Damage sensing in aeronautical structures: motivation, challenges and preliminary tests

S. P. S. Tita[1], D. E. T. Marques[1], F. D. Magalhães[2], D. Paiva[2], M. A. Z. Bertochi[3], G. F. Teixeira[3], J. R. Tarpani[1]

[1]University of Sao Paulo, Sao Carlos School of Engineering, Sao Carlos, SP, Brazil
[2]University of Porto, Faculty of Engineering of University of Porto, Porto, Portugal
[3]State University of Sao Paulo, Chemistry Institute, Araraquara, SP, Brazil
email: spatstita@gmail.com

Abstract

The development of sensors for damage detection in aeronautic structures, based on composites made of thermoplastic matrix and ceramic particles that combine good properties for monitoring, easy way to process, suitable mechanical properties (i.e. high flexibility), low density and capacity for healing evolves many challenges. Thus, in the present study, 50 µm-thick composite flexible films based on EMMA co-polymer poly(ethylene-co-methacrylic acid) partially neutralized with zinc ions (SZn0), known as Surlyn™ from DuPont, were developed. Different volume fractions of ceramic lead zirconate titanate (PZT: $Pb(Zr_{0,52}Ti_{0,48})O_3$) micro/nanoparticles were used to produce films of SZnPZTx, where x equal to 1, 3, 5 e 7 wt%. Twin conic screw extruder and hydraulic hot press were employed for dispersing PZT particles and manufacturing the thin films. DSC, TGA, DMA and tensile test results showed that the thermal and mechanical properties of the thermoplastic films were not impaired due to PZT particles addition. Finally, preliminary tests of damage detection in a metal beam showed the potentialities and limitations of the flexible films as a sensor.

Keywords: Smart films; Ionomers; flexible polymer films-PZT.

Introduction

Different types of sensors for damage detection in aeronautical structures can be found in the literature, mainly made entirely of PZT. In fact, PZT sensors show excellent dielectric and piezoelectric properties. However, in terms of mechanical properties, they are very fragile, exhibiting quite low flexibility.[1] This is a relevant limitation, because it restricts their use as malleable sensor in structures that show high deformation. In addition, PZT sensors have high density, which is not suitable for aeronautic applications in very large structures, such as wings, fuselages and empenages. Thus, one alternative consists in developing sensors based on thermoplastic matrix and ceramic particles. The ionomers show attractive mechanical and thermal properties due their low molar ratios (in average, lower than 15 mol%) of ionic groups, which forms covalent bonds with the non-polar polymer chain and provides ionic interactions with its contra-ions. This results in molecular portions known as ionic aggregates. These ionic substructures strongly affects the volumetric properties of the material and, consequently, provides new insights for the development of new hybrid materials. [2]. Based on the above mentioned limitations and challenges, composite flexible films based on EMMA co-polymer partially neutralized with zinc ions (SZn0) were produced using different volume fractions PZT micro/nanoparticles. Thermal, mechanical and thermal-mechanical properties of the films with and without PZT were obtained. Also, preliminary tests of the composite flexible films as damage sensor were carried out.

Experimental Procedure

PZT particles (molar ratio Zr/Ti = 52/48) were prepared via Pechini's process. A mini extruder (Xplore™ Netherlands) with a twin conic screw was employed to disperse/distribute them in the melted ionomer matrix. Processing temperature was 170ºC under rotation force of 4.5 kN. Screws rotation speed was 100 rpm (during the feeding stage) and 350 rpm (during the mixture stage). Four different volume fractions of PZTs (1, 3, 5 e 7 %) were used. 50 µm-thick composite EMMA-PZT films were manufactured via two-stage hot compression process, where the hydraulic press was heated at 175ºC during 10 min with no applied pressure, and, after that, a compressive stress of 21.3 MPa was applied by 2 min. The steel-made mold was 25.4 mm x 25.4 mm in area. The flexible films were investigated by using: (a) SEM-FEI Inspect, models S50 and F-50™ (with EDS and EBDS); (b) TGA-Netzsch, Jupiter™, 40 mL/min flowing N_2 and heating rate of 10ºC/min. Samples with 4.5 mg were essayed from room temperature up to 550ºC; (c) DSC-Netzsch, model DSC 214 Polyma™, 40 mL/min flowing N_2 and heating rate of 10ºC/min. Samples with 5.0 mg were essayed from -120 up to 150ºC; (d) DMA-Netzsch, Artemis™ in tensile mode using specimens with dimensions 12x0.05x4 mm^3 heated at a rate of 2 ºC/min from -140 up to 60ºC. 5Hz load-frequency, 12N maximum force and 40 µm maximum displacement amplitude were used; (e) Tensile testing-Mecmesin™ with 200 N load cell at a displacement rate of 10 mm/min using 25x0.06x10 mm^3 test coupons. Preliminary vibration tests were performed using a metal beam covered with the composite EMMA-PZT film to monitor the response of the structure when subjected to quasi-static, cyclic and vibration loadings.

Results and Discussion

Figure 1 shows TGA curves for SZn0 and SZnPZTx films. Weight loss begins only from 400ºC, indicating that thermal stability of all materials is high enough to withstand the in-service conditions experienced by airframes.

