High-temperature acoustic emission tests using lithium niobate piezocomposite transducers

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High-temperature-resistant piezoelectric sensors have been used as acoustic emission sensors over a temperature range from room temperature up to 400°C. The sensors were made from lithium niobate 1-3 piezocomposites, using the dice and fill method, with high-temperature-resistant cement as the passive material. Good results in detecting simulated acoustic emission signals were obtained at high temperatures, with little change from the same measurements at room temperature. Of the devices tested, a 4 mm-thick piezocomposite with 45% volume fraction of y/36°-cut lithium niobate gave the best results. In addition, the possibility to use these devices to locate an acoustic emission source was verified.

1. Introduction

Acoustic emission (AE) analysis is used for testing materials in structural components and machinery. Acoustic emission frequently consists of ultrasound in the frequency range 100 kHz to 1 MHz, generated either from growing cracks or from mechanical failure in rotating machinery. In the case of crack growth, individual AE events correspond to the release of elastic energy as the crack grows step by step. In machinery it may result from abrasion of damaged components. With the data obtained, information can be determined about the kind of process taking place in the test specimen, the condition of the specimen, and the location of the defect. In the case of machine monitoring and in some structural applications, acoustic emission testing may be required at high temperatures. As AE often involves monitoring over a period of time, permanently attached sensors would be most suitable and would preferably be high-temperature-resistant to remove the need for cooling systems or buffer rods.

The emitted AE spectrum for crack growth in metals is relatively broad-band, extending from about 100 kHz into the MHz region[1]. Frequencies emitted from shaft-seal rubbing in large-scale power generation turbines are between 100 kHz and 1 MHz[2, 3]. Lower frequencies are detected when testing over large distances, for example pipeline testing at around 30 kHz, in which case lower attenuation enables detection up to 100 m from the source[4]. Due to the nature of the generating process for AE, the signals are not precisely repeatable.

We have produced piezoelectric sensors to measure acoustic emission signals at high temperatures and tested them up to 400°C[5]. The sensors were 1-3 piezocomposites consisting of pillars of piezoelectric material embedded in a high-temperature-resistant cement matrix. Lithium niobate was used as the piezoelectric material as its Curie temperature is around 1200°C and it can generally be used up to 600°C[6]. Lithium niobate single-crystal material has previously been used for high-temperature-resistant single-element transducers[7] and phased arrays[8], and lithium niobate piezocomposites have already been investigated for ultrasonic testing using phased arrays[9, 10].

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2. Fabrication of lithium niobate piezocomposites

Lithium niobate piezocomposites were developed for use as ultrasonic transducers for high-temperature applications[11]. The reasons for using lithium niobate piezocomposite rather than a single crystal of material are: reduced lateral modes, increased bandwidth, better mechanical properties, and better impedance matching. An enhancement in the electromechanical coupling coefficient k_t is not expected. The properties of lithium niobate piezocomposites have been examined in detail by experiment and finite element modelling[11, 12].

The piezocomposites consisted of lithium niobate pillars in a passive matrix of high-temperature cement. The lithium niobate was from Sinoceramics (LLC, State College, Pennsylvania, USA) and the passive filler was an alumina-based cement (C920, Cotronics, Brooklyn, NY, USA) with high thermal conductivity. Three samples were made using two different thicknesses and two different crystal cuts of lithium niobate: z-cut, 4 mm-thick; y/36°-cut, 2 mm-thick; y/36°-cut, 4 mm-thick. The two different crystal cuts have different properties, with y/36°-cut having a higher k_t of 0.49 compared to around 0.2 for z-cut. On the other hand, the z-cut is more highly symmetrical and produces a more well-behaved beam profile which is important in ultrasonic phased array applications. The expected resonant frequencies for these piezocomposites were 1-2 MHz (4 mm, ≈ 1 MHz; 2 mm, ≈ 2 MHz).

