LOW-FREQUENCY ACOUSTIC MICROSCOPY

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Since acoustic microscopy was first invented by Quate and Lemons,[1] many workers in the field have built acoustic microscopes ranging in frequency from tens of megahertz to hundreds of gigahertz, and for a wide variety of applications in materials characterization, integrated circuits evaluation, and medical applications. In this work, we use the acoustic microscope as a quantitative nondestructive evaluation tool, our main purpose being the detection and characterization of defects present within 1 mm of the surface of a sample.

A schematic diagram describing the principle of operation of an acoustic microscope is shown in Fig. 1. A focused transducer, operating at a frequency of 3 MHz , is focused on the sample to be tested. The focused transducer is excited with an rf tone burst and the signal reflected from the water-sample interface is amplitude detected and its value stored. The amplitude of the interface signal is used to modulate the brightness of a display monitor at a position corresponding to the location of the transducer.

The transducer is raster scanned mechanically over the object, and an acoustic image is thus generated. The amplitude of the reflected signal from the water-sample interface depends on the local impedance of the sample, and on the location of the interface with respect to the location of the focus of the acoustic beam. If a defect is present below the surface, the acoustic impedance of the sample above the defect location is different from the impedance of a sample without a defect; consequently, the amplitude of the interface signal will change when the acoustic beam is scanned from one region to another. In this mode of operation, when the focus of the transducer is located at the water-sample interface, the transmitted/reflected longitudinal wave is responsible for subsurface defect detection.

It is possible to use the acoustic microscope in a defocused mode in order to enhance subsurface defect detection. Defocusing

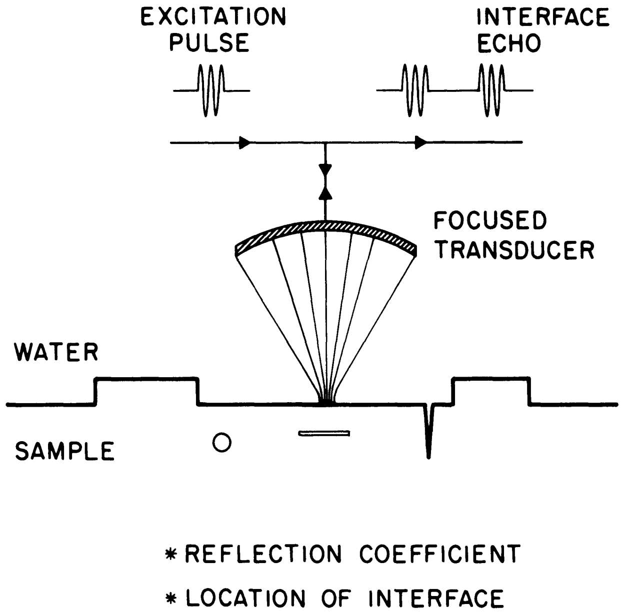

Fig. 1. Schematic diagram showing the principle of operation of the acoustic microscope. The interface echo is shown to be a function of the local reflection coefficient, and the location of the reflector.

is the process of bringing the focused transducer closer to the sample as if to focus inside the sample. In the defocused mode, some angular components of the spherical wave excited by the transducer are incident on the sample at the appropriate angle to excite leaky Rayleigh waves. The leaky Rayleigh waves radiate their energy back into the transducers after interacting with the sample. These leaky Rayleigh waves, and surface skimming bulk waves, are responsible for the famous "V(z) phenomenon" that was initially explained by Wickramasinghe and Atalar, and that is now being used by several workers in the field for materials characterization. In our work, our interest is in subsurface defect detection. When leaky Rayleigh waves are propagating on a sample, they behave like Rayleigh waves in that they penetrate the sample to a depth of one Rayleigh wavelength. Thus, if a defect is present up to one Rayleigh wavelength below a surface, it will interrupt the leaky Rayleigh wave and cause a change in the output. In order to enhance our subsurface defect detection, we defocus the transducer in order to excite leaky Rayleigh waves, and we scan the sample to take images of the defects.

Because we are interested in finding defects within 1 mm of the surface of a metal sample, and because most metals of interest have Rayleigh wave velocities of the order of 3000 m/sec , we decided to operate at a center frequency of 3 MHz yielding a surface wave wavelength of 1 mm . Thus, the surface wave will be disturbed by defects within 1 mm of the surface of a sample. We

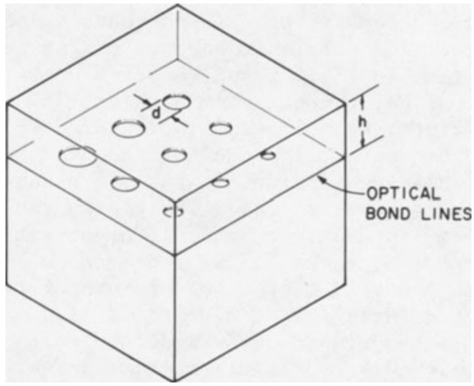

Fig. 2. Schematic diagram of fused quartz block with seeded, subsurface, horizontal cracks.

use a focused transducer with an F-number equal to one, a round trip insertion loss of 3 dBs, and a bandwidth of 50% . It is very important to use a well made, efficient transducer in order to have a large signal-to-noise ratio, and a well defined focal spot.

