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Thick film, Acoustic Emission sensors for embedded structural health monitoring systems.

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ABSTRACT

Structural heath monitoring of engineering structures is of growing interest due to increased complexity of such structures and the ability to schedule maintenance when it is needed thus preventing unnecessary work or preventing failure. One such method for monitoring the structural health of large scale structures is through the detection of Acoustic Emissions (AE). A novel thick film Acoustic Emission sensor is presented. Piezoelectric thick film AE sensors were fabricated by creating and pattering lead zirconate titanate (PZT) thick films using a powder/sol composite ink deposition technique in conjunction with mechanical patterning of the subsequent films. The resultant AE sensors exhibit a response comparable to commercially available AE sensors. Comparative results between the thick film and commercial sensors will be reviewed and discussed.

Keywords: Acoustic Emission, Sensor, PZT, Thick film.

1 INTRODUCTION

Non-destructive testing (NDT) is used in many applications, structural monitoring, process monitoring and biomedical research for example. Industries such as aerospace, nuclear and civil engineering make widespread use of NDT. A vital technique used in NDT is Acoustic Emission (AE) monitoring. Whilst traditionally used for static applications there is a focus on developing miniaturized sensors for use in both static and non-static NDT applications [1]. It is vital that whilst devices are miniaturized cost effectiveness is maintained. One proposed solution to this challenge is micro-electromechanical systems (MEMS). This work details the deposition of a thick film AE sensor directly onto a structural element. An artificial AE event is simulated in the element and the response compared to responses of commercially available sensors for benchmarking purposes.

2 BACKGROUND

2.1 Acoustic Emission Signals

AE waves come in two distinct types, transient and continuous. The most pertinent wave form for AE monitoring is transient. Typically the transient type emission, caused by material phase transformation, crack growth or the movement of dislocations within the material, is a short time period event. The event contains, within its waveform, important information that can provide much information about the signal source. These important characteristics include the event duration, maximum amplitude, rise time and count [2].

The measured area under the rectified signal is related to the magnitude and velocity of the emission source. The maximum amplitude is proportional to the surface area created during a cracking event and the velocity of crack propagation. Event duration can be used to differentiate an AE event from background noise signals and can also be used in conjunction with the rise time and the count information to identify the position and source of the AE.

2.2 Acoustic Emission Sensor Design

Almost all AE sensors are piezoelectric and are similar in design to acceleration sensors [3]. Different types of piezoelectric sensors are available to carry out the task of detecting AE events. Piezoelectric sensors started to appear shortly after the First World War. Förster and Scheil are recognised as the first to use the piezoelectric effect to detect AE signals in 1936 [3]. Originally sensors were piezoelectric crystals. Quartz (SiO2) was the most common single crystal material as it has good piezoelectric properties and a high mechanical strength. Several other crystals showed sufficient qualities to be used in commercial AE sensors including tourmaline, gallium orthophosphate and crystals of the CGG group [3]. Several ceramic material groups were also investigated but none surpassed single crystals for AE applications. Lead zirconate titanate was subsequently invented and was found to show properties that were promising for sensing applications.

Other sensor types include capacitive transducers and active filament sensors. In capacitive transducers the AE wave moves internal conductive elements producing a capacitance change directly related to the amplitude of the input AE. It is known that capacitive transducers can record a good approximation of surface movement however the sensitivity of these sensors is insufficient for actual Acoustic Emission testing according to Miller and McIntire [2]. Active filament sensors are made with uniaxially orientated piezoelectric fibres embedded in a polymer matrix between two interwoven electrodes [4] this structure is also known as an active fibre composite elements or AFC. Barbezat et al. [5] identified that AFC are superior to traditional AE sensors in that they are lighter, more flexible and could be combined with existing polymer products. AFC sensors exhibit anisotropic sensitivity caused by the orientation of the fibres within the material. This combined with the fact that AFC sensors have a lower sensitivity to AE events than traditional piezoelectric sensors does limit the applications that they are suitable for. Work is also being carried out on adapting piezoelectric paint for use as an in-situ Acoustic Emission sensor [6].

A typical piezoelectric element AE sensor design is shown in figure 1. The sensor case acts as the conductive element for the earth and helps to shield the signal from external noise sources. The backing reduces noise caused by reflection of the signal from the back face of the piezoelectric element which would otherwise give a false reading.

