FAST LEAKY MODES ON CYLINDRICAL METAL-CERAMIC INTERFACES

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ABSTRACT

The QNDE application of theoretically predicted and experimentally detected fast leaky modes propagating along cylindrical metal ceramic interfaces has been studied. Our approach utilizes the leakage of acoustic energy out from the interface to yield valuable information on the mechanical and physical properties near the interface. The theoretically predicted sensitivity of the maximum phase velocity of leaky modes to changes in matrix density is discussed as a possible means for sensing the interface zone in metal-ceramic cylindrical geometries.

INTRODUCTION

In our previous work [1,2,3,], we have studied in detail the radial-axial modes in an infinitely clad isotropic rod. We have shown that in metal matrix composites, where the fibers are stiffer than the matrix, many of these modes are leaky, transmitting energy into the surrounding medium. The existence of this leakage energy offers a potential means for monitoring and imaging the characteristics of the interface zone [2,3,4,]. Detailed numerical methods have been developed for analyzing radial-axial leaky modes in composite systems [1]. The present paper shows an example of these methods applied to determining the sensitivity of the maximum phase velocity to the matrix density changes for leaky modes.

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A comparison between the calculated dispersion curves and the measured dispersion relation for the radial-axial leaky modes at the interface in the Al/SiC system shows differences between calculated and measured phase velocities. Measurements taken on shrink-fitted Al/SiC models of cylindrical interfaces using 6 mm wavelength leaky interface mode have detected the presence of a low density medium around the SiC rod at several inspected sections of the interface. In fiber reinforced Al/SiC composites the extended annealing creates a reaction layer of Al$_4$C$_3$ at the interface zone. This reaction layer has much lower density (2.36 g/mm$^3$) than aluminum. We have calculated how the cladding density change affects the speed of the interface wave at Al/SiC interfaces.

**THEORY**

The topic of normal modes in clad rods has a substantial literature, but in most cases attention has been concentrated on the use of such structures for wave guides. In our previous work [1,2,3,4], we emphasized the ultrasonic interface wave propagation at cylindrical and planar interfaces as a potential method for inferring the modulus of the interface between metals and ceramics. In one of our preliminary papers [4], we discussed how the velocity of these waves depends sensitively upon the local moduli and provides a potential basis for measuring these quantities. The use of ultrasound for determining the elastic properties of bulk materials is well known. The work reported here explores the extension of this theory to interfaces where a third phase is formed in a geometry representative of that found in fibrous composites. Assuming that the elastic constants of the cladding do not change significantly during processing, we have gradually changed the density of the cladding at the input of the computer code developed for simulating the interface wave propagation at the cylindrical interfaces [1]. The numerical results of these calculations, comparisons with experiments, and the future implications of these procedures for the development of an ultrasonic sensor for high temperature processing of metal-ceramic interfaces will be discussed in the paper.

The theoretical framework for the calculations is the isotropic elasticity for both the matrix and fibers, without an intermediate anelastic interface zone [1,2,3,4]. It was confirmed experimentally in Al/SiC that the assumed elasticity describes properly the propagation of the acoustic waves along the well bonded interface [2]. Every measured deviation from the theory is caused by the changes of the physical and mechanical properties in the interfacial region. The phase velocity measured directly at the interface contains the information about the elastic constants and the density of the two interface components. In the present calculations, we assume that the elastic constants of the cladding remain constant.
a) Dispersion curves

Since a clad rod consists of the conjunction of a bare rod with an infinite cladding, it seems natural to seek the relationship between leaky modes and the modes that exist in a bare rod or in an infinite material with a cylindrical tunnel. As long as the density of the rod is not zero, most leaky modes are leaky rod modes. Fig.1 shows the dispersion relations for silicon carbide rod in aluminum cladding. All bare, real or partly real SiC rod modes are shown as dotted lines. The associated leaky modes are plotted as solid lines. The dispersion curves in these figures have been arbitrarily truncated at their maximum value for clarity of graphical presentation. It is worth emphasizing that in the dispersive region (when the the wave length is comparable with the radius of the rod) the radial-axial modes in the bare rod correspond to the limiting case of infinite phase velocity. The leaky interface modes in the embedded rod propagate with a finite phase velocity. This velocity can be measured directly at the interface.

Fig.1 Dispersion curves for the real part of the modal phase velocity for leaky modes [1] and rod modes as a function of rod radius x frequency (r x f) in the system consisting of SiC fibers in an Aluminum matrix.

