Nondestructive evaluation of layered ceramic materials using terahertz imaging

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Nondestructive evaluation of layered ceramic materials using terahertz imaging

by

John R. Nagel

A thesis submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Aerospace Engineering

Program of Study Committee:
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Leifur Leifsson

The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this thesis. The Graduate College will ensure this thesis is globally accessible and will not permit alterations after a degree is conferred.

Iowa State University

Ames, Iowa

2019

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<td>THz-TDS</td>
<td>Terahertz Time-Domain Spectroscopy</td>
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<tr>
<td>NDE/NDT</td>
<td>Nondestructive evaluation/testing</td>
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<td>CMC</td>
<td>Ceramic Matrix Composite</td>
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<td>EBC</td>
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ABSTRACT

As the combustion temperature of modern turbine engines climbs higher for greater fuel efficiency, new materials are needed to survive the increase in temperature. As a result, there is much research interest in the areas of ceramic coatings, such as environmental barrier coatings (EBC) along with abradable sealant coatings and ceramic matrix composites (CMC’s). These advanced materials can withstand the higher operating temperature of new generation turbines and offer significant weight savings as well. As such, it is essential to be able to evaluate the integrity of these materials as manufactured and in service. It is also increasingly important to do so nondestructively.

Recently, terahertz time-domain imaging has emerged as one of most promising modalities for inspecting and evaluating dielectric materials such as ceramic coatings and composites. This thesis aims to improve the understanding of the interaction of terahertz radiation with abradable/EBC coating systems and oxide/oxide CMC’s, as both are expected to be vital components of future gas turbine engines. The first half of this work performs an experimental validation of how THz signal amplitude variation is affected by the porous abradable top coat. An ad-hoc model was developed to correlate the signal amplitude variations in an experimental C-scan image with the density of voids over slices of the abradable coating. In the second half of the work, an automated data processing procedure was developed for detecting embedded test flaws in a group of oxide/oxide ceramic matrix composites and then evaluating their signal-to-noise ratios. In addition, signal processing was done to remove most of the predictable signal variation resulting from the terahertz reflections in the multilayered material.
CHAPTER 1. GENERAL INTRODUCTION

Nondestructive Evaluation Background

Nondestructive testing/evaluation (NDT/NDE) is a series of methods for examining a material for flaws or determining its material properties in such a way that the integrity of the material is not compromised. Many techniques have been developed over the years for examining the large variety of structures and materials that are involved in our everyday lives. Many in the general public are actually familiar with a few modalities of NDE such as with X-rays looking for broken bones or ultrasound to determine the health of a baby in the womb. For industrial applications, a much wider range of tools are readily available including liquid penetrant, vibration testing, flash and vibrothermography, and the electromagnetic methods of eddy current and microwaves. This thesis investigates the applicability of another electromagnetic method, pulsed terahertz imaging, to inspect ceramic materials.

Terahertz

Terahertz (THz) radiation occupies the part of the electromagnetic spectrum roughly between 100 GHz to 10 THz between microwaves and the infrared [1]. This corresponds to a vacuum wavelength between 3 mm and 3 µm respectively. Terahertz also offers a middle ground between microwaves and the infrared in terms of penetration depth and resolution. At higher frequencies, into the infrared and up, usually optical technologies are used, and the radiation is commonly thought of in terms of discrete photons. Whereas in frequencies below the THz region, the energy is often thought of as waves and usually measured and generated using antennas.

Up until the last 30 years there has been what is called a “terahertz gap” between the two, where a lack of technology that was fast enough and sensitive enough to manipulate terahertz
energy had not been developed yet. The first real breakthrough in terahertz development was the invention of the photoconductive switch in the 1970’s [2]. This device allowed for stable generation and detection of pulsed THz radiation and will be discussed below. In 1995 the first THz image was created by measuring the THz transmission through an integrated circuit package [3]. Since then research interest in terahertz has exploded. The highly publicized use of THz for the inspection of the external tank spray on foam insulation during the space shuttle program [4] introduced it to the NDE community. Since then it has been studied for a number of NDE applications ranging from the inspection of fiberglass composites, paint thickness, and monolithic ceramics.

The THz system at the Center for Nondestructive Testing at Iowa State University is custom made by TeraView Ltd. and based on their TPI Imaga 2000 system. A diagram of the system’s internal structure is shown in Figure 1.1 and an optical image of the system with its gantry is shown in Figure 1.2. As can be seen, it is set up in pitch-catch reflection mode at an angle of 17.5° relative to the normal. The transmitter and receivers are photoconductive dipole antennas driven by a femtosecond titanium sapphire laser. This allows the system to generate pulses of THz radiation with spectral content ranging from 50 GHz to 4 THz. The THz pulse that is emitted is then focused by lenses to a full width half maximum spot size of 800 µm at a distance of 5 cm. Since there are water vapor absorption lines in the THz frequency range [1, 5] a plastic tent was constructed to help isolate the air around the transmitter and receiver. Dry air was then pumped into the tent to reduce the effects humidity on the THz waves.
Figure 1.1. A diagram showing the internal structure of the THz system at ISU.

Figure 1.2. Image of the THz system at ISU the transmitter and receiver are located inside of the plastic tent.

After interacting with a sample, the emitted THz pulse is reflected back, and its electric field amplitude is measured by the receiving antenna as a time sequence. This is considered a single THz measurement and is commonly known as a “waveform” or an “A-scan” in the NDE community. An example of a THz waveform measurement is presented in Figure 1.3. The electrical permittivity of the base material or defects such as delaminations or inclusions that the
THz wave interacts with alter the strength and shape of the returning THz pulse. This allows the material properties of the sample to be determined and defects to be detected.

Figure 1.3. An example of a THz waveform captured from a thin piece of plastic. The front and back surface echoes are visible as the two largest “spikes” in the A-scan.

The mechanical gantry that is visible in Figure 1.1 is able to move the sample in a grid like pattern to collect a series of THz waveforms in a raster-scan. This creates a 3-dimensional data structure where the x and y axes of the data correspond to the sampling location and the z-axis has units of time. A diagram of the structure of the data that is collected by the system is shown in Figure 1.4. As seen, a time gate, represented by the dashed horizontal lines, can be used to select a time zone of interest in the data, and this time zone in turn determines a horizontal cross section of the data structure. From each waveform, some feature is selected as the representative value for that waveform. Usually this is the peak-to-peak amplitude of the waveform within that time gate. In Figure 1.3 above, this would be the difference between the maximum and minimum value of the A-scan. Using the featured value from each waveform as a pixel value, an image known as a C-scan can be created from the data, which essentially equates to a horizontal cross section. C-scan images are commonly used because they make it easy to see
changes in the entire scan area at a certain point in time and thus are useful for quickly determining the state of a material.

Figure 1.4. A Diagram of the structure of the data. Note that all the A-scans, such as from Figure 1.3, are placed along the time axis.

**Background on Ceramics Materials for Turbine Engines and NDT**

In the near future, gas turbine engines are expected to operate at much higher temperatures to produce more thrust and provide more fuel efficiency. The current nickel and cobalt based superalloys will no longer be suitable in this environment, so manufacturers are turning towards ceramic matrix composites (CMC’s) [8]. CMC’s consist of either ceramic or carbon fibers imbedded in a ceramic matrix. These materials offer superior temperature and creep resistance compared to their metallic counterparts, while also being significantly lighter and as such are the focus of intensive research.

Typically, CMC’s are classified into one of two categories, oxide or non-oxide. As the name implies oxide ceramics contain oxygen in their chemical formulation, such as aluminum oxide ($\text{Al}_2\text{O}_3$), while non-oxide ceramics, such as silicon-carbide ($\text{SiC}$) do not [6]. Non-oxide ceramics are being considered for the hot section components of gas turbine engines as they offer superior creep resistance and are able to withstand extremely high temperatures. However, they
are susceptible to oxidation which makes the CMC brittle [7]. To protect SiC/SiC composites from oxidation environmental barrier coatings (EBC) must be used. EBC’s, typically made from mullite or rare earth silicates such as zirconia, yttrium, or other more complicated compounds, are applied to the top of the ceramic composite and act as a barrier to high temperature oxygen molecules and water vapor that may be present in airflow through the turbine during operation [9, 10]. They also serve a secondary purpose as a thermal barrier coating since they have very low thermal conductivity and a melting point which will allow for even higher combustion temperatures in the future.

Several failure mechanisms such as cracking and delamination [11] occur in the EBC during service. If not detected these can cause spallation of the EBC and expose the underlying CMC to oxidation and prove to be disastrous during operation. Several nondestructive test methods have been proposed for the inspection of EBC’s such as thermography [12, 13], X-Ray computed tomography, photoluminescence spectroscopy [12, 14] and high frequency microwaves [15]. Within the last 10-15 years THz-TDS has been also been investigated as a method to inspect coating systems for turbine engines [12, 16].

In aircraft engines, abradable sealant coatings are also commonly used. These sealant coating are designed to be intentionally porous to make them slightly fragile, which allows for rub clearance control to occur in the engine. This increases the fuel efficiency by preventing leakage between different stages in the compressor and turbine section of the engine and allows for savings in fuel costs [17, 18]. Depending on the location in the engine it is desirable to have both of these coatings present with the abradable sealant coat as the top layer, in which case it would be necessary to inspect the EBC through the abradable coating. As a result, it is necessary to understand how the THz waves interact with the abradable coating material.
Even though oxide ceramics are not able to withstand as high a temperature as non-oxide ceramics, they are still being studied for applications in structural and exhaust components for turbines as their implementation would again impart significant weight savings over metallic components. Since oxide ceramics offer natural oxygen resistance [8] and are not expected to reside in as extreme of an environment as non-oxide SiC/SiC composites there are usually left uncoated. However, when exposed to loads at high temperatures it has been observed that the oxide fibers will degrade leading to reduced strength [8]. As with other composites, oxide/oxide composites also have problems with matrix damage, delaminations, and debonding when put under cyclic loading, so nondestructive testing can be of use here as well. Several more traditional methods have already been proposed such as thermography [8, 6], X-ray CT, and air-coupled ultrasound [6]. Along with those, THz-TDS has begun to be investigated as well [19-21].

