THE FOCUSED-BEAM REFLECTION-MODE ACOUSTIC MICROSCOPE AT LAWRENCE LIVERMORE NATIONAL LABORATORY - DEVELOPMENT AND PRESENT CAPABILITY

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INTRODUCTION

A focused-beam, reflection-mode acoustic microscope (FRAM) has been developed for the evaluation of surface and near surface regions in monolithic and layered structures. This new ultrasonic system, though it bears some similarity to other ultrasonic and acoustic microscope systems is sufficiently unique in at least four important aspects:

1. The ultra broad (10 to 1) frequency range through frequency--contiguous transducer/lens system.
2. Two selectable signal source options that include coherent RF pulse burst or incoherent video impulse excitation.
3. Precision imaging (color as well as black and white) and metrological algorithms implemented through digital control.
4. Large digital storage capacity that permits near real-time replay and comparison.

The FRAM system uses two frequency contiguous transducers with wide-angle acoustic lenses excited with coherent pulse bursts in the 10 to 100 MHz frequency range. The wide-angle lens feature, combined with coherence and digital control realizes quantitative metrology and imaging of near surface regions.(1) In this report, the capabilities of the FRAM system are discussed. For a description of the FRAM instrumentation and further discussion of its capability, the reader is referred to Ref. 2.

Two different modes of operation have been designed into the FRAM system; 1) imaging and 2) metrology. In the imaging mode, the system is similar to a high resolution precision ultrasonic scanning system with "special" zoom and image enhancement features. It can perform A, B, or C scans and display the data in a number of formats so as to

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enhance the features of interest. In the metrology mode, the microscope employs surface acoustic waves (SAW) in conjunction with longitudinal waves to interrogate the surface and near surface region. The combination of the imaging and metrology modes provide a rapid and quantitative means to evaluate surface properties, layered structures, solid state bonds and self-supporting membranes.

IMAGING AND METROLOGY

The following discussion is divided into two sections dealing separately with the imaging and metrology results. Wherever possible, the pertinent discussion will be descriptive and explanatory. Interpretation is not always possible because the science of diagnostic acoustic imaging applicable to microscopy has progressed only to a limited degree. Quite similar comments are appropriate regarding the acoustic material signature (AMS).(3) While the first-order ray model has been most useful in conceptualizing the physical picture through which the AMS is produced,(4) its limitations are only now being encountered and explored.(5) Therefore, future applications in this field rest to a large extent on more detailed understanding and explanation of current poorly understood phenomena.

Imaging of Surface Layer Elastic Properties (Lincoln Penny)

The ability to visualize the elastic modification of surface material layers in a completely nondestructive way is demonstrated in the following example. The specimen consists of a Lincoln penny in which the face opposite the Lincoln image (the Lincoln Memorial) has been removed by machining and subsequent polishing. An optical photograph of the machined front face (not shown) would reveal little surface detail when optically inspected. The total mean thickness of the penny after machining is approximately 1.50 mm reduced from an original thickness of approximately 2.0 mm. The penny consists of copper surface layers clad onto a zinc central plate.

A raster-scanned image (C-scan) of that coin was obtained (Fig. 1) by focusing on the Lincoln face (back face) through the machined face of the penny. A 12.7 mm focal length lens/transducer system with half-angle of convergence 14.5° and nominal frequency of 50-MHz was used. The transducer was excited by an impulse signal.

An inspection of the image shown in Fig. 1 reveals two distinct patterns: (1) the mirror image of the Lincoln face as seen through the machined face, and (2) the Lincoln Memorial, whose topographic surface had been removed earlier by machining and polishing. The fact that this image persists implies that the material beneath the machined-away topographic layer, created in the original coining (embossing) process, has been modified. The introduced change may be due to changes in the material stiffness of the surface layer resulting in a change of wave velocity and/or due to increased elastic wave absorption, resulting from the plastic deformation. Differentiation between these two effects (and possibly others) must be preceded by careful calibration of the microscope's image transfer function and by a subsequent reflection imaging procedure with planar specimens of known characteristics. It will also be instructive in this quantitative study to determine the acoustic absorption and scattering of the copper and zinc materials of the penny. Attenuation in these

Figure 1. Images of modified Lincoln penny; front face (Memorial was machined to remove all copper material, leaving flat zinc face; raster-scanned acoustic image of front face, focused at plane of back face (head).

soft materials varies considerably with deformation history because of their plastic nature.

