NEW APPROACHES TO DEFECT CHARACTERISATION WITH HIGH RESOLUTION NON-CONTACTING LASER UTRASOUND

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Abstract - This paper discusses how laser ultrasonic imaging technology may be used for defect detection. The poor single to noise ratio and the consequent potential for damage to the sample have hindered the widespread application of laser ultrasound. We discuss how our approach overcomes many of these problems. Moreover, we discuss the specific and potentially important advantages that arise from the frequency flexibility, absence of couplant and the ability to control the generated wavefront.

INTRODUCTION

For many years laser ultrasonics has offered a powerful approach for non-contacting characterization of materials. The obvious advantage of laser ultrasonics lies in the ability to access components where contacting transducers cannot be used appropriately; the reasons for the unsuitability of contacting transducers may arise either from the remoteness of the components, elevated temperature or toxicity. One established advantage of non-contacting ultrasonics compared to contact transducers is the wide bandwidth for both generation and reception. The overriding disadvantage of laser ultrasonics is the relatively poor signal to noise ratio, due both the inefficiency of converting light to sound energy and perhaps even more important the relatively inefficiency of optical detection compared to piezoelectric detection. A useful comparison between the different methods may be found [1]. To overcome the relative inefficiency of optical detection hybrid techniques using optical generation and contacting detection are often used-many of the advantages of contacting ultrasound are lost with this approach. The improvement in signal to noise of these hybrid methods does mean the optical powers used for generation can be reduced so that the sample damage associated with operating in the ablation regime is reduced. In this paper we discuss an approach that overcomes some of the signal to noise limitations of all optical laser ultrasonic techniques and moreover we discuss other crucial advantages that give the method wide applicability and potential.

THE OSAM SYSTEM

The OSAM (Optical Scanning Acoustic Microscope) system we have constructed has been described elsewhere [2]. The system operates by generating and detecting surface acoustic waves, the salient features of which are described below. The system uses a mode-locked Q-switched Nd-YAG laser source, which generates approximately 30 short (approx. 200ps) pulses separated by 12ns. This results in a generation signal which produces tone bursts of 82MHz and harmonics thereof. The ultrasound is detected using a modified knife-edge detector. The distinguishing feature of our laser ultrasonic system is the light delivery onto the sample. This is performed using a 512x512 (Boulder Non-linear Systems) spatial light modulator; this allows patterned optical distributions to be projected onto the sample surface. Projecting a periodic pattern on the sample allows the frequency of the generated sound waves to be controlled. An arc pattern on the surface will focus the generated sound waves thus increasing the local energy density. Combinations of focusing and frequency selection may be readily addressed using this approach, moreover, the surface patterns generated can be controlled very finely. Projecting a focused grating onto the sample is of considerable importance since it means the optical power may be spread over the sample surface thus avoiding ablation. Indeed large signals may be generated without averaging and with *no* damage to the sample. This also allows us to use rapid custom electronics to perform measurements so that imaging limited only by the pulse repetition rate (2kHz) of the

laser may be achieved. This allows images of 200 by 200 pixels to be obtained in approximately 3 minutes even on non-ideal samples. The electronics also allows images of different frequencies as well as amplitude and phase to be acquired simultaneously.

ADVANTAGES OF NON-CONTACTING ULTRASONICS

The unique advantages of laser ultrasonics, from the point of view of quantitative defect detection, arise from three principal factors, namely: (1) frequency agility, (2) the absence of couplant, and (3) the ability to generate adaptive generation geometries.

Frequency agility: Figure 1 shows a phase images of Vickers indentation in a silicon nitride ceramic, the indentation produced a series of cracks around the sample.

