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Study of Methods for Automated Crack Inspection of Electrically Poled Piezoelectric Ceramics

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ABSTRACT

The goal of this project was to identify a viable, non-destructive methodology for the detection of cracks in electrically poled piezoelectric ceramics used in neutron generator power supply units. The following methods were investigated: Impedance Spectroscopy, Scanning Acoustic Microscopy, Lock-in Thermography, Photo-acoustic Microscopy, and Scanned Vicinal Light. In addition to the exploration of these techniques for crack detection, special consideration was given to the feasibility of integrating these approaches to the Automatic Visual Inspection System (AVIS) that was developed for mapping defects such as chips, pits and voids in piezoelectric ceramic components. Scanned Vicinal Light was shown to be the most effective method of automatically detecting and quantifying cracks in ceramic components. This method is also very effective for crack detection in other translucent ceramics.

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INTRODUCTION

Brittle materials, such as ceramics, are prone to cracking from a variety of stress sources. For example, stresses generated from inhomogeneous density distribution in the green body during ceramic forming and sintering, component machining and handling, as well as thermal stresses developed during sudden temperature changes can result in crack initiation in ceramics. For piezoelectric ceramic components, such as voltage bars and current stacks used in neutron generator power supply units, electromechanical stresses can be created during the hot poling process which can also result in cracking. Unlike cracks created by forming and thermal-shock, cracks generated during machining, handling, and hot poling are small and difficult to detect. These narrow (less than $1\text{ }\mu\text{m}$), shallow cracks are typically found near the edges of the component. Figure 1 shows a representative scanning electron microscopy (SEM) image of a short crack in lead zirconate titanate (PZT). The presence of cracks, as well as other microstructural inhomogeneities, is a potential source of unreliable functionality, thus routine yet robust methods are needed for crack detection.

Figure 1: SEM image of a typical crack in PZT.

To assure the weapons reserve (WR) quality of active ceramic components, a tedious manual visual inspection process has been implemented using a vicinal illumination technique. The process not only uses a large amount of labor resources, but also creates work fatigue for operators who must examine components through a microscope, which can take up to two and a half weeks per voltage bar production lot. Furthermore, manual visual inspection is highly subjective due to subtle differences in light responses during crack measurements. Therefore, the development of an automatic inspection

technique is needed to provide consistent results by removing operator subjectivity and inspection station variations from the process.

In the last two years, there has been a significant effort to develop an automatic visual inspection system (AVIS) to detect chips, voids, and pits in ceramic components. The technique uses a structured light source with image analysis capability to screen the parts. This process will help reduce the total labor hours involved in the manual visual inspection process by as much as 70%. Over this period no solution was developed for automating crack detection. However, in the design of AVIS, an extra space in the AVIS workstation was created to permit the installation of a crack detection capability. Therefore, the objective of this investigation is to develop a new nondestructive evaluation (NDE) technique that can detect and measure cracks in translucent ceramics which can later be integrated into AVIS.

Generally, cracks create an interface within the material that disrupts the transfer of energy across the crack opening. Current nondestructive crack detection of electrically insulating materials is based on using some type of energy (electrical, thermal, mechanical, or visible light) to detect a change in energy transfer through the material. The most effective means of locating cracks in a particular material is to determine what type of energy transfer will generate an effective contrast between the bulk of the material and a cracked region. With this in mind the following methods were evaluated: Impedance Spectroscopy, Scanning Acoustic Microscopy (C-SAM), Lock-In Thermography, Photo-acoustic Microscopy (PAM), and Scanned Vicinal Illumination.

An exhaustive study on each NDE technique was not undertaken; rather preliminary feasibility evaluations were performed with the emphasis that the selected NDE system should be easily operated. This was done to avoid arduous calibration, and preserve consistency between operators. In addition to choosing the most effective NDE technique for crack detection, the advantages and disadvantages of each NDE technique are discussed.

RESULTS AND DISCUSSION

Each method will be presented in the following format. The general principle of the method will be discussed followed by the results of the evaluation. Finally the benefits and limitations are presented.