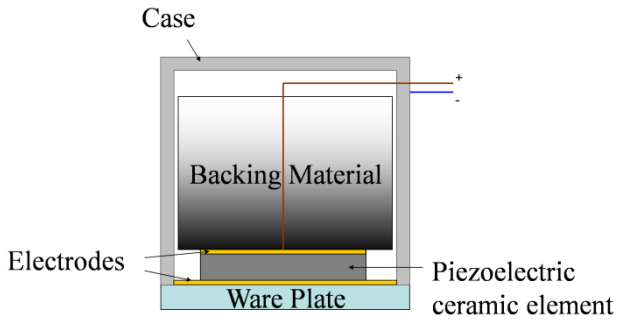

Figure 1. Schematic of traditional single element AE sensor design.

2.3 Material Selection

There are several thick film piezoelectric materials. The material with the best properties for Acoustic Emission devices is lead zirconate titanate (PZT). PZT can be used as a bulk material, as in existing AE devices, or deposited as a thick or thin film. Thick films have the advantage of being more durable than thin films. There are various methods for depositing thick films onto a substrate material

including screen printing, sputtering, direct writing, electrophoretic deposition, micro-stereolithography and composite sol-gel techniques [7]. Composite sol-gel is the intended production method for PZT deposition in this work and so will be presented here.

Composite sol-gel techniques have been researched extensively and provide a promising avenue for advancing thick film technology. In this method firstly a sol is produced. The sol is then mixed with powder to produce a composite slurry. The slurry is spun onto a flat substrate to ensure an even film thickness. Each layer is then heated to remove the solvent. Several layers can then be deposited onto the previous ones. In this way a thick film can be built up [8]. It is possible to increase the density of the porous film by repeated sol infiltrations. These infiltrations fill the pores in the material before being dried. Several infiltrations can be carried out on each layer deposited. These infiltrations can be used to lower the sintering temperature and have previously been investigated [9][10]. Once the required film thickness has been achieved the material is sintered to increase the density and piezoelectric properties [11]. This process produces a film with a consistent thickness and good piezoelectric qualities.

3 DEVICE MANUFACTURE

PZT sol and composite slurry were produced with a Zr/Ti ratio of 52/48 [9][12]. A Kovar substrate with dimensions 100x100x3.2mm was cleaned in an acetone/IPA ultrasonic bath. A spin coating technique was used to deposit a 4(2C+5S) composite PZT film of 17.6µm thickness onto the substrate. 2000rpm spin speed was used. The film was dried at 310°C for 180 seconds and pyrolised at 525°C for 60 seconds after each deposition. Upon completion of the composite film deposition process sintering was carried out at 720°C for 20min. To reduce thermal stress between Kovar and PZT a ramp rate of 5°C/min was employed. A mask was applied to the PZT film and then patterning was carried out by powder blasting. Discrete piezoelectric elements were produced by the application of a mask prior to the sputtering of an 8mm diameter Cr/Au top electrode, of 11.2nm/150nm onto the PZT film surface. The PZT was poled by a corona poling process. The film was initially heated to 135°C before poling was carried out for 15mins at 16kVwith a needle to sample gap of 30mm. To prevent depoling the PZT was left to cool under the electric field. The top electrode and the Kovar substrate was electrically connected using a BNC connecter. The poled thick film device was found to have a capacitance of 2.18nF and a dielectric loss of 0.102, measured at 100kHz. The finished device is shown in figure 2 alongside a Physical Acoustics Corporation (PAC) PICO commercial sensor.

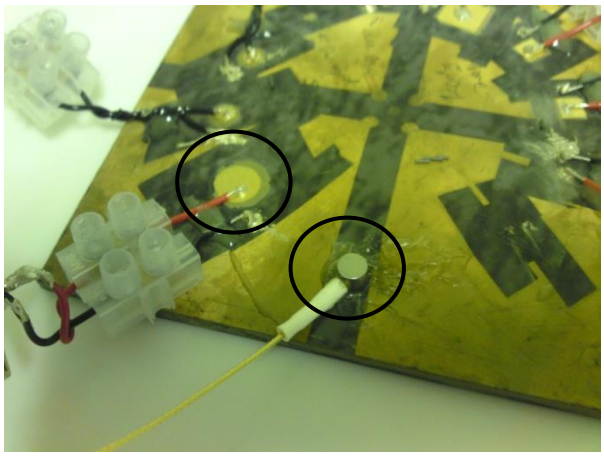

Figure 2. A thick film PZT Acoustic Emissions device (left) alongside a commercially available PICO sensor (right).

