GENERALIZED LAMB MODES IN FRICTION WELDED STEEL LAYER ON ALUMINUM

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INTRODUCTION

The evaluation of bond quality between two dissimilar materials is one of the most difficult problems in NDE. Most previous work consisted of analysis of the spectral components of the normal incidence reflected spectrum. In this study, the quality of bond between steel layer and aluminum substrate is investigated using generalized Lamb waves. The dispersion curve for these waves, which has been studied for layer-substrate structures by Farnell and Adler [1], is extended for the fluid-loaded case in this paper. The combinations used in this study where the shear velocities of the two materials are close to each other show interesting behavior in the lowest mode. The slope of the lowest mode at very low values of frequency times layer thickness can be either positive or negative depending on the longitudinal velocities of the two materials followed by a turning point and a slope reversal. The objectives of this paper are: i) to experimentally verify the predicted dispersion curves (to our knowledge this is the first time), and ii) to utilize the dispersion curve as an NDE method for bond quality of such material combinations.

THEORETICAL CONSIDERATIONS

There are numerous analytical developments on elastic wave propagation in a layer bonded to a half space [2-5]. The dispersion relation, i.e. the phase velocity, as a function of frequency is sensitive to the material combination of the layer and the substrate. Tiersten [5] has shown that the slope of the dispersion curve at low frequency depends on the shear and longitudinal velocities of the two materials and it is positive if the inequality is satisfied, i.e.

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$$\frac{V_{t_1}}{V_{t_2}} > \left\{ \frac{1 - \left(\frac{V_{t_1}}{V_{\ell_1}}\right)^2}{1 - \left(\frac{V_{t_2}}{V_{\ell_1}}\right)^2} \right\}^{\frac{1}{2}} \tag{1}$$

where V_{t_1} and V_{t_2} are the shear velocities of the wave in the layer and the substrate, respectively. V_{ℓ_1} and V_{ℓ_2} are the longitudinal velocities of the wave in the layer and in the substrate. The extreme values of the right hand side of the inequality are

$$V_{t_1} = \sqrt{2}\, V_{t_2} \text{ and } V_{t_1} = 1/\sqrt{2}\, V_{t_2}. \tag{2}$$

Fig. 1 summarizes the different material combinations in order of the elastic constants and density. If $V_{t_1} > \sqrt{2}\, V_{t_2}$, the slope is positive and the surface wave velocity increases above the substrate Rayleigh velocity. This case is called stiffening. If $V_{t_1} < 1/\sqrt{2}\, V_{t_2}$ then the slope is negative, and the wave velocity decreases below the Rayleigh velocity of the substrate. This is called loading. Very little attention was given to the case where the two shear velocities were nearly equal as in the case of the steel layer on aluminum or aluminum layer on steel. Our calculations for the dispersion curve of the steel layer on aluminum substrate immersed in water are shown in Fig. 2a. The lowest mode shows the interesting behavior of a turning point. Both the initial slope and the turning point depend on the longitudinal velocities. The dispersion curve for aluminum layer on stainless steel substrate is given in Fig. 2b. These calculations were obtained by using rigid boundary conditions between the layer and the substrate which should be the case for good bonding. The calculations can be modified for "weak bonds" or for "no bond" cases. The effect of these conditions on the dispersion curve will be described later.

DESCRIPTION OF THE SAMPLES

The aluminum-steel samples were prepared by standard inertia-friction solid-state welding process. The dimensions of the two dissimilar cylindrical samples were 75 mm in diameter and 100 mm in length before machining one of the materials to obtain a thin layer (on the order of a few hundred microns). Depending on the selection of the welding parameters (pressure,

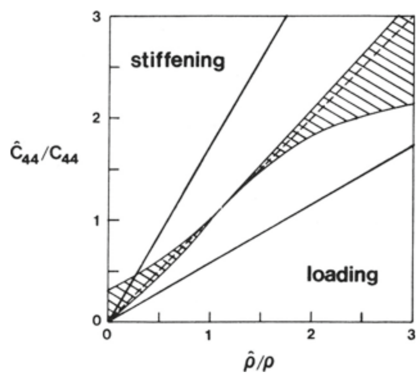

Fig. 1. Regions of layer substrate combinations based on elastic constants and density ratios. Steel layer on aluminum case is shown by X on the figure.