Impedance Spectroscopy

Principle of Operation

Impedance Spectroscopy measures the change in the electrical impedance response to detect defects, density variations, and cracks in materials. When a material or an equivalent LCR (inductance (L), resistance (R), and capacitance (C), see Figure 2 (a)) circuit is at its resonant mode, the impedance will drop significantly. The dramatic change of the impedance at the resonant mode for the material can be simply illustrated by the motion of charged particles (or dipoles in dielectric materials) in an electric field.¹ It can be shown that at the natural resonant (ω_0) frequency the imaginary part of the dielectric function (k'') reaches a maximum (see Figure. 2 (b)) when the friction force and the restoring force are counter-balanced. Since the ac conductivity is determined by the reciprocal of the imaginary part of the dielectric function at the resonant frequency, the impedance will drop to a minimum. Similarly, when all reactances in the mechanical LCR branch of an equivalent circuit (see the bottom branch in Figure 2 (a)) cancel each other at resonance, minimum impedance is measured. As the frequency increases, the phase angle between the responses from the two branches will change. When the responses of the two branches are 180° out of phase, which represents the anti-resonant frequency, the impedance reaches a maximum. The intrinsic resonances in a dielectric material occur at different frequencies, ranging from dipolar at low frequency ($\sim 10^9$ Hz), to ionic ($\sim 10^{13}$ Hz), and finally to the electronic resonance ($> 10^{15}$ Hz). Additional resonant conditions can be generated by a mechanical vibration where the resonant frequency strongly depends on the density, elastic properties, and geometry of the specimen.

Figure 2 (a) Equivalent circuit for dielectric materials and (b) dielectric functions (k' - solid line, k'' – dotted line) as a function of frequency.

Because of the simplicity of the experimental setup and interpretation of the results, impedance spectroscopy measurements are of great interest for NDE of multilayer capacitors^{2,3} and polycrystalline ceramics.⁴ The impedance spectroscopy method has been used to detect internal cracks that propagate through multiple layers inside of multilayer capacitors.^{2,3} Furthermore, the relatively simple electrical equivalent circuit model permits one to decipher dimensional and elastic moduli information and compare responses for failure analysis.⁵ In the case of piezoelectric materials, such as PZT ceramics, once they have been electrically poled these materials can generate volume elastic waves through the inverse piezoelectric effect by a small ac signal. Because of the physical size of these components, the electromechanical resonance can be induced at a frequency far below the relaxation of the dielectric dipoles in the lattices ($\sim 10^9$ Hz). As the dielectric dipoles in the material are excited by the electromechanically induced resonance, the impedance of the material drops to a minimum value. Since the resonant mode is generated by the elastic waves, defects that weaken the structural integrity, such as cracks, will shift the resonant mode to a lower frequency. Based on these principles, the sample is electrically excited with a small ac signal and the resulting impedance is measured as a function of frequency.

Procedure

The first step taken in examining the impedance spectra was to determine the frequency range of interest for a given geometry of a PZT ceramic part. The resonant modes of the experimental bar were confirmed by finite element analysis (FEA). Using an HP4941A impedance analyzer, a typical impedance spectra plot of a test specimen is shown in Figure 3.

Figure 3: Typical impedance spectra of a ceramic sample bar

Three characteristic resonant signals were detected by the spectroscopy method, as indicated by a change of impedance responses from a lower value to a higher value as frequency changed from a resonant mode to an anti-resonant mode.⁶ These resonant frequencies correspond to the electromechanical resonant responses based on the dimensions of the part.⁶ Assuming that the

electromechanical resonance creates a compressive standing wave at the lowest frequency, the wavelength (λ) is equal to twice the length dimension (l); therefore, the dimension of the specimen can be determined using

$$l = \lambda / 2 = v / (2f) \quad (1)$$

where v is the sound velocity in the PZT ceramics, and f is the resonant frequency. Figure 4 shows the data between the sample physical dimensions and the reciprocal of the resonant frequency, where the original data have been removed. The line in Figure 4 was determined by a least squares fit of 2 sets of data based on parts that have unclassified sample geometries. According to Eq. 1, the sound velocity determined by the slope from Figure 4 is approximately 3852 m/sec, which is in excellent agreement with ultrasonic measurements (3854 m/sec).⁷

Figure 4: Physical dimensions of PZT samples as a function of the reciprocal of the resonant frequency.