Samples with different types of seeded defects were made out of fused quartz. We use fused quartz because of the availability of acoustically transparent contacting techniques, such as optical bonding and color contacting. Also, the velocities and acoustic impedance of fused quartz are similar to those of aluminum. We expect our results on fused quartz to apply to aluminum, steel and titanium, and other metals.

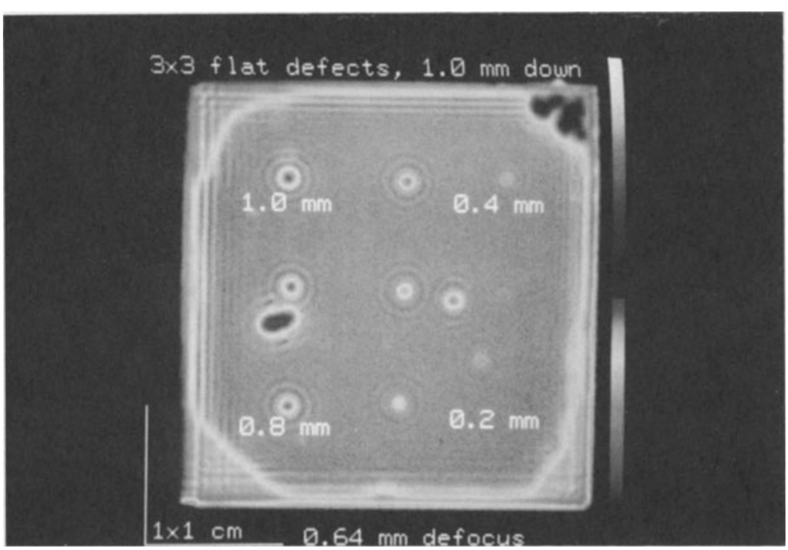

Fig. 3. Acoustic microscope picture of the sample of Fig. 2. The cracks are 1 mm below the surface, and the microscope is defocused by 0.64 mm . The diameters of the cracks vary from 0.2 mm to 1.0 mm .

Figure 2 is a schematic of a fused quartz block with seeded horizontal cracks. The sample is made by making thin (100 μm) circular depressions in a big fused quartz block, then polishing the surface and optically contacting a thinner block above it. Once this is done, the thin block is polished down to a thickness "h," indicating the depth below the surface at which the defects reside. The circular depressions in the big block are now circular, horizontal, subsurface cracks. The cracks range in size from 0.2 mm to 1.0 mm in diameter, and different samples were made where the depth of the cracks "h" varied from 0.25 mm to 1.0 mm. Figure 3 shows an acoustic microscope picture of the sample in Fig. 2, where the defects are at a depth of 1.0 mm below the surface, and where the transducer was defocused by 0.64 mm. All the cracks that are 0.4 mm in diameter or larger are detected along with some unintentional defects such as dust particles that exist at the bond surface. It is also possible to see disbonding at the level of the defects between the top 1 mm thick fused quartz plate, and the bottom block. The disbonding is clearly visible at the corners and at the edges of the sample. There are also straight crested fringes that are visible at the edges of the sample, and circular fringes around the defects. The fringes are a result of an interference between the specularly reflected signal from the sample surface, and the leaky Rayleigh wave that is reflected back to the transducer either by an edge or by a defect. The distance between fringes is one half of a Rayleigh wavelength and can be used to calculate the Rayleigh wave velocity.

Figure 4 is a schematic of a fused quartz block with seeded spherical voids. The sample is made in the same fashion as the sample in Fig. 2. However, because it would have been very difficult to align nine hemispherical voids on the bottom block to nine hemispherical voids on the top block, we made four samples each containing one spherical void only. The center of the spherical voids was 1.0 mm below the surface, and their radii varied from 0.5 mm to 1.0 mm. Figure 5 shows acoustic microscope pictures of these four samples with different values of defocusing. All the subsurface defects are clearly visible, along with disbonds and intentional defects.

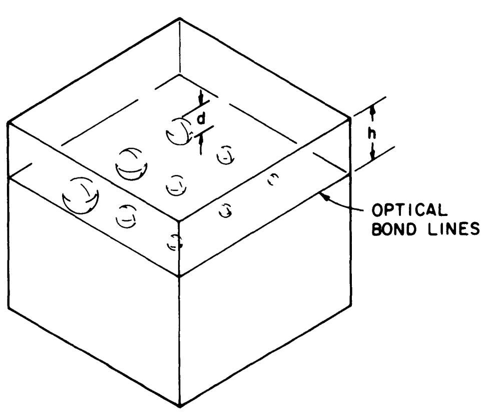

Fig. 4. Schematic diagram of fused quartz block with seeded, subsurface, spherical voids.

