APPLICATIONS OF PHOTOINDUCTIVE IMAGING

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INTRODUCTION

Photoinductive imaging is a unique dual-mode NDE technique that combines eddy current and thermal wave methods. The photoinductive effect, upon which this method is based, is the thermally induced change in the impedance of an eddy current probe in proximity to a conducting surface that is illuminated with a modulated light source. The change in probe impedance is caused by the temperature-induced change in the conductivity of the specimen. Typical changes in probe impedance are small, on the order of a few ppm, but because they are synchronous with the light-beam modulation, lock-in techniques can be used to detect the signals, which can then be used to image surface or near-surface defects, voids, inclusions, or other thermal or structural inhomogeneities.

Initial studies of photoinductive imaging demonstrated the feasibility of this technique by using commercial eddy current probes and instruments on foil specimens [1]. But to use this method successfully on typical structural materials requires development of special probes that permit a laser source to be focused on the surface underneath the probe. We have designed a special eddy current coil for this purpose using printed circuit technology and fabricated a probe based on this coil design. In this paper we describe the new coil and probe and report preliminary results from using the probe to image flaw-like objects.

THEORY

As described in standard texts on heat conduction [2], the temperature distribution $T(x)$ in a specimen with a heat source at the surface is governed by the diffusion equation

$$\nabla^2 T - \alpha \frac{\partial}{\partial t} T = 0,$$

(1)

where the thermal diffusivity $\alpha$ is related to the specimen density $\rho$, specific heat $C$, and thermal conductivity $\lambda$ as $\alpha = \sqrt{\rho C / \lambda}$. The temperature fluctuation caused by an external heat source can be obtained by solving this differential equation under the boundary condition imposed on the normal derivative $\partial_n T$ at the boundary,
where $J$ is a thermal current density describing the heat source. This fluctuation $\delta T$ then results in local variations of material properties. For instance, if the temperature coefficient of the electrical conductivity is $(\partial \sigma / \partial T)$, the conductivity will be altered by $\delta \sigma$, where $\delta \sigma = (\partial \sigma / \partial T) \delta T$. The basic principle of the photoinductive method is to detect $\delta \sigma$, hence $\delta T$, with an eddy current probe.

The eddy current method itself has been described thoroughly in the literature. The fundamental equations are the single-frequency Maxwell equations

$$\nabla \times \vec{E} = -i \omega \mu \vec{H}, \quad \nabla \times \vec{H} = -\vec{j} + (\sigma - i \omega \epsilon) \vec{E},$$

(3)

where $\vec{j}$ is the current density if the probe, and where $\sigma(\vec{x})$ is equal to the conductivity when $\vec{x}$ is inside the material, and zero outside. When the thermal effect varies $\sigma(\vec{x})$ by $\delta \sigma(\vec{x})$, the electromagnetic fields $\vec{E}$ and $\vec{H}$ vary correspondingly. Let $\vec{e}$ and $\vec{h}$ denote the respective variations. Since these changes are small, the second order term $\delta \sigma \delta \vec{e}$ can be ignored. One therefore finds the equations for $\vec{e}$ and $\vec{h}$,

$$\nabla \times \vec{e} = -i \omega \mu \vec{h}, \quad \nabla \times \vec{h} = -\vec{s} + (\sigma - i \omega \epsilon) \vec{e},$$

(4)

where $\vec{s} = \delta \sigma \vec{E}$. Then it is necessary to solve equations (1), (3), and (4) to evaluate the impedance signal from the definition

$$\Delta Z = -(1/2) \int dV \vec{J} \cdot \vec{e},$$

(5)

where $I$ is the total probe current. Fortunately, however, Eq. (4) need not be solved explicitly. Instead, Eqs. (3) and (4) can be used to derive the following reciprocity relation,

$$\int dV \vec{J} \cdot \vec{e} = \int dV \vec{E} \cdot \vec{s}.$$

(6)

Consequently, the task of calculating photoinductive signals can be carried out in three separate phases: (i) solve Eqs. (1) and (2) to find $\delta T$. (ii) Find the electric field $\vec{E}$ by solving Eq. (3). Notice that this is the usual eddy-current problem, independent of thermal fluctuations. (iii) Finally, the signal $\Delta Z$ can be calculated from the relation

$$\Delta Z = -(1/2)(\partial \sigma / \partial T) \int dV \vec{E}^2 \delta T,$$

(7)

which results from Eqs. (5) and (6) and the definitions of $\vec{s}$ and $\delta \sigma$.

