HIGH RESOLUTION PHOTOINDUCTIVE IMAGING

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Photoinductive imaging is an implementation of thermal wave imaging with eddy current detection. Because the principles and equipment of photoinductive imaging have been covered in detail in prior volumes of this series [1,2,3], the emphasis here will be on the images that can be produced, with only a brief introduction to the principles. Gas cell detection, which is used for comparison with the photoinductive images, has also been covered in detail elsewhere [4].

When a laser is focused to a spot, and the intensity is varied, the temperature, and hence a considerable number of material properties dependent on temperature, also change. Other energetic beams can be used for heating but lasers have proven to be convenient sources. The two effects of the heating of importance here are the heating of the air above the heated spot and the change in the electrical conductivity.

Gas cell detection involves the periodic heating of the spot, the resulting temperature variation of the heated spot and the subsequent heating of the air above the heated spot and its resultant pressure change. The surface to be examined is enclosed in a cell with a window to admit the laser radiation. The heating of the air from the irradiated spot causes a pressure change in the cell which is detected via a microphone. The term photoacoustic was coined by Allan Rosencwaig [5] to emphasize how the incoming light generates sound in this process.

In photoinductive detection [1], an eddy current coil induces eddy currents in a material. A spot in the eddy current pattern is heated periodically using a laser and the resulting changes in the eddy current coil response are detected. In analogy to the photoacoustics term, the photoinductive label was coined by John Moulder to denote laser heating of the specimen with inductive detection of the material’s response. In
practice, a differential coil pair is used to enhance the signal. A key attraction has been the considerably improved eddy current resolution now possible. Resolution now becomes related primarily to the size of the focal spot rather than to the size of the detection coil. In practical terms of course, the coil needs to be small also so that the heated spot is not too small a fraction of the material volume sampled by the coil.

For these images, the laser and sample are fixed in position. The focal spot is moved by reflecting the laser beam off of mirrors on crossed, computer controlled stages. The nose of the stage carrying the second mirror also carries a microscope objective which receives the laser beam from the second mirror and focuses the beam onto the sample. This objective also collects light reflected from the focal spot and brings it, via a microscope cover slip used as a beam splitter, to a photodiode, also riding on the nose of the second stage. A map of the optical reflectivity is thus obtained at the same time as the photoacoustic or photoinductive scan. This set of optical reflectivities is labeled "scanned optical" in the image sets to be shown. For the gas cell scans, the cell, with its hearing aid microphone and window to admit the laser radiation [4] is sealed to the sample surface with a water soluble glue. For the photoinductive scans, the small printed circuit of the differential coils [2] is mounted under the microscope objective.

ALUMINA/TITANIUM MONOTAPE

The images in this paper were obtained on an early 'monotape' sample produced by 3M under a DARPA program aimed at producing lower cost metal matrix composites. The composite consists of 10 μm alumina fibers in a titanium matrix. In an intermediate step to producing final parts, a layer of titanium coated fibers is produced as a tape. These tapes are more convenient for handling in the final layup of a composite than the individual fibers are. Since the tape is basically one layer thick, it is called a monotape. Since the layer in these early tapes is not completely uniform and has additional titanium for bonding, the actual average tape thickness is 50 μm compared to the average coated fiber diameter in this sample of 12.36 μm ± 2.57 μm.

Figure 1 shows a micrograph of the monotape sample in which the scanned area can be seen clearly. The general direction of the fibers can be seen. A few fibers on the surface, straying out of the general pattern can be seen. These stray fibers on the surface will be distinguishable in some of the scans to be shown.