4 RESULTS AND DISCUSSION

4.1 Thick Film and Single Element Sensor Comparison

The thick film device deposited directly onto the Kovar substrate is a single element design. This provides high sensitivity to AE signals independent of the sensor orientation relative to the incoming acoustic wave. A PICO sensor from PAC was chosen for comparative testing as it is of a similar design to the thick film device. The PICO sensor has an operating frequency of 200-750kHz. A commercially available PICO sensor was mounted at 32mm from the center of the Kovar substrate with grease used as a coupling agent. Signals produced by the PICO and the thick film PZT devices were monitored using MI-TRA a commercial transient recorder-analyzer system from PAC 2001. Variable gain 2/4/6 pre-amplifiers from PAC were used. Pre-amplifications of 40dB and 60dB were used for the PICO and thick film sensor signals respectively. A 10MHz sampling rate was used to give a good resolution in signal analysis. A schematic of the Acoustic Emission monitoring set up is shown in figure 3.

AE events were simulated using the Hsu Nelson test carried out at the centre of the Kovar substrate. The Hsu Nelson test consists of breaking a 0.5mm diameter HB pencil lead [13].There is a variation in waveform arrival times between the PICO and the thick film sensor suggesting that the simulated acoustic source was not exactly central between the two sensors, this effect is apparent in all tests performed using the Hsu Nelson test. It is clear from figure 4 that, qualitatively, the waveforms exhibit similar properties. The PICO sensor signal exhibits a concentration of higher frequency wave components within the initial 100μs of the waveform compared to the thick film device as shown by the spectrogram in figure 5. The maximum amplitude of the PICO sensor is1.9 times that of the thick film device with the rise time of the thick film sensor being 25μs greater and the signal duration 0.5ms greater than that of the PICO sensor. The signal energy of the thick film waveform is 1.2 times greater than that of the PICO sensor. The properties of the PICO and thick film waveform frequency spectrum, shown in figure 4, are comparable, both exhibiting a frequency response to the simulated emission between 50kHz and 250kHz. The thick film device lacks the sensitivity peak at 400-500kHz which is characteristic of the frequency response of the PICO device.

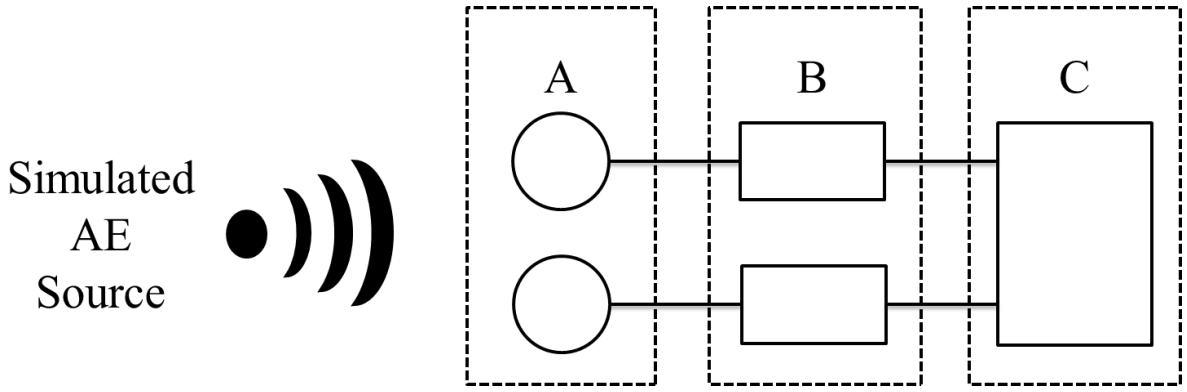

Figure 3. Schematic of the AE monitoring system, Simulated AE signals are received by two different AE sensors at A. The received signals are pre-amplified by 40/60dB as specified at B. The pre-amplified signals are received by the MI-TRA PCI card for analysis at C.

The greater amplitudes of the raw signal and frequency response can be explained as being a result of the relative thickness of the active piezoelectric element in the PICO sensor compared to that of the thick film device and the differences in electrical matching between the sensors and the commercial monitoring system. A flatter frequency response is desired in Acoustic Emissions applications and therefore the thick film frequency response lacking the sensitivity peak between 400kHz and 500kHz

is of benefit. The increased signal duration of the thick film sensor is explained by a lack of acoustically matched backing to attenuate signal reflections from the top surface of the device.