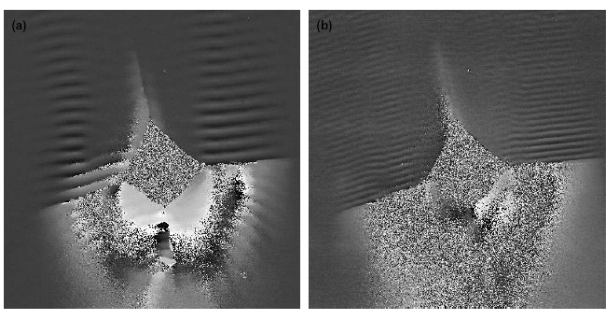

Figure 1. 0.8×0.8mm SAW phase images of a Vickers hardness test indentation on a silicon nitride sample, covering the same area as the images in figure 5.4. (a) 82MHz SAW phase image; (b) 164MHz SAW phase image. Sound source from 'above'.

The images of figure 1 show the ability to image at different frequencies simultaneously. The reflection fringes are formed by standing waves arising from the interference between incoming waves and waves reflected from the crack. These are similar to those observed in the scanning acoustic microscope [3], except that the attenuation of these waves arises from intrinsic material absorption rather than from the fluid attenuation, which is the dominant mechanism in the scanning acoustic microscope. The ability to image at two or more frequencies simultaneously is of particular value when determining the crack depth. Figure 2 shows a series of 82MHz and 164MHz line scans of the detected phase across the right hand crack, at different positions. We note that close to the Vickers indentation—where the crack is relatively

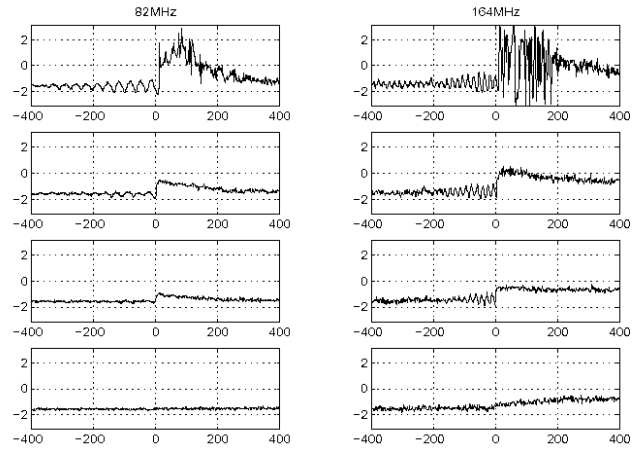

Figure 2 On the left are line scans of the 82MHz SAW phase at various points along the right-hand crack emanating from the Vickers indentation; on the right are 164MHz SAW phase line scans at the same positions. The horizontal and vertical scales are the same on all the plots x-axis is in microns and y-axis degrees.

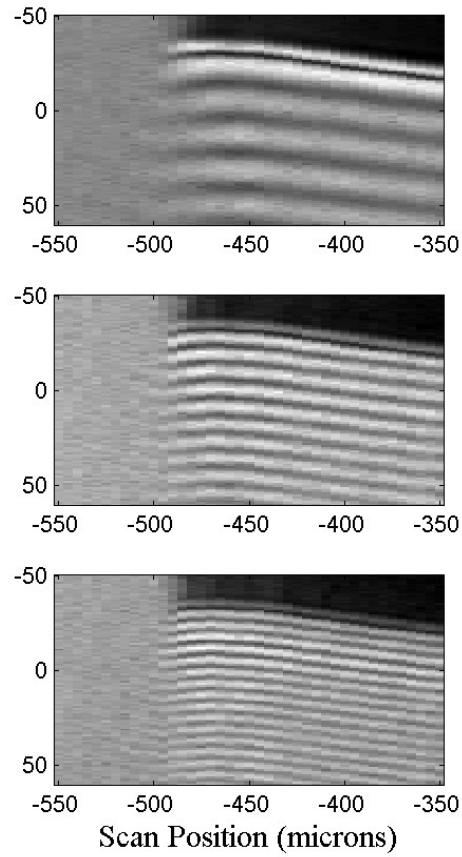

Figure 3 Reflection fringes observed at a crack in a coated glass sample. Top image taken at 82MHz, middle 164MHz and lower image 246MHz.

deep—the observed phase change is similar at both frequencies. As we move further to the right, we note that the phase jump at the lower frequency begins to

decrease rapidly, while the phase jump at the higher frequency decreases more slowly. This is due to the relative penetration depths of the two frequencies of acoustic waves. The 164MHz SAWs, have a correspondingly smaller penetration depth, and are therefore more sensitive to very shallow cracks. Figure 3 shows the reflection fringes around a crack in coated glass taken simultaneously at *three* frequencies 82MHz, 164MHz and 246MHz; this shows reflection fringes characteristic of the wavelength used, but also shows the fringe patterns ending at the same position for each frequency suggesting that crack is relatively deep until it ends.