The laser power turned out to have been set high enough that the scanned area was discolored in general, and in some areas, damaged to blackening, melting and even burning through. This high an intensity is not essential. However, the variation in the scorching pattern does reveal inhomogenities in the sample which can be compared with the image sets to be shown later. In comparing this to the thermal wave images, note that the scorch pattern depends on peak temperatures, while the thermal wave images depend on the amplitude of the periodic temperature swings. The burned holes can be used as landmarks in the images to be shown. Beside the holes burned in the sample are areas where tiny holes were burned at the sampling positions of the scan which show as a grid. These grids were fragile and partially burned off in subsequent scans so that the hole shape is different in some of the later scans.
Figure 2 compares photoinductive images and gas cell images at 11 Hz of the area shown in Fig. 1. The top image in each column is the concurrently collected scanned optical reflectivity. These are followed by the magnitude and phase images. The scanned optical image in the gas cell set exhibits fringes that are an artifact, but this image is included since the photoinductive and gas cell areas are not strictly identical and the larger burned hole, which is distinguishable in the gas cell scanned optical, serves as a landmark.

The gas cell images are cleaner than the photoinductive, reflecting the decade of development from which gas cell detection has benefitted. The detail in the photoinductive scans is remarkable for eddy current imaging. The gas cell images are useful for comparison since they represent simply the periodic temperature response of the sample. Since the monotape is nonmagnetic, the photoinductive response reflects the temperature dependence of the electrical conductivity. While there are general similarities, it can be seen how different the photoinductive response is from the gas cell response. The monotape is thermally thin for thermal waves at 11 Hz but the eddy skin depth is on the order of the tape thickness. The thermal diffusion length is on the order of 1/2 mm.
Fig. 2 Comparison of photoinductive on the left and gas cell response on the right taken on the monotape of Fig. 1 at 11 Hz, 2 X 2 mm.

The considerable variation in the photoinductive response is particularly evident in the phase response. There was 360° of phase response in the data over the image. 360° of phase variation cannot be represented well with a black to white scale suitable for publication, therefore there is an area in the image where the phase changes from -180°, black, to +180°, white, which overemphasizes the actual phase change. This area is in the upper left and can be identified by the very black areas next to the very white areas. The location of this display discontinuity in the 360° of phase represented within the data is arbitrary. The presence of the full 360° response within the image shows the intense change over the sampled area.

105 Hz IMAGES

Figure 3 shows photoinductive images at 105 Hz and two sets of gas cell images for comparison. The area imaged photoinductively at 105 Hz is only 1 X 1 mm, compared to the 2 X 2 mm area imaged at 11 Hz. Consequently, there are gas cell images of about the same 1 X 1 mm area in the center column and gas cell images of a 2 X 2 mm area, incorporating the 1 X 1 areas, to the left for better comparison with Fig. 2. The gas cell images are larger than the photoinductive images simply because they contain more points. For an example of gas cell and photoinductive response, note the band of fibers running diagonally across the center of the 1 X 1 mm gas cell scanned optical image. The 1 X 1 mm gas cell magnitude shows a broad featureless dark band.
Fig. 3 Comparison of photoinductive and gas cell response on the monotape of Fig. 1 at 105 Hz, photoinductive, 1 X 1 mm, on the left; gas cell, 1 X 1 mm, center; gas cell, 2 X 2 mm, right.

for this area, indicating uniform thermal contact between the fibers in this region. The photoinductive response corresponding to the dark band in the gas cell magnitude is not uniform however, indicating electrical conductivity variations.

The detail in the gas cell images is better than the photoinductive images, as was the case at 11 Hz. The gas cell images in the center were taken with a 25X objective having a focal spot of 6.5 μm and with a 4 μm step size compared to the 15 μm spot provided by the 5X objective and 10 μm step size of the photoinductive image at 105 Hz on the left. The step size for the gas cell image on the right was 8 μm. In the gas cell images (and hopefully in the reproduction of this figure), one of the stray fibers mentioned in the discussion of Fig. 1, which has a diameter of about 11 μm, can be seen running from the feature in the upper right to the lower right. This is clearest in the 1 X 1 mm gas cell phase image.