4.2 Thick Film and Dual Element Sensor Comparison

The PICO sensor was replaced on the Kovar substrate by a dual element, differential WD sensor from PAC with an operational range between 100 and 1000kHz. The sensor design alleviates issues of electromechanical interference in the signal. The WD sensor includes a 24dB common-mode rejection giving a signal with reduced interference. The WD sensor was mounted in an identical position on the Kovar substrate as the PICO sensor to ensure that there were no variations in the waveforms due to plate geometry. The signal processing parameters utilized were the same as those used for the thick film/PICO test. Pre-amplifications of 40dB and 60dB were applied to signals from the WD and thick film sensors respectively.

An AE event was simulated using the Hsu Nelson method and the signal was received by the devices. The waveform from the WD sensor has a peak amplitude an order of magnitude greater than that of the thick film waveform as shown in figure 4. The commercial sensor waveform has a rise time 50µs greater than that of the thick film device. The thick film sensor signal duration is 180µs greater than that of the WD device. The signal energy of the WD sensor is 6.6 times that of the thick film waveform. The WD sensor signal frequency spectrum indicates a frequency response intensity of a greater magnitude than both the thick film and PICO sensors. The frequency spectrum also indicates that the WD sensor exhibits sensitivity to the simulated AE between 75kHz and 350kHz. The WD frequency response is flatter than either the PICO or the thick film devices over a greater bandwidth.

The increased frequency response bandwidth present in the WD sensor (figure 4), along with a piezoelectric active element of greater thickness and an electrical impedance matching explain why the commercial WD time domain waveform amplitude is of greater magnitude than the thick film device. The WD sensor exhibits an initial amplitude peak before a second higher peak as a possible result of the dual element sensor design with the element closest to the transmission media being activated initially and then the second element being activated.

4.3 Dual Element and Single Element Sensor Comparison

As control the PICO sensor was tested against the WD sensor. Both devices were mounted on the Kovar plate using grease as a coupling agent. An Acoustic Emission was simulated at 32mm from the centre of both devices. A pre-amplification of 40dB was applied to the signals from both devices. The WD sensor signal had a peak amplitude and a signal energy of 4.3 and 5.7 times that of the PICO sensor respectively. The PICO sensor exhibits a rise time 90µs greater than the WD sensor and an event duration 128µs greater. The signal generated by the PICO sensor exhibits much greater frequency intensity during the first 32µs, particularly between 350kHz and 650kHz. Despite this greater initial intensity, the frequency spectra of the signals show the WD sensor to be sensitive to a greater frequency range than the PICO.

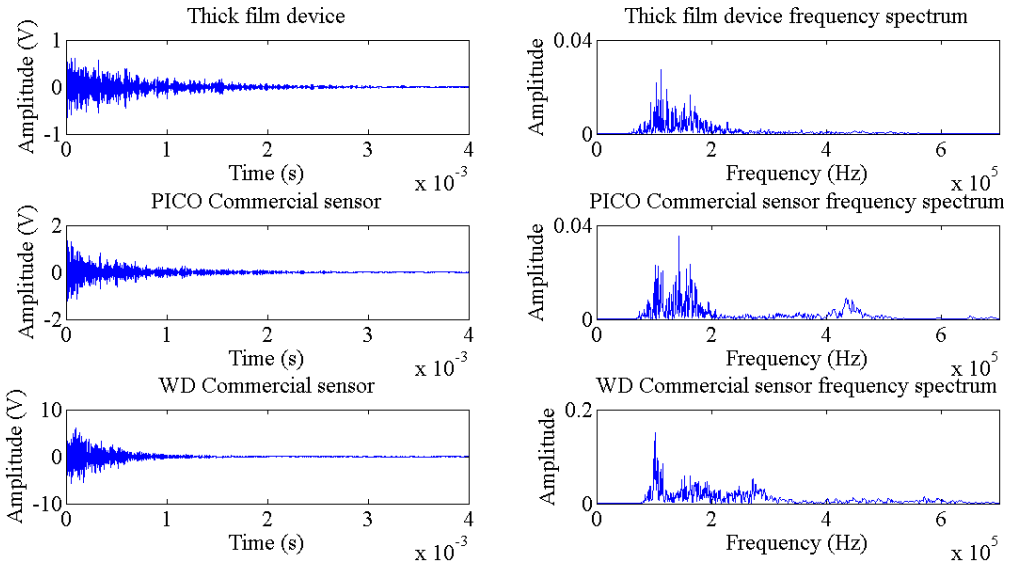

Figure 4. Time domain (left) and frequency domain (right) plots of the simulated AE signal received by thick film, PICO and WD sensors (top to bottom).