Crack Formation

Two methods were used to create cracks in the experimental bars. The first was focused ion beam (FIB) machining and the second was with a Knoop indenter. Figure 5 shows the cracks generated by the two methods.

Figure 5: (a) FIB trench and (b) Knoop indentations.

FIB was chosen because it could generate extremely fine structures at a controlled depth. The average length of the FIB created trenches and the average length of the indentations are, 0.2 mm and 1.68 mm, respectively. Unfortunately, the removal of a small amount of mass from the test specimen using FIB resulted in a slight shift in the resonant modes which convoluted data analysis, because the artificially induced crack could also contribute to such behavior. As a result, the Knoop indentation technique was chosen to artificially induce larger, deeper cracks without changing the mass of the specimen. However, due to complexities in creating realistic cracks, resonant data was acquired from declassified, cracked production parts.

Finite Element Analysis

Finite element analysis (FEA) was performed using a FEMLAB software package (FEMLAB 2.3LCS1, COMSOL Inc., Los Angeles, CA) to model the resonant behavior of PZT. In this analysis, an electrostatic computation is coupled to a structural mechanical computation via the inverse piezoelectric relationship. The resonant behavior was analyzed using the harmonic analysis module with an adequate number of modes to cover the frequencies of the applied loads. Details of this analysis are beyond the scope of this work. Readers who are interested in this subject can reference some of the work^{8,9} cited in this report.

The shift of resonant frequency was studied as a function of crack location, length, and depth. Finite element analyses indicate that crack locations contribute significantly to the shift of the resonant frequency. FEA were focused on the shifting of the resonant frequency for cracks located at 0.25 of the length from sample edge. In this study, crack length varied from 0.25 to 0.5 of the component height, and crack depth was varied from 0.25 to 0.5 of the width (see Fig. 3 for orientation of depth and width). Crack length was determined to have much less impact on shifting of the resonant frequency than crack depth.

Figure 6 illustrates the shifting of the resonant frequency as a function of vibration modes and cracks of different depths (0.25 and 0.5 of total width of the specimen). The insert gives a pictorial illustration of sample distortion of sample under the vibration mode (mode 37). Results show that for every single vibration mode as the crack deepens the amount of frequency shift increases. Vibrations

with normal modes seem to have much stronger responses to the depth change, which is consistent with our impedance spectroscopy measurement.

Figure 6: Shift in resonant frequency as a function of crack depth.

FEA revealed that very long and deep cracks were required in order to be detected with impedance spectroscopy. In fact, the crack would have to be so large as to constitute a fracture in the material. For the impedance spectra to shift noticeably the crack was easily visible to the naked eye. Figure 7 shows an example of the shift in frequency as the result of cracks in PZT bars.

Figure 7: Frequency and impedance shift in resonant mode of the sample width due to cracking.

Results

As shown in Figure 7 the spectra change in two key parameters: (i) the resonant frequency shifts to a lower value and (ii) the spectrum becomes more distorted. The apparent change in the spread of the spectra is an artifact of the sampling process. The experimental data show that shifts in the resonant frequency strongly depends on crack depth. In order to detect a crack using impedance spectroscopy, the crack was always found to be large enough to degrade the overall integrity of the component. Occasionally, additional modes (as shown by the distortion of the spectra) will be introduced by through cracks where the material, separated by the crack, creates independent vibrational modes.

Although impedance spectroscopy has been shown to be an effective method in detecting internal through cracks for ceramic multilayer capacitors, this technique was unable to detect cracks in PZT ceramics. Presumably the cracks of interest are too short and shallow to weaken the structural integrity and shift the resonant frequencies.