Detailed numerical methods have been developed for analyzing radial-axial leaky modes in composite system [1,2,3,]. Fig.1 shows an example of numerical results in the Al/SiC system. The dispersion curves for a number of modes are plotted as a function of the geometrical parameter r x f.
The leaky mode with maximum phase velocity at $r \times f = 9 \text{ mm/us}$ was experimentally studied. The schematic diagram of the experiment used to detect radial axial leaky modes in the Al/SiC model sample is shown in Fig. 2. The transmitting transducer was placed at the silicon carbide rod in order to generate a surface acoustic wave which converts into a radial-axial leaky mode at the interface. This mode radiates the acoustic energy into the matrix when it travels along the interface. The receiver, a movable conical transducer, used in this simple scanning system was placed directly against the outer aluminum surface of the sample. A special couplant was used to maintain uniform reproducible results. A narrowband pulse gated from the frequency synthesizer was sent to the ultrasonic transmitter. The receiving transducer detected the signal and the waveform was stored in the memory of the digital scope. After a small translation of the receiver, $dx$, the new waveform was compared with a previously stored one and the time difference, $dt$, between the two positions of the receiver was used for the phase velocity evaluation, $c = dx/dt$.

This technique, shown in Fig. 2, compares two sinusoidal waveforms with respect to a maximum or minimum of the wave amplitude and measures the phase velocity of the traveling interface wave if the receiving pulse does not differ significantly from the stored reference.

Fig. 2  Schematic diagram showing detection of leaky modes in a specimen composed of a SiC rod of radius 3.2 mm embedded in an aluminum cylinder with outer radius 14.2 mm. The phase velocities of the interface wave were measured using the leakage energy radiating through the aluminum matrix out of the interface.
The dotted line in Fig.3 shows the attenuation of the leaky mode expressed in dB/MHz mm (cylindrical case). It is worth emphasizing that the maximum measured phase velocity of this mode of 18.65 mm/us is about twice that of the longitudinal velocity in SiC and about three times that of the longitudinal velocity in aluminum. The difference in phase velocities between the bare rod mode and the leaky mode in the embedded rod depends strongly on the density of the cladding surrounding the rod. Intuitively, the smaller the density of the matrix, the higher the maximum phase velocity of the interface mode. One can numerically "dissolve" the matrix around the fiber in order to calculate the relationship between the density of the cladding and the maximum phase velocity of the interface leaky mode.

**Figure 3**

The theoretical and measured dispersion curves for one of the fast radial-axial leaky modes in the Al/SiC model sample. The measurements were taken at different frequencies for the fixed radius of the rod.

So called "type 0 modes" [1] (see fig.1) have one leaky mode for each rod mode. At each value of $r \times f$ there is a difference in a phase velocity between the bare rod mode and the leaky mode (the dispersion curve for the mode used in this study is shown in Fig.3).

It was possible to determine the local velocities of this mode over a section of the interface by measurements carried out over an outside section of the matrix (see Fig.2). It was then possible to map out the variation in phase velocity along the interface. The variation in measured phase velocities along the section of the Al/SiC interface is plotted in Fig.4.
A small change in the density of the matrix surrounding a fiber or rod causes a significant difference in the phase velocity of the propagating interface wave. The results of the numerical calculation of velocity dependence on density for the leaky Al/SiC cylindrical mode (used for "interface mapping") are shown in Fig. 5.

The microscopic studies of the heat-treated Al/SiC interface [5] have shown the presence of Al₄C₃ layer at the interface. The density of the Al₄C₃ compound is about 10% less than the density of aluminum (2.34 compared to 2.7 g/mm³). The thickness of this layer will grow with annealing time, with resulting decrease in the mechanical strength of the composite material. It is worth noting that, at the present time, nondestructive methods do not exist for studying the interface "in situ", during processing. The results presented in this paper have shown the sensitivity of the velocity of leaky interface waves to cladding density changes. This means that an interface wave ultrasonic sensor can monitor the kinetics of chemical reactions of this type at the Al/SiC interface as a function of time and temperature, although more sophisticated modelling is required for quantitative results.

Fig. 4. The variation in phase velocity along the section of the Al/SiC interface. The measurements were carried out over an outside section of the aluminum matrix, as it is shown in Fig. 2.
Fig. 5. Sensitivity of the phase velocity of the interface leaky mode to the matrix density changes. Numerical calculation for the interface leaky mode in SiC/Al system at r x f=9.2 mm/us. The dispersion curve of this mode is shown in Fig. 3. The calculations were done numerically by gradual changing the cladding density. We have marked on the calculated curve the densities of SiC, Al, and Al₄C₃.

Fig. 6. The microscopic studies of the Al₄C₃ layer at the Al/SiC cylindrical interface subjected to the high temperature treatment. (Courtesy of Carol Handwerker and Alexander Shapiro from NIST).
CONCLUSIONS

The results discussed in this paper are part of our research on interface acoustic sensors for process modelling and process control, where high temperature (up to 1000° C) sensing techniques could be applied to monitoring the properties of interfaces subjected to long term annealing [6].

This "interface mapping" technique can be used to study the chemical reaction kinetics "in situ" of the growing Al₄C₃ layer at the Al/SiC interface. The study of the density changes at the interfaces in metal matrix or metal ceramic composites is a practical extension of the existing elastic solution to the interface zone.

REFERENCES

1. J.A.Simmons, E.Drescher-Krasicka, H.N.G. Wadley "Leaky Axisymmetric Modes in Infinitely Clad Rods-part I" (submitted to JASA)