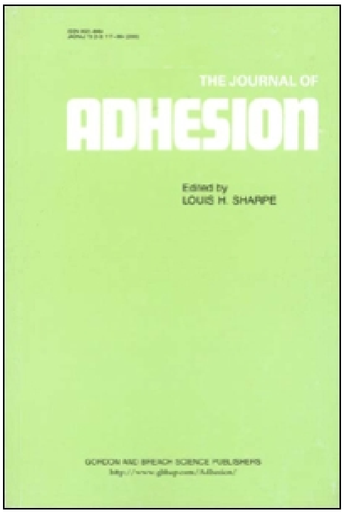

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Thermosonics: Detecting Cracks and Adhesion Defects Using Ultrasonic Excitation and Infrared Imaging*

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We describe a new nondestructive evaluation technique which makes cracks and adhesion defects visible to infrared cameras. This is accomplished by infusing the sample with a short pulse of low frequency ultrasound. The sound causes the faying surfaces of defects to heat up by friction or clapping and, thus, makes them visible in the infrared. Surface or near-surface defects appear to the camera within milliseconds of the initiation of the ultrasonic pulse, while the appearance of subsurface defects is delayed by the thermal propagation time from the defect to the surface being observed.

Keywords: Nondestructive evaluation; Infrared; Ultrasound; Cracks; Disbonds; Delaminations

INTRODUCTION

Historically, many different nondestructive evaluation (NDE) techniques have been used to detect cracks and adhesive defects such as delaminations in composite structures, disbonded adhesive joints, *etc.* These techniques include such things as X-ray imaging, various ultrasonic methods, eddy current methods, magnetic particle

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inspection, fluorescent dye infiltration, and so on. Some of these techniques, *e.g.*, X-rays, involve health hazards, others, *e.g.*, eddy current and magnetic particle methods, work only on specific types of materials and, strictly speaking, one of them, *i.e.*, dye penetrant, should not be considered to be nondestructive, because it leaves a foreign material inside the defect.

In recent years, as a result of the development of sensitive infrared (IR) imagers for military applications and their subsequent conversion for civilian use, thermographic NDE methods have become popular. One of these, Thermal Wave Imaging [1] has been quite successful in imaging "lateral" defects, that is disbonds and delaminations which are both planar and more or less parallel to the surface of the sample under inspection. This method involves the use of high-power flashlamps to inject a short pulse of heat into the surface. This pulse then propagates into the material as a plane thermal wave, which, when it encounters an air-filled disbond, is reflected back to the surface of the sample. After a delay time corresponding to the pulse's propagation time down to the defect and back, the surface temperature distribution is modified in a pattern that closely mimics the shape of the defect. An IR video camera and computer/frame-grabber combination is used to image and record the surface temperature as a function of time after the pulse. The recorded images provide pictures of the shape of the defect, and the timing of the appearance of the images is used to determine the defect's depth. However, this type of thermal wave imaging cannot detect planar defects that are perpendicular to the surface: so-called "vertical cracks". This is because the plane thermal wave that is launched into the sample by the flashlamps sees the crack as a "knife-edge" and is not reflected back to the surface. Thus, this important class of defects is invisible to ordinary thermal wave images. It was an attempt to solve the "vertical crack" problem that led to the development of the technology described in this article [2, 3]. This technology is similar to ordinary thermal wave imaging in that it uses an IR camera to record the surface temperature of an object over a defect, but is dissimilar in that it uses an ultrasonic pulse to cause the temperature of the defect to rise. When a sound wave passes through a material with a crack in it, the two faces of the crack do not move in unison. The resulting rubbing or "clapping" of the crack surfaces causes them to heat up.

The existence of such an effect is not surprising, but, as we will demonstrate below, the size of the effect is astonishingly large. This pulse of heat, generated by frictional processes within the crack, is a source rather than a reflector of thermal waves, and produces a bright image against a dark background in the camera. As it turns out, this method is not only excellent for imaging vertical cracks, but is able to image "kissing disbonds", which are also invisible to conventional thermal wave imaging, and to many other NDE methods as well. Although much more development work must be done, there are indications that the technology may ultimately be useful for providing a measure of adhesion strength for some systems.