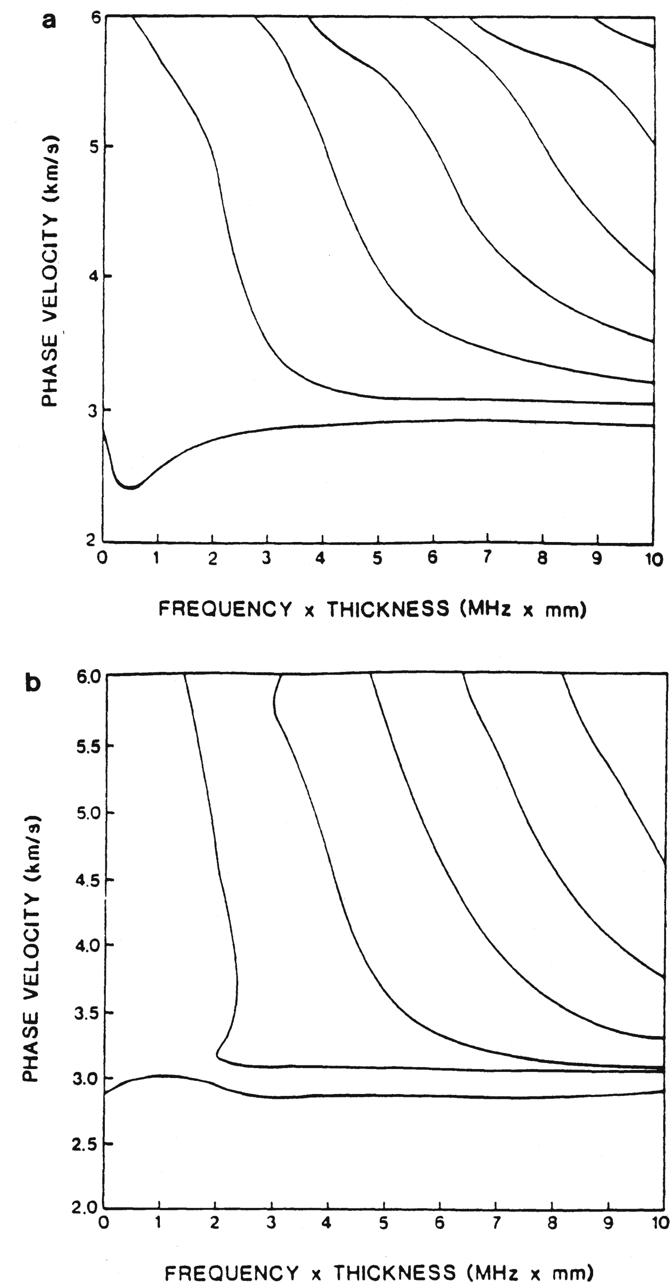

Fig. 2. Calculated dispersion curve for generalized Lamb wave for a) steel layer on aluminum substrate with water loading and b) aluminum layer on steel with water loading.

rotational speed, etc.), "good" bonded or "weak" bonded samples were obtained. In Fig. 3a and 3b, the metallography of "good" and "weak" bonded steel layer on aluminum substrate are shown, respectively.

The physical parameters of the two materials are listed in Table I.