**Thesis Organization**

This thesis contains two papers. Chapter 2 and Chapter 3 each represent one paper with its own introduction, background, methods, results and discussion. Chapter 2 seeks to improve the understanding of how THz waves are affected by the porosity in abradable sealant coatings and is planned on being submitted to *Optics Express*. Chapter 3 introduces an algorithm for detecting defects and calculating their signal-to-noise ratios in an oxide/oxide CMC inspected with THz imaging and is planned to be submitted to *Journal of Nondestructive Evaluation*. A conclusion for the entire thesis is presented in Chapter 4. Since Chapter 2 and 3 each represent a separate journal article, they each contain a separate list of references. Any references that are cited in the General Introduction (Chapter 1) or General Conclusion (Chapter 4) are cited at the end of this document.
CHAPTER 2. EXPERIMENTAL VALIDATION OF SCATTERING FROM A POROUS CERAMIC IN THE TERAHERTZ REGION

Modified from a manuscript to be submitted to *Optics Express*.

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Abstract

An experimental study was conducted to verify the presence of porosity as a major cause of signal amplitude variation seen in the terahertz images of an abradable ceramic coating. The coated surface of the samples were scanned using a terahertz imaging system and a laser profilometer to generate terahertz reflected C-scan images and topographical maps of the front surfaces, respectively. The topographical maps were used as the input to an ad-hoc model to account for both the general terahertz reflection from the ceramic base surface and the energy losses due to the exposed pores. It was found that the model images exhibit high correlation with their experimental counterparts.

Introduction

Abradable sealant coatings are commonly used in aircraft power systems to improve efficiency by preventing air flow leakage in the compressor and turbine sections of engines [1, 2]. These coatings are designed to be porous to increase friability and to prevent damage to the rotating blades [1]. The abradable coating is often on top of a thermal or environmental barrier coating (TBC/EBC) that is critical to the safe operation of the engine. TBC/EBC failure, primarily through cracking and delamination [3, 4] is currently a major problem for the aerospace and power industries. Much work has been performed to address these issues,
including modeling the physics of the coating system and the investigation of several
nondestructive testing (NDT) methods such as photoluminescence spectroscopy, pulsed
thermography, mid-infrared backscatter, and high frequency microwaves [3-11]. These NDT
techniques are effectively used to detect cracks and delaminations and provide data for
predicting the remaining lifetime for a part. This paper reports an investigation into the
feasibility of applying the method of terahertz time-domain spectroscopy (THz-TDS) to the
nondestructive inspection of protective coating systems.

Terahertz (THz) radiation occupies the part of the electromagnetic spectrum between the
infrared and microwave regions from approximately 0.1 to 10 THz. It offers better spatial
resolution than microwaves or radio waves and can penetrate farther into materials than infrared
and optical light. It can be used to inspect many objects such as plastics, ceramics and common
packaging materials such as cardboard, providing information about the contents within [12]. As
a result of its ability to penetrate ceramic materials, THz has also been proposed as a possible
method for inspecting thermal and environmental barrier coatings, primarily using THz-TDS
[13-16].

As noted above, a TBC/EBC may lie under an abradable sealant coating when used in a
jet engine. In the THz inspection of the TBC/EBC, the THz wave must first travel through the
abrasable coating and interact with its microstructure including the pores and grain boundaries.
Such interaction has been seen to lead to significant scattering and absorption which make
inspection of the EBC difficult. A diagram which illustrates the scattering and absorption of THz
waves is shown in Figure 2.1.

Electromagnetic scattering and absorption phenomena are well known [17]. In the THz
literature, it has been shown that scattering due to porosity and rough surface effects will result
in a decrease in the amplitude of the frequencies seen in the power spectrum of the THz pulse, particularly at high frequencies [18-21]. When scanning a porous abradable coating in the present study, significant amplitude fluctuations were observed in the THz C-scan images. However, it is not clear to what extent, these amplitude fluctuations are due to scattering and absorption resulting from the interaction of the THz waves with the porosity of the material or the effect of inhomogeneity in the base ceramic material on the electromagnetic waves, for example. Thus, the objective of this study was the determination of the primary cause of the THz signal fluctuations seen in THz C-scan images on a range of porous samples.

Figure 2.1. Schematic illustrating scattering and absorption of the THz waves as the enter and travel through the abradable coating material.

In this work, the ceramic samples were first raster scanned using a terahertz time-domain pulsed imaging system to produce C-scan images from the THz signals reflected from the front surface of the samples. The sample surfaces were further scanned using a non-contact profilometer to provide a map of the surface topography of each sample. These maps were then analyzed using image processing to obtain the size and density distributions of the exposed pores. Separately, an ad-hoc model was developed to predict the general terahertz reflection from the ceramic base surface as well as the energy losses due to the random scattering of exposed pores, as illustrated in Figure 2.2. Given the pore distribution data, the model was found to be
able to predict signal fluctuations similar to those seen in the experimental C-scan images. A statistical correlation analysis was then performed to compare the model and experimental image data to determine the extent of the effect that the exposed pores had on the THz signal.

![Diagram showing wave scattering and absorption](image)

**Figure 2.2.** Schematic showing the effects of wave scattering and absorption from exposed voids on the natural surface of a coating

In addition to the exposed pores, there are natural rough surface effects present on the surface of the coating, as illustrated with Figure 2.2. This is another cause of signal fluctuations and it adds an additional complication to the analysis. First, the surface roughness causes additional variability in the measured surface topography and this makes it difficult for the profilometer to provide accurate data and then for the subsequent image processing to accurately determine the size and distribution of the exposed pores. Secondly, surface roughness also adds another level of complexity to the model. To reduce the difficulty of developing the model and minimize roughness effects from natural surfaces in this study, all surfaces of the ceramic samples were polished to be as smooth as possible.

**Experimental Set-Up**

The THz-TDS equipment used in this study is a custom-made system based on the TPI Imaga 2000 manufactured by TeraView Ltd. The sensing unit, consisting of a transmitter and a receiver, is configured in a small angle pitch-catch reflection mode as shown in Figure 2.3(a). The transmitter and receiver are both photoconductive dipole antennas, with the transmitted
spectra ranging from 0.050 to 4 THz. The THz beam is spherically focused with a focal length of 5 cm and has a full-width half-maximum focal spot size of approximately 800 μm. As is common in THz imaging setups [22], the transmitting antenna is triggered by a split laser pulse through a delay line of up to 300 ps. This allows measurement of the electric field of the returning THz pulse with respect to time. The sample is placed on a mechanical gantry to be raster scanned on the transverse plane, creating 2-dimensional images. Since there are several water vapor absorption lines in the frequency range of interest [22, 23], a small plastic tent is set up to help isolate the sensing unit from the surrounding ambient air. Dry air is then pumped into the tent to help minimize the interference of water vapor on the measured signals.

![Figure 2.3. THz imaging system (a) Schematic showing sensors set up in reflection mode. (b) Gantry showing tent used to contain gas volume, purged with dry air, to help mitigate the effects of water vapor.](image)

In this study, testing was performed on two abradable coating samples which were manufactured and supplied by Rolls-Royce North America. The abradable coating is on top of EBC and bond coat layers fabricated on a 25.4 x 25.4 mm substrate made from a woven ceramic matrix composite. The samples, with coating, are approximately 6.1 mm thick. A photograph of one of the samples is shown in Figure 2.4(a). The pores that are present in the abradable coating as discussed previously are visible in a magnified view of the surface (Figure 2.4(b)). Since both the wavelength (300 μm at 1 THz) and spot size of the THz beam is too large to resolve
individual pores, profilometry was employed to map the topography of the surface of the coating. Image processing was then used to determine the precise location and shape of the pores.

![Image](image1.png)  
(a)  
(b)  
Figure 2.4. Front surface of the ceramic coating (a). Optical image of the entire sample. (b) Magnified optical image of examples of exposed voids on sample. The size of the image in (b) is given by the red box in (b).

In this study, two profilometers were used for surface topography characterization. The first was a Solarius LaserScan non-contact profilometer. It uses a white light laser and a WLC-3 white light chromatic confocal sensor to measure the relative surface height of the sample under study. The WLC-3 sensor has a vertical resolution of $0.25 \, \mu m$, a horizontal resolution of $2 \, \mu m$ and a vertical range of $1400 \, \mu m$. The other profilometer was a Zygo NewView 6300 unit. This profilometer uses interferometry to take image-like measurements of a portion of the surface where each pixel in the image represents a height value. Since a single image was not able to cover the entire surface of the sample, a set of sequential images was gathered to cover the entire surface. These images were then stitched together to form a composite image covering the entire surface of the sample. This data set is similar to that which was generated by the Solarius profilometer and were considered interchangeable for the purposes of this study.

During testing, the samples were raster scanned using both the THz-TDS and laser profilometers. The THz-TDS system creates 3-dimensional data where the x and y axes
correspond to the location on the sample and the 3rd axis corresponds to the time-of-flight in pico-seconds. The magnitude of the data at each point then represents the electric field strength of the THz wave at a given (x, y, t) location. Each profilometer creates 2-dimensional data with the x- and y- axes representing the location on the sample and the value at each point in the data represents the height of the sample, relative to a reference location at that point.