The technology described in this paper is not without some historical antecedents. For example, in 1981, Mignogna *et al.* [4] used both resonant and non-resonant ultrasonic excitation, coupled with an IR camera, to observe the dissipation of energy in a variety of materials. One specimen, in particular, was similar to those shown in the present work. It was an aluminum bar that had a 4 mm deep crack and the authors presented "thermograms recorded 12, 15, and 25 s after the start of insonation". These thermograms showed widespread heating in the vicinity of the crack, but the crack itself was not delineated, presumably because of the long times of the insonification. Furthermore, these same authors also showed similar results in the vicinity of a sawcut in an aluminum alloy. In the present work, we present results using ultrasonic pulses two orders of magnitude shorter in duration, which demonstrate that artificially-induced defects, such as sawcuts, do *not* produce heating, whereas cracks *do*. Thus, the mechanism of heating in the present work appears to be different from that described in the 1981 paper. Subsequent related work concentrated more on polymer composite materials. For example, in 1988, Russell *et al.* [5] used swept frequency methods to determine the frequency for resonant ultrasonic excitation of composite structures. Resonant excitation was then used, together with IR imaging, to observe the steady state temperature distribution of the structure. The resulting patterns were attributed to viscoelastic effects in the polymer, even in the presence of delamination cracks. More recently [6], Rantala *et al.*, have carried out a lock-in version of ultrasonic excitation coupled with IR imaging. This technique uses ultra-low (typically $\sim 0.03-0.1$ Hz) amplitude modulation of the ultrasonic excitation, and then uses video lock-in techniques to extract phase and amplitude lock-in infrared images from the background heating. This technique requires averaging over several cycles of the modulation and, therefore, operates on times scales on the order of tens of seconds to minutes. The authors reported being able to extract an image of a crack from the processed phase and amplitude, even though the raw images did not reveal the crack.

In contrast to the previously reported methods for observing ultrasonically excited defects in materials, our method, described herein, uses a single short pulse of sound and the image of the crack appears on time scales on the order of milliseconds and is readily visible in real time in the raw IR images, so that no image processing or averaging is necessary.

EXPERIMENTAL METHOD

In Figure 1 we show a schematic diagram of the experimental arrangement. A low-frequency (say 10's of kHz) ultrasonic or high-frequency sonic transducer infuses the sample with a short pulse (50–250 ms) of sound. Where cracks, disbonds, delaminations or other adhesion defects are present, the sound field causes the defect to heat

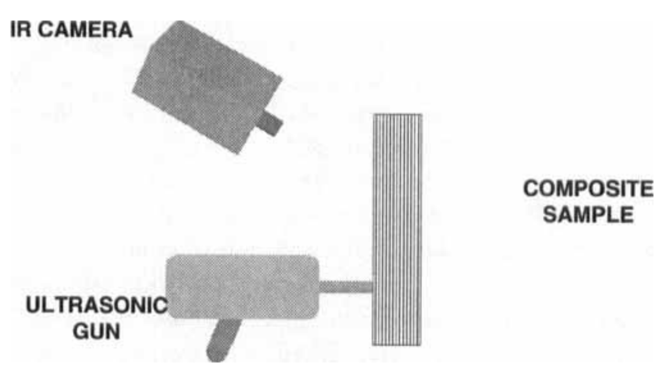

FIGURE 1 Schematic diagram of the experimental setup for sonic IR imaging of defects in a composite sample. Placement of the ultrasonic gun is not critical. It can be placed on either side, the end, or anywhere where a suitable contact surface is available. The low-frequency sound effectively infuses the entire sample, and makes wide-area imaging possible.

locally. The resulting surface temperature change, in turn, is imaged by an infrared video camera that is connected to a frame-grabber in a computer. The computer stores the images as a movie that is played back in slow motion to see the defect. Placement of the ultrasonic gun is not critical. It can be placed on either side, the end, or anywhere where a suitable contact surface is available. The low-frequency sound effectively infuses the entire sample.

While the ultrasonic gun is capable of producing a kilowatt of power, it is typically operated at only a fraction of that level, and is turned on for only 50 to 100 milliseconds. Thus, the ultrasonic energy delivered to the sample is only a few joules to a few tens of joules. This is in strong contrast to the few *kilojoules* of optical energy that are ordinarily delivered by the flashlamps in conventional thermal wave imaging. Even though the ultrasonic energy is small, temperature measurements (an increase of a few degrees) in the vicinity of surface-breaking cracks in metal samples indicate that almost all of the ultrasonic energy is dissipated at the crack faces. The resulting temperature contrast in the IR image of the defect is very large. In fact, it sometimes is large enough to saturate the detector in our InSb focal-plane array camera. This would seem to indicate that our source is unnecessarily powerful, or that the camera is more sensitive than is necessary for most defect detection. In fact, most of the sample cracks we have imaged can be seen with a simple uncooled micro-bolometer camera. However, if one is looking for very small cracks, or if the exact crack length or shape are important, a fast, sensitive camera is essential. The speed is essential because the heating occurs in milliseconds after the initiation of the pulse and, particularly in metals, the heat immediately begins to diffuse laterally and blur the IR image. Images of subsurface defects are always somewhat blurred, with the blurring increasing with increasing depth, because of the delay in the propagation of the thermal wave from the defect to the surface. On the other hand, just as is the case with conventional thermal wave imaging, this delay can be used to determine the depth of the defect.

