THERMAL WAVE TECHNIQUES FOR IMAGING AND CHARACTERIZATION OF MATERIALS

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IMAGING

Thermal wave imaging is proving to be a useful technique for the nondestructive evaluation (NDE) of subsurface features of opaque solids. This imaging is achieved with various intensity-modulated heat sources, such as laser or particle beams, and with various detectors, such as microphones, ultrasonic transducers, infrared detectors, and laser probes. The authors have recently reviewed these techniques and their application to NDE [1]. Common to the techniques is the fact that they each involve the interaction of a highly damped thermal wave with surface or subsurface thermal features. They also have in common the fact that the source is localized. The techniques differ in that the detectors may be local or non-local to a greater or lesser degree. For example, the focused infrared detector is a local point temperature detector; the mirage effect laser probe is a line detector; and the microphone is an area detector. The presence of the localized source gives all of these methods the potential for high spatial resolution. The symmetry of the non-locality of the detector, however, may seriously limit detection of particular kinds of flaws. For some of the detection schemes, comparisons between experiment and theory for imaging of flaws with simple geometry (planar cracks, cylindrical or spherical inclusions) are straightforward, and good agreement has been achieved in most cases. Other schemes, such as piezoelectric detection, are more complex in nature. For example, the details of the conversion from thermal energy to acoustic energy may involve several different processes, and no quantitative three-dimensional theoretical model yet exists to assess the relative importance of these processes. In this section we give a brief review of the principles of imaging in the extreme near field, followed by descriptions of three selected experimental thermal wave imaging techniques, including geometrical considerations, signal-to-noise considerations, and examples of NDE applications. For descriptions of other thermal wave imaging techniques the reader is referred to the literature [1].

The resolution of any microscope depends on its ability either to localize the illumination at the scatterer (typical of scanning microscopes) or to localize the region of the scatterer to which the detector is sensitive (such as in conventional microscopes, which focus different points of the scatterer on different detectors). In microscopes which use lenses as focusing elements to achieve this localization, the localization is limited by the wavelength of the radiation being focused (the Rayleigh criterion). For example, the resolution of high-quality optical microscopes is limited to about $\lambda/2$, where λ is the wavelength. On the other hand, if it is possible to localize, say, the source to much better than a wavelength, and to bring it into close (compared to a wavelength) proximity to the scatterer, resolution many times better than a wavelength is possible. This situation is perhaps best described as "the extreme-near-field limit" [1-3]. This limit was achieved with an optical microscope in 1984 by Pohl et al [4] and in the macroscopic domain using microwaves in 1972 by Ash and Nichols [5]. In the case of thermal wave microscopes, the sources are normally lasers or particle beams, which can be focused to dimensions which are small compared to the thermal wavelength. Therefore, it is much easier to satisfy the small source, close proximity criteria for thermal wave microscopy than it is for optical microscopy. Thermal wave imaging generally falls into the category of scanned microscopy with a localized source. Thermal waves by nature are heavily damped, dying out in distances of the order of a wavelength (typically a few microns to a few mm) or less. This appears to preclude the use of thermal wave lenses. However, it also means that the contrast of thermal wave images is dominated by scatterers located within a fraction of a thermal wavelength from the source. Thus, by varying the thermal wavelength one can vary the region of the specimen which contributes to the image. Another consequence of the heavily damped nature of these waves is that thermal wave imaging is especially well suited for the nondestructive evaluation (NDE) of near (submicron to a few mm) subsurface defects in opaque solids. This region is extremely important because very small flaws near the surface often lead to catastrophic failure.