Scanning Acoustic Microscopy

Principle of Operation

Scanning acoustic microscopy (C-SAM) uses focused ultrasound to scan a material and reconstruct a 'sonic' image of the part. Ultrasonic waves are focused by acoustic lens and then scanned across the target where the phase

and amplitude of the ultrasonic return signal is analyzed to create an image. Mode conversion of the Rayleigh surface wave is used to reveal the surface defects. Due to the complexity of such measurements, the analysis results are difficult to interpret without a thorough knowledge of the technique. In addition the penetration depth is limited to the wavelength of SAM, which is several millimeters. Furthermore, parts examined with C-SAM are submersed in water (the focusing medium) which presents the issue of effectively drying the part. Sometimes, transducers of different frequency bands and meticulous calibrations are required to obtain a higher resolution for subtle cracks. In spite of these drawbacks, this technique has been demonstrated successfully in detection of defects that are created by thermal fatigue at solder joints of the surface mount components.¹⁰ A commercially manufactured system available at Sandia National Laboratories was used to evaluate C-SAM.

Figure 8: Basic operation of scanning acoustic microscopy and recorded return signals.

Results

Figure 8 shows the basic principle of an acoustic microscope and the actual return signal generated for a PZT sample. The return signal must be adjusted by an experienced operator to produce an acceptable return signal. Then the correct region of the signal is selected (the white box in the return signal of Figure 8) for the imaging process. Crack detection using C-SAM in a sample PZT bar did not yield reproducible results. Figure 9 shows a C-SAM image of a PZT bar with a known crack. It is readily apparent from the image that distinguishing a crack from the background noise would be an exceptionally difficult and subjective task. This is not surprising since the resolution of this technique is approximately the wave length of the acoustic signal, which is about 25 micrometers at 100 MHz, while the openings of our cracks are far below 1 micrometer. This limits the application of this technique for our ceramic components. In addition, the surface roughness introduced during the grinding operation and the presence of induced porosity in the ceramic complicates the interpretation of the acoustic images (Figure 9). This technique is time consuming, requires an in depth knowledge for qualitative interpretation, and is

limited to the resolution of the acoustic wavelength. Therefore, it is not a suitable technique for quality control processes in a production operation.

Figure 9: C-SAM Image of Crack in PZT

Lock-in Thermography

Principle of Operation

Lock-in thermography uses thermal imaging and post processing of the images to reconstruct the propagation of a sinusoidal heat source through the material. This method requires the sample to be heated with a sinusoidal wave while images are acquired to sample thermal differences as a function of time. Thus the phase and amplitude of the thermal wave can be reconstructed into an image. This technique has proven to be very effective for detecting interfacial defects or delamination cracks in composite plates that are normal to the direction of heat propagation, such as laminated composite structures,¹¹ carbon-fiber-reinforced polymers,¹² and ceramic coatings on metal substrates.¹³ The theoretical treatment and practical applications based on thermal transfer and sample geometry have also been well documented.¹²⁻¹⁴

Figure 10: Schematic diagram of Lock-in Thermography System

Figure 10 shows a schematic diagram of the Lock-in Thermography method. A Dell Latitude C810 laptop with custom LabVIEW software was used to trigger a function generator that sent a sine wave to a silicon controlled rectifier (SCR) package. The SCR package was connected to an infrared (IR) lamp that modulated its output at the frequency established by the function generator. The computer also sent the trigger signal to an image acquisition board that captured images from the thermal imaging camera (FLIR Systems, ThermoCam SC3000) at known intervals. The acquired images were then processed using the equations shown in Figure 11.¹³

Figure11: Equations to extract phase and amplitude from thermographs

Where $\varphi(x_1)$ is the phase of the reconstructed thermal wave, $A(x_1)$ is the amplitude, and $S_n(x_1)$ is an image at a 90° interval.