To illustrate the distinction between the present technique and earlier studies, in Figure 2 we show results of thermosonic imaging of a sample containing two sawcuts, one with a fatigue crack, and one without. The image shown in Figure 2 was selected from a sequence of images recorded at 8 ms intervals during the application of a 50 ms

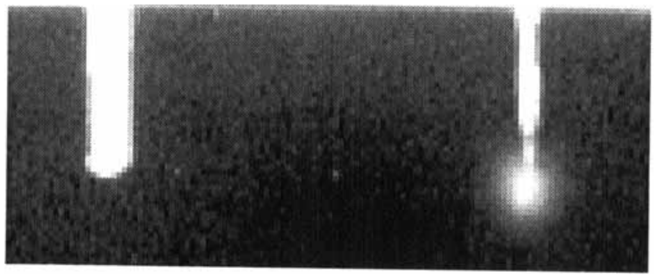

FIGURE 2 One frame from a sequence of thermosonic video images of a sample containing two sawcuts, one with a fatigue crack (right), and one without (left). The image was selected from a sequence of images recorder following the application of a 50 ms pulse of 20 kHz sound.

pulse of 20 kHz sound. This particular image was taken shortly after the sound pulse was turned on.

The result shown in Figure 2 is to be contrasted with that described in Ref. [4], in which a sawcut produced the same effect as a fatigue crack. It should also be noted that the heating seen in Figure 2 is localized and is clearly visible in this raw IR image.

In the next section we will show examples of the application of thermosonic imaging to a variety of defects in several different materials, include examples with adhesive defects.

RESULTS

In Figure 3, we show the result of applying this technique to a laminated graphite-fiber-reinforced composite slab, which had been

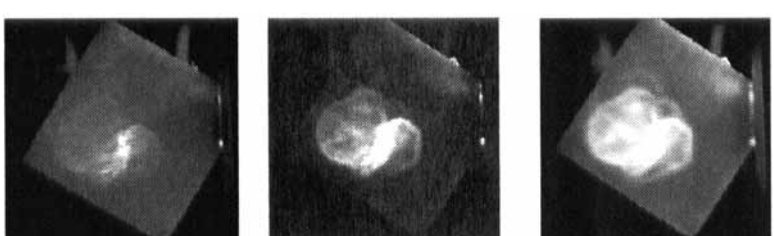

FIGURE 3 Three frames from a sequence of thermosonic video images of impact damage in a laminated graphite-fiber-reinforced composite slab, which had been subjected to an impact. The frames are at progressively later times and were chosen to illustrate the time evolution of the thermosonic image.

subjected to an impact that caused severe interply delaminations. The three images shown are video frames from a sequence taken during a 500ms, 20 kHz, sound pulse. They were selected to illustrate the time evolution of the defect pattern. In the laboratory, the entire sequence can be played back as a movie. Such a movie gives a graphic display of the progressive appearance of successively deeper defects. In the three frames shown one can see a little of this progression. The features that appear first represent the defects that are closest to the surface. Deeper features appear later. Two sources contribute to the brightness of a feature in an image. One, of course, is the amount of ultrasonic energy deposited at the defect. The other is the depth of the defect. The thermal wave pulse initiated by the ultrasonic heating decays as it propagates toward the surface, making deeper features appear relatively dimmer than shallower ones with the same amount of heating. It should be noted that the images of defects appear bright against a dark background, making detection of disbonds and delaminations straightforward.