Thermal wave microscopes take on a number of different forms with corresponding advantages and disadvantages, depending on the nature of the source and the detector. Gas-cell detection [6-12] uses a microphone to detect the pressure variations in an enclosed volume of gas as a focused, intensity-modulated laser beam is scanned over the surface of a sample. Conceptually, this can be thought of as imaging with a point source and an area detector (the acoustic wavelength is typically larger than the dimensions of the cell, so that the microphone responds equally to all parts of the cell). For this type of thermal wave microscope, because the source is a laser and the solid is normally opaque, the source is localized on the surface to a region whose lateral dimensions are limited by the optical wavelength. The proximity of the source to the scatterers is determined by the depth of the scatterers, and thus the resolution is limited by that depth. An advantage of this imaging technique is that it lends itself readily to theoretical analysis. This ease of theoretical analysis originates in the planar symmetry of the detection scheme, which allows one to utilize plane-wave scattering theory [11]. This same symmetry can be a disadvantage, however, since it precludes the detection of an important class of defects, closed vertical cracks. [12]

A block diagram of the gas-cell technique is shown in Fig. 1. An acousto-optic modulator, controlled by the audio reference signal from the lock-in amplifier, is used to provide a modulated heating beam from the Ar-ion laser. This beam is focused through the window of the gas-cell (shown schematically in Fig. 2) to the surface of the sample to which the cell is attached. A miniature hearing-aid microphone, coupled to the fixed volume of air trapped between the sample surface, the cell walls and the wax gasket (see Fig. 2), is used to convert the area integral of the ac surface temperature of the surface into a corresponding electrical signal for phase-sensitive detection by the lock-in amplifier. Since the microphone is attached rigidly to the sample, if stepping motors are used to scan relative to the focal point of the heating beam, signal-to-noise considerations suggest that it is advisable not to monitor the microphone signal during the resulting accelerations and decelerations of the sample. Usually, the data are taken for one line (x-scan) by stepping the position of the focal spot with the sample stationary (see Fig. 1). The sample's y-position is then stepped between lines to complete the area scan for imaging. A disadvantage of this technique is the limited range (audio) of modulation frequencies and hence the limited range of thermal wavelengths. Perhaps a more serious disadvantage is that it involves contact with the sample surface. The quality of the gasket seals also plays an important role in maximizing the signal-to-noise ratio.

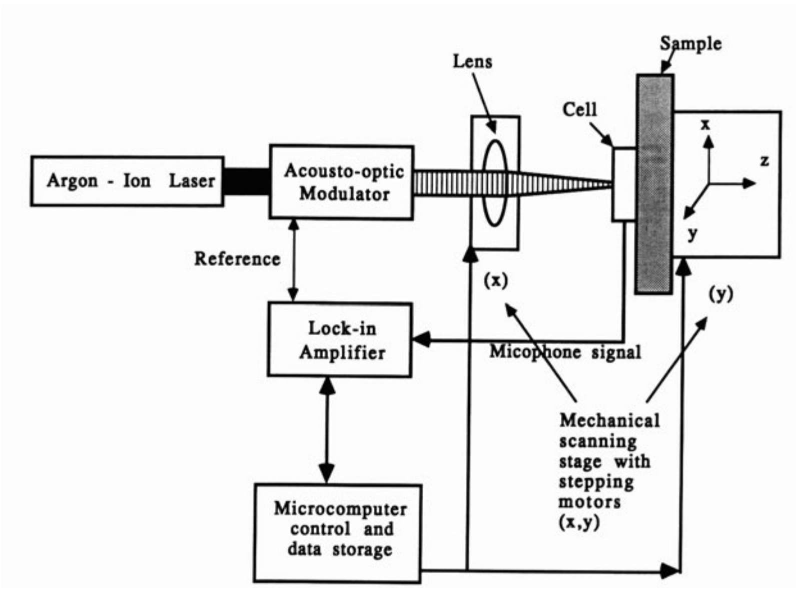

Fig. 1 Block diagram of the gas-cell method for thermal wave imaging.

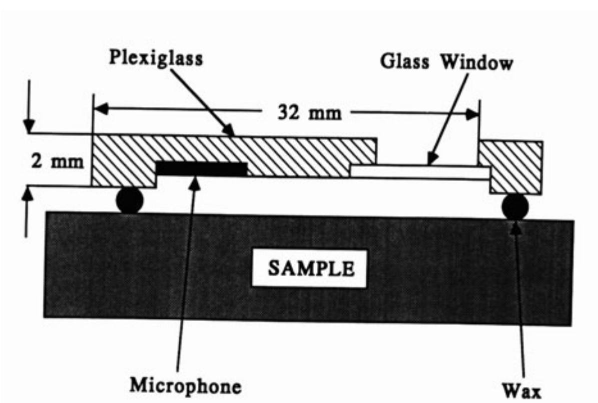

Fig. 2 Schematic diagram of the gas cell.