ACOUSTIC MATERIAL SIGNATURE (AMS) RESULTS

A variety of preliminary acoustic material signature diagnostic investigations have been conducted[6] with the results of two specific cases reported here; AMS of a steel bearing race and that of a copper foil.

(1) Steel Bearing Raceway

The elastic and metallurgical characteristics of the 43.1 mm diameter bearing raceway were not known at the time of this study. However, the cylindrical geometry of the bearing was suitable for an imaging trial. No work has been performed or reported previously of curved surface acoustic microscopy involving a cylindrical surface.

Therefore, the present AMS result described below is to be viewed in the light of present limited understanding of curved surface imaging.

Standard stationary AMS data can be obtained by z-motion between the wide-angle transducer and specimen. This standard stationary method has been discussed in detail in earlier reports.[2,6] The AMS discussed below shows a lateral scan AMS along the centerline of the raceway path, normal to the lens axis z. This lateral scan (horizontal) AMS is shown in Fig. 2. Some explanation of its significance is in order at this point.

The figure plots relative reflected power in dB (set up to read zero at the focal point) versus the axial focal plane to specimen-surface distance, called z-movement. While in general z-movement denotes the lens translation relative to the specimen, z-movement in the present case is accomplished by the lateral scanning of the bearing race. Thus, the z-movement is a measure of the lateral translation and a function of the raceway radius (22.22 mm in this case) where the lateral distance covered by the AMS of Fig. 2 corresponds to 9.53 mm.

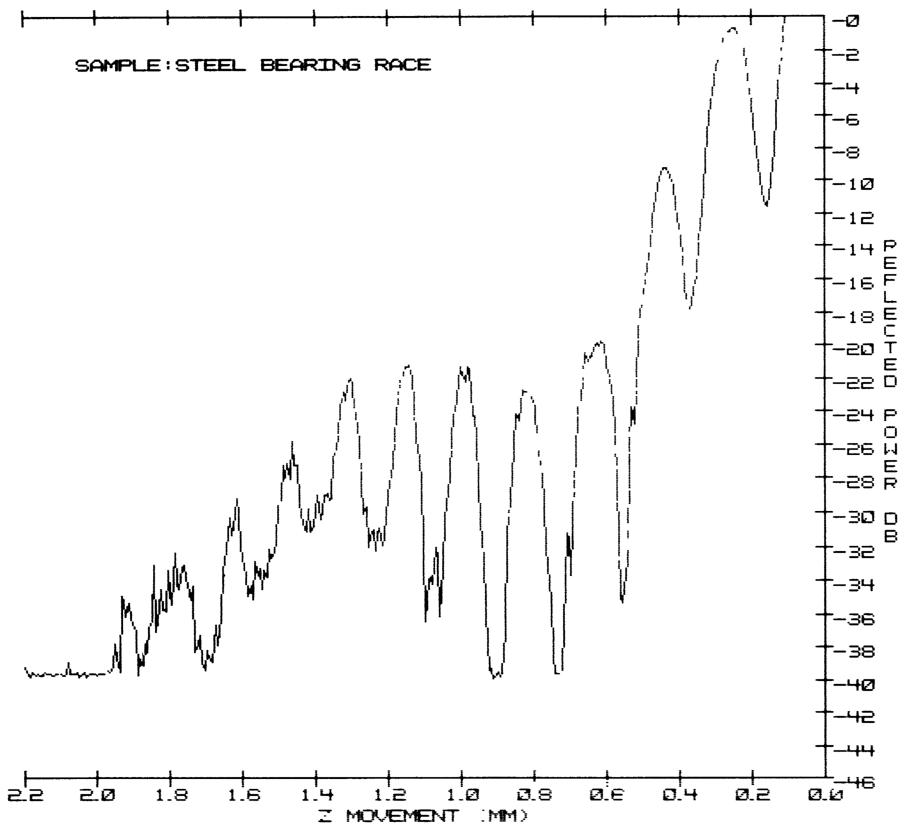

Figure 2. Lateral scan (horizontal) AMS of steel bearing raceway at 35 MHz.

