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SHM
Structural Health Monitoring

# Development and Testing of High-temperature Piezoelectric Wafer Active Sensors for Extreme Environments

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Development of high-temperature piezoelectric wafer active sensors (HT-PWAS) using high-temperature piezoelectric material for harsh environment applications is of great interest for structural health monitoring of high-temperature structures such as turbine engine components, airframe thermal protection systems, and so on. This article presents a preliminary study with the main purpose of identifying the possibility of developing PWAS transducers for high-temperature applications. After a brief review of the state of the art and of candidate high-temperature piezoelectric materials, the article focuses on the use of gallium orthophosphate ($GaPO_4$) samples in pilot PWAS applications. The investigation started with a number of confidence-building tests that were conducted to verify $GaPO_4$ piezoelectric properties at room temperature and at elevated temperatures in an oven. Electromechanical (E/M) impedance measurements and material characterization tests (scanning electron microscopy, X-ray diffraction, energy dispersive spectrometry) were performed before and after exposure of HT-PWAS to high temperature; it was found that $GaPO_4$ HT-PWAS maintain their properties up to 1300°F (~705°C). In comparison, conventional PZT sensors lost their activity at around 500 F (~260°C). Subsequently, HT-PWAS were fabricated and installed on metallic specimens in order to conduct an *in situ* evaluation of their high-temperature performance. A series of *in situ* tests were performed using the E/M impedance and pitch-catch methods; the tests were conducted in two situations: (a) before and after exposure to high temperature and (b) inside the oven. The experimental results show that the fabricated HT-PWAS can survive high oven temperatures up to 1300°F (~705°C) and still present piezoelectric activity. The article also discusses fabrication techniques for high-temperature PWAS applications, including the wiring of the sensor ground and signal electrodes, bond layer adhesive selection, and preparation.

**Keywords** structural health monitoring · SHM · turbine engines · reentry vehicles · high temperature · HT-PWAS · piezoelectric wafer active sensor · space vehicles.

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## 1 Background and Motivation

Structural health monitoring (SHM) using *in situ* active sensors has shown considerable promise in recent years. Small and lightweight piezoelectric wafer active sensors (PWAS), which are permanently attached to the structure, are used to transmit and receive interrogative Lamb waves that are able to detect the presence of cracks, disbonds, corrosion, and other structural defects. Successful demonstrations of active SHM technologies have been achieved for civil and military aircraft components and substructures. The two major new aircraft programs (e.g., Boeing 7E7 and Airbus A380) both envision the installation of SHM equipment throughout the critical structural areas to detect impacts and monitor structural integrity (http://www.boeing.com/news/releases/2003/q2/nr_030612g.html) [1]. However, the use of active SHM in areas subjected to extreme environments and elevated temperatures has not been yet explored. The main reason for this situation is that the commonly used piezoelectric materials – for example, PZT, that is, $PbZrTiO_3$ – cannot be used above $\sim$200°C ($\sim$400°F).

Nevertheless, a considerable number of critical applications, which are subjected to extreme environments and elevated temperatures, are in need of SHM technologies. Turbine engines contain a number of components that fail due to high cycle fatigue damage. Critical engine components sustain temperatures of up to 700°C ($\sim$1300°F), speeds of up to 20,000 rpm, high vibration loads, and significant foreign object damage potential [2]. The active SHM principles could be applied for in-service detection and monitoring of critical engine damage provided the active sensors would survive the harsh high-temperature environment.

The US Air Force is developing the Space Operations Vehicle, which is going to be subject to extreme operational conditions [3]. Affordability requires reduction in launch costs. Reducing the turnaround time is the key to reducing costs. The rapid assessment of vehicle health is essential to reducing the turnaround time. Of considerable interest is the structural health of the thermal protection system (TPS) [4]. The active SHM principles could be applied for detection and monitoring of critical TPS damage if the active sensors could survive the harsh temperature environment.

This article presents a preliminary study with the main purpose of identifying the possibility of developing PWAS transducers for *in situ* interrogation of damage state in structural materials subjected to extreme or harsh environments.

## 2 State of the Art: Attempts to Use Active SHM in Harsh/Extreme Environments

Elevated temperature effects on guided waves for SHM using piezoelectric transducers have been reported by a number researchers for temperatures up to 150°C [5,6]. For harsh/extreme environment applications at even higher temperatures (e.g., up to $\sim$700°C), only a few tentative trials have so far been reported [2]. However, the experiments were impeded by the low-temperature tolerance of the PZT material and the need for transferring data from a rotating frame. Other researchers considered the use of built-in piezoelectrics for indirectly detecting impacts and damages in TPS panels by monitoring the cooler attachments points with ingeniously conceived piezo washers [7]. Olson et al. [8] studied the feasibility of using active SHM on TPS panels to indirectly detect TPS fastener damage by placing piezoelectric transducers not on the TPS panel but on the cooler support structure. It is apparent that the temperature limitations of conventional piezoelectric materials present an important obstacle in the direct implementation of active SHM methods to harsh/extreme environment applications.

Developments in piezoelectric materials have brought forward classes of materials that preserve their piezoelectric properties at elevated temperatures. There are several requirements that must be rigorously addressed when considering piezoelectric materials for high-temperature applications [9,10]. The Curie transition temperature must be well above the operating temperature; otherwise, the piezoelectric material may depolarize under combined temperature and pressure conditions. The thermal energy causes displacement of domain walls, leading to the large power dissipation and hysteretic behavior, especially when temperature is close to the Curie transition temperature. The temperature variation may produce pyroelectric charges, which may interfere with the piezoelectric effect. In addition, many ferroelectrics become conductive at high temperatures, leading to the charge drifts and partial loss of signal. The conductivity problem is aggravated during operation in atmosphere with low oxygen content, in which many oxygen-containing ferroelectrics may rapidly loose oxygen and become semiconductive. In our study, we investigated the available literature in order to identify piezoelectric compositions that could be used to construct high-temperature piezoelectric wafer active sensors (HT-PWAS), such as aluminum nitride (AlN) [11–13], polymer-derived ceramics [14], gallium orthophosphate ($GaPO_4$) [15], and so on. Considering the availability, we chose $GaPO_4$ to fabricate HT-PWAS in this study.

