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Integrated ultrasonic transducers made by the sol–gel spray technique for structural health monitoring

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Abstract

Integrated piezoelectric-based ultrasonic transducers (UTs) have been developed for potential structural health monitoring. Fabrication techniques and performance evaluation of these transducers at selected monitoring sites are presented. Our novel transducer fabrication approach focuses on the use of handheld and readily accessible equipment to perform sol–gel spray coating, including the use of a heat gun or a torch, to carry out drying and firing, poling and electrode fabrication. The application of these integrated UTs for thickness measurement of graphite/epoxy composites, thickness monitoring of ice build up on aluminum plates at low temperatures, viscosity measurement of a cooling oil flow at temperatures up to 160 °C and monitoring metal debris in cooling oil engines is demonstrated.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The increasing demand to improve the performance, reduce downtime, increase reliability and extend the life of transportation vehicles, structures such as nuclear power plants, and engineering systems such as molding and casting devices, requires the use of smart or adaptive materials and structures [1–5]. These can be defined as systems that have integrated capabilities with built-in sensors that perceive and process in-service information and take actions to accomplish desired operations and tasks. It is established that ultrasonic methods employing piezoelectric ultrasonic transducers (UTs) are widely used for real-time, *in situ* or off-line nondestructive testing (NDT) and evaluation of large metallic and polymeric composite structures including airplanes, automobiles, ships, pressure vessels, and pipelines. Because of their subsurface inspection capability, fast inspection speed, simplicity and cost-effectiveness [3–9], there has been considerable interest in the use of piezoelectric materials. Some of these can be

integrated with metals or polymer composites for structural health monitoring (SHM) purposes [3, 4, 10, 11] subjected to high-temperature environments [3–5, 12, 13]. Common limitations of the current UTs are

- (1) the requirement of a couplant;
- (2) the lack of suitability for use on curved surfaces;
- (3) the difficulty for use in pulse-echo mode; and
- (4) the difficulty for use at temperatures higher than 60 °C.

In this investigation, some of these limitations will be addressed, and we will focus on lowering the process temperatures of sol–gel sprayed lead–zirconate–titanate (PZT)/PZT composite UT films, of thickness greater than 40 µm, reported in [3, 4]. To integrate these PZT-based films onto flat and/or curved metallic or graphite/epoxy substrates, handheld equipment was used. The process temperature achieved using a handheld heat gun should not affect the performance of graphite/epoxy (Gr/Ep) composites or metal components. These UTs can be fabricated as arrays and at desired sensor

Figure 1. Flow chart of the fabrication process for a piezoelectric thick film UT.

locations with ease. The application of these integrated UTs targets thickness measurement of Gr/Ep composites, thickness monitoring of ice build up on aluminum substrates, viscosity measurement of cooling oil flow, at elevated temperatures, and engine oil metal debris monitoring.

2. Transducer fabrication and characterization

Sol-gel fabricated thick piezoelectric films were initially reported by a group at Queen's University [14]. The aim of the development was not for high-temperature NDT applications and the fabrication techniques used did not consider the integrated sensor approach at specified monitoring sites. Taking this into consideration, transducer material and processing techniques were properly selected for this development. In this investigation, piezoelectric PZT powders were purchased with a particle size distribution of 1–3 μm . The powders were dispersed into a PZT sol-gel solution by a ball milling method to achieve desired transducer characteristics. The final PZT mixture (paint) was estimated to be of submicron size. An airbrush was then used to spray the PZT/PZT sol-gel composite directly onto selected substrates, such as graphite/epoxy, aluminum and steel. With the sol-gel spray technique, the PZT/PZT films can be produced with specified thickness at desired locations using a paper shadow mask. After spraying the coating, thermal treatments such as drying, firing and annealing were carried out using a heat gun or a gas torch. Multiple layers were made in order to reach the desired transducer thickness. The film was then electrically poled using the corona discharging technique [15]. For corona poling, the temperature of the stainless steel substrate was around 120 °C. A high positive voltage was supplied from a 28 kV DC power supply. This was fed into a thin and sharp needle located several centimeters above the PZT/PZT film coating on the top of the metal substrate. The substrate served

Figure 2. Manufacturer's recommended cure cycle for Gr/Ep composite.

as the ground electrode for corona poling. The distance from the film surface and the voltage were optimized for different PZT/PZT film thicknesses and geometries. The poling time was about 10 min. The corona poling method was chosen because it could pole the piezoelectric film over a large area with complex geometries. Finally, silver paste painting was used to form the top electrode at room temperature. This convenient approach makes the selection of electrode size and sensor size simple. The silver paste has been tested, and its operating temperature could reach 200 °C. The flow chart of the fabrication process is shown in figure 1. The novelty in this study is that the thermal treatment is carried out by a heat gun or torch in lieu of a furnace as used in a previous study [3]. In addition, here aluminum substrates are used instead of steel substrates. Because of the low temperature used, the firing and annealing of the PZT/PZT film is not complete; the piezoelectric strength will therefore be lower than that of completely fired and annealed films reported in [3].