The AMS is similar to that described previously in Ref. 7 with some important differences. (1) The peaks of the AMS fall off more rapidly than for a planar specimen as a direct consequence of the convex surface curvature that disperses the reflected energy to the transducer. (2) Some evidence of changing period in the AMS versus lateral distance is seen as well. This effect is not well understood and deserves attention if curved-surface acoustic microscopy is to attain quantitative metrology status in the future.

The same cylindrical bearing was raster-scanned to obtain an AMS map of a sector of the bearing race. Such a two-dimensional AMS map of a 19 mm-wide sector scan is shown in Fig. 3, where the raceway width in the image has been magnified 2 times for clarity. Some evidence of the raceway shoulder is also seen in the lower part of the figure. Irregularities are seen in this two-dimensional AMS image that requires further study. In principle, these irregularities are similar to those listed in connection with the lateral scan line AMS. Additional questions that relate to the image must be correlated with precise gray-scale calibration, if good interpretation is to result.

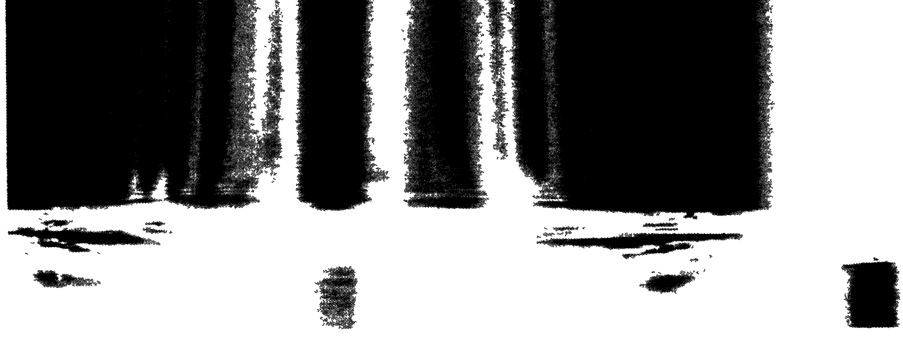

Figure 3. Lateral scan AMS map (two-dimensional scan) or raster scan of cylindrical steel bearing raceway.

(2) Copper Foil

Elastic material parameters, such as velocity and attenuation of plates and foils, may be obtained with the AMS technique, provided it is understood that mode propagation other than Rayleigh waves are involved here. Lamb waves are supported by plates or thin sheets[8] and limited experiments in this area are reported here. Further details may be obtained from Ref. 9.

A typical AMS, obtained on a 0.90 mil (22.9 μm) copper foil, at 35 MHz is shown in Fig. 4. The foil is a 25 mm-diameter circular plate loosely supported on double-backed tape supported on a fused quartz substrate, such that only one liquid-solid interface exists on top of the foil. The AMS shows typical structure, yielding a Lamb wave velocity of 3.97 mm/μs.