$GaPO_4$ is considered the 'high temperature brother of quartz' [15]. It shows remarkable thermal stability up to temperatures above 970°C (1778°F). Furthermore, it displays no pyroelectric effect and no outgassing. It has a high electric resistivity that guarantees high-precision piezoelectric measurements. The first industrial application of $GaPO_4$ single crystals was in miniaturized pressure transducers for internal combustion engines using the direct piezoelectric effect [16]. These sensors have been produced since 1994 and are now well established in the market [17]. In our work, we have identified a supplier (Piezocryst Inc., Austria) that was able to provide $GaPO_4$ wafers as per our specification. The wafers were x-cut $GaPO_4$ single crystal disks of 7 mm diameter and 0.2 mm thickness. All the PWAS transducers discussed in this article have the same dimensions. The wafers had a triple-layer structure: electrode, $GaPO_4$ thin film crystal, and electrode (Figure 1). The electrodes were sputtered Pt layers with a thickness of 100 nm. These wafers were used to construct HT-PWAS and subjected to a series of tests to characterize their properties at room temperature (RT) and at various elevated temperatures.

## 3 Tests of Free $GaPO_4$ HT-PWAS

A series of confidence-building tests were performed on free $GaPO_4$ HT-PWAS in order to determine their intrinsic behavior at increasing temperatures. This intrinsic behavior will serve as a baseline before testing the behavior of HT-PWAS attached to structural specimens. The testing of free $GaPO_4$ HT-PWAS consisted of the following:

- Electromechanical (E/M) impedance tests of free $GaPO_4$ HT-PWAS after exposure to oven high temperature;
- E/M impedance tests of free $GaPO_4$ HT-PWAS during exposure to high-temperature environment in the oven; and
- Microstructural, crystallographic, and chemical investigation of $GaPO_4$ HT-PWAS.

Details of these tests and their results are given in the following subsections.

### 3.1 E/M Impedance of Free $GaPO_4$ HT-PWAS after Exposure to High Temperature

The presence of piezoelectric response in the high-temperature PWAS after exposure to high-temperature conditions was determined with the E/M impedance method [18]. The principles of the E/M impedance method are as follows: when excited by an alternating electric voltage, a

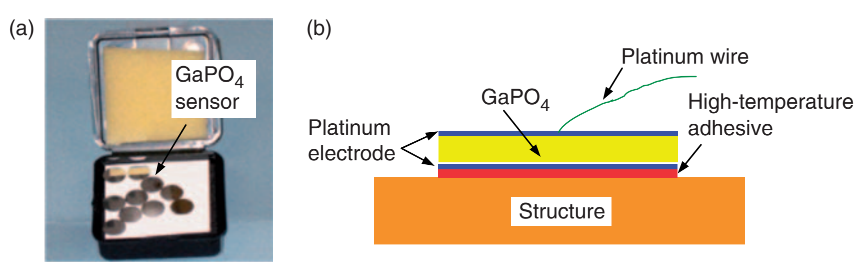


**Figure 1** $GaPO_4$ sensors: (a) photo of sensor and (b) schematic of sensor bonded on structure.

piezoelectric sensor acts as an E/M resonator converting electrical energy into acoustic mechanical energy back and forth through the piezoelectric effect. The spectral peaks observed in the real part of the E/M admittance spectrum follow the PWAS resonances, whereas those observed in the real part of the E/M impedance spectrum follow the PWAS antiresonances. When the PWAS piezoelectric activity diminishes, these spectral peaks will also diminish. Thus, the presence of such spectral peaks is an indication that the PWAS is maintaining its piezoelectric properties. Changes in the location and amplitude of these spectral peaks would be indicative of changes in the piezoelectric and mechanical properties of the PWAS due to high-temperature exposure. If the spectral peaks 'die out', then we would infer that the PWAS piezoelectric property has been lost. To understand the behavior of high-temperature materials (e.g., $GPO_4$) in comparison with conventional piezoelectric materials (e.g., PZT), both $GaPO_4$ and PZT PWAS transducers were tested.

In our experiments, we used PZT piezoceramic round PWAS and $GaPO_4$ single-crystal round HT-PWAS of 7-mm diameter and 0.2 mm thickness. For each set of PWAS, we first measured the E/M impedance at RT and then after exposure to increasingly higher temperatures in an oven. Each oven exposure lasted 30 min, after which the PWAS were extracted from the oven and allowed to cool in air at RT. The E/M impedance spectrum of the cooled PWAS was measured, and the procedure was repeated up to the oven maximum temperature of 1300°F (~705°C). Figure 2 compares the behavior of PZT PWAS with that of $GaPO_4$ HT-PWAS for various temperature levels. Figure 3 shows impedance spectra of $GaPO_4$ HT-PWAS at further elevated temperatures, that is, 1000°F, 1200°F, and 1300°F (~540°C, ~650°C, and ~705°C, respectively). The $GaPO_4$ PWAS maintained piezoelectric properties and showed strong spectral peaks after oven exposure to 1300°F (~705°C), while the PZT PWAS failed after oven exposures above 500°F (~260°C) indicated by the flat impedance spectra at 600°F and 700°F (~315°C and ~370°C, respectively). Frequency locations of the strong spectral peaks vary a little with respect to temperature, which indicates that the piezoelectric and mechanical properties are well maintained. These results are very promising and warranted the continuation of the investigation. However, it is also worth to note the vertical shift of the spectra caused by temperature variations. Future work is recommended to understand this phenomenon.