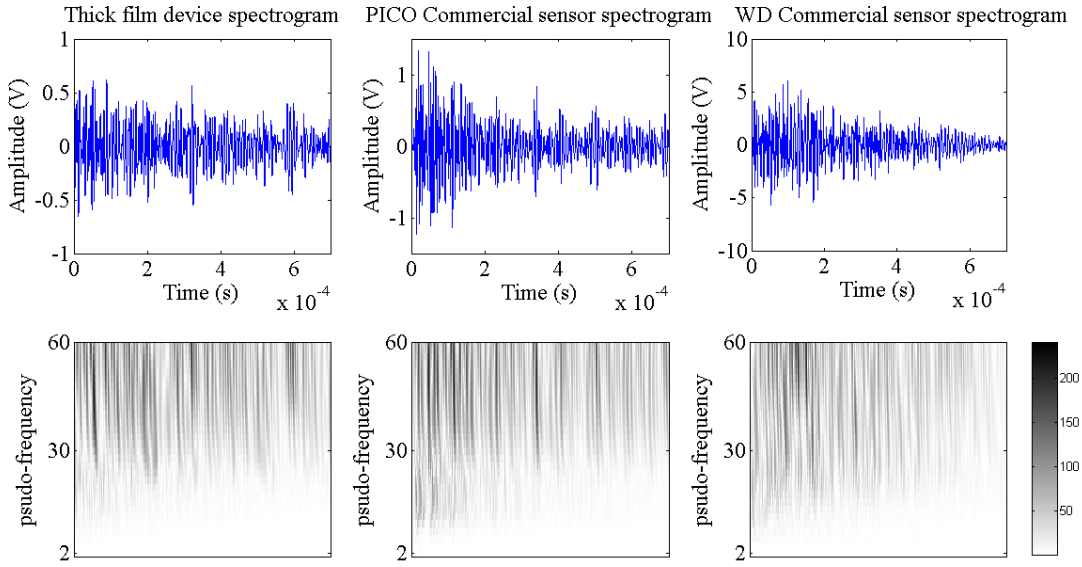

Figure 5. Time domain plot (top) and spectrogram (bottom) of the initial 700µs waveforms received by thick film, PICO and WD sensors (left to right).

5 CONCLUSIONS

The thick film device performed well when compared to the commercial sensors. The thick film device exhibited acoustic properties similar to those of the PICO commercial sensor. This was expected due to the similar design of the thick film and PICO sensors. An active element of greater area in the thick film device partially compensates for the lack active element thickness in the PICO sensor. The active element material in the commercial devices has not been exposed to the same stresses as the thick film PZT during the manufacture process. Stress during manufacture is known to result in the PZT exhibiting poorer piezoelectric properties as a thick film than as a bulk material

utilized in commercial devices [14]. These poorer piezoelectric properties can result in devices having a reduced response to excitation from an external source.

The waveform exhibited by the WD commercial sensor has a far greater response with less noise than the thick film device waveform. This can be explained by the similar area and much greater thickness of the active element within the WD sensor compared to that of the thick film device. The dual element design of the sensor eliminates much of the electrical noise and improves the signal resolution. The rise time of the WD sensor is greater than that of the PICO and thick film devices. Factors affecting the rise time are the electrical properties of the sensor and detection equipment meaning that commercial devices should exhibit better properties than the thick film device. The simulated AE signal is detected earlier by the thick film device. The reason for this that the thick film device is deposited directly onto the surface of the transmission media whereas the commercial sensors both have coupling media and wear plates. These obstacles extend the travel time of the acoustic wave to the active element and may cause distortion in the AE signal as well as signal attenuation [15].

This is the first known attempt at the deposition of an integrated, thick film, piezoelectric Acoustic Emissions sensor directly onto a structural element. The success of this work in producing a thick film device capable of detecting Acoustic Emissions could lead to significant uptake and deployment of thick film devices in the field of continuous non-destructive condition monitoring.

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