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IN-SITU FABRICATION OF COMPOSITE PIEZOELECTRIC WAFER ACTIVE SENSORS FOR STRUCTURAL HEALTH MONITORING

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ABSTRACT

Structural health monitoring (SHM) is important for reducing maintenance costs while increasing safety and reliability. Traditionally, structural integrity tests required attachment of sensors to the material surface. This is often a burdensome and time-consuming task, especially considering the size and magnitude of the surfaces measured (such as aircraft, bridges, structural supports, etc.). Temporary sensors are a hassle to install; there are some critical applications where they simply cannot accomplish the task required. Piezoelectric wafer active sensors (PWAS) can be permanently attached to the structure and offer a permanent sensor solution. Existing ceramic PWAS, while fairly accurate when attached correctly to the substance, may not provide the long term durability required for SHM. The bonded interface between the PWAS and the structure is often the durability weak link. Better durability may be obtained from a built-in sensor that is incorporated into the material.

This paper describes the work on the in-situ fabrication of PWAS using a piezoelectric composite approach. The piezoelectric composite was prepared by mixing small lead zirconate titanate (PZT) particles in an epoxy resin matrix; the mixture was then directly applied onto the surface of a host structure using a designed mask. The curing of the piezo composite was carried out at elevated temperature. After curing, the cured composite was

sanded down to the desired thickness. Finally, the piezo composite was poled under a high electric field to activate the piezoelectric effect. The resulting in-situ composite PWAS was utilized as a sensor for dynamic vibration and impact. Characterization of the in-situ composite PWAS on aluminum structure have been recorded and compared with ceramic PWAS before and after poling. To evaluate the performance of the in-situ composite PWAS, both vibration and impact tests were conducted. In-situ composite PWAS are believed to be a good candidate for reliable low-cost sensor fabrication for SHM.

INTRODUCTION

Structural health monitoring (SHM) addresses an urgent need of our aging infrastructure. In recent years, several investigators (Keilers and Chang^[1], Chang^{[2][3]}, Wang and Chang^[4], Lin and Yuan^{[5][6]}, Ihn and Chang^[7], Giurgiutiu et al^{[8][9]}, and others) have explored the generation and detection of structural waves with piezoelectric wafer active sensors (PWAS). Most of the methods used in conventional NDE, such as pitch-catch, pulse-echo, and phased arrays, have also been demonstrated experimentally with PWAS (Giurgiutiu et al.^{[9][10]}). These successful experiments have positioned PWAS as an enabling technology for the development and implementation of active SHM systems. PWAS are inexpensive, non-intrusive, un-obtrusive, and minimally invasive. They can be surface-mounted on

existing structures, inserted between the layers of lap joints, or placed inside composite materials. Figure 1 shows an array of 7 mm square PWAS mounted on an aircraft panel, adjacent to rivet heads and an electric discharge machined (EDM) simulated crack. The minimally invasive nature of the PWAS devices is apparent. A PWAS weighs 0.068 g, is 0.2 mm thick, and costs around \$7 each. In contrast, a conventional ultrasonic transducer weighs 50 g, is 20 mm thick, and costs around \$300. PWAS are used in SHM applications are able to detect structural damage using Lamb waves. PWAS are small, lightweight, unobtrusive, and low cost PWAS achieve direct transduction between electric and elastic wave energies. PWAS are essential elements in the Lamb-wave SHM with pitch-catch, pulse-echo, and electromechanical impedance methods.