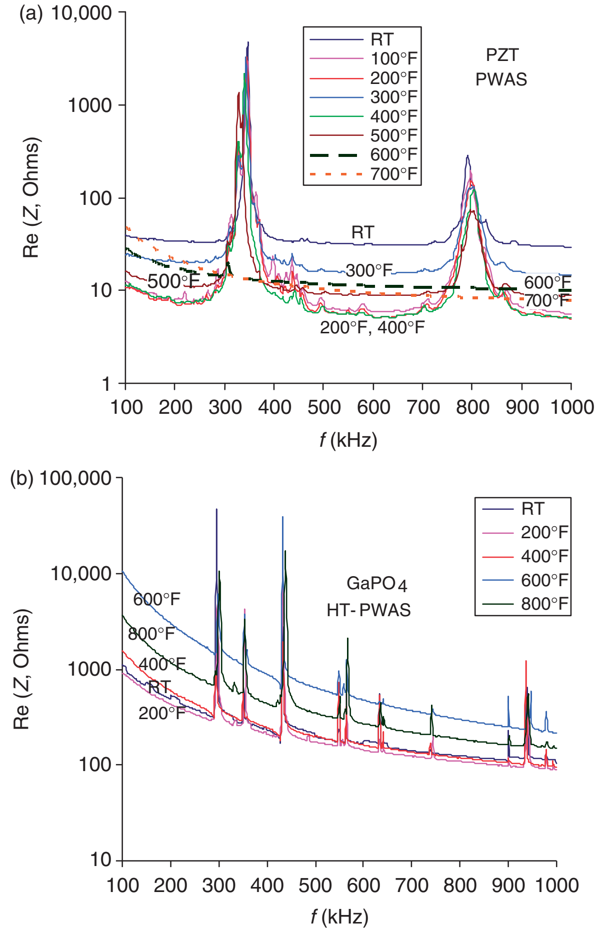


**Figure 2** PWAS impedance spectrum variation with temperature (measured at RT after exposure to the elevated temperatures): (a) low-temperature PZT PWAS 'dies' out between 500°F and 600°F and (b) high-temperature $GaPO_4$ HT-PWAS remains active.

## 3.2 E/M Impedance of Free GaPO4 HT-PWAS Instrumented in Oven High-temperature Environment

In these tests, we aimed to prove that E/M impedance can be measured while the HT-PWAS is being exposed to high temperatures inside an oven. Figure 4 shows the experimental setup for these tests. A free $GaPO_4$ HT-PWAS was inserted

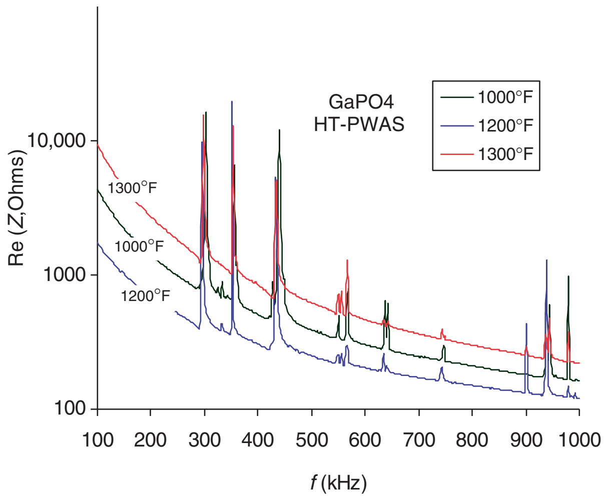


**Figure 3** $GaPO_4$ PWAS maintains its activity during high-temperature tests (measured at RT after exposure to the elevated temperatures, 1300°F was the oven limit; the $GaPO_4$ PWAS may remain active even above1300°F).

in an oven and its electrode wires insulated by ceramic tubes were fed out of the oven through a ventilation port and connected to an impedance analyzer (Figure 4).

A high-temperature electrically conductive adhesive PryoDuct 597 was used for wiring the HT-PWAS electrodes, as shown in Figure 5. The oven temperature was gradually increased from RT to 1300°F (~705°C) in 200°F steps. Both the HT-PWAS and wiring survived oven high temperatures. The E/M impedance spectrum was measured while the HT-PWAS was remaining in the oven, as shown in Figures 6 and 7. It was found that

(1) Below 1000°F, the impedance spectra overlap well with each other. This indicates that the oven temperature difference does not affect $GaPO_4$ HT-PWAS E/M impedance and piezoelectric properties much.