The eddy current skin depth, 20 MHz excitation frequency, is the same as in Fig. 2, but the thermal diffusion length is 1/3 of its length at 11 Hz. Consistent with this, the 2 X 2 mm gas cell images on the right of Fig. 3 at 105 Hz show more detail than the 2 X 2 mm gas cell images at 11 Hz on the right of Fig. 2. It is then interesting to compare the gas cell response at 11 Hz and 105 Hz on a scale of 1 X 1 mm as is done in the next figure.
In Fig. 4, finer detail can be seen at 105 Hz than at 11 Hz, as would be expected, but the more interesting change is the quite different response around the small burned hole in the upper right at 105 Hz, indicating thermal wave interference in this region at 105 Hz. The shape of this excited region corresponds approximately to the scanned optical feature at the same location. Conversely, the area around the larger burned hole in the lower left responds more strongly at 11 Hz than at 105 Hz, indicating that the tape is thicker around the larger burned hole than around the smaller burned hole in the upper right. Individual fibers can be seen inside the larger burned hole in the lower left at both 11 and 105 Hz.

PHOTOINDUCTIVE RESPONSE AT 11 Hz AND 105 Hz

Figure 5 shows a side by side comparison of the photoinductive response at 11 Hz on the left to the response at 105 Hz on the right. Since the 11 Hz image was of a 2 X 2 mm area compared to the 1 X 1 mm area at 105 Hz, the 1 X 1 mm area scanned at 105 Hz is extracted from the 11 Hz images for the center column of the figure. In the 11 Hz scanned optical image, the 1 X 1 mm area which had been previously scanned at 105 Hz is noticeably brighter.
Fig. 5  Comparison of photoinductive response on the monotape of Fig. 1 at 11 Hz, 2 X 2 mm, on the right, and 105 Hz, 1 X 1 mm, on the left. The center column shows the extracted area from the 11 Hz scan that was scanned at 105 Hz.

In comparing the photoinductive images, it can be seen that, as could be expected, the photoinductive image at 11 Hz is different than that at 105 Hz. What is different than would be expected is that the image detail at 11 Hz is about the same as at 105 Hz, contrary to what was seen in the gas cell images. This could indicate that the controlling resolution for the photoinductive scans here is not the thermal wavelength but the eddy current skin depth which remained unchanged.

For comparing the image detail, note that the burned hole areas seem to have changed somewhat between the scan at 105 Hz which was the first set of images taken on this sample and the scan at 11 Hz which was the second set of images in this series. In contrast, Fig. 4 shows the eighth and ninth set of images gathered, by which time the damage had stabilized. The optical micrograph of Fig. 1 shows the state after the photoinductive scans.

The 360° phase variation in the 11 Hz photoinductive phase scan is consistent with a resonance phenomena. The phase variation present in the 105 Hz photoinductive scan is also 360°, but the real phase variation in that image seems closer to 250° when an allowance for apparent noise in that image is made. In contrast, the gas cell image most comparable to the 11 Hz image, the right hand set of images in Fig. 2, varies by 78° throughout the image. Again in contrast, the gas cell image most comparable to the 1 X 1 mm 105 Hz photoinductive image, the middle set of images in Fig. 3, varies by 77°, even though the gas cell images at 11 Hz and at 105 Hz have notable differences as
seen in Fig. 4. It is apparent that interesting work remains to be done in elucidating the photoinductive response and the interplay of the eddy current skin depth and thermal diffusion length.

SUMMARY

These images demonstrate that the photoinductive technique can provide resolution exceeding standard eddy current images on technologically interesting materials. The photoinductive response differs from both optical detail and gas cell response, showing that it is not solely dependent on optical absorption and/or the temperature variation of the excited spot.

The enhanced detail compared to standard eddy current imaging and the occurrence of apparent resonance phenomena in the photoinductive images will hopefully provide fruitful research opportunities.

The most significant improvement to be made in photoinductive imaging for the near term would probably be more sensitive eddy current coils. The present coils have only about 5 turns [2]. It is hoped that photoinductive imaging would improve like gas cell imaging improved over the last decade with the use of better microphones and cell design.

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REFERENCES