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STRUCTURAL DAMAGE DETECTION USING THIN FILM OF NANOCOMPOSITES

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Abstract. *Many techniques for structural health monitoring (SHM) have been studied with the objective of ensuring the structural integrity of aeronautic structures. One of the most recent solutions for this problem is the use of continuous sensors, constituted by thin films made of nanocomposites. Since the nanocomposites, as any other composite material, can be tailored according to the application needs, there is a vast range of material that have the properties needed to detect damage, what makes them widely studied. This work proposes the use of a new kind of sensor to coat the surface with nanowires or nanobelts of ITO (indium tin oxide) inserted in a polymeric matrix, such as PMMA (Poly(methyl methacrylate) or acrylic). PMMA is transparent and it gives a very nice appearance in the monitored surface. In order to evaluate the effectiveness of this method, several tests are proposed. These tests consists on monitoring the behavior of the nanocomposites when affected by some kind of damage, which can be a mass addition, excessive strains or even a cut made with a saw. Preliminary tests showed promising results, where the constructed sensors do form a neural network capable of sensing structural variations. The present work is still at its preliminary phase and more tests are going to be performed to test the viability of this method.*

Keywords: *Structural health monitoring, nanocomposite, continuous sensors, neural network, ITO*

1. INTRODUCTION

The objective of structural health monitoring is to ensure the structural integrity, therefore maintain its functionality without risking the user's safety. For this reason, SHM is widely applied in aerospace projects in order to try to predict when the monitored structure is going to fail and with this avoid catastrophic failures (Boller, et al, 2004).

Among the most commonly used structural damage detecting methods are the electromechanical impedance and Lamb waves methods. In both cases the types of surfaces which can be monitored are limited. In order to monitor a larger area, higher number of sensors are needed, which means a higher number of wires and a bigger acquisition system, turning these methods limited in terms of geometry and range.

Another limitation for these methods is the difficulty to bond the sensors in irregular surfaces or in pieces with complex geometry such as joints, ribs, fasteners, hybrid materials, and highly damped devices, such as honeycomb sandwich structures (Yun, et al, 2005).

One way to solve this problem is suggested by Lee, et al., (2006) in which in order to cover a bigger area, there were used long piezoelectric sensors (PZT), resulting in a bigger range compared to conventional sensors. By using several ribbons like sensors positioned perpendicularly forming a net of sensors, which they called a "neural network", they were able to detect and localize the damages by mapping all the sensors simultaneously. One problem with this method is the use of long PZTs, which are very fragile, making then very difficult for manipulating, and sometimes impossible to attach on surfaces with small irregularities. To overcome this weakness, the authors proposed the use of nanocomposite sensors made of PMMA and CNTs (Carbon Nanotubes).

The CNTs are long carbon chains, made of tubular sheets of graphite. They present high electric conductivity, depending on the chirality they can be metallic or semiconductors, high mechanical resistance and piezoelectric properties. The greatest advantage of the CNTs is that they can be used to produce composite materials with polymers, in which they enhance the composite material's properties with the addition of very little mass percentage. By using this advantage, one can create several types of materials with properties such as piezoelectricity, piezoresistivity, electrochemical actuation, higher mechanical resistance, higher electric or thermal conductivity, etc.

There are several ways to apply CNTs as SHM sensors. In general they are applied as coatings or inserted in the material itself. The advantage of the first case is that with the use of continuous polymeric sensors (since the most of the

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composite material is a polymer) makes it easier to attach them into large areas, or in irregular or complex surfaces. The advantage of the second case, is the structure itself already has the sensor inside, which can be a good option for polymeric or composite structures.

Rainieri, et al., (2011) studied the use of SWNT (single-wall carbon nanotube) in the shape of films, commonly called “buckypaper”, inserted in a cement matrix for civil structure applications. Their studies show that pure CNT films are fragile because of their intermolecular forces (Van de Waals forces), therefore it is necessary to utilize the CNTs inserted in a polymeric matrix in order to avoid the sliding between the NTs (nanotubes). It permits the insertion of the sensors in the monitored structure without the risk of breaking them before the structure does.

Kang, et al., (2006b) proposed the use of a PMMA/MWNT (Multi-Wall carbon Nanotube) nanocomposite, applied by aerosol spray on the monitored surface, forming a conductive composite with easy application process. After the coating of the surface, they monitor the electric resistance of the film that rise with the appearance of cracks. This process continues until the crack is big enough to cut the film completely and with this the conductibility becomes null, indicating that there is a crack in the surface and there is a need for maintenance stop.

