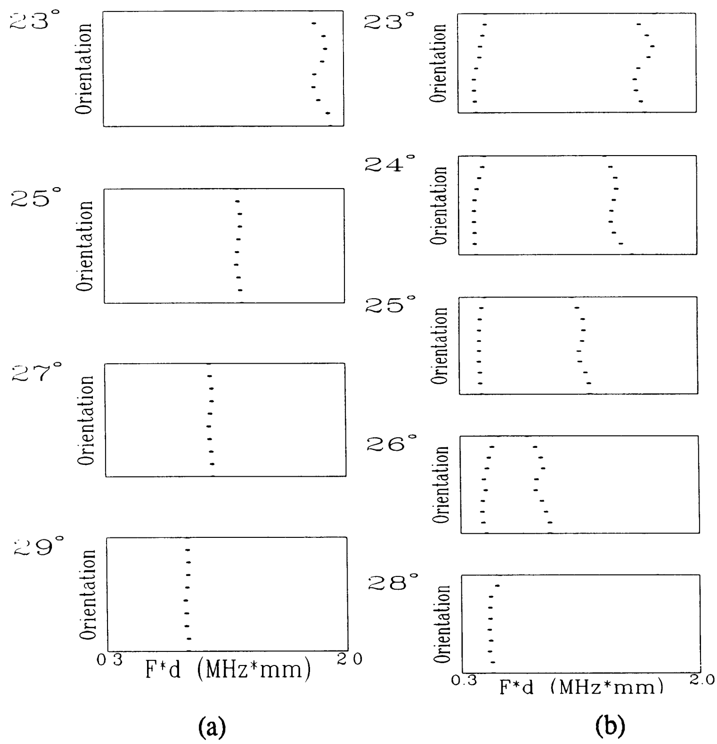

Figure 6 Measured data show variation of F*d with orientation for (a) a completely misbonded layered substrate and (b) a partially bonded layered substrate. The range of each orientation shown here is 90^0 (from $[\bar{1}10]$ to $[11\bar{2}]$).

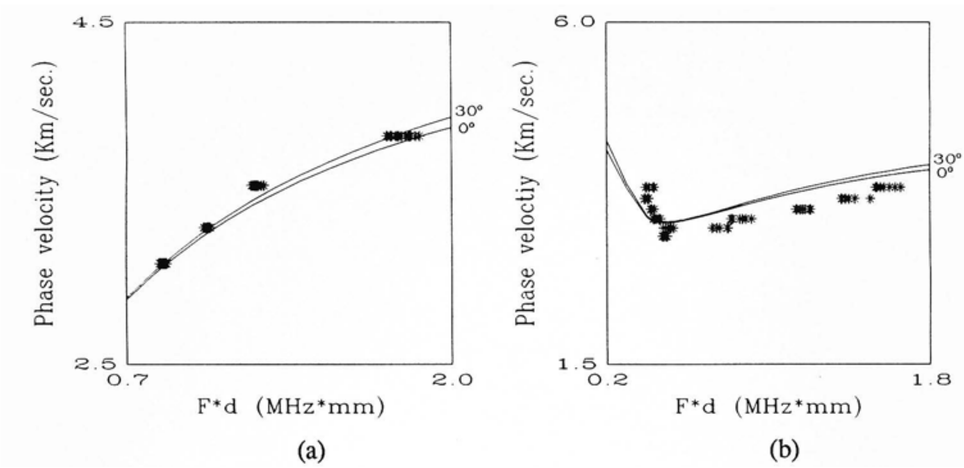

Figure 7 Measured (*) and calculated (—) dispersion curves for (a) a completely misbonded layered substrate and (b) a partially misbonded layered substrate.

SUMMARY AND CONCLUSIONS

The lowest order mode of the generalized Lamb wave was used to examine the interfacial properties of imperfect layered substrates. Specimens of controlled interface conditions were made with a meshed intervening layer technique. The results showed that the position of the turning point in the dispersion curve was sensitive to bond quality variation.By incorporating an effective interface layer into a multiple layer formulation and comparing the calculated results with the experimental data, the interfacial properties of the layered substrate were evaluated. Moreover, the shape of the dispersion curve of this lowest order mode was found to be dependent on the bond quality and anisotropy, but the dominating factor was the bond quality. Consequently, the turning point in the dispersion curve of the lowest order mode can be used to assess bond quality in an anisotropic layered substrate.

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