The piezocomposites were produced using the dice and fill method. A 1.2 x 1.2 cm^2 lithium niobate plate was diced using a 250 μm saw blade into vertical planks and again at an angle of 90° to the first cuts to produce pillars. The shift between cuts was 1.04 mm, which produced pillars approximately 0.8 mm wide and corresponded to a lithium niobate volume fraction of 45%. A stock of about 0.3 mm of the piezoelectric material was left during cutting to stabilise the pillars. After dicing, the piezocomposite was filled with cement. Excess cement and the stock were removed by lapping after curing the cement. The finished piezocomposite is shown in Figure 1. Silver paint electrodes were applied to the front and back surfaces.

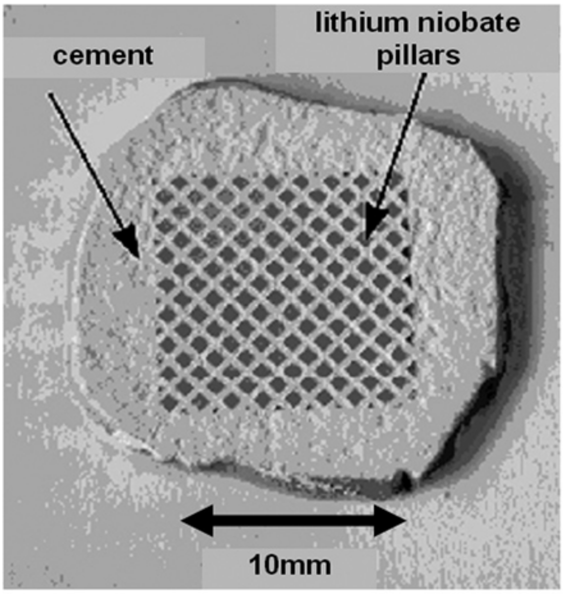

Figure 1. Lithium niobate cement piezocomposite with pillar width 0.8 mm and volume fraction of lithium niobate 45%

3. Sensor connection and measurement system

A steel block of dimensions 130.0 x 9.2 x 48.5 mm^3 was used for the acoustic emission tests. Figure 2 shows the mounting and connection of the piezocomposite to the test sample. Note that no electrical shielding was used. The steel test block itself serves as the ground connection to the device. The other electrical connection was provided by a screen-printed conductive electrode on a high-temperature-resistant alumina substrate. High-temperature couplant (UCA-HT, Ely Chemical, Ely, UK) was used, which works best at 200-600°C.

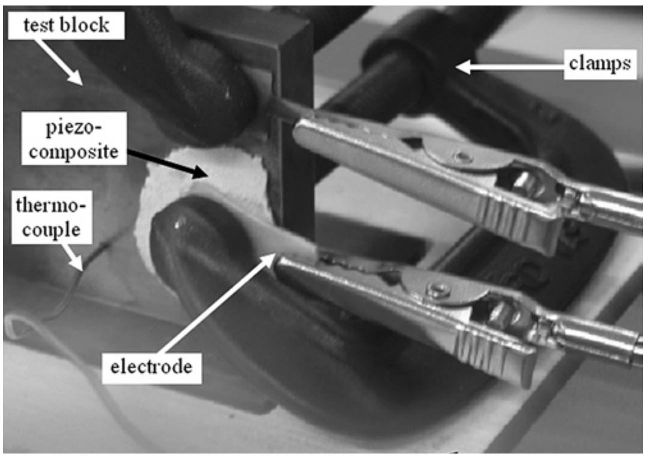

Figure 2. Lithium niobate piezocomposite mounted onto the test object (metal block standing vertically on hotplate)

An AE signal was simulated using a Hsu-Nielsen source, which is a pencil lead break on the surface of the test object. The source generates an acoustic emission signal, which is quite similar in duration and frequency content to a natural acoustic emission source such as a transient signal caused by crack growth[13].

The acoustic emission signals detected by the piezocomposite transducers were amplified using the receive channel of an ultrasonic pulser/receiver (DPR300, JSR Ultrasound, Pittsford, NY, USA). The through-transmission mode was used, with the acoustic emission sensor connected to the receiver port. The high-pass filter of the pulser/receiver was switched off and the low-pass filter was set at 5 MHz, which was the lowest possible setting for this filter. During tests the gain was set at 40 dB or 50 dB. The amplified acoustic emission signals were captured using a digital oscilloscope (Agilent 54641A, Agilent Technologies UK Ltd, South Queensferry, UK) linked via BNC cable to the output port of the pulser/receiver. The sampling rate was 4 MHz. Signals were recorded in single shot mode, triggered by the oscilloscope receiving a AE burst signal, and data was presented in both the time and frequency domain.

