Feasibility Study of Langasite Wafer Active Sensors for High Temperature Structural Health Monitoring

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Abstract

Piezoelectric wafer active sensors (PWAS) have been developed for structure health monitoring (SHM) for years, however, SHM at extreme environments has rarely been attempted due to the low phase transition temperature of common piezoelectric materials. In this paper, new piezoelectric materials-Langasite (LGS) has been selected for a pilot study for structure health monitoring applications. A preliminary study is performed to verify the possibility of developing the LGS high temperature piezoelectric wafer active sensors. The E/M impedance method is applied to detect the frequency behavior of the PWAS. Experiments that verify the basic frequency behavior of the LGS PWAS in high temperature environments have been carried out. Further validations are conducted by testing structures attached by LGS PWAS at elevated temperatures. The results, at the first time, show that LGS is ideal to make piezoelectric wafer active sensors for high temperature structure health monitoring applications.

Keywords: Structure health monitoring, Piezoelectric wafer active sensor, Langasite, E/M impedance, High temperature

1. Introduction

Structural health monitoring (SHM) assesses the health of structures through appropriate data that can be used to predict the remaining life of the structure. Small and lightweight piezoelectric wafer active sensors (PWAS) permanently attached to structures are used to transmit and receive ultrasonic waves that are able to detect the presence of cracks, corrosion, and other structural defects (Giurgiutiu, 2002). They are small, nonintrusive, inexpensive, non-resonant devices with wide band capabilities (Giurgiutiu, 2004). Demonstrating active SHM technologies based on piezoelectric material are very useful for construction and military applications.

Many achievements in the past have been made for the detection of the health information of structures based on the PWAS. Crawley and Luiz (1987) presented the use of piezo-ceramic wafers as elements of intelligent structures. Dimitriades et al. (1991), D’Cruz (1993) and Zhou et al. (1996) used piezoelectric wafer to produce structural excitation, and Banks (1996) developed experiments using Lead zirconate titanate (PZT) wafer for both excitation and sensing the free decay response. Wang and Chen (2000) proposed to use a PZT wafer to excite the structure and an array of PVDF film sensors to gather vibration response to generate the frequencies and mode shapes. Giurgiutiu (2002, 2003, 2004) has reported embedded ultrasonic structural radar with PZT for aging aircraft and thin-wall structures. Park et al. (2006) identified degradation of the mechanical/electrical properties of a PZT transducer and the bonding defects between a PZT patch and a host structure. Qing et al. (2008) presented an active SHM system with piezoelectric sensors for liquid rocket engines which are exposed to the flight vibration and shock environments under cryogenic temperatures. Olson (2007) reported the beam forming of Lamb waves for structural health monitoring. However, all of the work mentioned above focuses on SHM for structures at normal temperatures; when the structure components are exposed to extreme environment, in-situ SHM based on PWAS is extremely challenging due to the low phase transition temperature of PZT material. For example, PZT cannot be used for the in-situ SHM for thermal protection system (TPS) of future high speed aerospace vehicles in AFRL’s (Air Force Research Laboratory) integrated vehicle health management system, as the surface temperature is extremely high (~1000°C) (Rosenstengel, et al., 2004). One possible way to implement the PWAS for SHM of TPS is to attach the PZT sensors to the cool side of the backing structure; however, this will cause the inevitable
complexity of indirect actuation and sensing. A promising approach to address the difficulties for high temperature 
SHM is to use a high temperature piezoelectric material to make the PWAS. For instance, in a recent work, 
Giurgiutiu (2002) has performed a preliminary test using GaPO₄ as the PWAS for SHM application. In this paper, 
we present a preliminary study with the main purpose of identifying the possibility of developing PWAS 
transducers with a new high temperature piezoelectric material, Langasite (LGS), for in situ interrogation of 
damage state in structural materials subjected to high temperature environments. E/M impedance method 
generated by Liang, et al. (1994) will be used here to measure the frequency behavior of the PWAS. The 
interaction between the mechanical impedance of the host structure and the electrical impedance of the transducer 
could be an indicator of the health of the structure (Cawley, 1984).

2. Sample preparations

A LGS sample is cut into a thin, square plate, and the dimensions are shown in Table 1. The material 
orientation is YXI θ=75° and the sensor is operating at thickness shear mode. The averaged dimensions used in the 
calculation were measured at five different points with an electric caliper. The surface of this wafer has been 
coated by gold as electrodes.

<p>| Table 1  Dimensions of LGS samples. |</p>
<table>
<thead>
<tr>
<th>Geometry</th>
<th>Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (mm)</td>
<td>8.50</td>
</tr>
<tr>
<td>Width (mm)</td>
<td>8.50</td>
</tr>
<tr>
<td>Thickness (mm)</td>
<td>0.55</td>
</tr>
</tbody>
</table>

A Ti round plate was used as the host structure with 1mm thickness and 100 mm diameter as shown in Fig. 1. 
The reason to use Ti plate is that they can survive well at the high temperature range.