In thermosonic images, such as those shown in Figure 3, one sees any defects with surfaces that are in contact and free to move. This includes so-called "kissing disbonds" which present a difficult problem for many other nondestructive testing methods. Kissing disbonds are surfaces which are not bonded, but which are in such tight mechanical contact that heat and sound can propagate through them. Many of the features in the "halo" around the impact point in Figure 3 are probably kissing disbonds. To demonstrate this fact, in Figure 4 below we show three frames from a sequence of conventional pulsed thermal wave images of the same sample shown in Figure 3. These images show only those disbonds which have an air gap that is thick enough

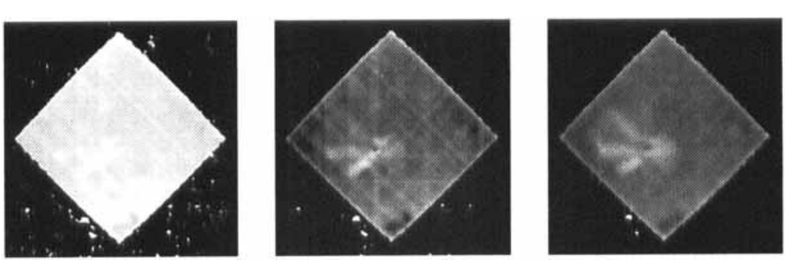

FIGURE 4 Three frames from a sequence of conventional pulsed thermal wave images of the impact damage in the same graphite-fiber-reinforced composite slab shown in Figure 3.

to reflect the incident plane thermal wave pulse back to the surface. Just as in the thermosonic images, deeper features appear at later times, and are less bright. However, the differences in the two patterns are rather striking. The conventional images show four delamination lobes, looking very much like a four-toed chicken foot, along the fiber directions in four consecutive plies with 45° rotations between them. The thermosonic images show a much more general delamination pattern, somewhat resembling a jellyfish, with a halo extending considerably beyond the severe delaminations in the immediate vicinity of the impact point.

As another illustration of the power of the thermosonic technique, in Figure 5 we show an image of a disbond between a boron fiber reinforcement patch and a cracked aluminum fatigue test bar. This disbond occurred during the fatigue process that produced a crack in the aluminum. The crack was initiated at a combination of a saw-cut and a drilled hole near one edge of the plate. On the right side of the bar one can also see some small disbonds along the edges of the sample. The difference in contrast between the left and right sides of the image probably results from the fact that the ultrasonic source was

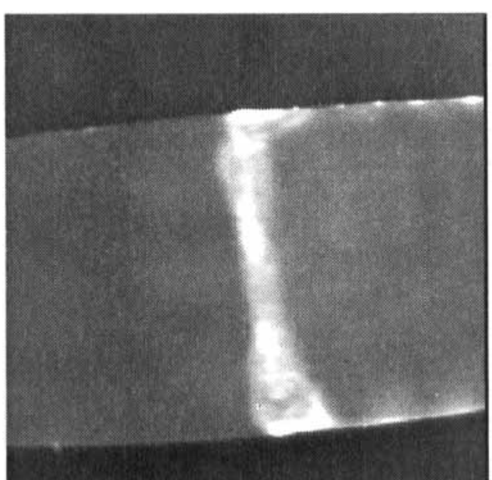

FIGURE 5 One frame from a sequence of IR video images of a disbond between a boron fiber reinforcement patch and a cracked aluminum fatigue test bar. Minor disbonding is also seen along the edges of the right half of this sample.

on the right side. The aluminum substrate was completely broken at the crack, greatly reducing the coupling of the sound from the right side to the left side.

In Figure 6, we show a single frame from a sequence of IR video images of two cracks under a thermal-barrier coating on a nickel-based superalloy part. Even though this coating was designed to retard heat flow, one has no difficulty seeing the cracks through it. The images are, of course, somewhat blurred by lateral heat flow during the time that the thermal wave from the crack is propagating to the surface of the coating. This image demonstrates that the technique has excellent capability to detect cracks, both surface breaking and subsurface in a variety of materials, and combinations of materials.

The cracks shown in Figure 6 were a centimeter or two in length. However, we have imaged cracks as small as a fraction of a millimeter with no difficulty. An example of this is presented in Figure 7, which shows a 0.7 mm-long crack in an aluminum alloy fatigue test bar. This crack was initiated at a diagonal saw cut which shows as a darker bar starting at the top edge of the sample.

Finally, in Figure 8, we demonstrate the ability of thermosonics to image variations in adhesion. This image shows two pieces of three-inch (7.4 cm) wide duct tape on a sheet of bare aluminum. Before the top piece of tape was pressed onto the aluminum sheet, an attempt was made to write the Chinese characters for "not good" on the sheet with a piece of ordinary blackboard chalk. Since chalk does not write well

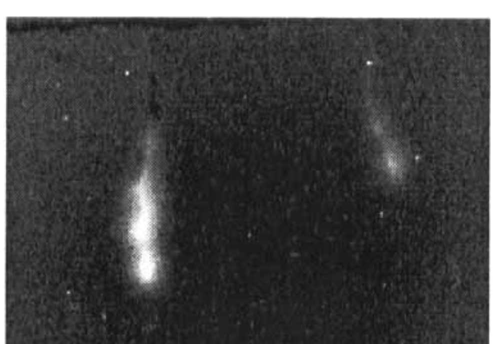

FIGURE 6 One frame from a sequence of IR video images of two cracks under a thermal-barrier coating on a metal part.

