INTRODUCTION

Many of tomorrow's technologies are dependent upon the emergence of new advanced materials with superior stiffness and strength but reduced density. Metal matrix composites (MMC's) consisting of light metal matrices (e.g., aluminum, titanium or magnesium) reinforced with very stiff ceramic fibers or particles (e.g. SiC, Al2O3 or graphite) show considerable promise for satisfying this need. However, the satisfactory performance of these materials has been found to be critically dependent upon the attainment of optimal properties at the metal-ceramic interface; a problem that is compounded by the possibility of chemical reactions between the reactive metal matrix and ceramic reinforcement. Of particular import are the interface adhesion and local elastic properties. Unfortunately no methods exist for the measurement of these quantities even for macroscopic interfaces let alone for the microscopic interfaces occurring within MMC's.

We are all aware of the use of longitudinal and shear waves to determine elastic constants of bulk materials and of the developing possibility of using surface waves to characterize free surface properties and their depth dependence. By analogy, it seems reasonable to hope that similar characterization of interfaces might be possible through the use of yet to be explored interface elastic waves.

The existence of interface waves at the planar interface between two media of differing elastic constants/densities were first predicted by Stoneley [1] and observed in seismograms following major earthquakes. It has since been shown that very restrictive conditions must be met by the two media in contact if the wavevector (or velocity) of the interface wave is to be a purely real number so that nonattenuating propagation occurs [2].

For most material couples, the restrictive rules are not exactly met, and the wave vector of the interface wave is found to be complex [3]. Thus, the interface wave suffers attenuation (at a rate determined...
by the magnitude of the imaginary component) as it propagates. The physical mechanism of attenuation is the radiation of elastic energy away from the interface. It is similar, for example, to the so called leaky surface waves at water-solid interfaces. Provided the attenuation is not too great, these more general guided interface waves may still be used to characterize the interface region provided the relationships between velocity and local elastic properties can be established.

The approach is somewhat further complicated by the cylindrical or spheroidal geometry of the interfaces in fiber or particulate reinforced composites. This aspect of the problem introduces dispersive behavior into the wave propagation [4]; this added complexity is, however, offset in the fiber reinforced case by the possibility of only slightly attenuated leaky interface waves occurring at frequencies where the attenuation for the planar case might be prohibitively large.

WAVE PROPAGATION THEORY

The normal modes of a cylindrical rod in an infinite matrix, including interface modes, are obtained from matching displacement and traction conditions at the interface. The conditions for such modes is the vanishing of a determinant [1] which depends on the phase velocity of the modes. Complex values of the velocity can also cause the determinant to vanish, and those velocities lying in the correct complex half plane correspond to leaky normal modes whose amplitude decays exponentially with distance from the driven end of the rod. The form of the determinant for radial modes (those whose displacement depends only on radius and longitudinal distance along the cylinder) is well-known. However, accurate computer codes for determining such modes may not exist. For instance, Lee & Corbly [3] use the incorrect asymptotic form for the modified Bessel functions \( I_0 \) and \( I_1 \) occurring in their secular equation.

We have developed new, accurate algorithms for calculating modified Bessel functions over the large complex parameter range needed for normal mode determination and modified the asymptotic form of the determinant so that it remains analytic and of limited dynamic range throughout this region. Rouche's theorem for analytic functions then permits calculating the number of zeroes inside a box shaped region by use of an adaptive integration scheme. Combined with Newton's method for obtaining roots and several search routines, the phase velocity for all useful ordinary and leaky radial modes has been mapped out over a range of frequency and cylinder geometry for a sample consisting of a stainless steel rod encased by an aluminum matrix.

The theoretical results for the nonattenuated radial mode in an isolated steel rod are shown in Fig. 1. The ultrasonic velocity depends on a curvature-frequency parameter expressed as a product of frequency times the radius of the rod (fR).

Two radial modes for an aluminum tunnel (containing no rod) have been identified to date in the frequency range 0-16 MHz. A nonattenuated radial mode for an aluminum tunnel is plotted in Fig. 2. In this case the wave mode appears to show a characteristic cut-off at about fR = 1.069MHz.mm when the velocity reaches that of the shear wave in aluminum.

Figure 3 presents the calculated dependence of the velocity (continuous line) and the attenuation (dotted line) for the attenuated radial mode in an aluminum tunnel. The attenuation is expressed in decibels per unit frequency and per unit length along the axis of the tunnel. These results are valid for all frequencies and all fiber radii.
Fig. 1. Nonattenuated radial mode in a steel rod. Calculated velocity versus parameter of curvature \( f \cdot R \) [mm MHz].

Fig. 2. Nonattenuated radial mode for an aluminum tunnel.
Two leaky radial interface modes have been predicted for a steel rod embedded in an aluminum matrix. The theoretical results are shown in Figs. 4 and 5. The mode presented in Fig. 4 appears to be an attenuated shear wave in aluminum at higher ranges of f.R. However, its damping increases rapidly with increasing curvature (decreasing f.R) so that at the values of f.R where the velocity deviates significantly from the shear velocity, this mode is already undetectable by ultrasonic means, assuming that the measurable attenuation range is ~80 db.
The weakly leaking wave which might have practical applications in interface characterization is shown in Fig. 5. This is the wave that was calculated and measured for a cylindrical aluminum steel interface at 10 MHz for $R = 8.75$ mm by Lee and Corbly [3]. Their calculated value agrees approximately with that calculated here. Attenuation of this interface radial mode does not exceed the value of 0.6 db/mm MHz up to $R.f = 0.6$ mm MHz. Thus for $R = 0.6$ mm, the attenuation along a typical interface of 60 mm length at a frequency of 1 MHz will be 36 db.

EXPERIMENT

A model sample composed of a 3.2 mm radius 316 stainless steel rod shrink fitted into a 2024 aluminum alloy cylinder (Fig. 6) was used to test the theoretical predictions. Shrink fitting created a good cylindrical interface between these two materials because of their large thermal expansion coefficient difference. A Matec 6600** was used to measure the ultrasonic characteristics of the sample. Interface waves were generated by the conversion of rod surface waves although many other methods and techniques have been investigated.

The interface wave velocities measured as a function of frequency for the model sample are compared with the theoretical solution in Fig. 7 for frequencies of 1, 2, 3.5, 5, and 10 MHz. The accuracy of measurements was 30 m/sec. Excellent agreement with theory was observed in contrast to that reported in reference [3].

**The naming of commercial suppliers of instrumentation is given only to identify its specifications and should not be construed as an endorsement by NBS of this product.
Fig. 6. Model aluminum-steel interface created by shrink fitting.

Fig. 7. Comparison with the theory for a good interface.

The results (triangles) shown in Fig. 8 were obtained on a cast aluminum matrix composite model which contained a number of rods of radius 1.195 mm spaced 4 mm apart (Fig. 9). There are small flaws at the interface (Fig. 10); these separations at the interfaces are thought to be the origin of the slight deviation of the experimental results from the theoretical predictions at higher frequencies. A much larger deviation from the predicted behavior occurs at low frequency for $fR < 2.0$ when the wavelength becomes comparable with the spacing between rods and neighboring interfaces interact.
Fig. 8. Cast interface. The experimental results deviate from the theoretical predictions.

Fig. 9. Cast metal matrix composite model. Visible interfaces between aluminum and steel.
CONCLUSIONS

Very good agreement has been obtained between the measured and theoretically predicted interface velocities in a model MMC material. High frequency deviations from theory serve to characterize the quality of the interface. We are now examining the displacement wavefields of these waves as a prelude to addressing the inverse problem for determining the elastic constants of the interfacial region.

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REFERENCES