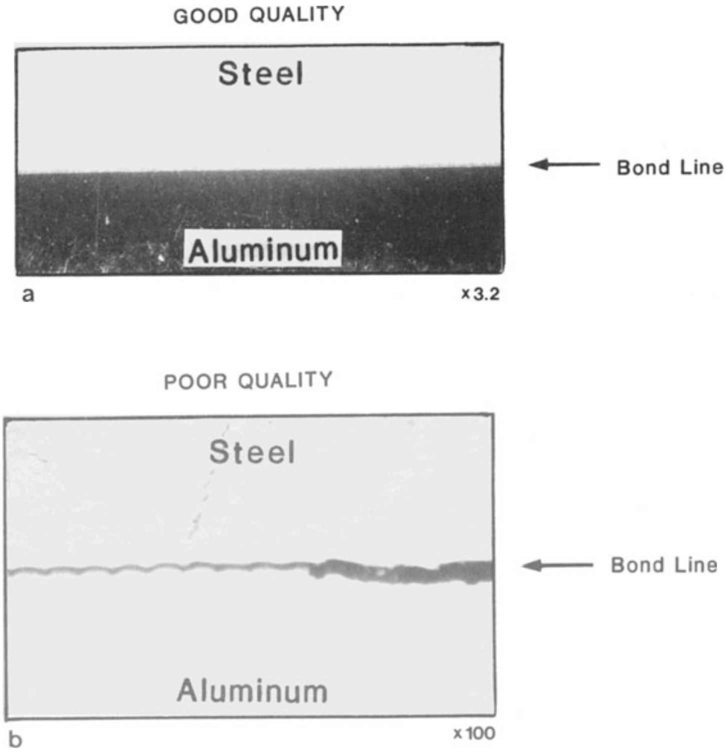

Fig. 3. Metallography of a) "good" and b) "weak" bonded steel layer on aluminum.

TABLE I. Physical Parameters of Aluminum and Stainless Steel.

	C_ℓ [m/s]	C_S [m/s]	C_R [m/s]	ρ [10 kg/m^3]
Aluminum	6370	3022	2825	2.7
304-L Stainless Steel	5640	3154	2912	7.9

EXPERIMENTAL TECHNIQUES

Two experimental techniques were used to measure phase velocity dispersion curves. The schematic diagram of the first method is given in Fig. 4. It is a two transducer angular analysis system. An ultrasonic tone burst is reflected from the sample producing an interference minima at certain angles. These minima are due to the destructive interference between a propagating leaky Lamb mode and the specularly reflected wave. The minima of the angular position shown in Fig. 4 then can be converted to phase velocity values using Snell's law.

The second experimental set up is shown in Fig. 5. Basically it is a single transducer experiment using broadband ultrasonic pulses. The particular modes are selected out at a given angle from frequency domain information.

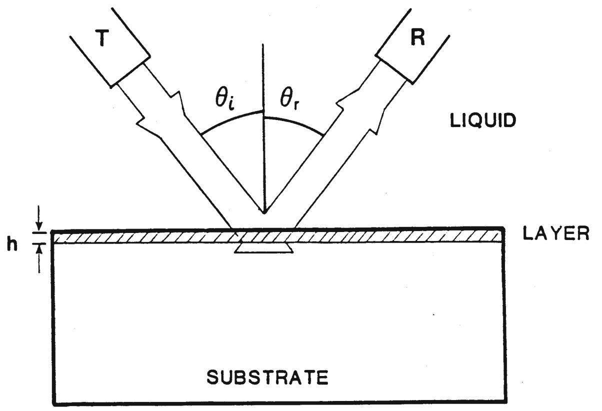

Fig. 4. Schematic diagram of two transducer measurement technique.

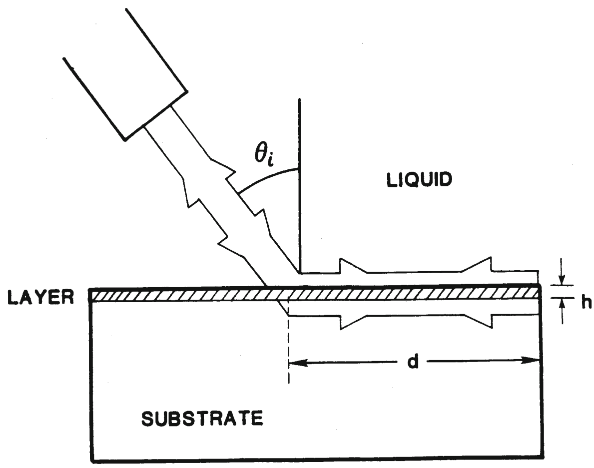

Fig. 5. Schematic diagram of one transducer measurement technique.

Both of these measurement techniques were used in this study to obtain the dispersion curve for layer-substrate bonded structure. The frequency used in the experiments ranged from 0.4 MHz to 15 MHz giving a range up to 6 MHz mm for the dispersion curve.

EXPERIMENTAL RESULTS AND DISCUSSION

Steel Layer on Aluminum

Fig. 6 shows the comparison between experimental data and theoretical prediction. The dispersion curve of the generalized Lamb waves is for the case of steel layer on aluminum substrate for "good" bonding conditions. The significance of this result is the excellent agreement between theory and experiment for the lowest mode, especially for the low frequency region.