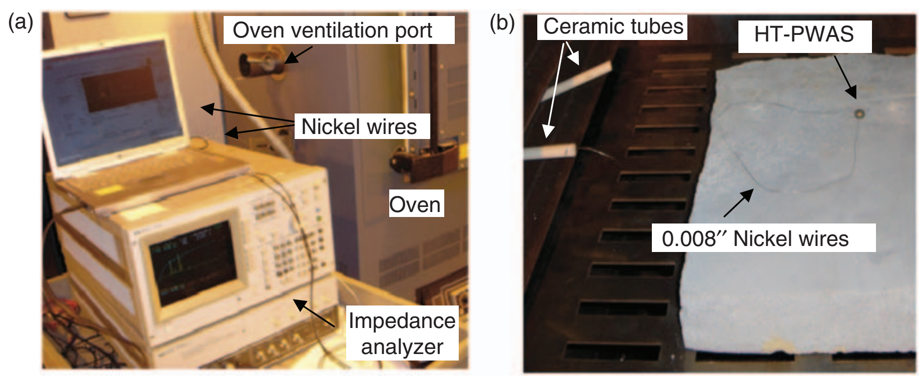


**Figure 4** Experimental setup of HT-PWAS impedance measurement in oven: (a) outside oven and (b) inside oven.

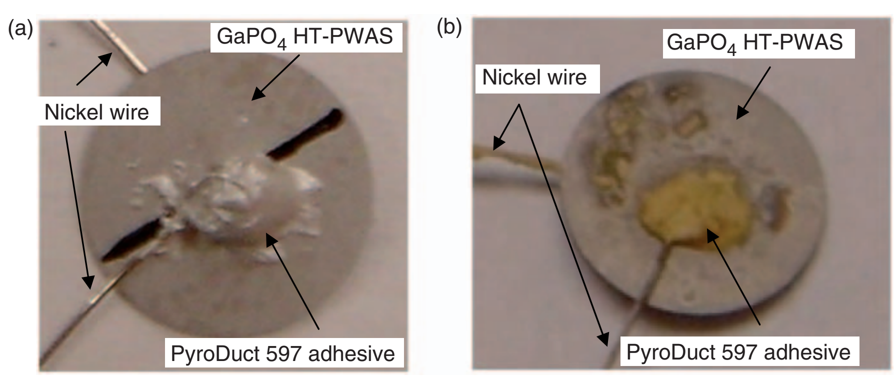


**Figure 5** Free $GaPO_4$ HT-PWAS with nickel wires attached on both electrodes using PyroDuct 597A adhesive: (a) before oven and (b) after 1300°F high-temperature exposure.

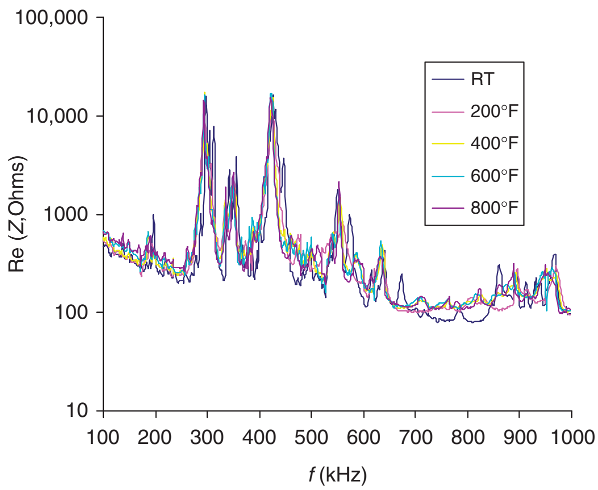


**Figure 6** $GaPO_4$ HT-PWAS impedance spectrum measured at temperatures ranging from RT to 800°F.

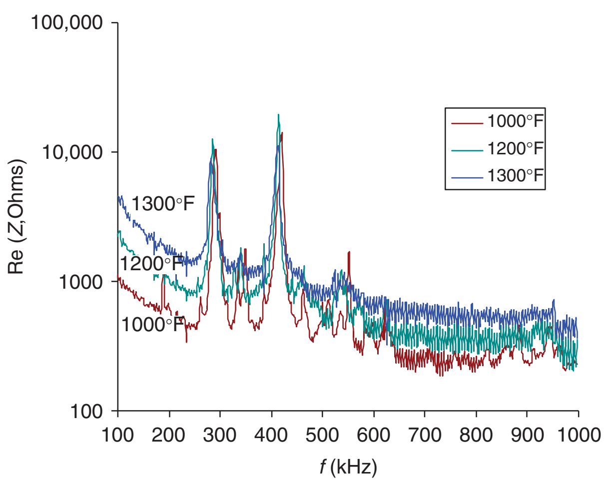


**Figure 7** $GaPO_4$ HT-PWAS impedance spectrum variation with temperature ranging from 1000°F to 1300°F.

(2) At higher oven temperatures (1000°F, 1200°F, and 1300°F), strong antiresonance E/M impedance peaks in low frequency were preserved and correlate well with the antiresonance peaks at the other temperatures. However, the real part of the impedance drifts toward negative values at high frequencies, implying that energy is flowing from the sensor to the instrument. This fact cannot be fully explained at this stage and should make the object of future investigations exploring various possible explanations such as pyroelectric effect, thermoelectric effect, electrochemical effect (oxidation acting as a battery), and so on. Vertical offsets were used when plotting Figure 7 to compensate for this effect. The offsets were set to 200 Ω at 1000°F, 500 Ω at 1200°F, and 1200 Ω at 1300°F, respectively.

(3) Impedance spectra shown in Figures 6 and 7 are not as smooth as those measured at RT, shown in Figures 2 and 3. This fact cannot be explained at this stage and should make the object of future investigations.

### 3.3 Microstructural, Crystallographic, and Chemical Investigation of $GaPO_4$ HT-PWAS

Since the HT-PWAS will be working in a high-temperature environment, it is considered useful to perform microstructural examination to identify if any degradation took place when the HT-PWAS was exposed to high temperatures. To achieve this objective, the microstructure of the HT-PWAS was examined using scanning electron microscopy (SEM), X-ray diffraction (XRD), and energy dispersive spectrometry (EDS) techniques. The examinations were performed on two $GaPO_4$ HT-PWAS cases (a) as received, that is, exposed to RT only and (b) after exposure to 1300°F (~705°C) for 4 h. The SEM images, XRD spectra, and EDS spectra for the two HT-PWAS cases are shown in Figures 8–10, respectively. Comparison of the results reveals that little variation could be identified between these two cases.

## 4 Tests of HT-PWAS Attached to Structural Specimens

The tests presented in Section 3 show that the $GaPO_4$ HT-PWAS could be a good candidate for high-temperature applications. This section is to investigate if $GaPO_4$ HT-PWAS can be employed for SHM applications, including (1) fabrication of $GaPO_4$ HT-PWAS, (2) E/M impedance experiments with $GaPO_4$ HT-PWAS, and (3) pitch-catch experiments with $GaPO_4$ HT-PWAS.