It is noted that the PZT sol-gel solution acted as a bonding agent between the PZT powder and the substrates. The dielectric constant of the PZT/PZT films was 60, measured by a Hewlett Packard 4192A LF impedance analyzer at 1 kHz. The piezoelectric constants d_{33} and d_{31} were 30×10^{-12} and $-26 \times 10^{-12} \text{ m V}^{-1}$, measured by an optical interferometer and optical coherence tomography, respectively. The measured piezoelectric coupling constant k_t using the standard method described in [16] was about 23%.

3. Performance of the UT for potential ultrasonic SHM

3.1. Integrated UT on graphite/epoxy composites for thickness measurement

The fabrication of the Gr/Ep composite follows the manufacturer's recommended cure cycle shown in figure 2 for Gr/Ep. In the curing stage the highest temperature was 176 °C and the duration was 120 min. During the PZT/PZT composite film fabrication, thermal treatment such as drying, firing and heating for corona poling was carried out using a heat gun producing gentle heat. The torch used in [4] proved to be difficult for controlling the heating speed and temperature. In order

Figure 3. Integrated PZT/PZT composite film UT on a 13.1 mm thick Gr/Ep composite.

Figure 4. Ultrasonic performance of a 70 μm thick PZT/PZT UT film deposited on the 13.1 mm thick Gr/Ep sample shown in figure 3 in the (a) time and (b) frequency domain at room temperature.

to not affect the performance of the graphite/epoxy composite a thermocouple contacting the surface of the graphite/epoxy composite was used to ensure that each heating would not exceed 176 °C. It is the intention of this study to evaluate the performance of the novel PZT/PZT film sensor for thickness measurement under such low-temperature thermal treatments. A 70 μm thick PZT/PZT film UT deposited on a 13.1 mm thick unidirectional Gr/Ep composite is shown in figure 3. The 70 μm film thickness was achieved through applying the process shown in figure 1 eight times, where each layer of coating proceeded for 150 s. The Gr/Ep composite has sufficient conductivity to serve as the bottom electrode for the produced piezoelectric film-based UT.

Figures 4(a) and (b) show a typical ultrasonic performance of the integrated UT shown in figure 3 operated in pulse-echo mode at room temperature. In figure 4(a) the measured signal-to-noise ratio (SNR) of the ultrasonic signal L^1 is about 15 dB. L^1 , L^2 , L^3 and L^4 are respectively the first, second, third and fourth round-trip reflected echoes through the thickness of the Gr/Ep composite. The SNR is defined as the ratio of the amplitude of the first echo, L^1 , that has traveled one round trip in the through thickness direction over that of the signals, which are undesired, between the echoes traversing back and forth in the sample. The measured center frequency and 6 dB bandwidth of L^1 are 1.6 and 1.5 MHz, respectively. The low center frequency and bandwidth were caused by the high ultrasonic attenuation within the 13.1 mm thick composite. In principle, the ultrasonic attenuation is proportional to the operation frequency squared. The higher-frequency components suffer significant ultrasonic attenuation. It is expected that improved SNR of L^1 can be obtained if the thickness of the PZT/PZT film increases and the center frequency of the integrated UT decreases. This is the first

Figure 5. Integrated PZT/PZT composite film UTs on a 25.4 mm thick aluminum plate.

Figure 6. Ultrasonic performance of 100 μm thick PZT/PZT film deposited on the aluminum plate shown in figure 5 in the (a) time and (b) frequency domain at 150 °C.

time that a piezoelectric UT can be directly deposited onto a Gr/Ep composite to carry out a thickness measurement provided that the ultrasonic velocity in the Gr/Ep composite is known. For such a Gr/Ep composite, the thickness would cause 2.96 mm μs^{-1} time delay in ultrasound for one-way travel along the thickness direction at 22 °C.