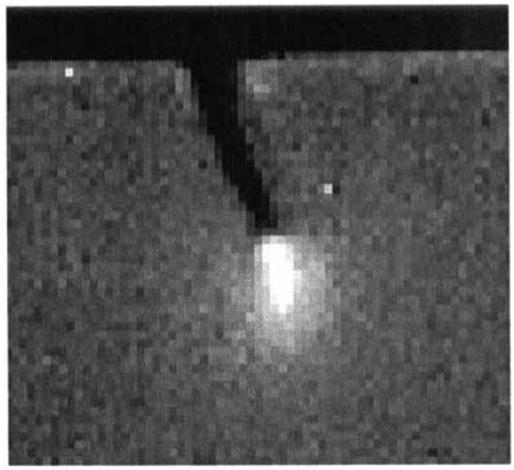

FIGURE 7 One frame from a sequence of IR video images of a 0.7 mm-long fatigue crack in a 3 mm-thick aluminum alloy test bar. The saw-cut used to initiate the crack appears as a slanted dark slot at the top of the image (edge of the bar).

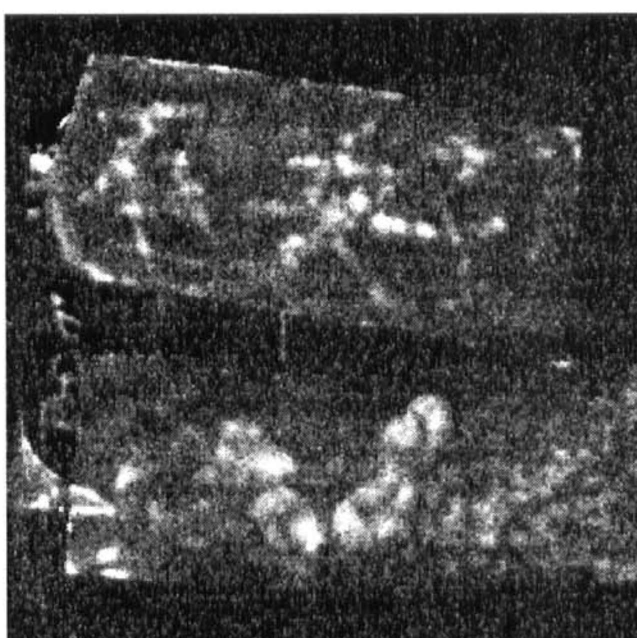

FIGURE 8 One frame from a sequence of IR video images of two pieces of 3 inch (7.4 cm) wide duct tape on a bare aluminum sheet. The Chinese characters for "not good" were written on the aluminum with chalk under the top piece of tape. Four fingerprints from talc-dusted fingers were placed on the adhesive on the bottom piece of tape before it was placed onto the aluminum sheet. The variations in adhesion caused by these foreign materials between the tape and the aluminum show clearly in the thermosonic image.

on bare aluminum, this attempt met with varying degrees of success. The duct tape was then placed over the writing, smoothed out as well as possible, and pressed down. A second piece of tape was then placed adhesive side up on the table, and four fingerprints were made on the adhesive with fingers that had been lightly dusted with talcum powder. This second piece of tape was then adhered to the aluminum sheet just below the first, and a thermosonic image was made of the resulting assembly. The variations in adhesion that resulted from the presence of the chalk or talc are clearly visible as bright areas in the thermosonic image. In addition, one sees many other more or less bright areas. These presumably resulted from the handling of the tape before it was placed on the aluminum, contamination such as fingerprints on the aluminum surface, and/or variations in the pressure with which the tape was pressed onto the surface. This gives one reason to think that thermosonics may eventually be able to provide some degree of quantification of adhesive bond strengths for adhesives that exhibit elastic hysteresis.

CONCLUSION

We have presented a variety of images showing the capability of the sonic/ultrasonic IR technique that we refer to as "thermosonics" to image subsurface impact damage, "kissing disbonds", and adhesion defects. The technique is also applicable to crack detection in a variety of materials. The technique can utilize hand-held ultrasonic sources, is insensitive to the position of the source on the sample, and yields wide-area images, with the defects showing as bright (higher temperature) regions against a dark (lower temperature) background. As such, it lends itself very easily to automation and potentially can be used in a production environment.

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