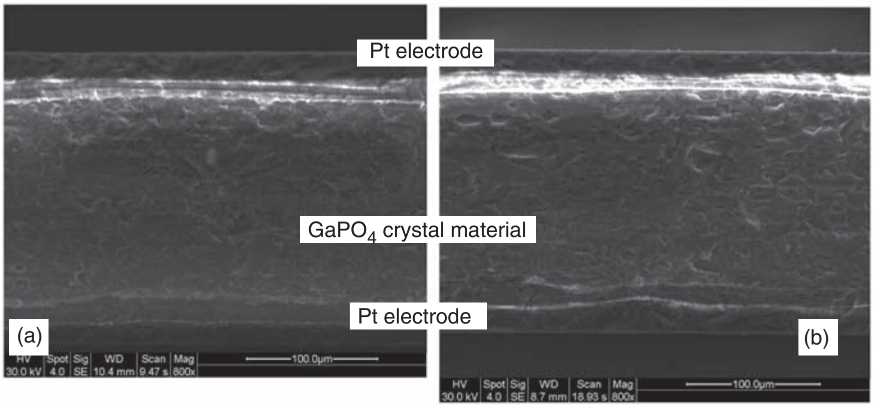


**Figure 8** Cross-sectional SEM images of $GaPO_4$ HT-PWAS samples: (a) before and (b) after exposed at 1300°F (~705°C) for 4 h.

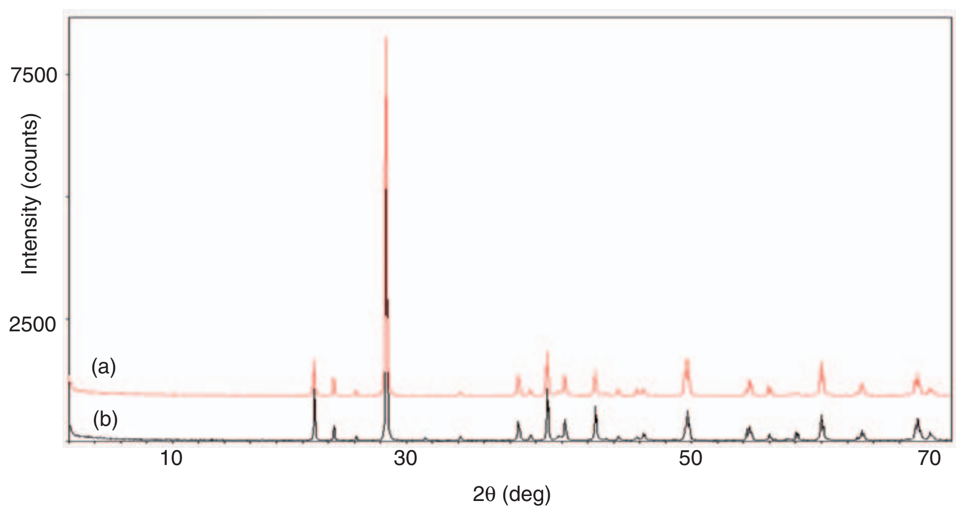


**Figure 9** XRD spectra of HT-PWAS samples: (a) before and (b) after exposure to 1300°F (~705°C) for 4 h (pictures were separated in the illustration by intentional vertical shift).

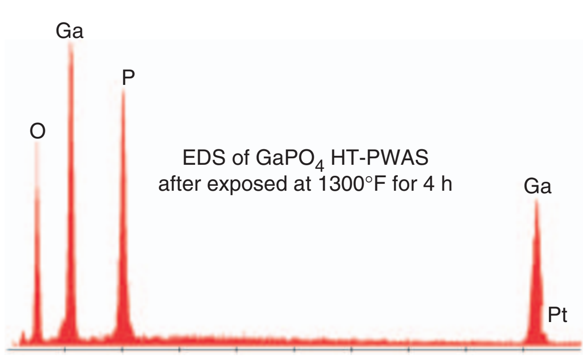


**Figure 10** EDS spectra of $GaPO_4$ HT-PWAS samples before and after exposure to 1300°F (~705°C) for 4 h are indistinguishably the same (for brevity, only one spectrum is presented).

### 4.1 Fabrication Aspects and Challenges of HT-PWAS Instrumentation on Structural Specimens for High-temperature SHM Experiments

It should be remembered that the HT-PWAS is not just of the piezoelectric material but the whole transducer consisting of piezo material, electrodes, adhesive, wire, and connections. In order to achieve successful high-temperature performance, all these components must work together in the high-temperature environment.

Instrumentation of structural specimens with HT-PWAS involves several specific aspects including (a) selection of appropriate instrumentation

**Table 1** High-temperature adhesives.

| *Adhesive Type* | *Cermabond 571* | *Sauereisen cement 33S* | *Cotronics 7030* | *Cotronics 989* | *PyroDuct 597A* |
|---|---|---|---|---|---|
| Base | Magnesium oxide | Silicate-based cement | $SiO_2$ | $Al_2O_3$ | Silver |
| Service Temperature (F) | 3200 | 1600 | 1800 | 3000 | 1700 |
| CTE ($10^{-6}$/°F) | 7.0 | 9.48 | 7.5 | 4.5 | 9.6 |
| Heat cure (°F, h) | 200, 2 | 180, 4 | 150, 4 | 150,4 | Air dry, 2, then 200, 2 |

wires, (b) connection of the signal and ground wires to the HT-PWAS electrodes and to the specimen, and (c) selection of the appropriate adhesive for bonding the HT-PWAS to the high-temperature structure. It was found that none of the polymeric adhesives, copper wire, and tin solder used in the conventional PWAS installations could be used for high-temperature applications. A fundamental requirement for a HT-PWAS experiment is that the piezoelectric material, the electrodes, the wire, the wire/electrode connection, the bonding layer between the HT-PWAS and the structural substrate, and the HT-PWAS grounding must all survive the high-temperature environment. In order to ensure *in situ* durability, the coefficients of thermal expansion (CTE) of the piezoelectric and electrode materials must be close; otherwise, the electrode/dielectric interface will suffer after cyclic high-temperature exposure.

