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A STUDY OF MECHANICAL PROCESSING DAMAGE IN BRITTLE MATERIALS

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A STUDY OF MECHANICAL PROCESSING DAMAGE IN BRITTLE MATERIALS

by

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During the last year, we have continued our work on the ultrasonic characterization of machining-induced cracks and residual stresses in brittle materials. We continued the development of two basic techniques to measure crack depths and surface residual stress. We also started developing an air-based transmission acoustic microscope to study porosity and velocity variations in green ceramics. Additionally, through some recent contacts with the Norton Company, we are adapting our residual stress measuring microscope to detect surface defects in ball bearings.

Our original technique, which consists of measuring the reflection coefficients of surface cracks as a function of frequency, is still being developed to characterize multiple cracks due to grinding damage. Our main work in that area has been to continue the development of the signal processing software (Cepstral analysis), which allows us to determine the depth of the deepest crack in a number of cracks. The original software was too cumbersome and difficult to use, and our aim is still to finish this part of the study by comparing our theoretical predictions to the actual fracture of real samples. Lately, we have begun developing a strong working relationship with the NDE group at Norton Co. in Northboro, MA, which is headed by Dr. K. Amin. The Norton Co. is very interested in the machining damage problem and is interested in acquiring our software and experimental methods for the evaluation of machining damage. We plan to carry out a study with Norton whereby we will test samples of hot, isostatically-pressed silicon nitride, and will correlate our results to fracture data obtained at Norton. Thus, we will put our methods to the acid test, and will transfer the technology and know-how that we have developed on this aspect of the machining damage problem.

We continued the development of the acoustic microscope lens that uses shear wave instead of longitudinal wave transducers. The use of the shear wave transducer allows us to excite directional surface waves on a sample with excellent spatial resolution. Thus, we have measured variations in surface acoustic wave velocity in single crystals with a spatial resolution of 100 μm while operating at a frequency of 50 MHz. We plan to use this approach at higher frequencies to measure variations of surface residual stress around crack tips in brittle materials. We have made new strides in the development of such acoustic microscope lenses and in the development of an instrument capable of measuring amplitude and phase up to a frequency of 200 MHz.

Instead of using a pure shear wave transducer, we now use a mixed-mode transducer. We have developed the theory for designing such transducers, which are capable of exciting both longitudinal and shear acoustic waves. Basically, the piezoelectric crystal cut is chosen such that when an electric field is applied across the thickness, both longitudinal and shear waves are excited. The crystal cut and the buffer rod orientation both have to be considered while designing a transducer to make sure that the excitation and propagation of the waves are collinear with the axis of the buffer rod. Both crystalline and amorphous buffer rods are usable and necessary, depending on their ultrasonic velocities and those of the material under test. We now have a complete theory that predicts the insertion loss of such devices for both the longitudinal and shear waves. Thus, we can design the lenses for any material we need to examine.

Figure 1 shows a comparison of the measured round-trip insertion loss of an X-cut lithium niobate transducer on fused quartz and (110) bismuth germanium oxide buffer rods. The theory shown contains a correction for diffraction losses in both buffer rods, and is in excellent agreement with the experimental measurements. We have made lenses in both buffer rods and plan to use these devices to measure variations in surface residual stress at crack tips. The main advantage of the mixed mode lens for our purposes is in having the longitudinal wave provide the reference phase for the shear wave while measuring variations in the surface acoustic wave velocity of a sample. This configuration is far superior to having the weakly-focused lens generate the reference signal, as we presented in our earliest publications on the subject.

Also, these lenses will be used to image machining damage induced cracks with both the longitudinal and shear waves. This capability will allow us to study the scattering by linear cracks to both circularly-symmetric and unidirectional surface waves. We expect to be able to make better estimates of machining damage by comparing measurements of the same region taken with the two types of waves. The transducer configuration has the inherent advantage of perfect alignment of the imaged region because both the longitudinal and shear waves are excited by the same transducer. We are now preparing a manuscript for submission for publication on the design, implementation, and use of such transducers.

We have also developed a new amplitude and phase electronic measurement system for the acoustic microscope. The new system is operable up to a frequency of 200 MHz. This frequency of operation makes it possible to measure variations in surface wave velocity with a spatial resolution of about 25 μm. The new measurement system is based on some earlier work we have done on making amplitude and phase measurements with the low-frequency (1-10 MHz) acoustic microscope. Appendix A is a paper that describes the low-frequency system, which taught us how to design the high-frequency system. Presently, we are characterizing the system for sensitivity and noise level, and we will undoubtedly publish our results on making this system in the very near future.