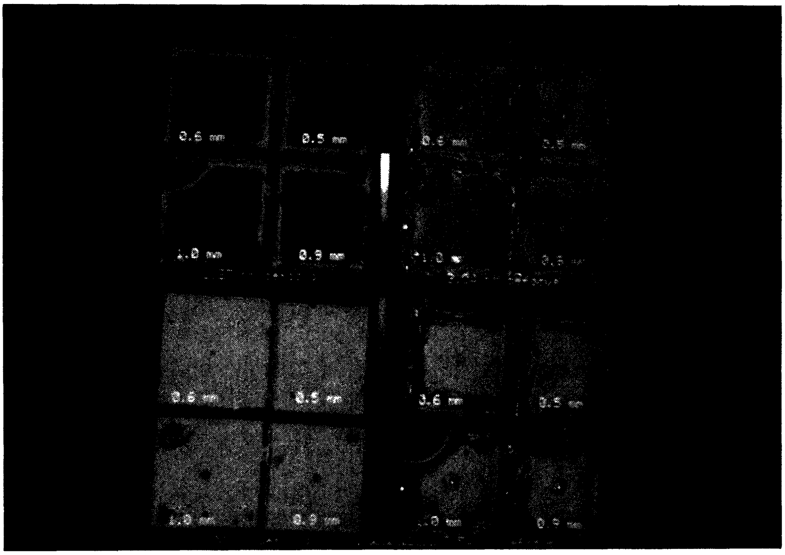

Fig. 5. Acoustic microscope pictures of four samples with one seeded subsurface void each. The diameters of the voids are 0.5, 0.6, 0.9 and 1.0 mm. The centers of all the voids are 1.0 mm below the surface. The four different values of defocus are 0.0, 1.27, 2.54, and 3.04 mm.

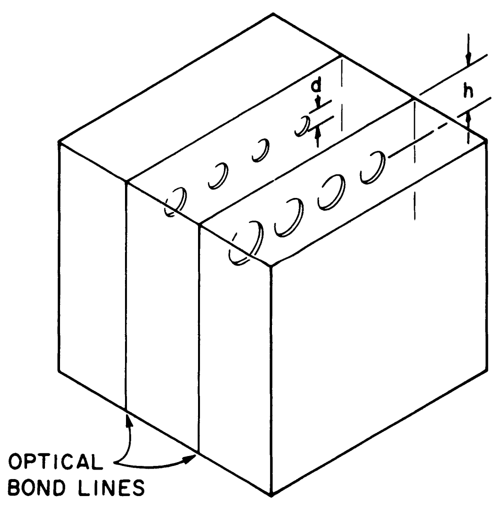

Fig. 6. Schematic diagram of fused quartz block with seeded, subsurface, vertical cracks.

Figure 6 is a schematic of a fused quartz block with seeded subsurface, vertical cracks. We use a similar procedure to the one desribed earlier to make these samples, except that we use a color contact instead of an optical contact to join the pieces of fused quartz together. The color contact consists of 3000 Å of parafin. This procedure was used because of the disbonding observed in Figs. 3 and 5. Such disbonding at the edge of the

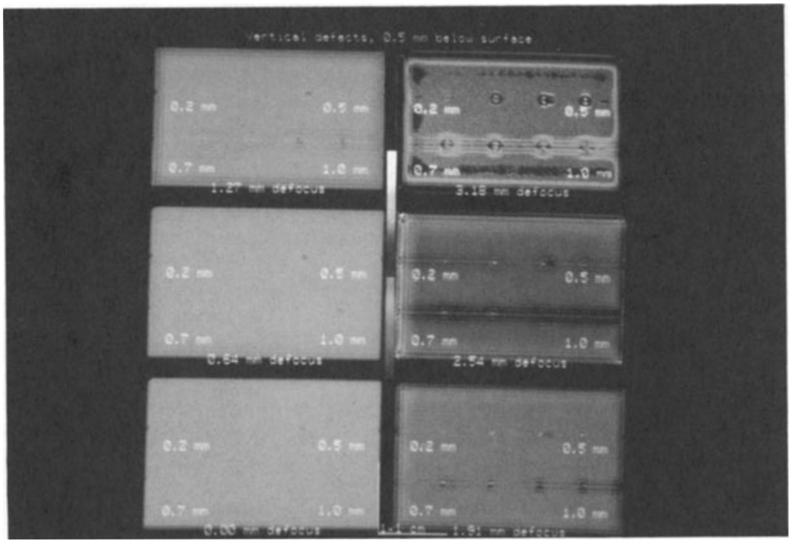

Fig. 7. Acoustic microscope pictures of the sample of Fig. 6 at six different values of defocus. The vertical cracks varied in size from 0.2 mm to 1.0 mm , and their center was at a depth of 0.5 mm .