After both the experimental THz-TDS and profilometer data were collected on the initial front surface, the effects of porosity and depth were investigated through several grinding steps of the top surface. In each grinding step, a thin layer of the front surface of the porous coating was removed using a grinding wheel. The abradable coating was initially approximately 1.4 mm thick and at each grinding approximately 400 µm was removed. An investigation into the average pore size revealed that the average pore depth was approximately 31 µm below the surrounding area, while the average diameter was about 110 µm. The assumption was then made that each grind exposes voids that are completely independent of the previous grind and thus has the effect of essentially creating an entirely new data set. With a new top surface exposed this shows a new pore population at the surface. The new front surface of the sample was then imaged again using the THz-TDS system and one of the non-contact profilometers. This process of scanning and grinding was repeated twice for the first sample and five times on the second sample to confirm similar results.

**Measurement Procedure**

The THz-TDS system collected waveform (A-scan) measurements reflected from the front surface of a sample at a lateral spatial resolution of 250 µm across the surface of the sample with the THz beam focused on the front surface. A C-scan image can then be generated using the maximum peak-to-peak amplitude from each of the reflected waveforms. The waveform amplitude is affected by the coating material’s index of refraction, the surface roughness and the
distribution of any scatterers, which are mostly exposed pores in this work, on the surface under the beam at that given location. The C-scan image of the first THz data set on Sample 1 is shown in Figure 2.5. Note that there are significant variations (~10%) in the amplitude across the front surface which are not normally observed from a non-porous material.

Following a raster scan pattern similar to the THz inspection, both profilometers were employed to generate maps of the front surface topography of samples by measuring their height values relative to a reference location. The Solarius profilometer took a surface height measurement every 15 µm across the sample surface in both x- and y- axes. Instead of being a raster scan of individual measurements, the Zygo profilometer produces a raster scan of height images that need to be stitched together. The entire sample surface was imaged with a 24x24 grid of slightly overlapped images that were combined by the system software into a single topographic image for each sample. Since the 15 µm resolution from the Solarius profilometer had already proven adequate, the images from the Zygo system were down sampled by an interpolation algorithm [24] from ~3 µm/pixel to 15 µm/pixel, so all profilometer data would be on the same scale. Optical images of the surface, similar the one shown in Figure 2.4(b) were also taken to verify the locations and characteristics of the exposed pores. A surface topographic map output from the Solarius profilometer is shown in Figure 2.6 in which the exposed pores are visible as dark speckles scattered nearly randomly across the sample.

To enable good matching of the data location coordinates, a common orientation was set for both the THz-TDS system and the profilometer. Further alignment is then accomplished by over scanning the sample and applying basic signal processing to ensure that the samples are aligned as best as possible in the combined coordinate system and they are not rotated or shifted with respect to one another.
Figure 2.5. Example of the C-scan image generated from the raw data that is gathered by the terahertz system. The pixel value in each image is the peak-to-peak amplitude of the measured THz waveform at that point.

Figure 2.6. Example of the relative height measurement of the sample (µm) surface obtained with the Solarius profilometer. Note that the pores are visible as black speckles spread across the surface of the sample.

Data Processing and Modeling

To determine the locations of the pores on the surface of the sample after each grind, a local Gaussian threshold [25] was applied to the surface height data that was obtained from the profilometer. This creates a locally varying threshold line that is the same size and shape as the input data. A binary pore map was then created by setting any pixel on the topographic map below the local threshold to 1 (in white color) to denote an exposed pore. If the pixel value is above the local threshold it is set at zero (in black) as the base front surface. The results of this
thresholding operation are shown in Figure 2.7. As can be seen in the image the exposed pores are reasonably uniformly distributed, but some local variations in pore density clearly do exist.

Figure 2.7. The binary pore map that is created by using an adaptive threshold on the height data in Figure 2.6. The locations of the exposed voids are noted by the white areas.

As stated, the goal of this work was to understand the effect of porosity on experimental data and we sought to do this by modeling the interaction of THz waves with the porous ceramic sample. However, after an extensive literature search it appears that no suitable analytical solution is readily available for modeling the signal response seen in this problem. For example, as a “building block” for modeling the pore, there were studies on the reflection of EM waves from indentations, but most appear to involve a conducting ground plane (e.g. [26-28]) and these formulations are not suitable for application to the dielectric materials used in the abradable coating. Numerical approaches to electromagnetic wave scattering from an indentation in a dielectric do exist [29]; however, implementation of this approach is far from trivial. Thus, for the current study, efforts were focused to develop a simple ad-hoc model to provide an initial proof-of-concept for understanding model-pore/THz interactions.
For simplicity, the base material of the ceramic sample is assumed to have uniform composition. As the front surface of the ceramic sample has been smoothly ground, each exposed pore can be treated as a locally rough cavity that disrupts the specular reflection of the THz beam from the otherwise smooth front surface. It has previously been shown that an increasing density of scatters will scatter more electromagnetic energy [30]. By the same logic, an increase in the density of exposed pores that intersect the THz beam at a given location on the sample should result in a decrease in the returning THz signal amplitude when compared to a flat surface at the same location. A further simplification is to assume that any THz “ray” interacting with a pore will result in that ray being scattered away in random directions or absorbed by the ceramic material beneath the pore. Thus, the pores are treated as energy sinks that reduce the returning THz energy to some extent. Given the relative size of the pores and the wavelengths produced by the THz system, it is not able to resolve the pores individually. Thus, each C-scan image essentially gives a map of the distribution of local energy sinks across the surface of the sample convolved with the point spread function of the THz beam. The various elements in the ad-hoc model are illustrated in Figure 2.8.

Figure 2.8. Schematic illustrating the THz interactions on the porous but smooth ceramic surface as described by the ad-hoc model: specular reflection from the smoothed surface and some energy losses to the exposed pores as a result of random scattering (the equivalent absorption is shown)
As the THz beam has a finite width and a focus that is very narrow relative to the size of the sample, the THz response will be sensitive to the changes in local pore density and distribution at different locations on the sample surface. It is therefore necessary to determine the THz beam coverage of the local pore region. As stated above, the THz system used in this work has been previously characterized and the full-width half-maximum beam diameter of the system was found to be approximately 800 µm [31]. It was reasonable to truncate the beam coverage at a boundary of 1% of the maximum amplitude of the beam. This results in a local circular area of beam coverage with a radius of 1.03 mm.

The ad-hoc model basically accounts for the intensity reduction of the returning THz response from a scan position on the sample. If there happens to be a very small number of pores present at a location, a near perfect specular reflection is expected. Contrarily, if there are many exposed pores under the footprint of the beam, very little specular reflection is expected, and a varying amount would be expected for porosity levels in between the two extremes. The simplest model for this is shown in Equation 2.1

$$I(x, y) = \frac{A_{beam} - A_{pores}}{A_{beam}}$$ (2.1)

In Equation 2.1, $I(x, y)$ represents the intensity of the returning THz response at location (x,y) on the sample, $A_{beam}$ is the total number of pixels under the THz beam and $A_{pores}$ is the number of pixels within the current THz beam footprint centered at (x,y) that have been designated as pores by the threshold. As can be seen, the output of the model ranges from zero to one, with zero representing no specular reflection at all (where every pixel under the footprint of the beam is in a pore), and one representing perfectly specular reflection (where there are no pore pixels in the footprint of the beam). In the simplest model, a uniform beam energy distribution is
taken; that is, the energy scattered and lost by a pore will be identical for pores of the same size regardless of where that pore is located within the THz beam footprint.

To further improve the model, a more realistic beam profile was considered. Since the THz system produces a spherically focused beam, it is customary to assume that the energy profile on the sample surface will resemble a two-dimensional Gaussian function. As a result, an object that is located in the center of the beam will scatter a larger fraction of the total energy than an object that is located near the edge. The equivalent Gaussian weighting factor was introduced into the model, as shown in Equations 2.2 and 2.3

\[
I(x_m, y_n) = 1 - \frac{\sum_{i=1}^{p} \alpha f(\eta_i)}{P}
\]

with

\[
\alpha = \begin{cases} 
0 < \alpha_0 \leq 1, & \text{if pixel is inside of pore} \\
0, & \text{if pixel is outside of pore} 
\end{cases}
\]

and

\[
f(r) = \exp \left[ -\frac{r_i^2}{2\sigma^2} \right]
\]

In Equation 2.3, \(r_i\) is the distance of the current pixel to the center of the beam and \(\sigma\) is a scaling factor of the Gaussian function that defines the width of the simulated beam profile. To generalize the model, the value of \(\alpha\) can range from 0 to 1 to represent the fraction of energy that is able to reach the receiver. If \(\alpha\) is 1, all the THz energy that interacts with a pore is considered to be scattered away and lost, thus treating the pores as a perfect energy sink. A value of \(\alpha\) less than 1 would represent a situation where some of the energy scattered by the pores is expected to return to the receiver. Changing the value of \(\alpha\) introduces a linear shift into the data. As will be shown later, in this work we employ the scale-invariant statistical correlation analysis to
determine the relationship between model and experimental data, so the value of the $\alpha$ will actually have no impact on the results of correlation analysis. Likewise, we do not include the electromagnetic reflection coefficient term in the model for the same reason. Equations 2.2 and 2.3 represent the reflected amplitude of a single THz measurement, a diagram of which is shown in the top part of Figure 2.9.

To generate a realization of a model THz image, a discrete raster scan was simulated to best emulate the actual THz-TDS scan. This was accomplished by translating the Gaussian weighting function across the surface of the sample in discrete intervals as shown in the bottom of Figure 2.9. In Figure 2.9 the edges of the Gaussian weighting function are denoted by the red circles, with each circle representing the beam footprint for a single simulated THz measurement. Within each circle there are pores of varying sizes and locations. Each pore pixel that happens to be within a circle (under the beam footprint) at a given location is multiplied by the appropriate Gaussian weighting value depending on its distance from the center of the beam and then summed according to Equation 2.2.