In some of our earlier work in NDE, we had developed ultrasonic transducers operating in air at a frequency of 1 MHz. These transducers were used to make an acoustic microscope for height measurements of printed circuit boards and other structures with feature heights of approximately 1 μm. More recently, we became aware of silica aerogels which are used for insulation and optical matching layers. These materials have very interesting mechanical properties and, on paper, are usable as matching layers for ultrasonic transducers. Such matching layers can improve the efficiency of air-operating ultrasonic transducers by about 20 dBs. This gain in insertion loss makes transmission C-scan ultrasonic systems for the inspection of green ceramics a real possibility. We are investigating this potential and have set up a measurement system operating at 1 MHz, using transducers that are matched into air with silicone rubber, a nonideal choice as compared to silica aerogels. We find that we can transmit through a 3 cm space in air and can have a signal-to-noise ratio of about 60 dBs with simple, off-the-shelf amplifiers and pulsers. This result is very encouraging, and we are proceeding with a modification of our scanner to allow us to do a controlled experiment on a green ceramic. We have also been in contact with Dr. Tewari of Norton Co. (earlier of Lawrence Berkeley Lab) who is willing to teach us how to make silica aerogels, and with a group at Lawrence Livermore Lab. Both groups are willing to help us make such devices a reality. Our expectation is that we will have, in the near future, a transmission focused C-scan system operating in air at a frequency of 1 MHz. We will test the system on various materials, such as green ceramics, polymer composites, and metals. Such systems will have a tremendous impact on on-line inspection of materials, especially since water immersion is no longer necessary.

Lastly, we were approached by Dr. J. Hannoosh of Norton Co. with the problem of inspecting ball bearings. We believe that our 50 MHz acoustic microscope is capable of detecting surface defects in the 10 μm range in silicon nitride. A focused transducer capable of exciting surface acoustic waves on ceramics is necessary for this application. The ball bearing is held under the transducer with a small defocus to allow the excitation of the surface waves, then the ball bearing is rolled, in place, under the transducer. Any change in the reflected signal level is detected by the transducer and recorded in a computer. After a certain period of time, when we estimate all points on the ball to have been tested several times, the scan is stopped and the count of defect indication will show the number of defects in the sample. We now have the software for this measurement, as well as the electronic system. We will be receiving ball bearings from Norton to evaluate this technique before we acquire the ball bearing rolling system which Norton will provide for us. We expect to have a viable method to evaluate ceramic ball bearings for small near-surface defects.

Publications

1. B. T. Khuri-Yakub, "Acoustic Microscopy," Presented at O/E Lase '88, Los Angeles, CA (January 1988).

2. C-H. Chou, B. T. Khuri-Yakub, and K. K. Liang, "Acoustic Microscopy with Shear Wave Transducers," Presented at the IEEE Ultrasonics Symposium, Denver, Colorado (October 14-16, 1987). To be published in Proc. IEEE Ultrasonics Symposium (1987).

3. J. T. Fanton, C-H. Chou, B. T. Khuri-Yakub, and G. S. Kino, "Evaluation of Solder Bonds in a Silicon Flip Chip Device," Presented at the Fourteenth Annual Review of Progress in Quantitative NDE, College of William & Mary, Williamsburg, VA (June 1987). Published in Review of Progress in Quantitative NDE, Eds: D. O. Thompson and D. E. Chimenti, Plenum Press, New York (1988).

4. C-H. Chou and B. T. Khuri-Yakub, "Acoustic Transducers and Lens Design for Acoustic Microscopy," Presented at the DARPA Review of Progress in Quantitative NDE, San Diego, CA (August 1986. Published in Review of Progress in Quantitative NDE, Eds: D. O. Thompson and D. E. Chimenti, Plenum Press, New York (1988).

5. B. T. Khuri-Yakub and C-H. Chou, "Acoustic Microscope Lenses with Shear Wave Transducers," Proc. IEEE Ultrasonics Symposium (1986).

FIGURE CAPTIONS

Fig. 1. Round-trip insertion loss of mixed-mode transducers on fused quartz and BGO buffer rods.

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