4. Results and discussion

4.1 Comparison of sensors at room temperature

Since the simulated AE signals are not precisely repeatable, a direct comparison between the different lithium niobate piezocomposite sensors was obtained by using two sensors simultaneously to record the same signal. Two identical pulser/receivers were used, connected to different channels of the same oscilloscope. The sensors were approximately the same distance from the acoustic emission source, and the oscilloscope triggered on the sensor closest to the source. Results are shown in Figures 3 and 4.

All three transducers show a broadly similar response to the simulated AE signal in both the time and frequency domains. Comparing the amplitudes of the signals in the time domain it

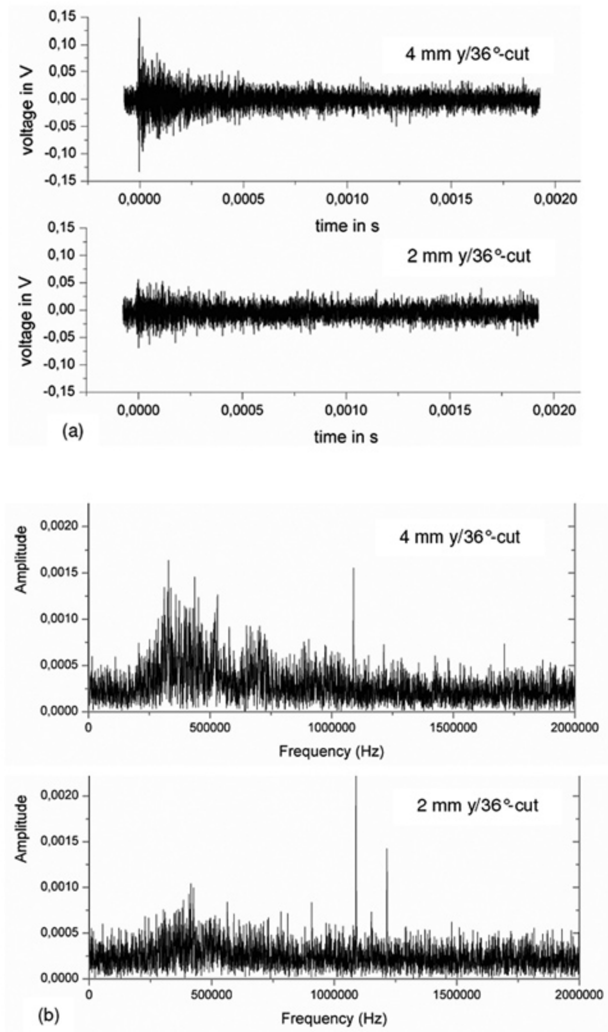

Figure 3. Comparison between 4 mm and 2 mm-thick y/36°-cut piezocomposites: (a) acoustic emission signal in time domain; (b) frequency spectrum. The 4 mm-thick transducer is more sensitive at low frequencies, due to its lower resonant frequency