Absence of couplant: There are several advantages that arise from the absence of couplant. One of these was alluded to in the previous subsection where we pointed out that decay of the fringes was determined by the material properties rather than the leakage into the fluid. This means that measurements of attenuation which are notoriously inaccurate in the scanning acoustic microscope may be performed much more accurately in the OSAM system. More generally the lack of couplant means that the microscope response is sensitive to the properties of the sample compared rather than a combination of those of the sample and the couplant. This means the OSAM is much more sensitive to subtle features of the sample. Figure 4 shows the amplitude image corresponding to the phase image of the Vickers indentation shown in figure 1.

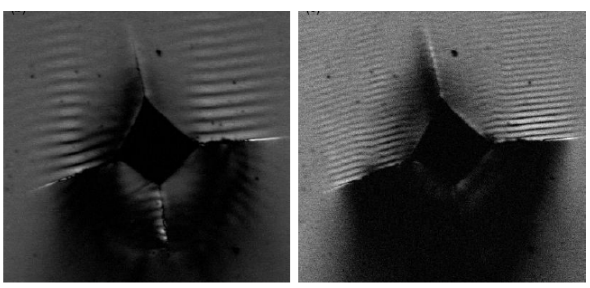

Figure 4 Amplitude images at 82MHz and 164MHz corresponding to phase images of figure 1.

These images show many of the features of the phase images such as the interference reflection fringes- what is interesting and not yet fully explained are the bright spots observed along the lower crack on the 82MHz image. These are particularly interesting as

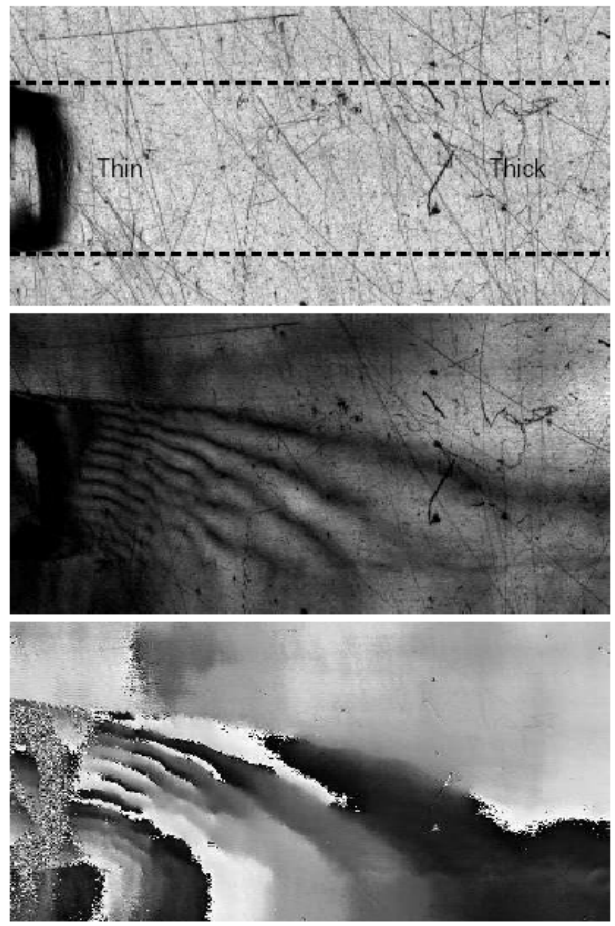

Figure 5: Optical (top), 82MHz SAW amplitude (centre) and 82MHz SAW phase (bottom) c-scan images of a 3.5 × 1.75mm area of the top surface of a piece of polished aluminum. The location of the slit is shown by dashed lines in the optical image. The slit breaks the surface on the left of the image, where the thickness of the aluminum is least.

they on the 'dark' side of the image. Similarly on the 164MHz image the upper crack appears bright. These features are common to many different images of discontinuities observed in the OSAM on many different samples they are most probably indicative of localized modes and significantly they are not observed on similar features in the fluid coupled acoustic microscope. We are currently investigating these bright spots for evidence as sources of non-linear signal generation.