When acquiring experimental THz data, the THz scan system outputs an array of coordinates where each individual waveform was recorded. This coordinate system was then used to define the simulated beam locations on the binary pore map for the model. This ensures that each value from the simulation has a one to one correspondence with the pixels from the experimental data. In comparing the model with the experimental C-scan images, the coordinates of THz scan and the profilometer scan were aligned, such that a given ($x$, $y$) coordinate in the experimental THz data corresponds as best as possible to the same coordinate in the data from the profilometer measurements, which produce the binary pore map (e.g. Figure 2.7) as the input to the model.
Results

Between the two samples, denoted as Sample 1 and Sample 2, seven different data sets were gathered. Five sets of THz and profilometer measurements were gathered on Sample 2 and another two sets of measurements were obtained on Sample 1. Samples were ground between each set of experiments to gather THz and surface topography data of the pores that were exposed. The profilometer data was then processed through the procedure described above to obtain the binary pore map as the input to model. If the scattering of the exposed pores is a major cause of the amplitude fluctuation in the THz C-scan images, then the model image should be correlated with the values in the experimental THz images since the ad-hoc model was developed under that assumption. To verify this assertion, the statistical Pearson correlation
coefficient (PCC), or “r”, was used to determine how well the ad-hoc model simulation agrees with experimental data. The Pearson correlation coefficient is well covered in the literature (see e.g. [32]). Here we reproduce the basic formula in Equation 2.4, in which \( x \) and \( y \) represent the pixel values from model and experimental C-scan images, respectively.

\[
r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2} \sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}}
\]  

(2.4)

Since the model and experimental images are aligned, the correlation analysis was performed by simply “flattening” the two-dimensional model and experimental images into one-dimensional arrays which were then input to Equation 2.4.

The PCC of the original model of Equation 2.1 with no beam Gaussian weighting factor is shown in Table 2.1, while those for the model with the Gaussian weighting factor are shown in Table 2.2. As can be seen, the correlation was significantly higher when considering the effect of the more realistic beam profile on the energy scattered by each pore. In Table 2.2 the PCC values for the first five data sets are relatively consistent, with values between 0.64 and 0.68. This suggests that the model will give data that correlate well with the experimental THz image and the exposed pores are a major contributor to the amplitude fluctuation seen in the THz C-scan images. The apparent anomalous PCC values for the last two data sets will be considered further in the discussion section of this paper.

In addition to the PCC, the two-tailed p-value was also computed, which is an estimate of the probability of an uncorrelated data set producing as large of a correlation through a random draw. For all samples, this value was numerically zero, which suggests that these PCC values are valid estimates.
Table 2.1. Pearson Correlation Coefficient (PCC) comparing the experimental data and the model with a uniform beam. The samples with the asterisk had the height information obtained with the Zygo profilometer.

<table>
<thead>
<tr>
<th>Sample # &amp; Polish</th>
<th>PCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1 - 1st Grind</td>
<td>0.3876</td>
</tr>
<tr>
<td>Sample 1 - 2nd Grind*</td>
<td>0.4569</td>
</tr>
<tr>
<td>Sample 2 - 1st Grind</td>
<td>0.4808</td>
</tr>
<tr>
<td>Sample 2 - 2nd Grind</td>
<td>0.4681</td>
</tr>
<tr>
<td>Sample 2 - 3rd Grind*</td>
<td>0.4563</td>
</tr>
<tr>
<td>Sample 2 - 4th Grind*</td>
<td>0.3079</td>
</tr>
<tr>
<td>Sample 2 - 5th Grind*</td>
<td>0.5174</td>
</tr>
</tbody>
</table>

Table 2.2. Pearson Correlation Coefficient (PCC) comparing the experimental data and the model. The samples with the asterisk had the height information obtained with the Zygo profilometer.

<table>
<thead>
<tr>
<th>Sample # &amp; Polish</th>
<th>PCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1 - 1st Grind</td>
<td>0.6677</td>
</tr>
<tr>
<td>Sample 1 - 2nd Grind*</td>
<td>0.6471</td>
</tr>
<tr>
<td>Sample 2 - 1st Grind</td>
<td>0.6547</td>
</tr>
<tr>
<td>Sample 2 - 2nd Grind</td>
<td>0.6831</td>
</tr>
<tr>
<td>Sample 2 - 3rd Grind*</td>
<td>0.6404</td>
</tr>
<tr>
<td>Sample 2 - 4th Grind*</td>
<td>0.5712</td>
</tr>
<tr>
<td>Sample 2 - 5th Grind*</td>
<td>0.6089</td>
</tr>
</tbody>
</table>

To visually compare the model and experimental images for each data set, each image was autoscaled by subtracting the mean from each pixel and then dividing by the standard deviation. This puts the two images from each data set on the same scale to allow for easier interpretation. The comparison images are shown for four selected data sets in Figure 2.10-2.13. The same colorscale is used for each pair of experimental and model images so the same color maps to the same value in each figure. Initially, the images may not appear that similar. However, on close inspection, one can see that the high, red areas and low, blue areas generally appear at the same location on each image.
Figure 2.10. Data from the 1\textsuperscript{st} grind of Sample 1. (a) The experimental data and (b) the results of the ad-hoc model.

Figure 2.11. Data from the 2\textsuperscript{nd} grind on Sample 1. (a) The experimental data and (b) the results of the ad-hoc model.

Figure 2.12. Data from the 2\textsuperscript{nd} grind on Sample 2. (a) The experimental data and (b) the results of the ad-hoc model.
Figure 2.13. The experimental data (a) and the results of the model (b) on the 4th grind of Sample 2.

The value of the model at a given point can also be used to predict the value of the experimental C-scan at the same point. For this, a regression analysis was performed. As an example, a scatter plot of the C-scan amplitude as a function of pore density map values is shown in Figure 2.14 for the 1st grind data of Sample 1. The best fit line is essentially the predicted value for that pore density. This allows for the creation of error images by using the pore density value at a given point as the input to the function \( y = \beta_1 x + \beta_0 \) to predict a C-scan amplitude value at the same \((x, y)\) location. Then the absolute difference of the prediction and experimental value is taken at each point. This gives an estimate for the error in units of C-scan pixel amplitudes. A summary of the error on each data set is presented in Table 2.3.

The error, i.e. difference between the experimental C-scan values and the best fit line for that data set, can be displayed as an image to show the regions in each data set where there is disagreement between the experimental data and the model prediction, with regard to the strength of the THz reflection at a particular point. This data is shown in image form in Figure 2.15 for two data sets. Note that the red dot on top right corner of Figure 2.15(b) is clearly an outlier in the otherwise relatively uniform background.
Figure 2.14. A scatter plot of the C-scan amplitude vs. the pore density values. The best fit line is the red line and the dashed black lines are the confidence bounds on the new values. Going from 95%, 90%, to 50%, outer to inner.

Figure 2.15. The error image for Sample 1 1\textsuperscript{st} grind (a) and Sample 2 2\textsuperscript{nd} grind (b).

Table 2.3. The average and maximum error (deviation from the best fit line) for each sample. Again, samples with an asterisk had their height information obtained by the Zygo Profilometer.

<table>
<thead>
<tr>
<th>Sample # &amp; Polish #</th>
<th>Standard Error ($\sigma_{est}$)</th>
<th>Max Error</th>
<th>$\Delta$ C-scan</th>
<th>$\sigma_{est}$</th>
<th>Max Error. $\Delta$C – Scan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1 1\textsuperscript{st} Grind</td>
<td>0.063</td>
<td>0.116</td>
<td>0.2055</td>
<td>0.31</td>
<td>0.57</td>
</tr>
<tr>
<td>Sample 1 2\textsuperscript{nd} Grind*</td>
<td>0.040</td>
<td>0.051</td>
<td>0.1361</td>
<td>0.29</td>
<td>0.37</td>
</tr>
<tr>
<td>Sample 2 1\textsuperscript{st} Grind</td>
<td>0.051</td>
<td>0.077</td>
<td>0.1647</td>
<td>0.30</td>
<td>0.47</td>
</tr>
<tr>
<td>Sample 2 2\textsuperscript{nd} Grind</td>
<td>0.051</td>
<td>0.152</td>
<td>0.2820</td>
<td>0.18</td>
<td>0.54</td>
</tr>
<tr>
<td>Sample 2 3\textsuperscript{rd} Grind*</td>
<td>0.056</td>
<td>0.068</td>
<td>0.1722</td>
<td>0.32</td>
<td>0.39</td>
</tr>
<tr>
<td>Sample 2 4\textsuperscript{th} Grind*</td>
<td>0.051</td>
<td>0.066</td>
<td>0.1411</td>
<td>0.36</td>
<td>0.47</td>
</tr>
<tr>
<td>Sample 2 5\textsuperscript{th} Grind*</td>
<td>0.037</td>
<td>0.162</td>
<td>0.1733</td>
<td>0.21</td>
<td>0.91</td>
</tr>
</tbody>
</table>
Discussion

The calculated PCC values were found to be relatively stable across the data sets as seen in Table 2.2, only varying between 0.68 and 0.64 except for the last two data sets of Sample 2, which gave slightly lower values. When examining the samples, it was seen that on the fourth iteration of the grinding process on Sample 2, regions of the EBC layer underneath the abradable layer were exposed. This change in material properties is a variable that the model did not consider and is most likely the cause of the lower correlation values for the fourth and fifth grind of Sample 2.