A thermal wave imaging technique which avoids the disadvantage of surface contact, and which reduces the symmetry of the detection scheme, utilizes the mirage effect or optical beam deflection (OBD) detection [13-16]. Again, the localization is achieved by focusing the source, but the detection is along a line rather than over an area. This method, in addition to being contactless, can operate over a much wider frequency range (1 Hz to a few hundred kHz). In contrast to the gas cell technique, which cannot detect vertical cracks, the mirage effect provides an excellent method for imaging such cracks [12,16]. An obvious disadvantage to this technique is the requirement of flat or cylindrical sample surfaces. Furthermore, there are the practical difficulties of maintaining two laser positions, as well as the height of the probe beam, during the scan. Also, the line symmetry of the detector means that a theoretical analysis requires, at the very least, considerations of scattering with cylindrical waves, and hence is considerably more difficult than that for gas-cell imaging.

A block diagram of the mirage effect technique is shown in Fig. 3. The heating beam is an intensity-modulated Ar-ion laser, and the probe beam is a HeNe laser which skims the sample surface with its (ac) position monitored synchronously by a quad-cell position detector and lock-in amplifier. Either the normal component or the transverse component of the ac deflection of the probe beam can be monitored by selecting the appropriate combinations of the four segments of the position sensor. A narrow band optical filter is used to prevent scattered (modulated) Ar-ion radiation from reaching the position sensor. For imaging, the positions of both beams are fixed during the x-y scan of the sample. In selecting the probe laser, it is important to achieve minimum intensity noise in the operating frequency range

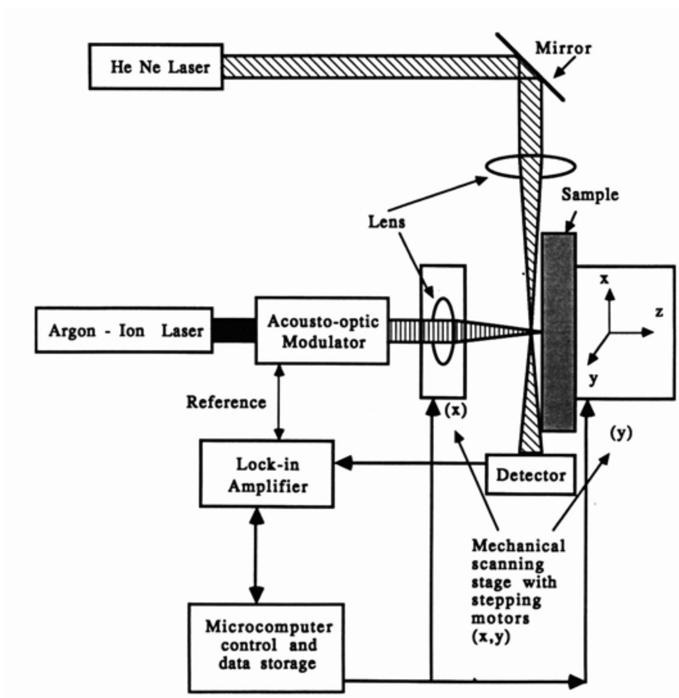

Fig. 3 Block diagram of the mirage effect method for thermal wave imaging.

and to have good pointing stability. Alignment of the beams relative to one another, the position sensor, and the sample surface is achieved with appropriate micrometer driven translation stages and tilt tables, and in mounting these components to the optical table, careful attention must be paid to the avoidance of relative motions in the operating frequency range.

Another contactless thermal wave imaging technique is photothermal radiometry[17-20], in which variations in the local surface temperature are measured with a focused infrared (IR) detector. The source is again a modulated laser beam, focused on the surface. In this case, one has a point source and a point detector, with the ultimate resolution in the extreme-near-field limit being provided by the optical, rather than the IR, focal spot because of the shorter optical wavelength. An advantage of this technique is that, in contrast to both the gas-cell and mirage effect techniques, it does not depend upon heat flow from the solid to the air and therefore does not have the complications associated with the additional phase delays and magnitude changes of the signal due to the presence of the air. This also permits the application of the technique in vacuum. A disadvantage of the technique is that variations in the emissivity of the surface can obscure the thermal wave image. However, the theoretical analysis is facilitated by the absence of complications associated with the presence of the air.

