HIGH-SPEED HIGH-RESOLUTION SUBSURFACE DEFECT DETECTION IN CERAMICS USING OPTICAL GATING TECHNIQUES.

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INTRODUCTION

Optical gating techniques and in particular optical coherence tomography (OCT) have recently been used as a noninvasive probe in the medical field\([1,2]\) and as a nondestructive probe in material analysis\([3-5]\). Indeed, any medium which has some light penetration below the surface can potentially be analyzed with OCT. The depth at which a signal can be detected depends both on light absorption and scattering, with the second playing a more critical role in most materials of interest. In this work we concentrate on the application of OCT towards defect detection in ceramic materials. For the various ceramics that we have analyzed in the laboratory, the maximum penetration depths ranged from a few tens of microns to approximately one millimeter below the surface. Because of this limited penetration depth, OCT can not be applied to detect defects buried deep below the surface in ceramic materials. However, because operational stresses of many ceramic components are greatest in the near-surface region, the defects at or just below the surface are the most important to detect.

In previous work \([3-5]\) we demonstrated that OCT can be used for defect detection in ceramics. In this work, we demonstrate a modified OCT apparatus that can acquire two-dimensional images in less than one second. Furthermore, we show how this technique can be extended to collect images in certain non-planar geometries. It is important to note that OCT utilizes inexpensive off-the-shelf components which could be assembled into a compact device.

EXPERIMENT

Experimental Setup

The experimental setup for our OCT device is shown schematically in Fig. 1. A light emitting diode (LED) produces optical radiation at 1.3 \(\mu\)m. The spectral full-width-half-maximum (FWHM) was measured to be \(~ 40\) nm at an output power of 130 \(\mu\)W. This corresponds to the FWHM of the correlation length of this LED in air of \(~ 20\) \(\mu\)m and this determines the depth resolution of the device. The LED radiation is coupled to a fiber and split into reference and probe beams using a 3-dB fiber coupler. The phase of the reference
beam is modulated at ~300 kHz with a piezoelectric transducer. The reference beam is retro-reflected from a mirror back into the fiber. The probe beam is scanned laterally with a fast galvanometer mirror and focused on the ceramic sample with microscope objective lenses of various magnifications, depending on the desire lateral resolution. The transverse FWHM of the probe beam’s focal spot on the sample was measured to be ~ 4 μm for a x20 objective. The back-scattered probe radiation is collected by the same lens, retraces its path through the fiber, and recombines with the back-propagating reference beam in the 3-dB fiber coupler. This combined radiation is then detected by a photodiode. When the pathlengths of the phase-modulated reference and probe beams are within the coherence length of the radiation, the two beams become correlated and the interference between them produces an alternating current (AC) component on the photodiode signal. The frequency of the AC component depends on the reference beam modulation. This AC component represents the gated signal and its magnitude is proportional to the amount of light reflected from the ceramic. The logarithm of the demodulated AC photodiode signal is digitized and stored on a computer.

In our OCT configuration, the phase modulation is decoupled from the depth (Z) translation of any component. This is done by using a low-amplitude, high-frequency PZT for phase modulation and a separate mechanical motion for scanning. Two-dimensional scans may be performed in any plane. In this experiment we used a fast galvanometer mirror scanner to raster the focus of the probe beam along a line parallel to the surface. Translation in the other dimension, either parallel or perpendicular to the surface, may be performed with a slower mechanical translation device. This configuration enables us to produce fast gated images in the X-Y plane as well as in the X-Z plane. Additionally, since the data is always collected in the focal plane of the lens, the best transverse resolution is achieved in all parts of all scans. The image collection time was 0.9 sec for results reported in this work. This time can potentially be improved to video rates with further modifications.

The ability to scan rapidly over non-planar surfaces is important when dealing with real ceramic components such as ball bearings or roller bearings. We have implemented a number of different scanning schemes to address this problem. As a reference, Fig. 2(A) shows the geometry needed to produce a scan of a focal spot in a plane. To produce a line scan in this well-known scan arrangement the lens has to be positioned between and exactly one focal length away from both the galvanometer mirror and the sample. Fig. 2(B) shows the geometry for scanning over a concave spherical surface. It is clear from the figure that to produce a scan on a concave surface of a certain radius the mirror has to be positioned exactly that radius away from the concave surface, while keeping the relative...
position between the lens and the surface constant.