The two error images in Figure 2.15 clearly show the disagreement between the experimental data and the model for the strength of the THz reflection at a particular point. For example, in Figure 2.15(a), there are brighter values in the image in the lower left corner. From the profilometer data, this region appears to be lower than the rest of sample surface (see also Figure 2.10(a)), which may be the cause of disagreement. Another large error value is seen in Figure 2.15(b) in the top right corner. This appears to be due to a slight misalignment between the data from the THz-TDS system and that from the profilometer. This effect is also visible when comparing the same location in the top right between Figure 2.12(a) and (b). The standard errors presented in Table 2.3 summarize the estimates of the standard deviation of the experimental C-scan values from the best fit line for each sample. Recall Figure 2.14 as an example for the first grind of Sample 1. The maximum error is likewise the maximum deviation of a point from that line.

Since the purpose of this work is to investigate the fundamental cause for the signal variation on the front surface echo, we present the standard error and maximum error as a percentage of the total change in C-scan amplitude. It can be seen that the standard error is typically about 30% of the total change in signal amplitude for each sample. Therefore, it can be
asserted that given a pore density value, the model would be able to detect changes of the order of 30% of the maximum change in C-scan pixel value with 68% reliability.

For the data sets that only have the abradable coating exposed, the strong correlation afforded by our simple ad-hoc model suggests the scattering losses from the exposed pores are likely the primary cause for the amplitude variation seen on the C-scan images of the front surface echo. It is also noted that the PCC values of the data sets scanned by Zygo profilometer are slightly lower. This is most likely due to higher noise that was seen to be present in Zygo profilometer in comparison with the height data gathered by the Solarius profilometer. The noise was difficult to eliminate as a reference baseline for noise removal cannot be obtained due to the presence of the massive pores.

It should be pointed out that the input data to the model actually lacks much needed information. One important omission is the size and distribution of the pores right beneath the surface. Since the THz beam can penetrate into the ceramic and interact with subsurface materials, the subsurface pores actually contribute to the C-scan amplitude fluctuation to some extent. We do recognize that such information is difficult to obtain in the first place, since the laser profilometer is only able to measure the surface profile. One remedy is to employ high resolution X-ray CT scans to provide a 3-D map for the sub-surface pores.

As mentioned previously, the model does not account for changes in material properties that are being experienced in the last two data sets of Sample 2. The model included the assumption that the base material has uniform composition. This seems to contradict one of the hypotheses that the material inhomogeneity may also be the cause of signal fluctuation. However, as the correlation between the model and experimental images are proven sufficiently
high, at least for these samples, the current data supports the validity of the uniform composition assumption of the model.

Lastly, it should also be noted that the model is far from a perfect physical model of the THz scattering from a porous surface. It is only based on a few basic principles and yet is able to describe well the signal fluctuation due to presence of porosities. In fact, the real THz beam propagation and the mechanism governing its interaction with objects are fairly complicated and are important research topics in their own right.

**Conclusions**

In this work, we experimentally verified that scattering of the THz wave due to surface porosity was likely the primary cause of signal variation on the THz C-scan image of a porous ceramic coating. This was done by developing an ad-hoc model to account for the scattering losses caused by the pores exposed to the surface. The model, although simple, was found to have good correlation with observed experimental results. Using the model, we were able to generate simulated C-scan like images that bear qualitative similarities to their experimental counterparts. This proof-of-concept study provides a working model and the justification for the development of more rigorous models for future research efforts in this area.

**Acknowledgements**

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References


CHAPTER 3. TERAHERTZ DEFECT EVALUATION IN OXIDE/OXIDE CERAMIC MATRIX COMPOSITES

Modified from a manuscript to be submitted to Journal of Nondestructive Evaluation

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Abstract

In this work, a data processing procedure for terahertz time-domain imaging was developed for detecting and evaluating defects embedded in oxide-oxide ceramic matrix composites (CMCs). In this procedure, several signal and image processing techniques were utilized to develop automated defect detection algorithms based on signal-to-noise ratios calculated using C-scan (2-D images) pixel amplitude data. The detection performance between C-scans generated by a single time domain wide-gate and by multiple narrow-gates applied to volumetric A-scans was examined. The effect of microstructural noise due to the presence of deterministic signals reflected from the sample layer interfaces was investigated to determine their effect on signal-to-noise ratio calculations after removing these interface signals from the noise data.

Introduction

Ceramic matrix composites (CMC’s) are presently in development for use in next generation turbine systems to help meet the increasing demands of power efficiency while saving weight. An important subset of CMC’s are oxide-oxide CMC’s, which are being used in aircraft engine structural components and exhaust systems [1]. As with most composites, delaminations, cracking, and porosity pose problems for ceramic composites [2, 3]. Thus, it is vital to be able to
assess the integrity of these CMC materials as manufactured and in service, and it is advantageous to do so nondestructively. Several methods of nondestructive testing (NDT) have been studied for the inspection of CMC’s including flash thermography [1, 3], immersion [4] and air-coupled ultrasound or Rayleigh waves [4], X-Ray through transmission and CT imaging [3, 5], and impact acoustic resonant spectroscopy [5]. Recently, terahertz time-domain imaging has emerged as one of the most promising NDT modalities for inspecting and evaluating oxide/oxide CMC’s.

Terahertz (THz) energy is electromagnetic radiation residing in the frequency range between microwave and infrared. Commonly considered to consist of the region from about 0.1 THz (3 mm wavelength) to 10 THz (30 µm) [6], it has greater penetration depth than infrared light and better resolution than microwaves. THz is able to penetrate many non-conducting materials, such as glasses, plastics, and ceramics and thus is an applicable method for investigating many structural materials. THz also has advantages over traditional methods such as X-Rays in that it is nonionizing and unlike traditional ultrasound it does not require a coupling medium. Several authors have applied THz for the inspection of CMC’s, including continuous wave THz for locating delaminations [7] and THz time-domain spectroscopy (THz-TDS) in detecting damage in SiNC CMC’s [8]. THz-TDS data from a CMC inspection has also been used as the input to a machine learning algorithm for detecting delaminations [9].

This work describes a data processing procedure for detecting flaws embedded in oxide/oxide CMC samples as inspected by THz-TDS. Image amplitude based and signal-to-noise ratio (SNR) based thresholds were compared based on their detection performance. In addition, two time gating schemes were investigated for improving defect detection. The removal of
deterministic material noise present in samples’ layered system was studied along with its impact on the SNR evaluation.

**Instruments and Materials**

The terahertz time domain spectroscopy (THz-TDS) system used in this study was custom built, based on the TPI-Imaga 2000 model manufactured by Teraview Ltd. The transmitter and receiver pair employ photoconductive dipole antennas driven by a femtosecond titanium-sapphire laser. The transmitter generates a THz pulse with a bandwidth ranging from approximately 50 GHz to 4 THz and has full-width-half-maximum spot size at focus of 800 μm. As is commonly implemented [6], part of the triggering pulse is diverged by a beam splitter and rerouted to the detecting antenna, which is also connected to a delay line of up to 300ps. As can be seen in Figure 3.1, the system is set up in reflection mode, since many industrial applications only allow one-sided accessibility. The system is also equipped with a computerized mechanical gantry capable of high-precision raster-scanning in both the x and y-axes. This allows for the acquisition of volumetric THz waveforms and the creation of two-dimensional images known as C-scans, which are formed by extracting some characteristic from the waveform data. In the THz spectral range, there are several known water vapor absorption lines [6, 10] that create artificial oscillations in the time domain signal. To minimize these effects, a small tent was constructed to isolate the ambient air around the sample. Dry air is then pumped into the tent continuously to remove as much water vapor as possible.

Four samples of commercially produced oxide/oxide CMC’s of varying sizes and thickness were tested. Each sample was fabricated with a variety of known embedded test defects ranging in size from 0.75 to 3.2 mm and at different locations and depths within the composite. These are to be used as targets during the inspection. The dimensions of the samples
are summarized in Table 3.1 below and a C-scan image of one of the samples is shown in Figure 3.2.

Table 3.1. The dimensions about the samples that were analyzed in this study.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Size</th>
<th>No. of Plies</th>
<th>Thickness</th>
<th>No. of Defects</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15.2 x 15.2 cm</td>
<td>12</td>
<td>2.1 mm</td>
<td>25</td>
</tr>
<tr>
<td>2</td>
<td>15.2 x 15.2 cm</td>
<td>5</td>
<td>0.9 mm</td>
<td>29</td>
</tr>
<tr>
<td>3</td>
<td>22.2 x 22.2 cm</td>
<td>12</td>
<td>2.6 mm</td>
<td>38</td>
</tr>
<tr>
<td>4</td>
<td>22.2 x 22.2 cm</td>
<td>5</td>
<td>1.1 mm</td>
<td>39</td>
</tr>
</tbody>
</table>

Figure 3.1. (a) The setup of the Terahertz pulsed system and scan gantry, (b) schematic showing the terahertz system set up in small angle pitch catch reflection mode

Figure 3.2 (a) Optical image of one of the CMC samples, (b) a CMC sample being scanned by the THz-TDS system
Methodology

Data Acquisition and Representation

The CMC samples were each raster scanned by the THz system, following a rectangular grid across the sample with data waveforms recorded at a spacing of 500 µm. As noted above, the scans resulted in volumetric waveform data sets. Each data set spans three dimensions: the first two dimensions correspond to the lateral x-y axes of the rectangular scan grid. The last dimension is the time axis, which constitutes the THz waveform trace acquired on a specific x-y grid point. Figure 3.3(a) plots a typical waveform trace of 60 picosecond (ps) time duration.