Figure 1 Piezoelectric wafer active sensors (PWAS) mounted on an aircraft panel

However, there is something that needs to be addressed:

- (1) Current PWAS are adhesively bonded to the substrate structure (Figure 2a) or incorporated between the layers of a laminated structure during fabrication. This adhesive bonding between the piezoelectric active sensor and the structural substrate is the weak link in the sensory system because it deteriorates in time under environmental attacks (humidity, temperature cycles, etc.). There is an acute need for a better approach that would seamlessly connect the PWAS with the structure.
- (2) Brittle PWAS can withstand very small bending. This brittleness of the PWAS imposes difficulties in handling and bonding of the sensor into the structure monitored.
- (3) In addition, the conformability to curved surface is extremely poor so as to require extra treatment of the surfaces.^{[11][12][13]}

Figure 2 PWAS is attached to a substrate structure through the adhesive bond layer, which is susceptible to environmental attacks

The focus of our research was to create in-situ piezo active sensors using composite fabrication techniques. Composite PWAS are suitable for structural health monitoring due to the ease with which their mechanical properties may be tailored, low cost, ease of implementation, conformability to curved surface and compatibility with polymeric materials.

STATE OF THE ART

In recent years, several investigators have researched the insertion of active material powders into composite materials to create active composites for actuator and sensing applications.

PIEZOMAGNETIC COMPOSITE

Terfenol-D is a magnetic anisotropy-compensated alloy $Tb_xDy_{1-x}Fe_2$ which shows a strong magnetostrictive behavior. When subjected to mechanical strain, Terfenol-D produces magnetic field. White^[14] reviewed the magnetostrictive tagging methodology of composites for structural health monitoring and measured the response of magnetostrictive-tagged composites under axial loading. Neat resin beams tagged 2.24% by volume with magnetostrictive Terfenol-D powder were used. Trovillion *et al.*^[15] studied the magnetic characteristics of neat resin and glass-fiber-reinforced magnetostrictive composites subjected to axial load. The fiber reinforced polymer composite (FRP) beams consisted of 4 layers of continuous strand glass mat fibers embedded in a polyester resin. The top lamina of the composite was impregnated with Terfenol-D powder at a volume fraction of 2.24% for that lamina. The beams were subjected to uniaxial loading under load control at a rate of 0.02 kN/s. Rearrangement of the magnetic dipoles chains of the magnetostrictive molecules through application of

strong magnetic field was performed by applying a magnetic field through the thickness of the beam using a pair of magnets to apply a field of 800 Gauss.

Armstrong^[16] presented a new model of non-linear magneto-elastic behavior of magnetostrictive particulate composite. The analysis assumed uniform external magnetic field that is operating on a large number of well-distributed ellipsoidal magnetostrictive particles encased in a elastic, nonmagnetic composite matrix. Nersessian and Carman^[17] studied five different volume-fraction of magnetostrictive particulate composites which were tested under two different conditions: (a) constant magnetic field and varying mechanical load; and (b) constant mechanical load and varying magnetic field. The results presented for the constant load indicated a strong dependence of strain output on applied pre-stress.

Krishnamurthy *et al.*^[18] consider health-monitoring detection of delaminations in composite materials using an excitation coil and a sensing coil. The open-circuit voltage induced in the sensing coil is proportional to the stress generated in the magnetostrictive layer by the presence of the delamination.

PIEZOELECTRIC COMPOSITES

The combination of polymer and piezoelectric ceramic to form composite PWAS offers the unique blending of the high electro-active properties of piezoelectric ceramics and the mechanical flexibility and formability of organic synthetic polymers. Recently, active composite PWAS have been developed, namely 1–3 composites by Smart Materials Corp, active fiber composite developed by MIT, and macrofiber composite (MFC) actuators at NASA Langley Center. These composite PWAS are capable of being repeatedly manufactured at low cost, are tolerant to damage, capable of conforming to complex or curved surfaces, and embeddable into structures. The uses of composite PWAS need to be investigated, and would provide the advantages of being robust, reliable, and easily adaptable for impedance-based health monitoring.