3. Experiment setup

Since we are going to validate the high temperature properties of LGS, an experiment with three steps needs 
to be conducted for both of them. During these tests, the piezoelectric property in high temperature environment 
will be measured by E/M impedance method. This section contains three parts test for LGS as follows and these 
steps will be conducted for LGT as well.

3.1 Tests of Free LGS PWAS in High-temperature Environments

For the first step, we are going to prove that a langasite wafer sensor could maintain its piezoelectricity while 
being exposed to high temperatures. The principles of the E/M impedance method are as follows: when excited by 
an alternating electric voltage, a piezoelectric sensor acts as an E/M resonator converting electrical energy into 
aoustic mechanical energy back and forth through the piezoelectric effect (Liang, et al., 1994). The E/M spectrum
obtained by E/M analyzer show spectral peaks which will disappear if the sensors are made by traditional piezoelectric material such as PZT at extreme temperature environment. Here we will heat the specimen in oven and get the E/M impedance spectrum to verify that LGS could survive at high temperatures.

Figure 2 shows the experimental setup for these tests. Since the experiment is operating under high temperature, both the glue and connected wire have to survive up to 700 °C. To satisfy this requirement, platinum wire (World Precision Instruments Inc.) and high temperature conductive glue PryoDuct597A (Aremco Inc.) were used. The oven temperature was gradually increased from RT to 700 °C in 100 °C steps. The E/M impedance spectrum was measured while the HT-PWAS was remaining in the oven. Figure 3(a) shows the box oven (model ST-1200C) made by Sentro Tech Corp. which can provide high temperature environment up to 1200 °C and Fig. 3(b) shows the Langasite sample attached with platinum wire by conductive glue in oven.

3.2 Test of Free LGS after Exposure to High Temperature

As a sensor to continuously monitor the structure integrity, the sensor will not only work during high temperature environments continuously, but also should work after cooling down. The properties need to be stable during the change of temperature to make sure the E/M impedance will not ‘die out’ after exposure to high temperature. For the langasite wafer, we measured the E/M impedance after exposure from room temperature to high temperature. Additionally, the E/M impedance spectrum was measured after cooling down for 30 minutes at each temperature, and the procedure was repeated up to 700 °C. Two results from these two steps will be compared with each other at elevated temperature to demonstrate the high temperature property.

3.3 Tests of LGS PWAS Attached to Ti plate

In order to obtain the high temperature performance when the sensor is bonded with a structure, the Ti plate mentioned before is used as the substrate. Since the sensor needs to be attached on the structure, Cotronics 989, an adhesive designed for ceramic at high temperature by Cotronics Corp., appears to be a good choice. The setup is shown in Fig. 4. The LGS sensor is bonded with Ti plate in the center with non-conductive adhesive Cotronics 989. In the meantime, the electrode is also connected with the Ti plate as ground by conductive adhesive PryoDuct597A. This setup works well after cyclic high temperature exposure based on the close thermal expansion coefficients of piezoelectric material, bond layer and structure.

4. Results

4.1 Test results

Figure 5 shows the measurement result of the free LGS PWAS exposed to high temperature environment. These clear peaks show that the free LGS PWAS maintains its piezoelectricity well at high temperature up to 700°C.

Figure 6 shows the spectrum of E/M impedance for test of free LGS after exposure to high temperatures from room temperature to 700°C. Compared to the result from Fig. 5, this E/M impedance spectrum has no significant
difference on the location of the peaks as well as their amplitudes. The test proves the LGS sensor can work continuously in high temperature environments.

Figure 7 shows the E/M impedance spectrum of LGS attached to a Ti plate, from which the peaks are clearly observed. These clear 'peaks' show this sensor is able to transmit signals when it is attached to a structure in high temperature environment and the spectrum can be used as a baseline to determine the health condition of a bonded structure.

5. Conclusions

This paper presents results to identify the possibility of developing LGS PWAS for high-temperature applications. The methodology is verified through three steps of experiments, free LGS sample in oven, free LGS exposed to high temperature and structure with LGS attached at high temperature environment, which prove the feasibility of this idea in different situations. This work not only shows free LGS remains their activity up to 700 °C but also works well when bonded with structure. From the presented results, we may conclude that LGS are good candidates to make PWAS for high temperature SHM applications. However, during the experiment, we found the high temperature wire as well as the bond lay are also critical to ensure a successful measurement. This study promotes and demonstrates a basic idea which still needs to be improved by additional modeling works to design the high temperature LGS PWAS. The working frequency and temperature range can be identified clearly in the future and a better bonded layer can be generated to improve the amplitude of signal. Generally, the concept proposed in this paper will be useful for the proper design of high temperature PWAS for structure health monitoring application.

Figure 5: E/M spectrum of free LGS in oven.
Figure 6: E/M spectrum of Free LGS after exposure to high temperature.

Figure 7: E/M spectrum of LGS attached to Ti plate.

References