Note that this three-dimensional THz data structure bears a strong resemblance to that of an ultrasonic immersion test. As can be seen below, similar ultrasonic techniques such as time gating and amplitude thresholding will also be applied to process the THz data. In time gating, a gate is set around a specific time zone of interest to examine some characteristic of the waveform with the gate. The two-dimensional C-scan was then generated with each image pixel value representing that specific characteristic inside of the time gate for each waveform taken on the scan grid. As a result, any spatial changes of the specific waveform characteristic within that time gate will be visible in the C-scan image. An example of a typical waveform acquired by the THz system is shown in Figure 3.3(a). The dashed black vertical lines are the time gates. The positive and negative peak points inside the time gates are specified by the + and x signs, respectively. As shown, the time gate was set between the sample’s front surface echo, at the 10 ps mark and back surface echo, at approximately the 45 ps mark, for all the individual waveform measurements. Figure 3.3(b) gives the C-scan image of Sample 1 generated by taking the peak-to-peak amplitude (as the absolute difference between negative and positive peaks) within the time gate as the image pixel values. Several of the known fabricated defects are visible as brighter regions with higher amplitudes. The waveform shown in Figure 3.3(a) was measured at
the scan location specified by the red dot in Figure 3.3(b). In this work, all C-scan images were generated using the peak-to-peak amplitude inside of the time gate of interest for each waveform.

Figure 3.3. (a) Typical waveform (A-scan) acquired by the THz system, (b) peak-to-peak amplitude C-scan image of Sample 1 generated by gating between the front and back surface echoes. The waveform shown in (a) was measured at the location specified by the red dot in (b).

**Single Wide Gate vs. Multiple Narrow Gates**

This study compares two different methods for creating the time zones of interest. The first utilizes a single time gate that is set to contain the time zone between the front and back surface echoes in each THz waveform, as shown in Figure 3.3(a). The corresponding C-scan image as shown in Figure 3.3(b) contains all defects found within this single wide gate which proportionally covers most of the interior of the sample. The main advantage of using a single wide gate is its simplicity and efficiency. However, the attenuation and beam spreading effects become more uneven in the temporal dimension due to the wide (longer) time gate. Given the tight focus of the THz beam, signals from features near the beginning of the gate will have higher amplitudes when compared to those from similar features at the end of the gate. Thus, the likelihood of mistaking noise components near the beginning of the gate as defect signals will increase. Conversely, defect signals near the end of the gate are more likely to be missed.
Extending this idea to the spatial dimensions, these uneven effects will also bring in more noise components to the C-scan images, as demonstrated in Figure 3.4(a).

The second and more advanced technique addresses the shortcomings of a single wide gate by resolving it into a series of narrow time gates with each narrow time gate inspecting only a slim section of the sample at a time. A similar approach has previously been applied to the ultrasonic inspection of CMC’s and was found to be effective in improving the detection of porosity [11]. By using the narrow gates, all values in the C-scan image are then created from approximately the same time delay and the attenuation and beam spread of the THz wave will be approximately equal at all scan points. This puts all possible defects and noise signals in each image at the same footing for comparison. An example demonstrating the advantage of using multiple narrow gates can be seen by comparing the C-scan images shown in Figure 3.4(a) and Figure 3.5(a). Even though the defect is easily visible in the A-scan in both cases, there is more large noise values captured in the area surrounding the defect as a result of using the wide time gate in Figure 3.4(a). The drawback of using multiple narrow gates is that additional effort will need to be made for analyzing the corresponding C-scan image “slices” that are generated. It also requires a more sophisticated procedure for data analysis, since defects and noise signals may appear in one or more gates depending on their size and shape. In this study, the universal width for all narrow gates was chosen to be 5 ps which is the spacing in time between the blue and green time gates shown in Figure 3.5(b). This width was chosen because it was close to the temporal width of one of the largest flaws seen in all samples.
Figure 3.4. (a) A C-scan image of a defect near the back surface. (b) The A-scan and single wide time gate (denoted by the vertical blue and green lines) used to generate the C-scan image.

Figure 3.5. (a) The same C-scan image as in Figure 3.4(a), but now it is generated by using the narrow time gates in (b).

In order to ensure that no defect can be skipped by a time gate, each succeeding narrow gate is set to only advance half of the gate width as illustrated in Figure 3.6. This creates a situation where a defect response can be present in more than one C-scan slice. In this case the SNR for that defect will be calculated for each C-scan slice in which the defect appears and the C-scan slice with the largest SNR will be the one that is used for that defect. This is the procedure suggested by Li et al. [12] and successfully used for analyzing a sequence of vibrothermography images where a defect is present in more than one image. An example of the
first two time slices of an A-scan from Sample 1 are shown in Figure 3.6. Letting the narrow gate be 5 picoseconds wide and using an overlap of 50% results in 10, 4, 14, and 4 time gates (and corresponding C-scan slices) for samples 1 – 4 respectively.

![A-scan from Sample 1 along with the first two time gates. The first gate is dashed black lines and the second gate is between the gray solid lines.](image)

**Figure 3.6.** An A-scan from Sample 1 along with the first two time gates. The first gate is dashed black lines and the second gate is between the gray solid lines.

**Automatic Detection of Defects**

As stated, the primary objective of this work is to establish a viable procedure to automatically detect defects embedded in the samples. As can be seen in the C-scan in Figure 3.3(b), there are several defects of varying sizes and contrast levels. The next step is to determine an appropriate threshold for all defects seen on the C-scan through image processing techniques.

The image processing method used in this work to automatically locate the defects is known as the triangle threshold algorithm. It is a method that was first introduced by Zack et al. [13] and used to detect chromosomes in microscopic images and is effective at separating a small number of pixel regions having strong contrast from a dominant background area. The histograms of C-scan pixel values from the samples used in this study is similar to those reported in the original paper [13] as seen in Figure 3.7 for Sample 1. The algorithm sets the threshold at
the location that maximizes the distance between the top of the histogram bins and the hypotenuse of the triangle drawn from the top of the tallest histogram bin to the longest tail. A diagram representing this procedure is shown in Figure 3.7. A feature is then declared an indication worthy of further investigation if the C-scan pixel amplitude (i.e. peak-to-peak amplitude for that waveform between the time gates) is above the calculated threshold.

![Figure 3.7. Illustration of the triangle threshold algorithm using the pixel value histogram for the C-scan of Sample 1 shown in Figure 3.3(b).](image)

In the current study some defects were fabricated as groups. For example, Figure 3.3 shows two defect clusters in Sample 1 that appear as 5-dot formations on the right along the line $y = -40$ mm. There are also several smaller defect formations below these two large formations. Each of these groups was treated as a single defect even though the triangle algorithm detects them as separate indications.

**Removal of Deterministic Interface “Noise”**

As a layered material system, ceramic matrix composites generate a complicated return signal pattern in THz-TDS. There are many standing wave like reverberations from the layer interfaces which make determining the thickness of individual layers difficult. This is also seen in the THz inspection of other composite materials [14]. The interface reverberations may also
obscure small flaw signals, posing similar inspection problem as in the ultrasonic inspections of CMC’s [11]. On top of the interface reverberations, there is also random microstructural noise and water vapor interference as noted above. These effects are shown in Figure 3.8, for a collection of waveforms from the same region of the sample. In Figure 3.8(b), notice that the overall interaction of the THz wave with the composite sample produces larger oscillations than are normally present in the THz reference signal, given by the black line. The THz reference signal is the signal directly reflected off a smooth metal plate, which is treated as a “perfect” reflector. Strictly speaking it also contains small “residual signals” from the THz scan system itself. These factors contribute to an increase in both the peak and average noise of a single THz measurement and the C-scan image. Fortunately, the interface reverberations, water vapor interference and system signal residual all are mostly deterministic and change little from scan point to scan point. Therefore, it should be possible to construct a common baseline that represents the average of all these deterministic signals and remove this common baseline from all THz waveforms. In the defect-free regions of sample, the data that remains will represent, as best as possible, the truly random microstructural noises. As will discussed below, this will give a more accurate SNR estimate.
Figure 3.8. 400 waveforms from a nearby region of Sample 1 plotted together showing similar overall structure. (b) Zoomed in version of (a) showing the area that is between the front and back surface echo given by the two large reflections in (a), with the reference signal plotted as the thick black line.

To determine the baseline waveform of a sample, the triangle threshold algorithm was first applied to the scan data from a sample to detect as many indications as possible. The baseline averaging was then performed using only the waveforms that contained no detected defect signals. Extra care must be taken when calculating the average waveform, as the samples in the current study are slightly bowed, and this curvature will produce a time shift in the waveform data. In order to resolve the issue of misalignment, the waveform acquired at the THz beam focus point was chosen as the reference to align all other waveforms. This allows the common baseline to be calculated with minimal distortion from the curvature of the sample.

Figure 3.9 shows a histogram of the C-scan image of Sample 1 before and after the baseline removal. The distribution of the corrected C-scan pixel values is down shifted as predicted.

A time cross-correlation between nearby corrected waveforms was performed to determine the randomness in the corrected waveform data. This is shown in Figure 3.10, where the value of the cross-correlation between a “home waveform” and the other waveforms located along the same x-axis is plotted for both the raw and corrected data sets. The cross-correlation lines are normalized by the peak value of the auto-correlation point (i.e. the home waveform
correlated with itself with zero lag). As can be seen, the value of the cross-correlation in the baseline corrected waveform data drops off faster from the central auto correlation point (the location with a correlation of 1) than that of the raw waveform data. This implies that each corrected waveform is now of a much more random nature, and thus the SNR that is calculated will be much more representative of the truth.

After the common baseline was removed from the raw waveform data, the triangle threshold algorithm was run again on the corrected C-scan image to determine the final call of an indication. Then the SNR for each indication was calculated.