Liu, et al., (2012) suggested the use of the MWNTs inserted in an epoxy matrix, with the objective of monitoring glued joints of two CFRP (Carbon-Fiber-Reinforce Polymer) slabs. Abot, et al., (2010) proposed the use of strings made of CNT coated with epoxy or polyurethane sewn between the fibers of a polymeric laminate, with the objective of detecting the delamination process. In both cases the sensors were put inside the material, trying to detect specific internal failures.

Ashrafi, et al., (2012) used two types of SWNT thin films using epoxy as matrices. These films were glued at the start and at the end of a crack. Both films had different composition, isolation and setups, and both of them were able to monitor the growth of the crack efficiently.

Zhou, et al., (2011) studied the use of a thin film similar to the SWNT film but instead of using SWNTs, they used magnetic strings. Although in this case there were no use of nanocomposites, the film sensor used by then were similar to the one proposed by Kang, et al., (2006) and it was equally effective in monitoring the crack’s growth.

The conclusion that can be achieved by evaluating all the state of the art methods for SHM using CNTs is that the key properties to effectively use nanocomposites as damage sensors are the electric conductivity and the piezoelectric effect. With this in mind, a partnership between the Department of Mechanical Engineering, UNESP – Ilha Solteira and the Department of Physical Chemistry, UNESP – Araraquara was formed with the objective of seeking alternative nanocomposite materials that have these properties and can be used for development of new methods for damage detection, based on the presented works with CNTs.

This work’s goal is to study several alternatives to the CNT nanocomposites applied in the form of thin films coating an aluminum surface. It is expected that this proposal can detect and localize cracks by monitoring the conductibility and the piezoelectric effect.

2. BASIC CONCEPTS FOR SHM

2.1 Structural Health Monitoring in aerospace applications

Statistical studies show that around 20% of the aircraft accidents in the period of 1918 until 2009 were caused by technical failures, while 31% of the failures on metallic structures in planes were caused by the development of a crack generated by fatigue, as shown in Tab. 1 and 2. With the objective of enhancing the reliability of aircrafts and therefore reduce the number of accidents caused by structural damages, many studies are being developed in order to improve advanced damage detection methods for metallic structures. For future studies, it is hoped that the SHM method presented here can be used to detect impact damages, which are responsible for 7% of the crafts structural failures.

Table 1. Accidents causes around the world.

Accident Cause	Percentage of responsibility
Human error	67.57%
Technical failure	20.72%
Bad weather	5.95%
Sabotage	3.25%
Other causes	2.51%

Source: Aircraft Crashes Record Office.

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Table 2. Failure causes in aeronautic metallic structures.

Failure type	Percentage of failures
Fatigue crack	30.96%
Corrosion	25.39%
Joints attachment/detachment	21.67%
Corrosion cracks by tension	14.55%
Impact damage	7.43%

Source: Boller, et al., 2004.

Generally most of the metallic structures in aircrafts are made of aluminum plates, which corresponds to 60 to 80 percent of the global craft's mass (Rezende, 2007). Taking this in account, the base material used for damage monitoring in this work is the aluminum plate.

There is a great tendency on using composite material in the primary aircraft structure, as in Boeing 787, which is the first plane with more than 50% of composite material present in its structure. The biggest problem brought by this is that composite materials are difficult to monitor its structural integrity by conventional methods because of its high damping rates. A secondary objective for the present work is to solve this problem by using the continuous nanocomposite sensors, which do not require the propagation of any kind of weave through the structure. The experiments using composite materials as base for coating is still to be developed.

2.2 Nanomaterials and nanocomposites

It is well known that the mechanical, thermal and electrical properties of polymeric materials can be manipulated through the fabrication of composite materials, which are made of the union of one or more different types of reinforcement phases. Usually polymeric materials have been reinforced with carbon fibers or glass microfibers to enhance its mechanical properties and several metals and/or organic materials are inserted to the mixture to obtain better electric and/or thermal properties. Within the past years, many researches have been done in order to obtain even better properties without losing the matrix's good properties. These researches were focused at producing composites using nanometric fillers, which have better properties and can enhance the properties of the composites without interfering with the already existing good properties of the matrix material. This can be achieved thanks to the extremely small size of the filler, resulting in a larger specific surface and interface area. With this, the mass percentage of the fillers can be greatly reduced. While the normal composites are constituted of 40% in mass of fillers, the nanocomposites uses around 10%. This difference reflects on how much of the matrix properties will remain in the composite. In the current work, the matrix's properties that are aimed to maintain are the transparency and flexibility of the PMMA.

2.2.1 Indium Tin Oxide (ITO)

One of the alternative fillers proposed in this work is the ITO nanowires. These nanowires are highly transparent and highly conductive ceramic materials and can be added as fillers to grant conductivity to the PMMA matrix, attaining percolation with about 5 wt % of filler without interfering significantly in the composite's optical properties (Arlindo, et al., 2012). Figure 1 shows the FEG-SEM (Field Emission Guns – Scanning Electron Microscope) images of typical ITO nanowires.