3.2. Integrated UT on aluminum substrates for thickness measurement

Aluminum (Al) alloys are common materials for aircraft structures and other transportation systems, such as automobiles. Typically, the melting temperature of these alloys is around 580 °C. For the Al specimen under consideration, all the fabrication procedures of the UT are identical to those reported in the previous section except that the firing and annealing for the PZT/PZT composite film were carried out using a gas torch which provides higher temperature than that of the heat gun. During the corona poling a heat gun was still used, though. Figure 5 shows that two areas of the PZT/PZT composite film were deposited onto a 25.4 mm thick Al plate. Since the Al substrate serves as the bottom electrode, the size and shape of the top electrode determines that of the UT. If multiple top electrodes are made, then a UT array is achieved. For this study only one top electrode of 10 mm diameter (not shown) was made. Figures 6(a) and (b) show the measured ultrasonic signals in the pulse-echo mode at 150 °C. L^1 , L^2 , L^3 and L^4 are respectively the first, second, third and fourth round-trip reflected echoes through the thickness of the Al. The measured SNR, center frequency and 6 dB bandwidth of L^1 in figure 6(a) are 29 dB, 3.4 MHz and 3.3 MHz, respectively. For this Al plate the thickness would be 6.30 mm per μs time delay in ultrasound for one-way travel along the thickness direction at 22 °C.

3.3. Integrated UT for ice build up thickness measurement

The accumulation of ice on wings of aircraft poses a serious safety concern for all aircraft operators. It may happen during

Figure 7. Schematic for thickness monitoring of ice growing on an aluminum plate using a UT.

Figure 8. Ultrasonic echoes, L_{ICE} , observed as ice is growing on the aluminum plate of figure 7.

taxiing and waiting for takeoffs in winter and/or during flight at high altitudes. Here a UT sensor was directly fabricated onto a 9.9 mm thick Al plate, analogously to the procedure in the previous section, and used to monitor the thickness of ice building up on the Al plate. Water droplets on the opposite side of the plate were cooled by liquid nitrogen, as illustrated in figure 7. The time delay of echo L_{ICE} , reflected from the ice–air interface, increased in the traces from top to bottom in figure 8, indicating growth of the ice thickness. L^1 and L^2 echoes are the first and second round-trip echoes, respectively, through the thickness of the 9.9 mm Al plate. The thickness (h) of the ice can be estimated using the time delay difference (Δt) between the L_{ICE} and L^1 echoes and the ultrasonic velocity ($V = 3230 \text{ m s}^{-1}$) in the ice using $h = V \times \Delta t/2$. The ice thickness was calculated to be 3.2 and 4.0 mm for the top and bottom traces, respectively. Additional experiments not reported here also supported the high performance of the sensors at operating temperatures below -100°C .

3.4. Integrated UT at elevated (100°C) temperature for thickness measurement

It is also of interest to know, when a structure or system, such as cooling pipes in nuclear reactors, operates at elevated temperatures, whether the developed sensor can still be integrated and respond to its designed performance requirement. To simulate such a situation a steel block with dimensions $56 \text{ mm} \times 75 \text{ mm} \times 61 \text{ mm}$ was first heated on a hot plate to 100°C and kept at this temperature. The value of 100°C was chosen because it is the temperature at which the cooling water becomes vapor. All transducer fabrication processes described in section 2 were carried out for this configuration. Figure 9 shows the integrated UTs on this

Figure 9. Integrated PZT/PZT composite film UTs deposited onto a $56 \text{ mm} \times 75 \text{ mm} \times 61 \text{ mm}$ steel block heated at 100°C .

Figure 10. Ultrasonic performance of one $100 \mu\text{m}$ thick PZT/PZT film deposited on the steel block heated at 100°C as shown in figure 9 in the (a) time and (b) frequency domain.

steel block, and figures 10(a) and (b) show the ultrasonic performance of the integrated UT operating in pulse–echo mode at 100°C . The measured SNR, center frequency and 6 dB bandwidth of L^1 are 20 dB, 2.1 MHz and 3.1 MHz, respectively. It is shown that although the SNR is not high, it is sufficient enough for thickness measurement of this steel block at 100°C . For such a steel block, the thickness would cause $5.54 \text{ mm } \mu\text{s}^{-1}$ delay in ultrasound for one-way travel along the thickness direction.

3.5. Integrated UT for viscosity measurement and oil debris monitoring

When engines, in particular, in aerospace vehicles are running, not only for cost but also for safety reasons, it is crucial to know the engine health condition. While in operation, engines are hot, and cooling oil is often used to lower the temperature. In addition, if the engines do not operate properly, gears may be damaged and metallic debris will be produced and carried by the flowing oil into cooling channels. Thus, it is of significant importance to have a viscosity and metal debris monitoring system operable at elevated temperatures.

Although integrated UTs made of bismuth titanium/PZT composite films can operate at 400°C and higher [3, 4], in this investigation only the performance of PZT/PZT film operating up to 160°C is presented. Figures 11 and 12 show, respectively, the schematic and actual set-up of a simulated oil viscosity measurement and debris monitoring system. The V-shaped probes, shown in figure 12, were used to measure the flow speed of the flowing oil [17]. Two pairs of integrated UTs,

Figure 11. Schematic of oil viscosity measurement and debris monitoring.