It is significantly harder to produce scans in a convex spherical geometry. Fig. 2(C) shows an arrangement required in this situation. The first lens and the mirror form a virtual concave spherical surface as seen from the right of the mirror. The light seems to originate from a focal spot that moves on the surface and crosses the mirror in the center. The radius of the surface is equal to the distance between the mirror and the focus of the first lens. Subsequently, two lenses in a 4-f arrangement are used to re-image the virtual concave surface on a real convex surface. The scanning radius can also be adjusted by choosing different foci of the last two lenses. It is important to use two lenses in re-imaging the virtual surface since a single imaging lens will produce significant distortions that will adversely affect the sphericity of the scan.

Results

In this work we investigated the applicability of OCT towards defect detection in ceramics and other materials. For ceramic materials, the scattering signal detected below the surface results from grain-boundary reflections. These reflections are enhanced by the refractive index mismatch, $\Delta n$, due to second phase, intergranular material present in most ceramics. In the absence of voids or defects, the return from the scattered light decreases exponentially with depth into the ceramic. With our current experimental setup, reflected light can be detected as deep as $\sim 500 \mu m$ [4,5] in some ceramics. Fig. 3 shows a depth scan of the cutting edge of a HIPed Zirconia razor blade. As expected, the subsurface signal due to the grain boundaries decreases as a function of depth. However, the back
surface, which scatters much more light, is visible at an estimated depth of as much as 300 μm. At this depth no other subsurface signal is detected. Note that the distance scale for depth in the figures with depth OCT scans relates to transmission in air. To obtain the true depth in various ceramics we have to divide by the index of refraction in the ceramics $n_{cer}$ which usually varies between 2 and 3.

Another material we studied using the OCT technique was a PZT ceramic. This particular sample was rejected by the manufacturer due to subsurface defects that manifested themselves as large diffuse spots observable on the surface. Fig. 4 shows reflection and transmission white light microscope images of the sample. No fine structure can be discerned in the images. Using our OCT apparatus, subsurface images reveal a small structure appearing at a depth of 50 μm, as shown in the Fig. 5. Based on the images in this figure we can postulate that the large diffuse spots observed on the surface are due to inclusions present inside the sample. The exact size and position of the inclusions can be measured from OCT images such as those shown in Fig. 5.

Figure 3. Depth cross-sectional image of HIPed Zirconia Ceramic razor blade showing front and back surfaces of the cutting edge.

Figure 4. Reflection and transmission microscope images of PZT sample showing large diffuse damage spot on the surface.
A final example of a material analyzed with our OCT technique is single crystal SiC. This sample was grown using chemical vapor deposition and had a large number of surface and bulk defects. OCT images of this material were taken at various depths and the combined images were rendered in three dimensions for better visualization. Fig. 6 is an example of such a rendering. By visualizing the OCT signal from the different sample planes, information can be obtained on the type and severity of the observed defects.

To demonstrate the ability to scan in a convex spherical geometry, we produced a round indent on the surface of a ½-inch diameter steel ball. The ball could be either translated or rotated with a specially-built slow mechanical device in the directions orthogonal to the scan. The results of various scans are shown in Fig 7. It is seen in the depth scan that the surface of the steel ball appears almost as a parallel line. The slight curvature of the surface in the scan is due to imperfect alignment and to the imperfection in the quality of the lens. Because no light can penetrate into the metal of the ball bearing, the subsurface images show circular shells of decreasing diameter as a function of depth, as expected from the indentation. Information from such scans can be used to measure the depth and volume of the indentation.
Figure 6. Three-dimensional visualization of OCT data on CVD SiC single crystal with defects.

Figure 7. A depth scan and subsurface scans at various depths of an indented steel ball.
SUMMARY

In conclusion, we have demonstrated the use of an optical gating technique, based on a low coherence fiber interferometer, for the detection of subsurface defects in various ceramics. We have also shown how different planar and spherical scanning geometries can be implemented in our OCT apparatus for rapid image acquisition. Future work will include characterizing the size and type of defects that can be detected using optical-gating techniques in various ceramic materials.

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REFERENCES