The OSAM can also be used to generate contrast arising from Lamb waves. Figure 5 shows an optical image, an amplitude image and a phase image arising from the OSAM as a Rayleigh wave is excited in bulk material and mode converts to a_0 and s_0 Lamb

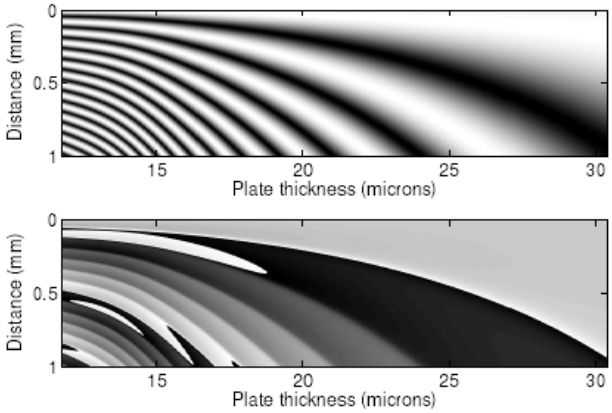

Figure 6: Simulated amplitude (top) and phase (bottom) responses from the O-SAM system for a_0 and s_0 Lamb modes propagating from top to bottom on plates of various thicknesses.

modes in a slit. The slit is milled at a slight gradient, so that it breaks the surface on the left hand side as shown on the optical image and gets thicker as we move to the right. When the slit is thin the difference in velocity between the two Lamb modes is greater and decreases as the sample gets thicker, the period of the beats between the two modes therefore increases with thickness. Figure 6 shows simulated amplitude and phase ultrasonic images of the sample, showing how the interference of the two Lamb modes accounts for the contrast.

Comparison of the measured fringe spacing with the predicted values allows the depth profile of the slot to be obtained. Indeed such depth profiling has been achieved on samples with different shapes and profiles. The principal point of this subsection is that the absence of couplant allows modes to propagate that would normally be damped. To examine this assertion in the case of the two excited Lamb modes the lower portion of the slit was filled with water and the interference pattern involving the presence of the a_0 and the s_0 modes was no longer formed. This indicates that at least one mode was damped, it is most likely that the a_0 mode with the lowest wave impedance is quenched first.

Ability to generate adaptive geometries:The use of the spatial light modulator allows the generation geometry to be controlled in a near arbitrary manner. This means that measuring the wavefront near the focus allows the effects of grain structure to be corrected by backpropagation. This gives clear images on granular materials. Some of the key concepts behind this work are discussed in these proceedings [4].

CONCLUSION

This paper has given a brief overview of some of the advantages of optical scanning acoustic microscopy. The signal to noise issues that are a major problem with non-contacting ultrasonics can be overcome if the generating optical distribution is properly engineered. The special feature of our instrument is the spatial light modulator that allows near arbitrary distributions to be imposed on the sample. We show that the instrument can produce images at a range of frequencies simultaneously, which can give important information about the subsurface properties of the sample. The absence of couplant allows wavemodes to be excited, which would be damped in a fluid coupled system such as the conventional acoustic microscope. The absence of couplant should also prove very important in non-linear imaging, since non-linear activity in the couplant normally dominates the activity in the sample. We have briefly discussed that the ability to produce arbitrary excitation distributions allows us to adapt for the presence of texture in the material. This will also facilitate non-linear imaging where the requirement to present the sample with a well focused excitation beam is paramount. In conclusion the need to overcome the difficulties that bedevil laser ultrasonics has enabled the development of a new microscope has that promises a richer range of contrast mechanisms than contact based methods.

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