Platinum (Pt) and Nickel (Ni) wires of 0.01 in. (25 μm) and 0.02 in. (50 μm) diameter were selected for wiring; they were procured from World Precision Instruments Inc. At the onset of the project, the largest obstacle was the electrical connection of the Pt/Ni wire to the platinum electrode of the HT-PWAS. Two wiring approaches were tested: (1) welding of the Pt/Ni wire using a spot welder and (2) bonding of the Pt/Ni wire using high-temperature electrically conductive adhesive. The first approach did not work in tests to weld a 25 μm or 50 μm Pt/Ni wire to the 0.1 μm thick Pt electrode existing on the $GaPO_4$ crystal is quite a challenge; however, such achievements have been reported elsewhere [19]. We were successful in connecting Pt/Ni wires to Pt electrodes with the high-temperature electrically conductive adhesive PryoDuct597A from Aremco Inc.

The high-temperature E/M interface, that is, the high-temperature bonding layer between the HT-PWAS and the structural substrate is another challenging step in the development of HT-PWAS. Several high-temperature adhesives of different composition, service temperature, and CTE were acquired and tested (Table 1). We found that most high-temperature cements are intended for rough usage, whereas the HT-PWAS are thin and fragile. The cements with large particles in their composition (e.g., Cermabond 571, Sauereisen cement, and Cotronics 7030) resulted in cracked HT-PWAS when used. However, we obtained good results with Cotronics 989, which is an $Al_2O_3$-based adhesive with fine composition particles. The bond layer formed with this adhesive was found to be thin, uniform, and strong; we believed that this bond is good for coupling the ultrasonic strains between the HT-PWAS and the structure.

### 4.2 Impedance Tests of Structural Specimens Instrumented with $GaPO_4$ HT-PWAS

The E/M impedance testing of structural specimens reveals the high-temperature structural resonance spectrum of the specimen in the form of the E/M impedance spectrum measured at the PWAS terminals; if damage appears in the structure, then its high-frequency resonance spectrum will change and the changed spectrum will be captured by the real part of the E/M impedance measured at the PWAS. So far this approach has been verified at RT (see Giurgiutiu [18] for an extensive description of this method).

An example of a fabricated $GaPO_4$ HT-PWAS on a structural specimen (Ti disk with 1 mm thickness, 100 mm diameter) is shown in Figure 11. The $GaPO_4$ HT-PWAS was bonded to the disk

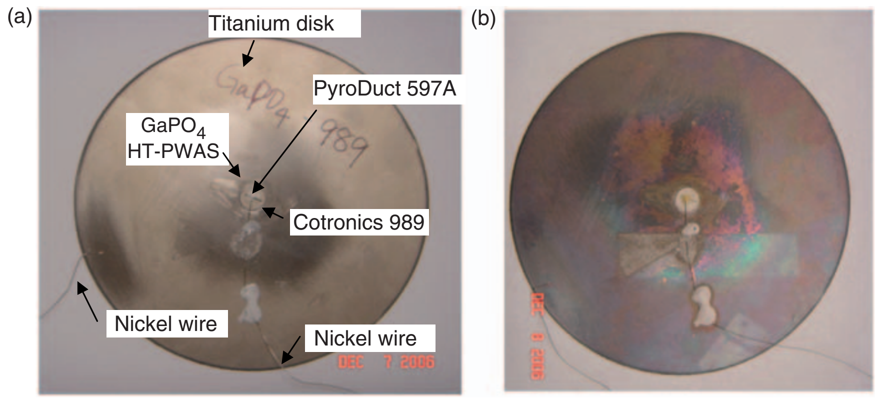


**Figure 11** $GaPO_4$ HT-PWAS mounted and wired on a Ti plate specimen: (a) before and (b) after exposure to high temperature up to 1300°F.

with Cotronics 989 high-temperature adhesive. A Ni wire was bonded with PryoDuct597A to the center of Pt electrode on the $GaPO_4$ HT-PWAS. Another Ni wire was welded with a Unitek Equipment 60 W·s spot welder to the edge of the Ti disk acting as electrical ground. The Ni wire was also affixed to the Ti disk with Cotronics 989 to ensure mechanical reliability. After heat curing the adhesives, the specimen was subjected to in-oven E/M impedance testing. Figure 11(a) shows the structural specimen instrumented with the $GaPO_4$ HT-PWAS when ready to be subjected to oven testing. Figure 11(b) shows the same specimen after being tested in oven at 1300°F (~705°C).

Both the HT-PWAS and the wiring survived the oven test. The real part of the E/M impedance spectra of the specimen instrumented with $GaPO_4$ HT-PWAS were measured before and after high-temperature exposure. This test was an extension of the confidence-building tests described in Section 3.1 and was intended to validate that the HT-PWAS instrumentation can survive the harsh high-temperature conditions. For practical applications, this situation would correspond to the situation in which a certain component is interrogated before and after high-temperature exposure in order to assess if damage was induced by the harsh environment. Test results are shown in Figure 12. It can be seen that, after exposure to 1300°F (~705°C) oven temperature, the HT-PWAS is still alive as indicated by the big peak in the impedance spectrum. However, the results are not as crisp as in the tests of free $GaPO_4$ HT-PWAS described in Section 3.1. The reason for this behavior may lie in the fact