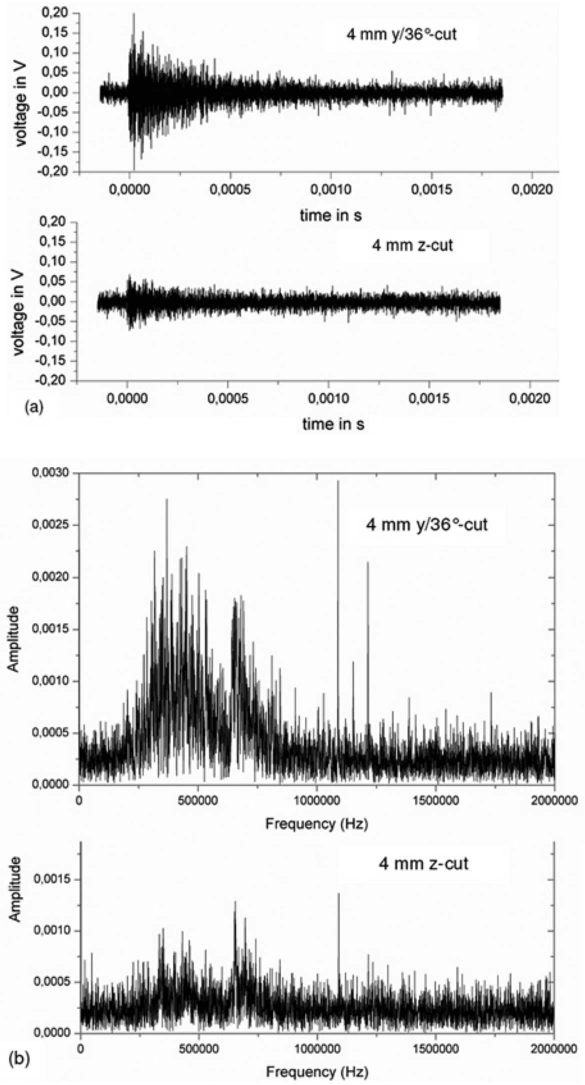

Figure 4. Comparison between 4 mm-thick y/36°-cut and z-cut piezocomposites: (a) acoustic emission signal in time domain; (b) frequency spectrum. The y/36°-cut transducer has greater sensitivity due to a larger k_t

can be seen that the 4 mm y/36°-cut piezocomposite shows higher amplitude than the 2 mm y/36°-cut piezocomposite because its lower resonant frequency gives better sensitivity in the frequency range of the simulated AE signal. It also gave a better signal-to-noise ratio than the 4 mm z-cut piezocomposite because the y/36°-cut material has a higher k_t.

4.2 Source location at room temperature

Measurements were made at room temperature to verify the possibility to locate an acoustic emission source using the lithium niobate piezocomposites. The location of the source of acoustic emission is obtained from the difference in arrival time at separate sensors, based on an AE wave propagating in concentric circles from its source and arriving at each sensor with a delay proportional to the distance between the sensor and the source. Normally, three sensors are needed for a full location measurement on a surface. Figure 5 shows the positions of the sensors and the source. Sensor 1 (2 mm y/36° piezocomposite) was positioned approximately 3 cm from the source and sensor 2 (4 mm z-cut piezocomposite) approximately 11 cm.

Figure 6 shows the results. The oscilloscope was triggered on sensor 1, which was closer to the acoustic emission source than sensor 2. The time delay between the signal arrival times was approximately 25 μs. Since the distance between the source and sensor 2 was 8 cm longer than between the source and sensor 1, a

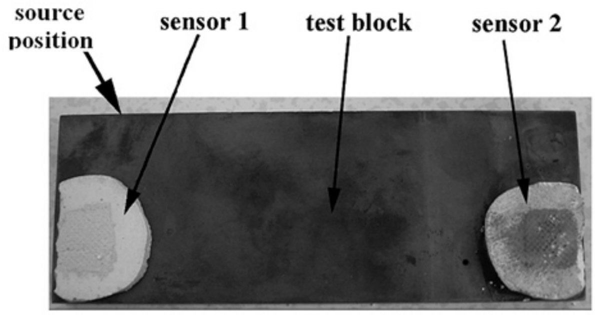

Figure 5. Sensor and source positions for source location measurement

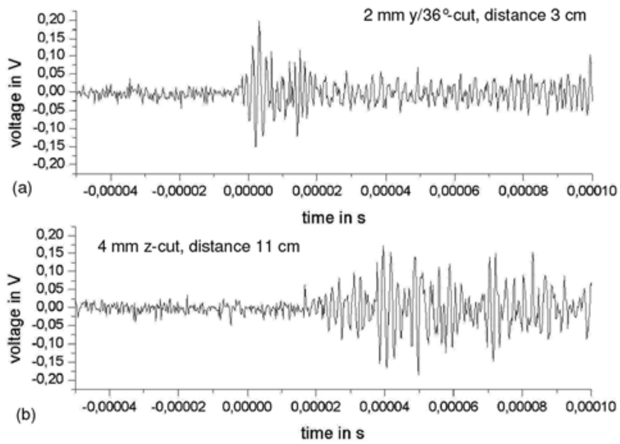

Figure 6. Acoustic emission signals in time domain detected by (a) sensor 1 (2 mm y/36°-cut piezocomposite) 3 cm from source; (b) sensor 2 (4 mm z-cut) 11 cm from source

sound velocity of 3200 ms^{-1} was calculated, which corresponds to the fundamental Lamb wave modes in a 9.2 mm steel plate. The amplitude remained fairly constant with distance, also consistent with propagation of Lamb waves.