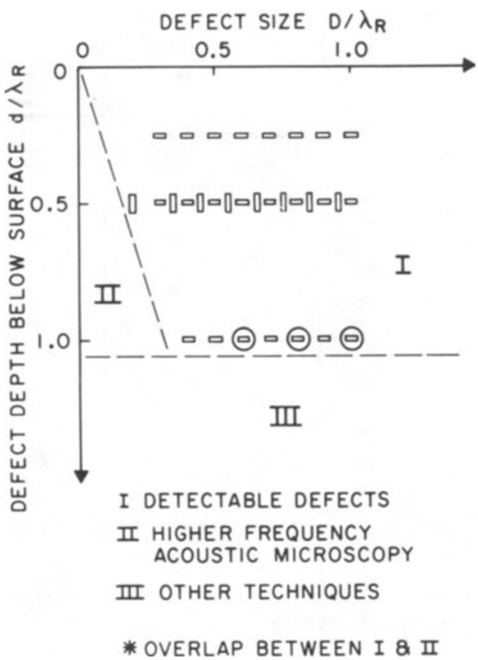

Fig. 8. Graph showing subsurface defect detection limit as a function of feature size (diameter) and depth.

sample would have made it impossible to test for near-surface vertical cracks, as shown in Fig. 6. The center of the vertical cracks was at a depth h , equal to 0.5 mm , and their diameter varied from 0.2 mm to 1.0 mm . Figure 7 shows acoustic microscope pictures of these defects at different values of defocus. When the aoustic microscope is focused on the surface of the sample, the cracks are almost undetected, because they present a very small (50 μm-100 μm) cross section to the incident longitudinal wave. However, when the microscope is defocused, leaky Rayleigh waves are excited, and their scattering by the cracks gives clear indication of the presence and lateral extent of the cracks. Thus, as seen for a defocus of 1.27 mm , all these cracks are detectable. Note that one parafin bond (at this site of the larger cracks) seems to be more than 3000 Å thick and is more easily available at the frequency of operation.

Figure 8 summarizes our results for subsurface defect detection. It is obvious that very small subsurface defects are detected and sized rather easily. Acoustic microscopy is superior to any other technique for detecting near-surface defects because both longitudinal and leaky Ryaleigh waves are used to detect and give images of defects. Defects such as the horizontal subsurface cracks would have been almost impossible to detect by other standard NDE techniques.

ACKNOWLEDGMENT

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DISCUSSION

P. Holler (Universitat des Saarlandes, West Germany): I would like one question without expecting an answer. What is an acoustical microscope?

B.T. Khuri-Yakub: In my mind, an acoustic microscope is something like what I described. Some call focused C-scan imaging acoustic microscopy.

P. Holler: Another point is why don't you test these surfaces just with straight Rayleigh waves?

B.T. Khuri-Yakub: The acoustic microscope is a very, very efficient way to excite Rayleigh waves. It's much easier to use the focused transducer to excite Rayleigh waves than it is to use plane wave transducers tilted to the surface at the right angle.

And you gain by that because when you use a lens to excite Rayleigh waves, you are actually exciting a circularly converging Rayleigh wave that focuses to a small spot.

P. Holler: But you see, the detectability you showed, I think, for Rayleigh waves, that's not extraordinary.

B.T. Khuri-Yakub: No.

P. Holler: These were subsurface defects?

B.T. Khuri-Yakub: Right. If you notice, there's one point also that we have that I didn't mention, is the maximum acceptance angle on the lens that we use so far is 30 degrees. For quartz, aluminum, and steel, this is right on the bare edge of exciting Rayleigh waves, so even if we are exiting Rayleigh waves, it's not an efficient excitation. We can detect smaller defects with a larger acceptance angle lens.

At the present time, we are waiting for a new transducer with a larger acceptance angle on the lens where we are certain that we are exciting the surface space effectively and see what the limits are.

P. Holler: In other words, if you excite your Rayleigh waves by other means, you should have the same results?

B.T. Khuri-Yakub: Maybe.

G.J. Gruber (Southwest Research Institute): Are there any limitations on the pulse duration or bandwidth of the transducer?

B.T. Khuri-Yakub: There are many different ways in which you can use this microscope. This is basically our first crack at it, and for that, I use a 10 cycle (tone burst) excitation. The bandwidth is not a very necessary criteria.

But you can, of course, excite this transducer with a delta function and then use a very good sample and hold circuit. You get more frequency information in the picture then. That's another way of using the device.