![Histogram of C-scan amplitude pixel values](image)

Figure 3.9. Histogram of the C-scan amplitude pixel values of Sample 1 before (black) and after (gray) the removal of deterministic noise.
Application of Signal-to-Noise Ratio

In the NDE literature, several SNR definitions have appeared to gauge the detectability of defects in C-scan images. Equations 3.1 - 3.3 express three common definitions [12, 15-20]:

\[
SNR = \frac{P_s}{\sigma_n} \tag{3.1}
\]

\[
SNR = \frac{P_s}{P_n} \tag{3.2}
\]

\[
SNR = \frac{P_s - \mu_n}{P_n - \mu_n} \tag{3.3}
\]

Where \(P_s\) is the peak flaw amplitude, \(\sigma_n\) is the standard deviation of the noise, \(P_n\) is the peak noise amplitude, and \(\mu_n\) is the average value of the noise.

An example of the location of these values for a defect in a C-scan image is shown in Figure 3.11 below. The average noise is calculated as the average of all the pixel values that are not considered to be part of the defect (denoted by the black pixels in Figure 3.11(b)) and within a specified region of interest (ROI) surrounding the defect. Note that in theory the noise term in
all three equations is assumed to be purely random and follows specific statistical distribution. In practice, however, the field noise is never completely random. Data reconditioning, wherever possible, is often carried out to remove the deterministic components of the noise. This is precisely what has been done in this work.

Figure 3.11. Expanded image data for one of the flaws in Sample 1, (a) showing the location of the peak noise and peak flaw signal, given by the red and blue dots respectively. (b) The boundary of the defect as calculated by the triangle threshold.

The definition of the SNR used in the NDE literature has evolved from that in Equation 3.1, to either Equation 3.2 or 3.3 depending on the application. The early use of Equation 3.1 can be traced back to the analysis of communication systems with white noise [20]. Equations 3.2 and 3.3 are more suited for NDE applications where the noise is often colored and are used for quantitative analysis of NDE images, e.g. [12, 15-19]. For applications such as the ultrasonic inspection of titanium alloys [15-19] where coherent grain scattering often generates large noise “spikes” and our THz inspection of CMC composites where microstructural noises are significant, the relationships given by Equations 3.2 and 3.3 are more appropriate. This is because they provide a direct measure of how much greater the defect amplitude is compared to the largest naturally occurring noise signals. This is demonstrated in Figure 3.12, where a C-scan
amplitude profile is taken from the dashed line in the C-scan image. Since the C-scan pixel amplitude is generated as the maximum peak-to-peak value of the waveforms, the average value in the C-scan is not zero. The SNR value given with Equation 3.3 seeks to show how discernable the defect signal is from both the average noise and peak noise in a nearby region.

Figure 3.12. Illustration of $P_S$, $P_n$, and $\mu_n$ terms used in SNR Equation 3.2, and 3.3. (a) An image amplitude profile taken from the vertical blue line in the defect image in (b).

In the analysis of the data shown in Figure 3.11, the average and peak noise are searched for only within the ROI surrounding the defect. The size of the ROI can affect the calculation of the SNR substantially. If the ROI is too small, the likelihood of sampling extremal values which can skew the average noise is high. However, if the ROI is too large, defects that are spatially far apart can have the same average and peak noise values. To illustrate how the optimal size of the ROI was determined for the SNR calculations in this work the average noise was plotted against the ratio of the size of the ROI to the size of the defect that it encloses. This is shown in Figure 3.13 in which three representative defects were selected for comparison. For this check, the triangle threshold algorithm was applied to the C-scan amplitude image and the ROI was initially created as the minimum rectangular area that enclosed the defect. The initial rectangular ROI was then iteratively expanded one pixel per side at a time and the average noise was calculated at each iteration. From Figure 3.13 we note that the average noise seems to level off with an ROI
that is approximately 10 times larger than the area of the defect that it contains. For a low ROI to defect area ratio, the average noise is skewed to be much larger due to the lack of true average noise samples. Figure 3.13(b) shows the size of the largest possible ROI used in Figure 3.13(a). Care was taken to ensure that any tested ROI did not include another nearby defect in the average noise calculations. It can also be seen from Figure 3.13(b) that the background noise of Sample 1 exhibits significant lateral variations across the sample. In contrast, the background noises in Samples 2-4 are weaker and are much more uniform laterally.

![Graph showing C-scan average noise vs. ratio of ROI area to defect area for three defects in Sample 1 using the wide gate data. The color of the line refers to the defect bounded by the box of the same color in (b).](image)

Figure 3.13. (a) The C-scan average noise vs. ratio of ROI area to defect area for three defects in Sample 1 using the wide gate data. The color of the line refers to the defect bounded by the box of the same color in (b).

**Secondary Signal-to-Noise Ratio Threshold**

After the triangle threshold was used to complete the initial detection, it was followed by another pass using a secondary threshold set by the SNR calculations, often effectively eliminating many false calls. This two-pass process has previously been used in several NDE applications, e.g. [12-16]. An example of the effects of applying both the image amplitude threshold by the triangle algorithm and the secondary SNR threshold on Sample 4 with the wide gate data set can be seen in Figure 3.14. An arbitrary value of 1.75 was chosen for the SNR threshold in this image for demonstration purposes. In the image the vertical dashed line
represents the output of the triangle threshold algorithm, while the horizontal dashed line represents the SNR threshold. In Figure 3.14, if an indication is actually associated with a defect it is a “true flaw” and is denoted by a red dot; if not it is deemed a “false alarm” and denoted by a blue plus sign. Any data point residing to the upper right of the crossing dashed lines in Figure 3.14 is considered a detection. It is seen that the dual thresholds as afforded by the triangle threshold algorithm and the SNR threshold have performed very well. The upper right area contains mostly true detections (i.e. “true flaws” actually being detected) and only includes a few false alarms. It was also found that two “true flaws” are below the SNR threshold in Figure 3.14. These will be counted as “misses” It is also possible that a “true flaw” may have an amplitude that is not high enough to pass the first threshold set by the triangle algorithm. This is the case for one of the flaws in Sample 4, which is shown as the red dot to the left of the vertical dashed line in Figure 3.14. This will also be counted as a miss.

In comprehensive studies on specified applications, the so-called operating characteristics can be theoretically determined in which proper thresholds are set to produce controlled probabilities of detection and false alarms [20]. In many industrial NDE applications involving SNR usage [15-19] however, such thresholds are difficult to calculate theoretically, often due to limited sample size, improper model or sample population. Additionally, a fracture mechanics study would also be needed to determine the minimum acceptable defect size. Generally, a large number of false alarms is not acceptable, but depending on the minimum acceptable defect size in the part, some misses may be permitted. To the best of our knowledge, SNR thresholds in industrial applications were often determined empirically. In the ultrasonic inspection of titanium billets; for example, a common threshold at 2.5 was used in practice [18]. Likewise, in the
present study we will limit our work to focus on the effect of the SNR on the performance of defect detection from an experimental point of view.

Figure 3.14. An example of the triangle threshold and a possible SNR threshold applied to the data from the wide gate on Sample 4. (a) The entire data set. (b) Zoomed in on the lower left half region.

Results

In this work, the primary interest was working with the corrected data, since it contains the “true” representation of the noise present in the sample. Hereafter all results that are presented were obtained using the corrected data.

Wide Gate

As discussed above, it is a common practice in an industrial setting to use a single SNR threshold for accept/reject decisions for everyday routine inspection [15-19]. The determination of the optimal SNR threshold and the corresponding probability of detection study are active research topics in their own right [12]. Both would require a sufficiently large sample/data population to be statistically sound and thus are outside of the scope of this work. Instead we elected to conduct a small-scale exercise on the four sample panels by setting the SNR threshold empirically at a value that minimized the average of the sum of the number of misses and false alarms per ply between Samples 2-4. Sample 1 is considered an outlier and will be discussed
later. Assuming that there is an equal probability of a false alarm in each ply, this criterion normalizes the number of false alarms between the thicker and thinner samples. It also punishes the algorithm more for a miss than a false alarm. This was desired because it is often better to reject a part with no flaws than accept a part with a flaw and have it entered into or continue service.

A manual optimization was performed by summing the number of misses and false alarms per ply at set SNR threshold levels in each sample. These results for the single wide time gate data are shown in Figure 3.15 for each sample. It can be seen that Sample 1 can be considered an outlier, due to the comparatively large number of defects missed by the algorithm. As a result, the optimal value was chosen from the average of the number of misses and false alarms for Samples 2, 3 & 4. This is shown as the thick black line in Figure 3.15 and results in an optimal SNR threshold of 1.375.

Figure 3.15. The optimization criterion for selecting the SNR threshold for the single wide time gate data.

The results of setting the SNR threshold at 1.375 are shown in Table 3.2 and a summary of the true defects and false alarms cut off by both the triangle amplitude threshold and the SNR
threshold when operating on the single wide time gate data are shown in Figure 3.16. In Table 3.2, it can be seen that some of the flaws are missed by the initial triangle threshold. These are also seen in Figure 3.16 as red dots left of the vertical dashed line in (a), (c), and (d). Since Sample 2 had no flaws that were missed by the triangle threshold, all of the red dots are to the right of the vertical dashed line in Figure 3.16(b). Each of the diagrams in Figure 3.16 is also zoomed on the lower left corner of the data set similar to Figure 3.13(b), as all of the high amplitude, high SNR signals belong to true defects and are easily detected. From Figure 3.16, it can be seen that there are several flaws with relatively low SNR’s that result in them being lost, so to speak, amongst the higher amplitude noise signals. These are especially present in Samples 1 & 3 in Figure 3.16(a) and (c). This suggests it is difficult to reach optimal detection with the combined amplitude and SNR thresholds by using the single wide gate method. In summary, the above results clearly indicate that switching to multiple narrow time gates was necessary for better detection performance.