Figure 12. Integrated UT set-up for oil viscosity and debris monitoring.

Figure 13. Relation between ultrasonic velocity in oil and temperature.

coated on the top and bottom sides of the pipe, were made at both sides of the V-shaped probes. They can operate in pulse-echo or transmission mode. The pipe is of square shape. The outer dimension is 12.7 mm by 12.7 mm and the inner dimension is 9.53 mm by 9.53 mm. The size of the sensor, determined by the top silver paste electrode, was 5 mm diameter, located at the center of the pipe surface. It is well known that the viscosity of oil is temperature dependent. For our experiment a Thermocast heater machine, used in connection with polymer and metal processing machines, provided a flow of Thermia-C oil (Shell), which simulates the engine oil. The temperature of the flowing oil was changed from 22 to 160 °C at increments of 10 °C. The measured ultrasonic velocity in this oil via the transmission mode as a function of the temperature of the oil is given in figure 13. In practice, the ultrasonic velocities in oil vary according to their viscosity. If the ultrasonic velocity of oil, at constant temperature, is lower than a set threshold that determines a must-change operation of oil, the integrated UT and acoustic electronics indicator will be able to issue commands to key operators.

Figure 14 shows the reduction of the transmitted ultrasonic signal due to steel bearing balls of 1.59, 2.38 and 4.76 mm

Figure 14. The reduction of the ultrasonic signal due to the presence of one metal ball of 1.59, 2.38 and 4.76 mm diameter flowing in the water.

Figure 15. The reduction of the ultrasonic signal due to the presence of one metal ball of 1.59 mm diameter flowing in the water.

in diameter flowing in water and passing through one pair of the integrated UTs' formed sensing zone along the pipe shown in figure 12. The pipe shown in figure 12 was placed vertically; the balls were freely dropped from the top open end and flowed through the sensor site in water. These steel bearing balls simulate metal debris of different dimensions carried by flowing oil in cooling channels. The results indicate that the larger the ball diameter, the higher the signal reduction. In addition, figure 15 shows the reduction of the ultrasonic signal due to the presence of one metal ball of 1.59 mm diameter flowing in the water, but for four times. It indicates that the repeatability is quite acceptable and that the ball is clearly identifiable. In figure 16 copper powders of 100–500 μm diameter with a total weight of 0.05 and 0.1 g were also freely dropped and allowed to flow through the sensor site. The signal strength reduction also occurred and was clearly recognizable, but the shapes were different from those of the single ball. Such reduction of signal strength can be used to identify the amount and size of the metal debris in the cooling oil, analogously to our previous work [18]. Thus, it is our conclusion that although the shape and the size of metal debris may vary much, the signal reduction pattern as a function of time may still be used effectively to assess the health condition of the engine. The integrated UT system can be used both as a viscosity and metal debris diagnostic tool.

Figure 16. The reduction of the ultrasonic signal due to the presence of copper powders of average size of 100–500 μm diameter with a total weight of 0.05 and 0.1 g flowing in the water.

4. Conclusions

Integrated piezoelectric-based ultrasonic transducers (UTs) have been developed for potential structural health monitoring and integration into prognostic health management systems. Fabrication techniques focused on the use of handheld and readily accessible equipment to perform sol–gel spray coating using a heat gun and torch to achieve drying and firing, poling and electrode fabrication in the manufacture of these transducers. These UTs can be fabricated at desired NDT sites. In this investigation, the PZT powders were dispersed into PZT solution as the piezoelectric composite material for spraying at room temperature. The merits of these integrated UTs are

- (1) no need for a couplant,
- (2) applicability to complicated and complex surfaces,
- (3) operability in the pulse–echo and transmission mode, and
- (4) ability to be used at temperatures up to 400 °C [3, 4].

For the first time these UTs have been successfully integrated onto graphite/epoxy composites for ultrasonic thickness measurement. The ultrasonic performance of integrated UTs on aluminum plates for thickness monitoring at 150 °C and for the monitoring of the ice accumulation on an aluminum plate was demonstrated. This simulated the accumulation of ice on wings of airplanes, which always poses a serious safety concern for operators. In addition, the integrated PZT/PZT UT can sustain 100 °C operation temperature. Integrated UTs were also deposited onto metal pipes for real-time viscosity measurement of a simulated cooling oil flow at temperatures

up to 160 °C. Metal ball bearings, of 1.59, 2.38 and 4.76 mm in diameter, and copper powders, of 100–500 μm diameter and with a total weight of 0.05 and 0.1 g, in flowing liquid, simulating metal debris in cooling oil engines, were clearly identified by monitoring the reduction of the transmitted signals through a metal pipe. Thus, the integrated UT system can be used as well for both viscosity and metal debris diagnostics.

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