Composites PWAS can be classified according to the connectivity of piezoelectric ceramics and matrix phases. The composite PWAS in this paper has a 0-3 connectivity pattern. The “0-3” means that the ceramic particles are randomly dispersed in a polymer matrix. 0-3 composites can be more easily fabricated in complex shapes than other forms of composites. Various approaches have been tried for producing 0-3 composites.^{[13] [19] [20]}

SELF-SENSING PIEZOMAGNETIC COMPOSITES EXPERIMENTS

An piezomagnetic composite beam was fabricated by combining 7 layers of a woven glass roving 36oz./sq.yd with Atlac 580-05 Urethane-modified Vinyl Ester resin. The beam was 1000 mm long, and had a 100 mm by 6.5 mm cross section. Terfenol-D tagging powder was used in the two outer laminae in the middle 500 mm of the span. Of the 1000 grams of resin used, 250 grams had the MS powder. The resin was cured with 1 % MEKP (methyl ethyl ketone peroxide) at room temperature for approximately 90 minutes. The target weight fraction of the glass fibers in the composite was $w_f = 30\%$. The weight fraction of MS Terfenol-D tagging was 15 %.

The beam was instrumented with strain gages in the mid-span section on the upper and lower surfaces. The magnetic flux density was measured with the gaussmeter. A special fixture was constructed to ensure consistent alignment of the gaussmeter probe with the composite surface and to mechanically protect it. The tip of the gaussmeter probe is made of ceramic and covers the magnetic sensor. On advice from the gaussmeter manufacturer (Lakeshore Cryotronics, Inc.) a protective wood fixture shown in Figure 8 was designed and fabricated. The distance from the tip of the sensor to the upper surface of the beam was 2 mm. The experimental setup is shown in Figure 3.

Figure 3 Experimental setup for measuring the strain-magnetic flux response of a self-sensing piezomagnetic composite beam

The magnetic flux density response of the beam is presented was measured for ten loading-unloading cycles. The zero load reading was subtracted from the other values in order to eliminate the influence of the environmental magnetic field. The relationship between magnetic flux density and strain is presented in Figure 4. The ten cycles considered in the experiment showed the reproducibility of the magnetic flux readings. The relationship between

strain and magnetic flux density was consistent and repeatable. Also noticed was that the magnetic flux had a small hysteresis. This phenomenon is present because of changes in the microscopic magnetic status of the piezomagnetic particles. The small difference between readings in different cycles illustrates the deviation expected from the use of general-purpose magnetic flux density measurement equipment.

Figure 4 Magnetic flux response with strain of a piezomagnetic composite beam

PIEZOELECTRIC COMPOSITES

Another approach considered in our research was that of piezoelectric composites. The piezoelectric composites have the advantage that electric signals can be collected directly, whereas in the case of piezomagnetic composites magnetic flux probes had to be used. Our purpose in pursuing the fabrication of piezoelectric composites was to eventually be able to achieve in-situ fabrication of PWAS of a quality comparable with that of ceramic PWAS. By fabricating the PWAS directly onto the structure a seamless bond would be achieved between the PWAS and the structure that would be impervious to environmental attacks can be created. Thus, we will eliminate the “weak link” in the present use of bonded PWAS and achieve a long time durability of the embedded sensory system.

PREPARATION OF PIEZOELECTRIC COMPOSITE PWAS PREPARATION

The epoxy resin used in the fabrication of the piezoelectric composite PWAS was EPO-TEK 301-2 from Epoxy Technology, Inc.. This epoxy has a good handling property, high dielectric strength and a low

viscosity. The mixture ratio for the epoxy part “A” and part “B” (hardener) is specified as 1: 0.35 by the supplier and was followed in this study.

Figure 5 Composite PWAS materials

The PZT particles in the composite PWAS were PZT-5B powders from Morgan Electro Ceramics. PZT-5B powders have a high sensitivity and high time stability (Figure 5).

The silver paint used for creating the electrodes was acquired from SPI Supplies and Structure Probe, Inc.

The poling workstation consists of an oven, a constant DC power supply, a high voltage power supply, a multimeter and a thermometer (Figure 6).