ITO nanowires are one-dimensional nano-structured material, which means they have only one significant dimension (length) compared to the other two (width and thickness), and that dimension is nanometric, furthermore they present different properties from their non nanometric counterpart. The reason for using ITO for this application is the fact that they present low electrical resistivity and transparency when used as fillers for thin film nanocomposites.

The ITO are synthesized by a carbothermal reduction method using coevaporation of oxides proposed by Orlandi, et al., 2005.

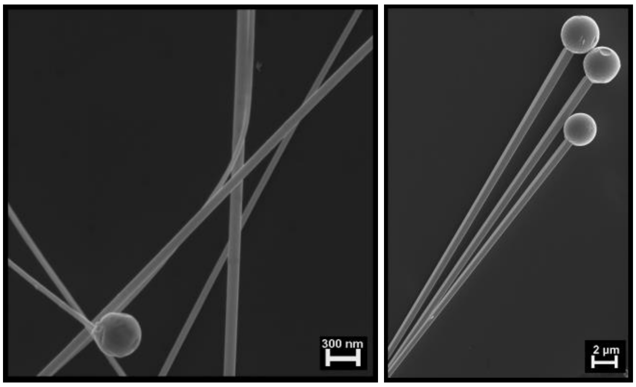

Figure 1. FEG-SEM images of ITO.

3. EXPERIMENTAL SETUP

The objective of this work is to develop new methods of damage detection using alternative nanocomposites. For this, it is hoped that it could be possible to use ITO/PMMA nanocomposite coatings as continuous damage sensors.

The idea is to use the “neural network” concept proposed by Yun et al. (2005) to form a net of conducting nanofillers. In case of the appearance of a crack one of the “wires” of this network would have its conductibility reduced or even nulled, which would indicate that a crack have appeared in the monitored system. One advantage of this method is that since there is a net of wires covering the system, it is possible to detect not only if there is a crack, but it would be possible to locate it by mapping all of the wire’s conductibility. The monitored “ways”, or the “wires”, are the ITO nanowires and one of the challenges is the fact that the position of all of the nanowires is not known. Figure 2 shows the neural network proposed by Yun et al. (2005), where the “r’s” and “C’s” represents the ways (wires) and the red lines represents different crack cases.

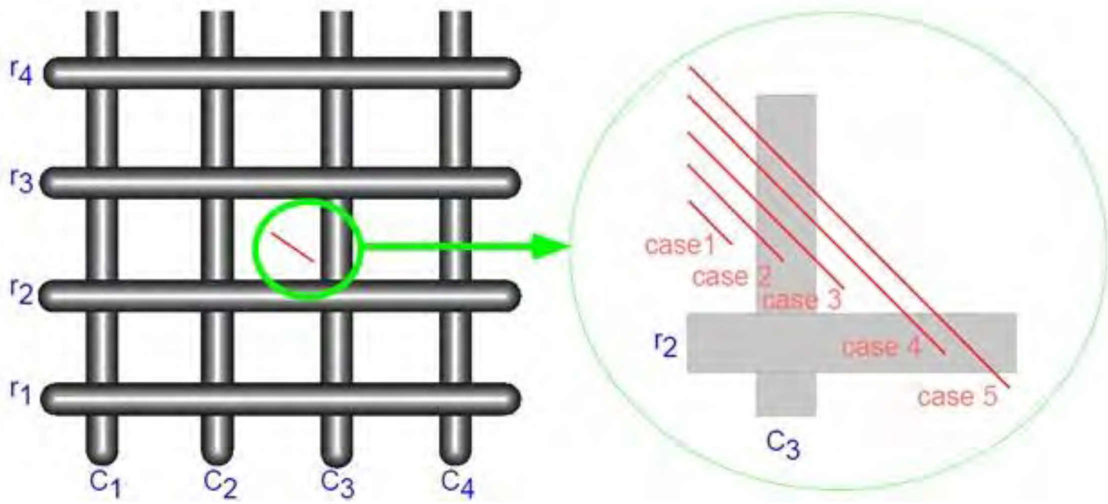

Figure 2. Neural Network proposed by Yun, et al., (2005).

The first step for the development of the sensor is the ITO synthesis. After synthetizing the fillers, several tests were performed regarding the casting method using different weight percentage addition of fillers.