Table 3.2. The number of misses, false alarms and false alarms per ply with the single wide gate method for each Sample after applying the optimal SNR threshold of 1.375.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Misses from Triangle Threshold</th>
<th>Misses from Triangle &amp; SNR Threshold</th>
<th>False Alarms</th>
<th>False Alarms per ply</th>
<th>Misses + False Alarms per ply</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>11</td>
<td>22</td>
<td>1.83</td>
<td>12.83</td>
</tr>
<tr>
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<td>5</td>
<td>1.0</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>4</td>
<td>16</td>
<td>1.33</td>
<td>5.33</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>1</td>
<td>12</td>
<td>2.4</td>
<td>3.4</td>
</tr>
</tbody>
</table>
Figure 3.16. Amplitude and SNR values for the single wide time gate data for Samples 1 – 4 (a – d respectively) zoomed in on the lower amplitude, lower SNR region on each (similar to Figure 3.14(b)). The vertical black dashed line represents the output of the triangle threshold on each sample’s C-scan image, while the horizontal line is the SNR threshold.

Multiple Narrow Gate Method

In the narrow gate method, a series of C-scan images is generated for each sample using the procedure that was discussed previously. The triangle threshold algorithm is then applied to each C-scan to produce a list of indications, and the SNR is calculated for each indication. Using the multiple gate method results in only one of the flaws in all samples being missed by the triangle threshold algorithm, clearly indicating a better detectability over the wide gate method.

A manual optimization, the same as what was done with the wide gate method, resulted in an SNR threshold value of 1.9375. A plot of the optimization for each sample and the average of the samples are shown in Figure 3.17. Similar to the case with the wide gate, Sample 1 is
considered an outlier, so the average is taken considering Samples 2, 3, and 4. As can be seen the low region around the optimal value is quite wide. As a result of the wide basin like area in the objective function and the small number of samples used on this work, it is difficult to tell if the same value would hold in a production environment. The misses and false alarm counts calculated with an SNR threshold of 1.9375 are presented in Table 3.3. Similar to Figure 3.16 for the wide gate case, Figure 3.18 plots the detection and false alarm distributions for all four samples for the multiple narrow gate case. The better detection performance of the narrow gate method is further shown by comparing the results of the image detection from both the wide and narrow gates overlaid on the C-scan images of Sample 1. This is shown in Figure 3.19.

Figure 3.17. The optimization criterion for selecting the SNR threshold using the multiple narrow gate data.
Table 3.3. The number of misses, false alarms and false alarms per ply with the multiple narrow gate method for each Sample after applying the optimal SNR threshold of 1.9375.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Misses from Triangle Threshold</th>
<th>Misses from Triangle &amp; SNR Threshold</th>
<th>No. of False Alarms</th>
<th>False Alarms per ply</th>
<th>Misses + False Alarms per ply</th>
</tr>
</thead>
<tbody>
<tr>
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<tr>
<td>4</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>0.6</td>
<td>1.06</td>
</tr>
</tbody>
</table>

Figure 3.18. Peak amplitude vs. SNR values for the multiple narrow gate data for Samples 1-4 (a-d respectively) calculated from the corrected data set. The vertical black dashed line represents the output of the triangle threshold algorithm, while the horizontal dashed black line represents the SNR threshold.
Figure 3.19. Detection of defects in Sample 3. (a) The single wide gate data and (b) the narrow gate data. The red boxes bound true flaw, while the blue boxes bound false alarms. The yellow boxes are true flaws missed cut off by the SNR threshold and the yellow dots are true flaws missed by the triangle threshold.
Comparison

The narrow gate method of generating multiple C-scan images at different depths has been found to be better at detecting defects in a ceramic matrix composite as opposed to the wide gate method and generating a single C-scan image. The triangle amplitude threshold applied to the C-scans generated by the narrow gate method was able to detect all of the flaws except one in Sample 4. This is superior to the wide gate method in which the triangle threshold missed six flaws overall. In addition, the optimal SNR threshold for the narrow gate data missed less defects and produced less false alarms than the optimal SNR threshold applied to the wide gate data. A comparison of the SNR between the wide gate and narrow gate methods for each defect is given in Figure 3.20, which shows that most detected flaws have a better SNR using the narrow gate method. Situations where a flaw was missed using the wide gate method are visible in Figure 3.20; for example, in the cases of defects 16 and 17 for Sample 1 (no solid bar).

In general, creating multiple C-scan images at different depths and running the flaw detection algorithm on each image allows for better detection because the likelihood of large amplitude noise values overcoming the amplitude of the flaw is significantly reduced. This occurs because the narrow gate method examines a much smaller volume of the sample in each slice with better uniformity of signal strength. In addition, the THz wave gets attenuated as it propagates through the material, so material noise near the front surface typically has a larger amplitude than that near the back surface. The narrow gate method helps alleviate this by only comparing the flaws near the back surface of the sample with material noise that is located at the same attenuation level, again with better uniformity. Thus, thicker samples benefit more from the using the narrow gates, as thicker samples suffer more from severe signal losses due to beam spreading and material attenuation. The effects of this on the SNR calculations can be observed in Figure 3.20 as well. The thicker samples, Samples 1 and 3, generally have a larger SNR by using the narrow
gate method compared to the wide gate method. This increase is not as noticeable in the thinner samples, 2 and 4.

Figure 3.20. A comparison of the SNR calculated for the both the wide and narrow gate data for all flaws in Samples 1 – 4 (a – d respectively) using the corrected data set.

**Future Work**

As shown above, by using the wide gate method, more of the flaws were missed by the first pass triangle threshold. One of the reasons for this is non-uniform background noise in the temporal axis due to beam spread and attenuation. It should be pointed out that the same non-uniformity of the background noise is also visible in the lateral spatial domain and can be seen in Figure 3.3(b). Some of the defects missed by the triangle threshold were found in spatial regions of lower amplitude signals. The global triangle threshold used in this work is not able to adjust to
these regions and that results in a miss. However, a local thresholding algorithm could be applied to different regions of the sample and can be expected to be able to compensate for the changes in background noise by dynamically adjusting the threshold. This would likely result in better detection of low amplitude flaws in regions with low amplitude background noise. It could also reduce the number of false alarms that are generated in the region with the high amplitude background noise. Local thresholding has been demonstrated to be of use with the variable levels of background noise that are found in ultrasonic titanium billet inspection [19].

To improve the experimental samples, a possible alternative to the inserts that are used in the present samples is aerogel. This approach has already been tested on carbon fiber composites [21,22]. It would likely produce more accurate representations of real world flaws if the aerogel can survive the manufacturing process of the CMC. As porosity is also a problem in CMC’s [2, 11] another future line of work would involve creating CMC’s with only increased porosity present, inspecting them with THz imaging and then sectioning the material to confirm their locations, similar to what was done in [11] with ultrasound. This would greatly expand the knowledge base of THz inspection of oxide/oxide CMC material.

**Conclusion**

This work has investigated an algorithm for automatic flaw detection and signal-to-noise ratio calculations applied to data obtained from oxide/oxide ceramic matrix composites using THz-TDS. Signal and image processing techniques such as the triangle threshold algorithm play important roles in the development of the automated defect detection procedure. In addition, a baseline removal technique was found to be effective at removing the deterministic noise that was present in the received signal due to the interaction of the THz wave with layers of the composite. This pre-processing step will in general be expected to give a more accurate calculation of the SNR.
It was also demonstrated that the time gating method of using multiple narrow time gates and generating multiple C-scans at different depths within the sample results in better flaw detection compared to using a single wide time gate which encompasses the entire volume of the sample. The narrow gate method also improves the signal-to-noise ratio of the defects in most cases, in conjunction with the removal of deterministic noises.

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References


CHAPTER 4. GENERAL CONCLUSION

Abradable/EBC coating systems and oxide/oxide ceramic matrix composites are poised to become vital parts of the aerospace industry. As such, understanding how THz imaging, a suitable candidate for the nondestructive inspection of these components, interacts with them is valuable knowledge. In this thesis an ad-hoc model was developed to explain the THz signal amplitude variation from the front surface reflection of a polished abradable coating. It was found that there was a strong correlation between the model and the experimental results. The ad-hoc model was also able to generate C-scan like images that had qualitative similarities to the experimental C-scans. It was concluded that the scattering loss due to the presence of the exposed surface pores in one of the major causes for the THz signal fluctuations.

Defect detection was also investigated in this study. A data processing procedure was developed to automatically detect embedded test defects in several oxide/oxide ceramic matrix composites. Signal processing techniques were employed to remove deterministic interference from the interfaces of the multilayered composite and a few other sources in order to provide a more accurate calculation of the signal-to-noise ratio. In addition, two different methods of generating C-scan images to detect defects were studied. These were the single wide gate method and the multiple narrow gate method. The wide gate method uses a single time gate that considers all information between the front and back surface echoes of the sample, while the narrow gate method uses multiple time gates to generate a series of C-scan images for each sample. The narrow gate method was found to produce better results in terms of detecting more flaws and producing less false alarms than the wide gate method.

In the future, there are several topics worth pursuing to improve the understanding of THz waves and ceramic materials. In regards to the first paper, X-Ray micro-CT data could be
captured of the coating that would provide a 3-dimensional map of the location of many pores without iteratively removing the surface of the coating. This would allow for the development of a THz scattering model the coating and an investigation comparing its results to experimental images of the back-surface echo. It would also be interesting to see if an analytical model for the scattering of an electromagnetic wave from a hemispherical indentation in an infinite dielectric plane could be developed as it would greatly enhance the capability of the current ad-hoc model. Future work relating to the second paper should continue to investigate the detectability of artificial flaws in oxide/oxide CMC’s. This could possibly be done using aerogel to simulate defects as has been done with carbon fiber reinforced polymer composites [22, 23]. Work can also be done advancing the state of the art on the THz inspection CMC’s that have been previously heat and mechanically stressed to examine for signs of creep.
REFERENCES