Figure 6 Poling Work Station

PIEZOELECTRIC COMPOSITE PWAS FABRICATION

Clean the surface of host structure and put a mask. The mask has a 7mm diameter, 0.2mm thickness hole and its center is in the desired position. PZT powder with a weight fraction of 85% was added to the epoxy matrix phase and was stirred thoroughly. The paste was then spread into the mask and let it cure at an elevated temperature (50 degree C) until hard. Remove excess and sand it down to final thickness. A small piece of copper foil was applied to one side of the cured composite PWAS to form an electrode. After curing and electroding had

been completed, poling of the composite PWAS was subsequently carried out to activate its piezoelectric effect. A constant DC voltage of 1 kV was applied to the composite PWAS to pole the sample for four hours at 80 degree C.

CHARACTERIZATION OF PIEZOELECTRIC COMPOSITE PWAS

We measured the final size of the composite PWAS. It is 7mm diameter and 0.2mm thickness which is same as the traditional PWAS. The electricity of the composite PWAS was measured before and after poling. The resistance is greater than 40 M Ω before and after poling. The resistivity is higher than 40 M Ω m. The capacitance of composite is only 0.02nF which is lower than the traditional PWAS value 3nF.

IMPACT TEST ON PIEZOELECTRIC COMPOSITE PWAS

The effectiveness of the composite PWAS for impact was investigated based on an impact test setup show in Figure 7.

Impact point showed in the Figure 7 and it is 20mm away from the center of the composite PWAS. The output of the composite PWAS was measured simply as a voltage signal using a digital oscilloscope.

Figure 7 Impact composite PWAS sample

We measured the voltage signal before and after poling. Before poling, the voltage signal damped out very soon. After poling, we can find the voltage amplitude is much higher than that before poling. And it also shows some vibration signal after the impact. From this figure, it is seen that upon hit, the beam vibrated first and then slowly damped out. The composite PWAS have a good repeatability in its output signal when subjected to similar impact forces.

Figure 8 The electric voltage signal measured by the impact hammer, (a) before poling (b) after poling

PIEZOELECTRIC COMPOSITE PWAS VIBRATION TEST

The effectiveness of the composite PWAS for dynamic measurement was investigated based on a vibration test setup show in Figure 9. The beam was mounted as a cantilever in a calibrated cantilever fixture. A composite PWAS was placed on the top of the beam and a traditional PWAS was place at the other side of the beam. The tip of the beam was displaced to a certain value (approx. 10 mm) and then suddenly released such as the beam entered in free vibration.

Figure 9 Piezoelectric composite PWAS fabricated on a cantilever beam: (a) experimental setup; (b) close-up view of the top surface showing the piezoelectric composite PWAS; (c) close-up view of the bottom surface showing the conventional piezoceramic PWAS

An oscilloscope connected directly to the PWAS was used to record the electric signals induced in both PWAS by the piezoelectric coupling between the mechanical vibration and the electric field (Figure 10). In Figure 10 (a), it is traditional PWAS voltage signal. We can easily see it reflected the beam vibration very well. But before and after poling, we still can't find the signal from the composite PWAS. Figure 10 (b) only showed the noise.

Figure 10 Measured electric signals during the plucked beam experiments: (a) conventional piezoceramic PWAS; (b) piezoelectric composite PWAS

CONCLUSIONS

A technique for fabricating composite PWAS has been established. The effectiveness of composite PWAS has been preliminarily characterized through a series of tests, which include impact test and vibration test. The experiment results of the composite PWAS have been compared with the traditional PWAS. The experimental results in this study gave the basic demonstration of the piezoelectricity of composite PWAS. The composite PWAS are capable of use as an active sensor.

Our future work is focused on perfecting the composite technology methods for the in-situ fabrication of composite PWAS. The composite fabrication methods considered for investigation are: (a) mask; (b) poling; (c) powders technology; (d) coatings. **The ultimate vision** is to create a methodology to create the composite PWAS directly onto the structural substrate through a easy technique followed by electroding and poling.

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