For the sample with the "weak" bond, experimental data is plotted in Fig. 7. The behavior of the lowest mode is quite different than for the other case. In order to obtain a better understanding of the effect of the bond quality on the dispersion curve, we cancluated the dispersion curve for different bonding conditions between steel layer and aluminum. Fig. 8 summarizes the calculated results for the lowest mode in the case of a)

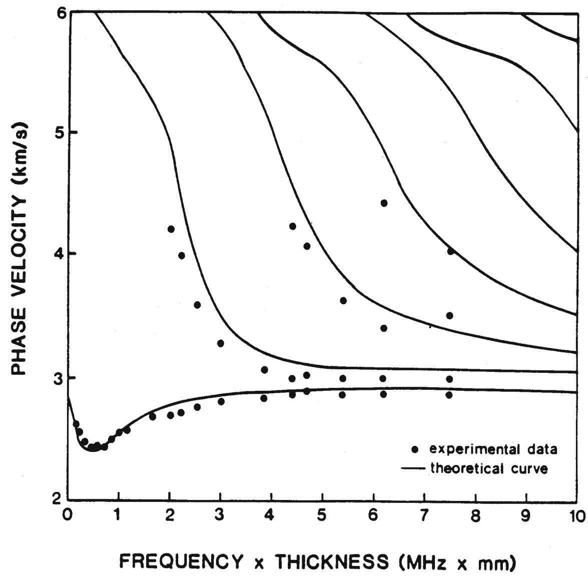

Fig. 6. Comparison of experimental data with theoretical prediction for dispersion curve of generalized Lamb waves on "good" bonded steel layer on aluminum.

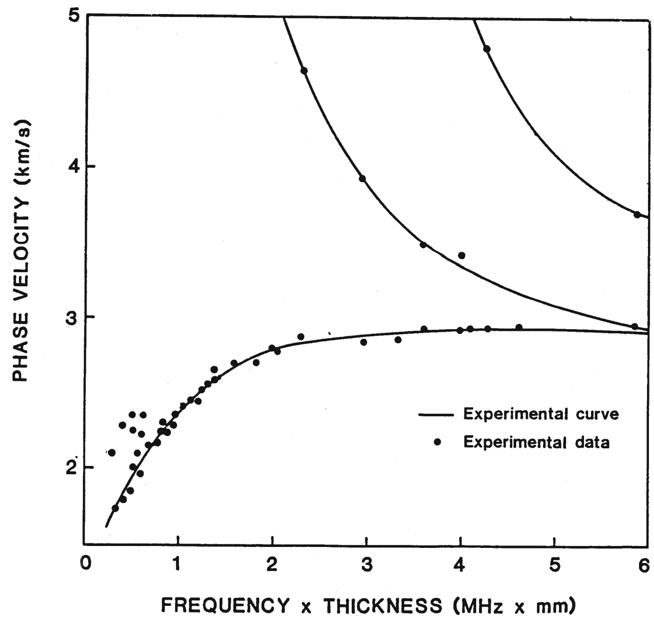

Fig. 7. Comparison of experimental data with theoretical prediction for dispersion curve of generalized Lamb waves on "weak" bonded steel layer on aluminum.

rigid, b) slip, and c) free boundary conditions. The solid line is a best fit to the experimental points. As a result of these calculations, one may separate friction welded samples into three categories: i) good bond, ii) weak bond, or iii) no bond. Initial experimental results shown in Fig. 9