Results

A series of 56 images were taken at precise times along the generated sine wave. Then the images were averaged over 90° intervals to create the single images for processing. In theory a crack should have a different thermal conductivity than the bulk ceramic. This should make the crack readily visible in the phase image. However, because the cracks were closed or very narrow, no differences were detected. Figure 12 shows a raw and a processed (phase) thermal image of an experimental bar.

Figure 12: Raw (right-hand image) and processed (phase) thermographs

As can be seen in the images no cracks are visible. The only feature of note is the metal mark in the lower, middle of the unprocessed image. Furthermore, the high degree of speckling from the surface roughness of the ceramics and the large-scale noise created by pore formers (possible dark spots on the processed image) of the PZT ceramics present a serious impediment to finding shallow, narrow cracks. In addition, attempts to improve the thermal contrast by additional latent heat absorption through the use of residual isopropanol alcohol and acetone in the crack regions were unsuccessful. However, only large cracks (visible to the unaided eye) were detected.

Conclusion

The intrinsic defects such as porosity and surface roughness prohibit obtaining sufficient thermal contrast to detect the cracks under investigation. Two key elements are critical to the success of the Lock-in Thermography method. The first is to improve the optical resolution, thereby making the crack width less of an issue and improving the change in observed temperature. The second element is to capture as many images as possible along the sinusoidal heating pattern.

Photo-acoustic Microscopy (PAM)

Principle of Operation

Photo-acoustic Microscopy (PAM) uses the pressure wave caused by heating a tiny area to detect cracks at a local level. Photo-acoustic signals, generated by the thermo-elastic expansion of materials, can be produced when materials (solids or gases) are illuminated with chopped light or a pulsed laser source. A quantitative derivation for the acoustic signal in a photo-acoustic measurement in terms of the optical, thermal, and geometric parameters is well established.¹⁵ This technique has been successfully used to study defects in integrated circuits made from single crystal silicon wafers,¹⁶ surface defects created by the grinding of ceramics,¹⁷ and residual stress in thin film coatings.¹⁸ Figure 13 shows the schematic diagram of a photo-acoustic microscope. The microscope works by focusing an intensity modulated laser on to the sample and then detecting the resulting pressure wave with an ultrasound transducer. A crack will have a different acoustic signal due to the variation in heating and expansion at the crack boundary compared to the bulk material.

Figure 13: Schematic of PAM System

PAM works by scanning the part beneath the pulsed laser to create a raster image of the pressure waves.¹⁹ A function generator was used to both pulse the laser and provide the reference signal for the lock-in amplifier. Once the lock-in amplifier was tuned to the reference signal the voltage from the transducer is recorded by the computer and an image was created. It has been well described in the literature that PAM can be used to create a depth profile of the scanned area.¹⁹ The depth profile is inversely related to frequency, higher frequencies equate to shallower depths. Because cracks in PZT components

can be very short, the highest frequency capability of the lock-in amplifier was chosen (10 kHz).

Results

With the specific goal of imaging cracks, PAM was unsuccessful in this preliminary investigation. The best result was that the edge of the PZT part could be found. Other results were completely inconclusive. Most reconstructed images lacked sufficient spatial resolution to image the thin, shallow cracks. Perhaps the polycrystalline nature of PZT as well as the induced porosity does not present a sufficiently homogenous background against which the cracks can be imaged. Furthermore, the thermal conductivity of PZT may be high enough that the localized heating is affecting a much larger area than the laser focal spot (minimum focal spot is around ~30 micrometers) and the cracks are simply averaged out. PAM has been used for detecting cracks in materials like silicon nitride which has a low thermal conductivity. The most successful results for PAM are with single crystal semiconductors that provide a highly homogenous background against which a crack can be imaged. The PAM crack detection technique can easily detect open cracks that are wider than 0.3 mm,¹⁷ suggesting that the photoacoustic signals produced in the PZT are simply not affected by the shallow narrow cracks under examination.