**EXPERIMENT**

To perform single-side inspection of thick materials with photoinductive imaging, it is necessary to focus a modulated thermal source such as a chopped laser beam onto the specimen in close proximity to the eddy current coil. This is not possible with commercial eddy current probes, which are potted and mounted in probe bodies, making the most sensitive regions of the probe inaccessible to an external light source. We designed a special differential pair of eddy current coils for photoinductive imaging using printed circuit technology. A flat, rectangular spiral coil with five turns was chosen and made as small as
practical using conventional commercial printed circuit board (PCB) technology. The design for the differential coils is shown in Fig. 1; each coil is about 4 mm on a side. A gap was left on one side of the coil between the 3rd and 4th turns to leave room to drill a hole for the laser beam so the energy could be concentrated where the eddy current density was greatest. Because the inductance of these coils was low, we operated them at 20-30 MHz, which had the additional benefit of operating with a very small skin depth.

Fig. 1. Design for a differential pair of eddy current coils on printed circuit board. Dashed lines show traces on the back side of the board. An optical fiber delivers the laser energy to the specimen surface through a hole in the gap between the 3rd and 4th turns of the coil.

With this design, it was possible to keep the coils close to the specimen surface, thus keeping the eddy current density high. At the same time, we could deliver the laser energy to the surface directly under the coil. Next, we constructed a probe using this coil as the basic sensor element. The probe is shown schematically in Fig. 2. To avoid a costly optical system to deliver the laser beam to the surface during scanning, we used an optical fiber to bring the laser energy to the specimen's surface. The fused silica fiber was 100 μm in diameter. Although we used this probe in a system where the scanning was done by computer-controlled scanners, its design illustrates the fact that a small, lightweight, hand-held probe could be used for photoinductive imaging.

The opto-electronic instrumentation we used to obtain signals for photoinductive imaging is shown in Fig. 3. The argon ion laser is a multi-mode, multi-line, 5-W laser. We always operated it at less than 2 W output to avoid damage to the fiber or fiber coupler. The light exiting the fiber was not focused on the specimen. For the results we report here, the chopping frequency was 10 Hz and the eddy current frequency was 25 MHz. The bridge and demodulator were custom built circuits, but the rest of the equipment was commercial instrumentation.
Fig. 2. Construction of the photoinductive probe used in these studies.

Fig. 3. Schematic diagram of the photoinductive imaging system.
RESULTS AND DISCUSSION

We used the photoinductive probe with a variety of specimens to explore its applicability to typical materials and flaws. Experiments with 1 or 2 cm thick plates of aluminum having EDM notches or fatigue cracks in the surface produced very noisy signals. Although the signals were not useful for imaging flaws in these thick, high-thermal-conductivity materials, flaw signals were in evidence. More recent results obtained with the laser source focused on the specimen surface have shown the ability to image flaws in thick specimens [3].

We had more success imaging with thin film or foil specimens. One specimen that gave very good results was a gold/chromium film 300 nm thick, evaporated onto a glass substrate. Very strong signals were obtained with these films. To illustrate the possibilities for imaging on these materials, we marked one film with the letters "NDE" and scanned it with the probe. The results are presented in Fig. 4. The signal-to-noise ratio is clearly adequate for imaging and flaw detection, and the spatial resolution is very good, even though the laser was not focused.

Figure 5 shows another example of the ability of the photoinductive probe to image flaw-like structures. These results are for a thin (20 μm) aluminum foil adhesively bonded to a plastic panel. Three black ink marks were drawn on the foil; these are visible in both the contour and surface plots. Also, a razor cut was made in a diagonal direction in the lower left-hand corner of the figure. Very large enhancements of the photoinductive signal are evident along the cut, especially near the ink marks.

Fig. 4. Contour and surface plots showing image of the letters "NDE" obtained with photoinductive probe. Letters were written with black ink on 300-nm Au/Cr film evaporated onto a glass substrate.
CONCLUSIONS

A differential eddy current coil was designed and fabricated using printed circuit board technology for use as a photoinductive sensor. A probe was constructed from the coil, using an optical fiber to deliver laser energy to the specimen surface underneath the probe. The probe was then used in a photoinductive imaging measurement system to explore the possible applications of this new NDE imaging technique. Early results with thick specimens were not adequate for imaging, but flaw signals were evident. Results with thin film specimens and thicker foil samples were much better. Images of flaws and thermally absorbing features were easily obtained. These images demonstrated the good spatial resolution of this photoinductive imaging system, even without focusing of the laser beam. Further development of this type of probe and imaging system is clearly warranted. Work is continuing to refine probe design and signal detection circuitry.

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