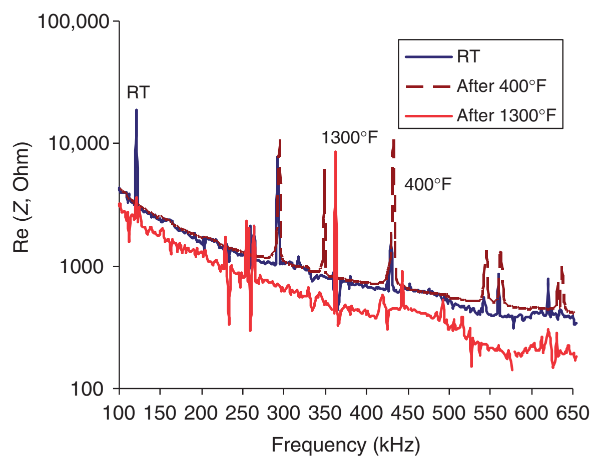


**Figure 12** Real part E/M impedance spectra of HT-PWAS on Ti disk measured at RT, 400°F, and 1300°F.

that instrumented specimen is more complex than a free HT-PWAS. The bonding between the HT-PWAS and the structure and the electrically conductive bonding of the wires to the HT-PWAS electrodes might have been affected by the high-temperature exposure. More tests and post-test evaluation together with modeling of the affected interfaces are required to clarify the origin of these changes. However, this could not be done during the investigation reported here and has to be deferred to future work. In addition, we suggest for future work the measurement of the E/M impedance of a disk specimen instrumented with $GaPO_4$ HT-PWAS while being exposed to high temperature in the oven. This corresponds to the case when a structure is continually monitored while being exposed to the harsh high-temperature environment.

### 4.3 Pitch-Catch Experiments between HT-PWAS

Pitch-catch tests of HT-PWAS consist of two parts. In the first part, pitch-catch tests of $GaPO_4$ HT-PWAS and PZT-PWAS at RT were compared. In the second part, pitch-catch tests were performed with the $GaPO_4$ HT-PWAS immersed in a high-temperature environment. For this purpose, structural specimens with attached $GaPO_4$ HT-PWAS were inserted in an oven and connected to the outside instrumentation through nickel wires insulated from the oven using ceramic tubes.

**4.3.1 Pitch-Catch Experiments of HT-PWAS and PZT-PWAS at RT** It is a known fact that the piezoelectric coefficients of high-temperature formulations (e.g., $GaPO_4$) are smaller than those of RT formulations (e.g., PZT). Hence, the question arises to whether $GaPO_4$ PWAS, though resistant to high-temperature exposure, has sufficient piezoelectric activity to act as a surface mounted ultrasonic transducer similar to PZT PWAS. To clarify this issue, we performed pitch-catch experiments on a 1-mm thick titanium plate on which ultrasonic waves packets were sent between PZT-PWAS and HT-PWAS transducers. The distance between the transmitter and receiver was 127 mm. The experimental setup consists of a HP33120 signal generator, a Tektronix TDS5034B digital oscilloscope, and a KH7602 wideband amplifier. A 3-count sinusoidal burst excitation of 360 kHz was amplified and fed into the transmitter PWAS to excite S0 mode guided Lamb waves into the specimen. High number averaging on the digital oscilloscope capture (64 and 128) was used successfully to reduce the noise level during these experiments.

The propagated Lamb waves were picked up by the receiver PWAS and displayed on the digital oscilloscope to record the amplitude of the first arrival. A summary of all the pitch-catch results is given in Figure 13.

These RT tests showed that

(1) $GaPO_4$ PWAS can be successfully used as both transmitter and receiver of ultrasonic guided Lamb waves in a high-temperature structure, for example, titanium plate.

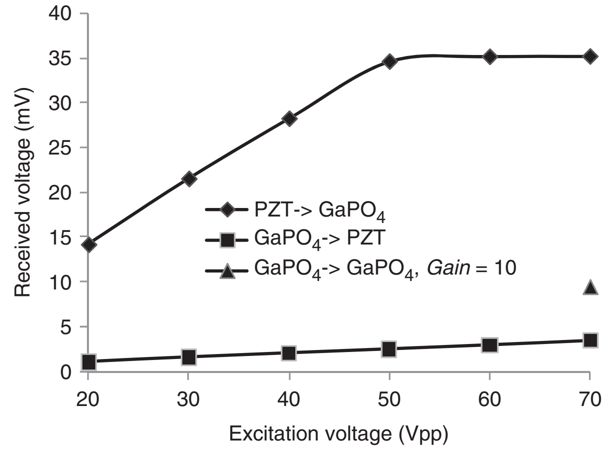


**Figure 13** Pitch-catch results of PZT PWAS and $GaPO_4$ PWAS.

(2) The piezoelectric property of $GaPO_4$ is weaker than that of PZT, and hence, a stronger excitation voltage is required.
(3) $GaPO_4$ PWAS pairs are weaker transmitter–receiver pairs than PZT–PZT or PZT–$GaPO_4$ pairs. A charge amplifier with *Gain* = 10 was used to boost the receiver signal level for the pitch-catch between $GaPO_4$ HT-PWAS transducers. The charge amplifier was custom built details can be found in Giurgiutiu and Lyshevski [20].

The strengths of the received signals indicate that long-distance propagation of ultrasonic signals produced by these high-temperature transducers is feasible.

**4.3.2 In-oven Pitch-Catch Tests of HT-PWAS Attached to Structural Specimens**

***4.3.2.1 Specimen Preparation for High-temperature Pitch-Catch Experiment*** The in-oven high-temperature pitch-catch experiments with $GaPO_4$ HT-PWAS were conducted on a rectangular steel plate, as shown in Figure 14.