Scanned Vicinal Illumination

Introduction

The use of vicinal illumination is not a new method for inspecting ceramics for cracks. The current method of manually inspecting voltage bars uses vicinal illumination.²⁰ For this method, the inspector scans a fiber optic wand across the surface of the voltage bar while observing a diffusely illuminated area of the bar. As the fiber optic wand approaches a cracked region, the light intensity on the wand side of a crack increases due to internal reflection of light from the crack surfaces. In addition, the opposite side of the crack shows up as a shadow. Thus, a subtle contrast is created and any cracks are readily visible as a discontinuity in the illuminated area. Because of the effectiveness of revealing the cracks by this method, an automated system was designed and built to mimic the manual process. A Technical Advance (SD-7614) was filed covering the design.

Principle of Operation

An illustration of the scanned vicinal illumination system is shown in Figure 14.

Figure 14: Schematic of Scanned Vicinal Lighting (or Illumination) System

The system works by placing the part on a XYZ stage and scanning the part with a fiber optic light source. Previous work using an 8-bit CCD camera was unable to discern the subtle contrast difference of a cracked region to the bulk. In this new setup, a 12-bit CCD camera is focused on the bar in front of the light source where the incident light is diffuse and a series of images are acquired. Results show that if the images are acquired near the light source the detectors in the CCD camera can be easily saturated by the intense light. Best image contrast can be obtained when images are taken at a position slightly away from the light source where subtle changes in contrast can be observed while the camera is not flooded with light. As the part is moved beneath the light source images are acquired and a 1 pixel wide row is extracted. Each of the single pixel rows is then stacked back together to create the image of the diffuse light just in front of the fiber optic light source. The image is processed using an edge detection algorithm that highlights the changes from dark to light in the raw image. After image processing, light regions above a particular intensity can be quantified. Furthermore, because the method requires only that the ceramic under investigation be translucent this method can be expanded to other ceramics.

Results

Figure 15 shows an example of an optical image of PZT illuminated by vicinal lighting. Cracks in the material are clearly visible. The stacked pixels of the Vicinal Illumination System are shown in Fig. 15a. In Fig. 15a the light source is scanned from right to left across the image. Two cracks are immediately visible in the top center of the image. The cracks create a distinct light to dark shift in the image which is used by the edge detection algorithm to highlight the cracks.

Figure 15a: Raw vicinal light image with cracks

Figure 15b shows the results of processing the image using the edge detection algorithm. In addition to the two large cracks another smaller crack is visible in the middle of the upper left quadrant of the image.

Figure 15b: Processed vicinal light image

As shown in Figure 15c, a computer can then detect the crack and quantify the vector components of the crack. The accepted method of measuring the cracks is to measure the vector elements in the X and Y directions. Thus the crack can be outlined by the computer and the dimensions of the box measured. This provides a numerical quantity for use in our automated inspection system.

Figure 15c: Results of computer detection of cracks

After comparing the results of the measurement system to human inspectors the system was within the standard deviation of the inspectors. Table 1 shows the results from three manual inspections and from a prototype automated system for the same two cracks. The cracks measured are the two large cracks shown in Figs. 15a, b, and c. The results show that the prototype system is comparable to human inspectors

Table 1: Comparison of Human and Computer Inspections

	Crack 1 (mils)	Crack 2 (mils)
Inspector 1	65	43
Inspector 2	60	40
Inspector 3	57	46
Average	60.67	43
Standard Deviation	4.04	3
Vicinal Illumination System	62.46	46.61

Final Conclusion

The key technical challenges involved detecting narrow and shallow cracks which were far below the resolution of most of the techniques considered for this study. Once an appropriate automated crack detection system was identified, the next issue was to create a prototype system to determine if the cracks could be quantified. A number of different methods were studied to determine a viable approach to inspecting the bars for cracks. While some of the methods generated interesting data, only the Scanned Vicinal Illumination procedure was able to image cracks successfully. Therefore, a prototype system was developed that indicates the potential of vicinal illumination for automated inspection of PZT bars.

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