4.3 High-temperature measurements

To measure acoustic emission signals at high temperatures, the test block was heated on a hot plate, reaching a maximum temperature of 400°C measured using a thermocouple inserted into a hole in

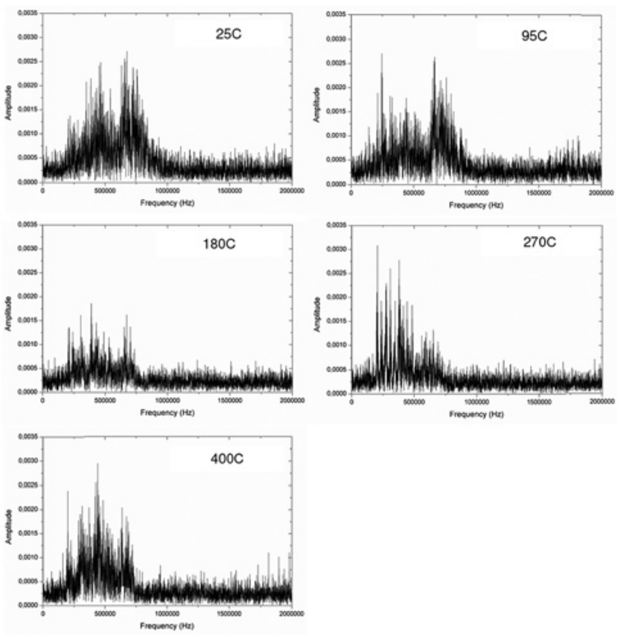

Figure 7. 4 mm-thick y/36°-cut piezocomposite, frequency spectrum measured at temperatures up to 400°C with 3 cm between sensor and source

the block. Simulated acoustic emission signals were successfully obtained with acceptable signal-to-noise ratio for the three different piezocomposites starting at room temperature and increasing to 400°C, at 3 cm and 10 cm distance from the source. Results are shown in Figure 7 for a the 4 mm-thick y/36°-cut composite, 3 cm from the source. The detected signal has a broad bandwidth and a good signal-to-noise ratio. Allowing for some variation in the signal from the Hsu-Nielsen source on each occasion, the signal amplitude remained approximately constant over the temperature range 25-400°C.

5. Summary, conclusions, and further work

In summary, lithium niobate piezocomposites were fabricated and used successfully to measure simulated acoustic emission signals at high temperatures up to 400°C. The piezocomposites consisted of lithium niobate pillars in a cement matrix with a lithium niobate volume fraction of 45%. Two different crystal orientations of lithium niobate were tested, y/36°-cut and z-cut, and two different thicknesses 2 mm and 4 mm. Three sensors were compared at room temperature, where it was shown that all were able to detect the simulated AE signal, although the y/36°-cut 4 mm-thick sensor was the most sensitive in the required frequency range. In addition, satisfactory room temperature operation of the sensors was verified by measurements of acoustic emission source location using two signals detected by two devices at different distances from the source. The high-temperature tests showed that all three piezocomposites were easily able to detect AE signals up to 400°C. There was some variation in sensitivity with temperature which may be due to couplant effects and should be further investigated.

Tests reported here used simulated AE signals and standard laboratory ultrasonic equipment. Connecting the sensors to a commercial acoustic emission system would enable their performance to be assessed more thoroughly in this application. Field tests with the sensors mounted on a high-temperature test system would be valuable in further developing the sensors in a more realistic environment. Electrical noise should be reduced by incorporating electrical shielding and improving the signal and ground connections of the transducers. Compared to standard AE sensors the piezocomposite high-temperature transducers operated at higher frequencies, and were more narrow band and less sensitive. However, their excellent high-temperature-resistant properties give great advantages in AE monitoring of hot machinery.

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