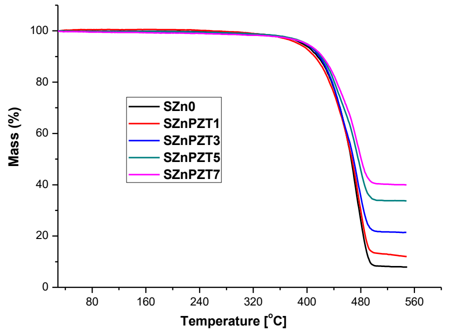

Figure 1 –TGA curves of flexible polymer films with and without PZT particles.

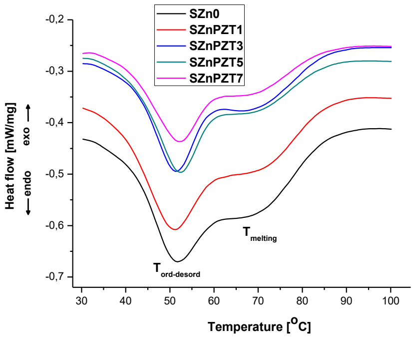

Figure 2 –DSC curves of flexible polymer films with and without PZT particles.

Figure 2 shows DSC curves of SZn0 and SZnPZTx polymer films. It is observed that the relaxation temperature of ionic aggregates present in the ionomer[3] with PZT particles did not increase for higher temperatures. There was not the intermediary endothermic peak, which could be between the peaks of the $t_{relaxation}$ and t_{melt}, this suggests that the molecular architecture of SZn matrix[4] and, consequentely, its molecular dynamic[2] do not favor the fusion of secondary crystallites of polyethylene, which is in the ionomer, and slows beginning of the primary crystallization.[4]

Table 1 – Temperature and energy for crystallization: t_{cryst} and ΔH_{cryst}.

PZT (% v/v)	0	1	3	5	7
t_{cryst} (ºC)	38.0	38.2	38.2	38.5	38.3
ΔH_{cryst} (J/g)	47.4	48.4	34.5	45.4	43.1

No significant variations in t_{cryst} e ΔH_{cryst} is noted with increasing PZT content (Table 1). This reveals that ionic aggregates do not restrict substantially the movements of molecular chains. Therefore, molecular interaction is favored and so the molecular ordering for cristalization.

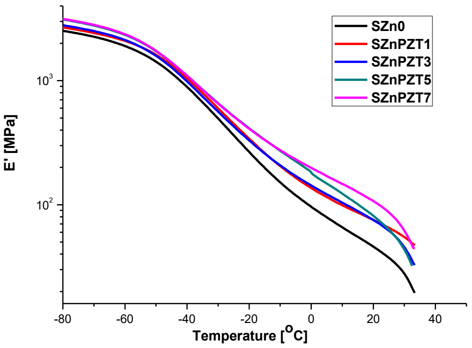

Figure 3– Storage modulus (E') in terms of temperature from DMA.

The storage modulus (Figure 3) shows that, regardless the temperatures, the composite film with 7% of PZT presented the best thermo-mechanical performance.

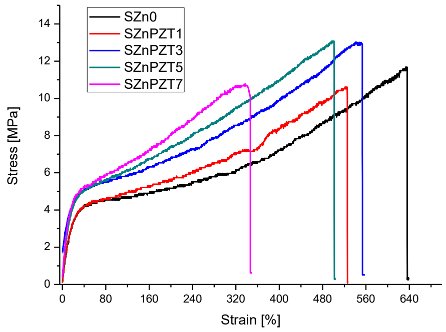

Figure 4 – Tensile tests: stress-strain curves.

The tensile tests (Figure 4) show strong reduction of strain with the increment of PZT, as predicted in the literature.[1]

Conclusions

Results of DSC, TGA, DMA and tensile test showed that the thermal, mechanical and thermal-mechanical properties of EMMA ionomer were not impaired by adding PZT particles. Preliminary tests for damage detection in a composite film-covered metal beam showed that it is necessary to develop a frequency filter and an amplifier to improve the response of the composite films. This drawback has been tackled by acquiring a powerful lock-in amplifier.

Acknowledgments

The Brazilian National Council for Scientific and Technological Development (CNPq).

References

[1]N. K. James, U. Lafont, S. van der Zwaag, W. A. Groen. "Piezoelectric and Mechanical properties of fatigue resistant, self-healing PZT–ionomer composites," Smart Materials and Structures, vol. 23, pp. 1-9, 2014.

[2]J. Sampath, L. M. Hall, "Morphological origin of the multistep relaxation behavior in semicrystalline ethylene/methacrylic acid ionomers," Macromolecules. vol. 51, pp. 626–637, 2018.

[3]K. Tadano, E. Hirasawa, H. Yamamoto, and S. Yano, "Order-disorder transition of ionic clusters in ionomers," Macromolecules, vol. 22, no. 1, pp. 226–233, Jan. 1989.

[4]Y. L. Loo, K. Wakabayashi, Y. E. Huang, R. A. Register, and B. S. Hsiao, "Thin crystal melting produces the low-temperature endotherm in ethylene/methacrylic acid ionomers," Polymer, vol. 46, no. 14, pp. 5118–5124, Jun. 2005.