Laser Photoacoustic Technique for NDE

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Laser Photoacoustic Technique for NDE

Abstract
The technique of laser photoacoustic spectroscopy is applied to the studies of surface and sub-surface structures of solids in a nondestructive fashion. In the present case, special attention is focused on reaction-bonded Si N ceramics, which are used for the manufacturing of turbine blades. Good correlation is obtained between the observed photoacoustic signal and surface microstructures. In addition, the photoacoustic signal reveals inhomogeneities that are not visually detected under a microscope.

Keywords
Nondestructive Evaluation

Disciplines
Materials Science and Engineering
ABSTRACT

The technique of laser photoacoustic spectroscopy is applied to the studies of surface and sub-surface structures of solids in a nondestructive fashion. In the present case, special attention is focused on reaction-bonded Si₃N₄ ceramics, which are used for the manufacturing of turbine blades. Good correlation is obtained between the observed photoacoustic signal and surface microstructures. In addition, the photoacoustic signal reveals inhomogeneities that are not visually detected under a microscope.

INTRODUCTION

Recently, there has been considerable interest in a "new" spectroscopic technique called photoacoustic (or optoacoustic) spectroscopy. Although the photoacoustic effect was discovered by A.G. Bell in 1880, it was not until 1973 that this effect was developed into a spectroscopic tool for the optical investigation of solid materials. In the last four years, photoacoustic spectroscopy has been found to be a very useful technique for research and analysis, not only in Physics and Chemistry, but also in Biology and Medicine. It is especially well suited for investigating amorphous and powder systems in which the Rayleigh scattering makes transmission and reflectance studies difficult.

EXPERIMENTAL

In this technique, a sample is placed inside a specially designed cell (resonant or non-resonant acoustically) containing a suitable gas and a sensitive microphone. A non-resonant PAS cell used in the present study is shown in Fig. 1. The sample is then illuminated with chopped radiation as shown in Fig. 2. Light absorbed by the sample is converted, in part, into heat by non-radiative de-excitation processes within the sample. The resulting periodic heat flow from the sample to the surrounding gas creates pressure fluctuations in the cell, which are detected by the microphone as a signal which is phase coherent at the chopping frequency. The signal is subsequently analyzed by a lock-in amplifier and displayed on the x-y recorder, either as a function of the wavelength of the incident radiation, or as a function of the scanning position.

The resulting photoacoustic signal is directly related to the amount of light absorbed by the sample. This is especially the case for highly opaque and low fluorescence systems. Furthermore, since only the absorbed light is converted to sound, scattered light presents no difficulties. A quantitative treatment shows that, in addition, both the magnitude and the phase of the photoacoustic signal depend on the thermal properties of the sample and those of the gas in the cell, as well as on the chopping frequency.

RESULTS AND DISCUSSIONS

In the present report, we demonstrate that the technique can be applied to study the microstructures of solid surfaces, i.e. for nondestructive evaluation (NDE) of surface flaws and sub-surface inhomogeneities. The geometric considerations for flaw detection at or near the surface are shown in Fig. 3. As the laser beam illuminates the sample, a well-defined effective volume, V_{eff} = ax_{eff} is heated because of absorption of the electromagnetic radiation. The area A depends on the focusing of the laser light and can be as small as 10^{-6} cm^2. A characteristic optical penetration depth d_{op} = (absorption coefficient)^{-1} exists, which depends on the wavelength of the incident light. In addition, the chopping frequency dictates an effective thermal diffusion length d_{th} = \sqrt{\kappa/\omega} for the heat to couple to the gas environment. Here, \kappa is the thermal conductivity, C is the specific heat, \rho is the specific gravity of the sample, and \omega is 2\pi (chopping frequency). It is a combination of these two effects which limits the depth of the material evaluated. Therefore, we define an effective absorbing depth d_{eff} given by

\[ d_{eff} = d_{th}, \text{ for } d_{th} < d_{op} \]

\[ d_{eff} = d_{op}, \text{ for } d_{th} > d_{op}. \]

The presence of flaws or inhomogeneities in the illuminated region will change the effective volume (optically and thermally). If the flaw is a different material (foreign inclusion) than the host, the absorption coefficient will also differ. If a crack or a void is present, the effective volume will differ. The combination of these effects will give rise to a change in the magnitude and phase of the acoustic signal.

We have investigated a number of silicon nitride ceramic samples with chopping frequencies ranging from 50 to 2000 Hz. Some of the samples have surface cracks approximately 50\mu m x 100\mu m, which are visible under the microscope. Others show no obvious surface cracks. In Fig. 4, typical traces are shown of the photoacoustic
signal' (f = 800 Hz) as one scans across such surfaces. The surface profile is very reproducible for repeated scans along the same line, as illustrated by traces (a,b) and (d,e). Also, as one improves the focus, the resolution improves accordingly, and more detailed microstructure is revealed as illustrated in traces d and e in Fig. 4. For these traces, the diameter of the minimum focal point is ~30 μm. The difference between samples with and without cracks is also evident in Fig. 4. This is further illustrated in Fig. 5 and 6, where an x-y scan is presented. We find a reasonably good correlation between the photoacoustic signal with features which are observed under the microscope. Furthermore, the photoacoustic signal shows features not detected visually with a microscope. These sub-surface features may be related to the presence of nitrogen deficient clusters or to precipitated impurities such as silicides. Spectroscopic experiments utilizing a tunable dye laser should provide information for more precise identification, both of the chemical composition and the depth of these inhomogeneities. Such studies are presently in progress.

In conclusion, the photoacoustic technique has the capability of characterizing surface and sub-surface structures in condensed matter, as illustrated in these preliminary studies on the technically important silicon nitride ceramics. We believe that the technique also shows excellent promise for nondestructive evaluation applications to other materials.

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8. The samples are small pieces of turbine blade made of reaction-bonded Si₃N₄ and appropriately sliced to the size of 1 cm x 1 cm x 1 mm.
9. It was noted that on the cross-section after cutting the turbine blade into small pieces and ultrasonic cleaning, there exists spots of the size of 0–100 μm beneath the surface. This, we think, may be due to nitrogen deficient clustering of the silicon atoms in the formation of the ceramic material.

Fig. 1 Non-resonant PAS cell with Si₃N₄ turbine blade sample.

Fig. 2 Schematic diagram of the laser photoacoustic scanning system.
Fig. 3 Geometric consideration of flaw detection with the photoacoustic technique.

Fig. 4 Typical traces of the photoacoustic signal (F=800 Hz). (a,b) Repeated scan on surface with no obvious crack; (c) scan on surface with obvious cracks; (d,e) repeated scan on surface (c) with better focused laser beam.

Fig. 5 An X-Y scan of surface with obvious cracks; (hot pressed Si₃N₄).

Fig. 6 An X-Y scan of surface with obvious cracks; (reaction-bonded Si₃N₄).