The method tested for coating consisted on just pouring the dissolved nanocomposite over the base material. This method ensured that the fillers were uniformly distributed in the entire composite. Since the structural material monitored in this case is already conductive (aluminum) it is necessary to ensure that the nanowires do not touch the aluminum. One of the proposed solutions for this is the use of a pure PMMA layer under the nanocomposite layer, forming insulation between the aluminum and the nanowires. This method showed to be not effective, since the addition of the pure PMMA layer interfered with the nanocomposite composition and turned it difficult to achieve the percolation even using high values of weight percentage. The effective solution was the use of a pure PMMA layer over the aluminum and then the nanowires were mixed with a solvent and poured over the PMMA layer, resulting in the

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mixture of ITO only at the surface of the PMMA layer. By doing this, it was possible to achieve percolation in the most of the area of the aluminum plate. Figure 3 shows the resulted coatings using different coating methods.

Preliminary tests using the "two points" conductibility evaluation method showed that the electric resistance of the nancomposites varied from 7 to 270 kΩ, which are small enough to be used as monitored values for damage detection. This method is still not good enough to ensure constant thickness and uniform percolation, but results obtained up to now shows that it is a promising method that can still be tuned in order to achieve the desired goals for this work.

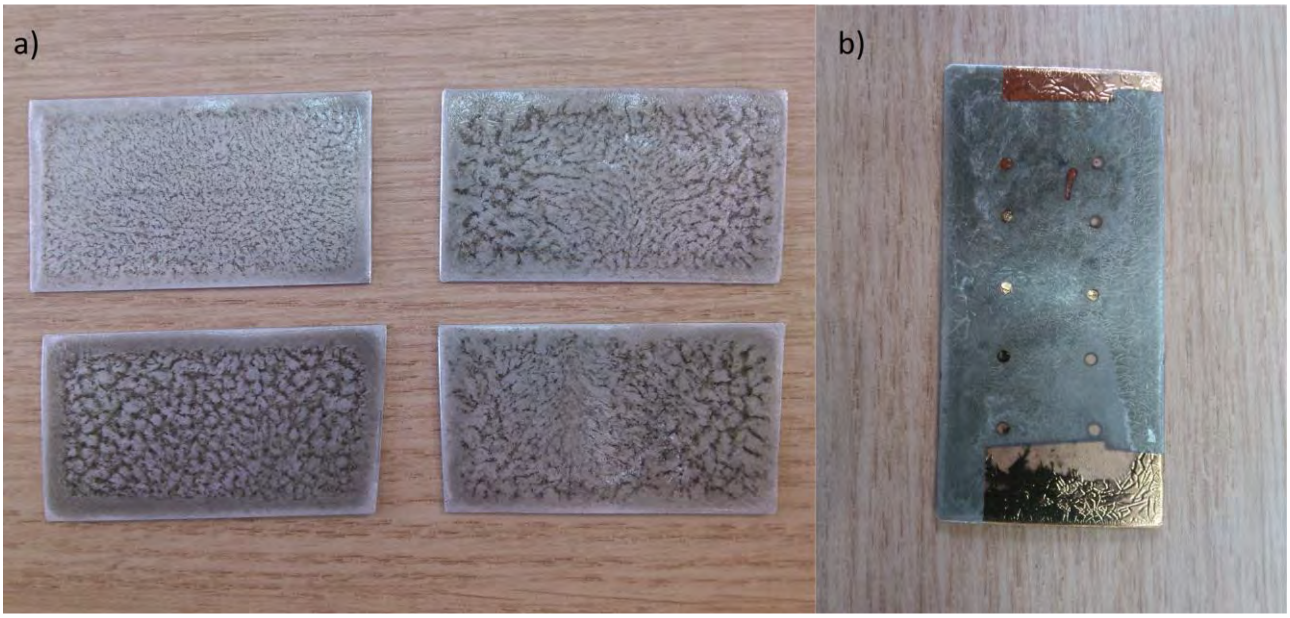

Figure 3. Examples of coated aluminum plates. a) Coated by pouring dissolved nanocomposite. b) Coated by pouring ITO mixed with a solvent over a PMMA layer.

The next step of this research is the attachment of the data acquisition systems to the coated plate. The electric signal will be monitored in function of the time and it is hoped that a crack over the surface of the coating will cause a difference in the signal.

4. CONCLUSION

The objective of this paper was to present the progress up to now on the research around nanocomposite continuous sensors for damage detection applications. Experimental tests performed to obtain the best coating method and the best filler mass addition percentage of ITO showed promising results, in which it was possible to obtain a flexible conductive continuous sensor coating an aluminum plate. More experiments will be conducted to obtain more uniformity of the coating process and better percolation ratios. Aside from the difficulties to find the best coating method, it was proven that the proposed method has great potential on damage detection applications. The next step for this work is the development of the data acquisition system to monitor the conductibility of the film sensor using several acquisition channels (forming the network) and the data processing software, which is planned to be developed at LabView environment and/or Octave programming language.

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