The specimen was subject to a series of oven temperatures ranging from 300°F to 1000°F, with step size of 100°F. The excitation applied to the HT-PWAS transmitter was a 3-count sinusoidal burst (70 Vpp strength, 65 kHz central frequency). A charge amplifier located outside of the oven is used for the data acquisition. The charge amplifier

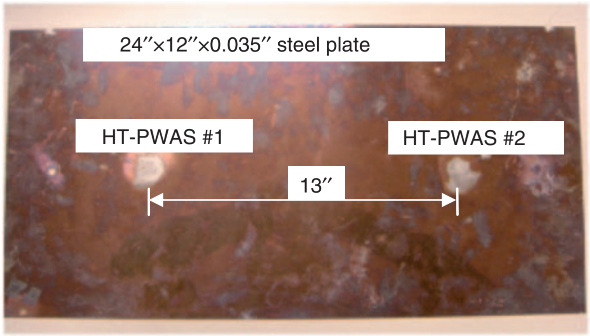


**Figure 14** HT-PWAS pitch-catch specimen after oven high-temperature exposure.

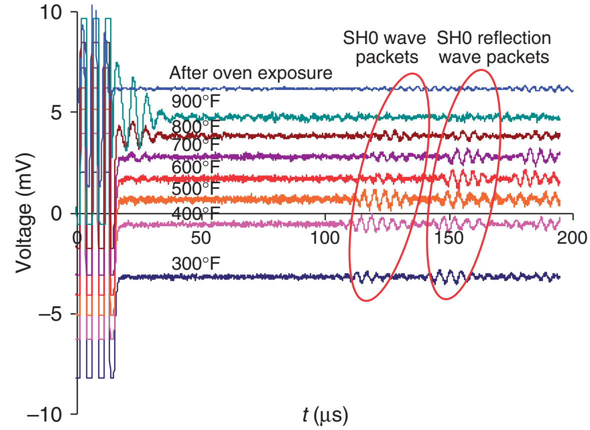


**Figure 15** HT-PWAS in-oven pitch-catch waveforms at different temperatures.

was custom built in LAMSS; details can be found in Giurgiutiu and Lyshevski [20, pp. 830–832]. The wave packets received at the HT-PWAS transducer were recorded on a digital oscilloscope. Signal averaging on the oscilloscope was set to 128. The first arrival wave packet in the received signal corresponds to the Lamb wave SH0 mode with a group velocity of around 2.9 mm/μs (13 in./115 μs), which is close to the theoretical value of ~3 mm/μs. One notices that the SH0 wave packets reflected from the edge. From 300°F to 800°F oven temperature, all the wave packets could be easily identified; some amplitude changes and time shifts were noticed. This implies that the piezoelectric properties of $GaPO_4$ sensor did not undergo severe change. After the temperature reached 900°F, no wave packets were observed in the received waveform, as shown in Figure 15. After the specimen was removed from the oven and cooled down to RT, the pitch-catch experiment was conducted once again. Attentive examination of top trace in Figure 15 reveals that the HT-PWAS transducer was still active, but the amplitude of the wave packet was very small. We believe that this may be due to the failure of the bonding layer between the HT-PWAS and the structure because the study of free HT-PWAS has indicated that the HT-PWAS can successfully maintain its activity after exposure to this temperature (e.g., Figure 3). To examine the pitch-catch waveforms at the other elevated temperatures, more pitch-catch experiments with improved HT-PWAS bonding layer are suggested in the future work.

## 5 Conclusions

This article presented the development of HT-PWAS using $GaPO_4$ material for SHM applications in harsh environments. The work reported in this article is exploratory in nature with the main purpose of identifying the possibility of developing PWAS transducers for high-temperature applications. From this view point, the present work has reached its objective and has shown that a certain class of HT-PWAS (e.g., those using $GaPO_4$) remains active at the tested high temperatures. $GaPO_4$ HT-PWAS has weaker piezoelectric properties but much higher working temperature than PZT-based PWAS. In this study, the $GaPO_4$ HT-PWAS were tested and shown to maintain their piezoelectric properties at up to 1300°F (~705°C), whereas conventional PZT sensors lost their activity at around 500°F (~260°C). Material characterization tests (SEM, XRD, EDS) showed that the high-temperature exposure did not affect the microstructure and chemical ingredients of the $GaPO_4$ HT-PWAS. On the positive side, this study has shown through the E/M data for the free HT-PWAS that strong peaks are displayed after exposure to high temperatures as well as when measured in the oven high-temperature environment. This is indicative of piezoelectric transduction capability being retained at the tested high temperatures. Also on the positive side, this study has shown that HT-PWAS attached to structural elements maintain their activity at the indicated high temperatures being able to act as modal sensors (E/M impedance method) as well as pitch-catch transducers. On the negative side, some premature loss of piezoelectric activity was noted with the HT-PWAS attached to structural elements, which possibly can be attributed to the failure of the high-temperature adhesive.

Therefore, $GaPO_4$ material can be considered a good candidate for the fabrication of HT-PWAS. With careful selections of the high-temperature wiring and bonding layer adhesive, $GaPO_4$ HT-PWAS trials were successfully fabricated and used to instrument structural specimens. Tests of these instrumented structural specimens were performed at elevated temperatures using E/M impedance and pitch-catch techniques. However, loss of activity was observed at temperatures at which the free HT-PWAS were found to perform successfully, indicating that the weak link may be the bonding layer. Therefore, it is pointed out that a reliable high-temperature bonding layer is essential for ensuring the performance of structurally attached HT-PWAS at high temperatures.

It is apparent that this exploratory study needs to be followed by additional work to investigate the details of behavior of such HT-PWAS at various temperatures and explain some intriguing aspects (e.g., shifts toward negative values in the real part of the E/M impedance). Future work should also aim at developing reliable high-temperature bonding agents and surface electrodes and to further verify the capability of structurally attached HT-PWAS for damage detection in harsh environment for SHM. Future work should also include the temperature effects on the guided waves propagation in structures during the SHM process.

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