A block diagram of the photothermal radiometry technique is shown in Fig. 4. A Ge lens is used to collect the 8-12 micrometer black-body radiation (modulated by the varying sample temperature in the presence of the heating beam) on a suitable IR detector. An inexpensive version is to use a pyroelectric IR detector. Such detectors also have reasonable sensitivity at low modulation frequencies (< 40Hz), a frequency region which is quite useful for deep probing of the subsurface region of the sample. Cooled IR photon detectors (e.g. HgCdTe) are more expensive but have very fast response times and better sensitivity. If one combines that feature with a suitable scanned array or IR camera and operates in the time domain instead of the frequency domain (pulsed source, rather than modulated source), considerable improvements in imaging speed can be achieved [21].

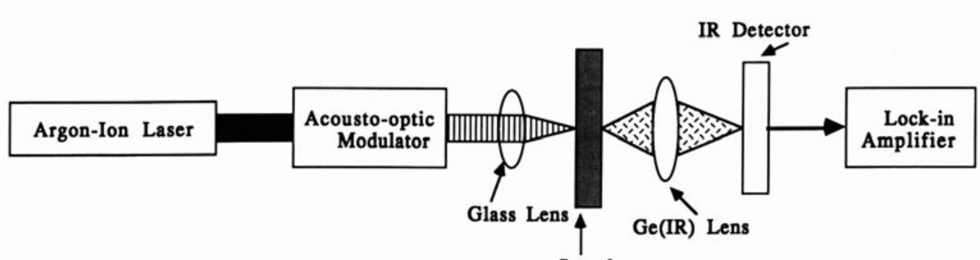

Fig. 4 Block diagram of the photothermal radiometric method for thermal wave imaging.

CHARACTERIZATION OF MATERIALS

The mirage effect method for thermal wave imaging (Fig. 3) can also be utilized for the characterization of thermal properties of pure and coated materials [22-26]. The experimental technique is to measure the transverse deflection of the (stationary) probe beam as the heating beam is scanned across the sample surface at right angles to the probe beam with a constant probe beam height and with the sample held stationary. In a pure material, to a good approximation, the separation of the two points on either side of the center of such a scan where the phase of the transverse deflection signal reaches ninety degreees effectively measures the thermal wavelength in the solid. The determination of the thermal diffusivity is then accomplished by plotting this separation versus the inverse square root of the frequency. More detailed agreement can be obtained, and the technique can be extended to the case of coated surfaces, by comparison to three dimensional thermal diffusion calculations of the mirage effect signal for this geometry. The reader is referred to two papers [25,26] in this volume for further details of the method and the accompanying theoretical developments. Several other papers in this volume and other volumes of this series describe thermal wave measurements in the time domain which have been used to measure thermal diffusivities of bulk materials and thin films.

DISCUSSION AND CONCLUSIONS

The general principles of thermal wave imaging have now been established experimentally and theoretically. At least for the simpler detection schemes it is possible to carry out detailed calculations of images for subsurface defects having simple geometries, and quantitative agreement with experiments has been obtained. All of these thermal wave techniques are capable of producing high resolution images under the right experimental conditions. Different detection techniques have different degrees of symmetry, and this symmetry, or lack of symmetry, can be exploited for the detection of flaws with particular geometries. A number of the imaging schemes involve the generation and detection of acoustic waves in addition to the thermal waves. Interpretation of such images is necessarily more complicated, but such microscopes present the possibility of making high resolution images with both thermal waves and acoustic waves using the same instrument. It should be noted that as compared to optical, and even acoustic imaging, thermal wave imaging is very young, with the first images having been obtained just a few years ago. Clearly, much more instrumental development will occur. A primary objective of such development will undoubtedly be to improve the imaging speed. This probably will be accomplished through some form of parallel processing, rather than point by point scanning. The potential for production applications for NDE of thermal wave imaging would then be established.

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