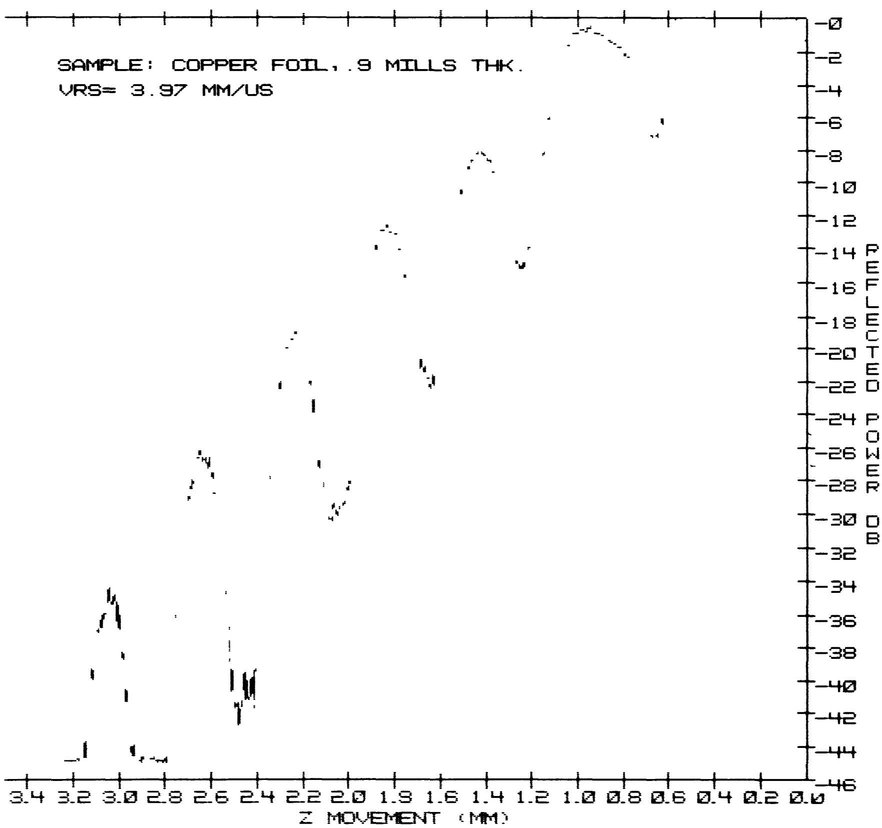

Figure 4. AMS on 0.90 mil copper foil at 35 MHz; foil support is loose adhesion on double-backed tape.

The computed Lamb wave dispersion for copper is not available at this writing. However, zirconium, exhibiting virtually identical elastic wave velocities can be used to estimate the Lamb wave dispersion with reasonable accuracy. A preliminary examination of the wave modes shows that the measured AMS is most likely due to the lowest symmetrical Lamb mode and exhibits relatively dispersionless behavior near 4.0 mm/μs for the normalized thickness parameter $2\pi h/\lambda_R$, such that $0 < 2\pi h/\lambda_R < 2.0$. The measured copper foil has a normalized thickness parameter of 2.32.

In this parameter range, asymmetrical Lamb modes may propagate as well. The lowest such mode increases linearly from zero velocity, while both lowest modes, symmetrical and antisymmetrical, asymptotically approach the Rayleigh velocity for normalized thickness parameters large compared to 1. The antisymmetrical mode has been observed earlier in the acoustic microscope on a silicon membrane.[1] At present the necessary conditions for the launching of either mode are not known. Knowledge of these factors would substantially enhance the NDE capability of platelike structures using the FRAM.

SUMMARY AND CONCLUSIONS

The development and preliminary evaluation of the Focused-Beam, Reflection-Mode Acoustic Microscope has been described in this report. This unique system has a 10:1 frequency range (by use of two frequency-continuous acoustic lenses), complete digital control, and extensive imaging and image enhancement capability for quantitative analysis and precision metrology of materials. An additional feature is the choice of coherent RF pulse burst or incoherent impulse excitation in a compatible and complimentary way. The low-frequency lens designs extending from 10 to in excess of 100 MHz represent departures from earlier design criteria. The low-frequency lens designs have yielded a somewhat unexpected new diagnostic capability, whose potential has hardly been explored. An "extended AMS" region[(2)] is now possible where two propagating modes are sequentially excited in "dense on light" layered structures. Subsurface regions substantially deeper than before may now be probed in these composites.

The wide frequency range capability brings, for the first time, the possibility of depth profiling of surface regions within our reach. In turn, this may lead to a more quantitative measurement of bond integrity between interfaces.

Imaging and metrology case histories conducted to date have been largely qualitative. Imaging of the Lincoln penny has revealed information of residual elastic modification in the subsurface material from which the topography has been removed by machining. The imaging capability combined with pertinent AMS characterization have revealed the complimentary nature of these two FRAM modes. Their combined use will prove important in the quantitative definition of defects.

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