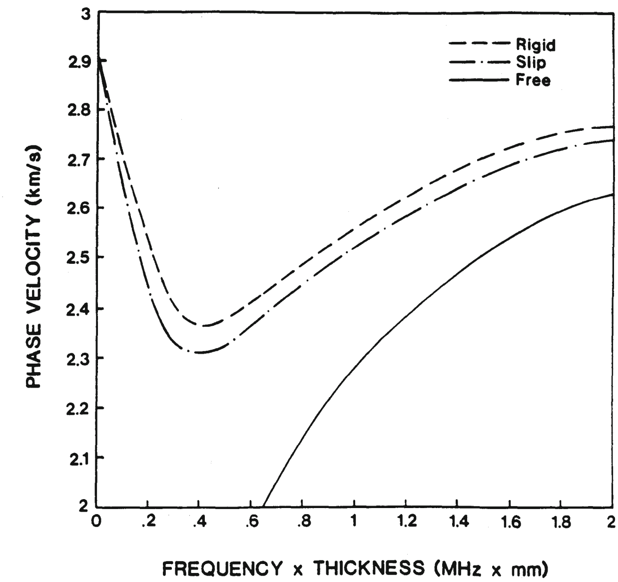

Fig. 8. Calculated dispersion curves for steel layer bonded on aluminum substrate with various boundary conditions.

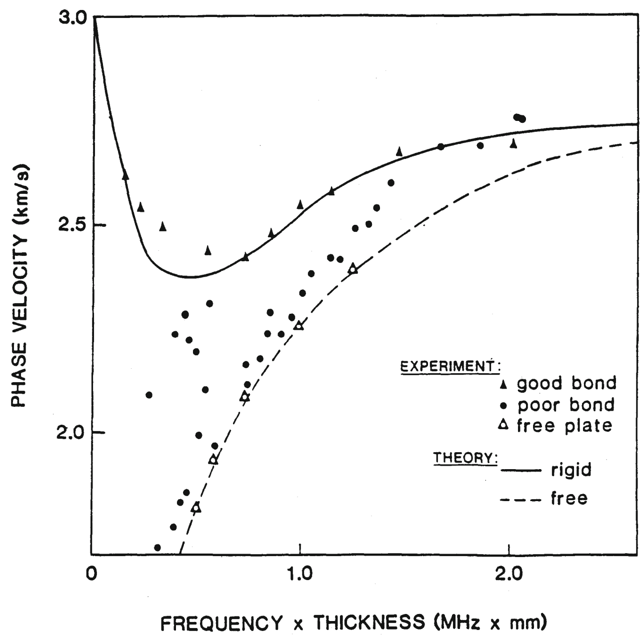

Fig. 9. Comparison of experimental data to theoretical prediction for the lowest generalized Lamb modes for bonded steel layer on aluminum.

show that the data follows well the prediction for the "good" bond and for the "no" bond case (free plate). The data points for the "weak" bond sample scattered between these two extreme cases.

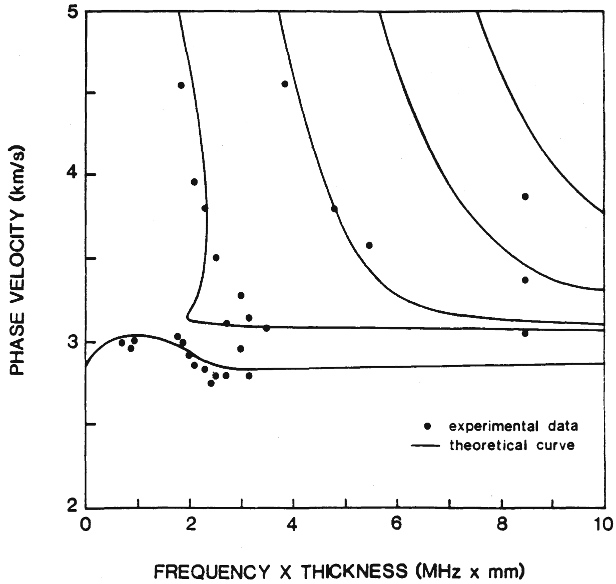

Fig. 10. Comparison of experimental data to theoretical prediction for dispersion curves of generalized Lamb wave for aluminum layer on steel substrate.

Aluminum Layer on Steel

Preliminary work on the dispersion curve for the case of steel substrate was carried out and is shown in Fig. 10. The agreement between experiment and theory is reasonably good.

CONCLUSION

In this study we presented the behavior of the dispersion curve for generalized Lamb waves in layer-substrate structure for aluminum-steel combination. Because the shear velocities of these two materials are almost the same, the initial slope of the lowest mode changes direction. We have obtained good agreement between theory and experiment for friction welded samples. We have also shown that the lowest mode of the dispersion curve can be used as a new NDE method to evaluate bond quality.

ACKNOWLEDGEMENT

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