Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

Magnetostrictive Materials for aerospace applications

To cite this article: A. Al-Taher *et al* 2017 *J. Phys.: Conf. Ser.* **903** 012010

Magnetostrictive Materials for aerospace applications

A. Al-Taher[1], **R.W. Reiss**[1], **A.D. Lafferty**[3], **S.A. Hayes**[1], **N. Lupu**[2], **I. Murgulescu**[2] **and N.A. Morley**[1]
[1]Department of Materials Science and Engineering, University of Sheffield, Sheffield, S1 3JD, UK
[2]National Institue of R&D in Technical Physics, Iasi, Romania
[3] Institute for Materials and Processes, University of Edinburgh, Sanderson Building, Edinburgh EH9 3JF, UK

n.a.morley@sheffield.ac.uk

Abstract. Structural health monitoring of composite structures to detect barely visible damage is vitally important for the aerospace industry. This research has investigated amorphous magnetostrictive wires ($Fe_{77.5}Si_{7.5}B_{15}$ and $Co_{72.5}Si_{12.5}B_{15}$), as a possible solution to monitoring aerospace composites. The different amorphous wires were either embedded into the composite or epoxied on to the surface. How the wires effected the structure of the composite along with ultimate tensile strength was studied. Inductance measurements were used to study the strain within the composite, which provided a non-intrusive method of monitoring the composite.

1. Introduction

Composites are an ever-increasing material of choice across a wide variety of industries (aerospace, automotive and medical), as they possess superior mechanical properties combined with relatively low weight, compared with their metallic counterparts. However in the presence of a defect the composite is liable to severely deteriorate [1] this drives research into damage sensors. Thus to ensure the composite material integrity throughout the materials lifetime, various sensing techniques have been developed in the past decade, with the demand turning it into a multi-billion dollar industry [2].

There are two primary failure modes for composites: fibre rupture in tension or fibre buckle in compression [3], both of which result in an increase stress in the material. Thus the stress state of the composite material is the most important determinant of the structure safety [4]. However, it is difficult to obtain a direct reading of the stress within the material, so a measure of the strain, which is the deformation of a solid due to stress is used instead. There are a number of different sensors being developed for composite damage detection, these include self-sensing in the carbon fibres [5], glass fibre optical sensors [6] and piezoelectric sensors [7]. Each method has advantages and disadvantages, i.e. self-sensing in carbon fibres requires no added materials, but is limited to carbon composites, while piezoelectric sensors require the sensors to be attached to the composite surface, but multiple readings can be obtained simultaneously.

Magnetostrictive sensors using embedded magnetostrictive wires within the composite are also a promising option. Cristopolous et al [8] demonstrated that it was possible to embed a single magnetostrictive wire within composite material and detect a strain of 0.25 mStrain using a transducer. This paper presents studies of how two different amorphous magnetostrictive wires (FeSiB and CoSiB) embedded in the composite or epoxied onto the surface change the structural properties. Along with inductance measurements to determine the strain sensitivity of the wires on the composite surface.

2. Experimental procedure

For magnetostrictive sensing, two different amorphous wires were studied, these were $Fe_{77.5}Si_{7.5}B_{15}$ (FeSiB) and $Co_{72.5}Si_{12.5}B_{15}$ (CoSiB). For both wire types uncoated and glass-coated wires were studied. They were produced via the melt spinning method with the glass-coated wires being produced using the improved glass-coating melt spinning method developed at the National Institute of Research and Development for Technical Physics in Iasi, Romania [9]. The uncoated FeSiB wires were 122μm in diameter and the glass coated wires were 20μm in diameter both with a magnetostriction constant of 30ppm. For the CoSiB wires, the uncoated wires were 110μm in diameter and the coated wires were 5μm in diameter, with a magnetostriction constant of -2.6ppm.

The composite samples were made from a 0^{O}, 90^{O} woven pre-impregnated carbon fibre epoxy system (VTC401®) from SHD Composites. It consisted of T300 carbon fibres in a 3k tow, indicating 3,000 fibres in each cluster combined with an epoxy based resin system. All the samples tested were 150mm x 50mm x 1mm in dimensions, which corresponded to 4 pre-preg layers. The magnetostrictive wires were evenly spaced, either 26mm, 13mm or 6.5mm between the second and third layers (Fig. 1a) or laid on top. The samples were then cured in the autoclave under vacuum, for 60 mins at 80^{o} and then 60 mins at 120^{o}. The samples produced contained either 2, 4 or 8 wires of each different wire type, along two samples with 2 uncoated wires epoxied to the surface and one sample with no wires as a reference.

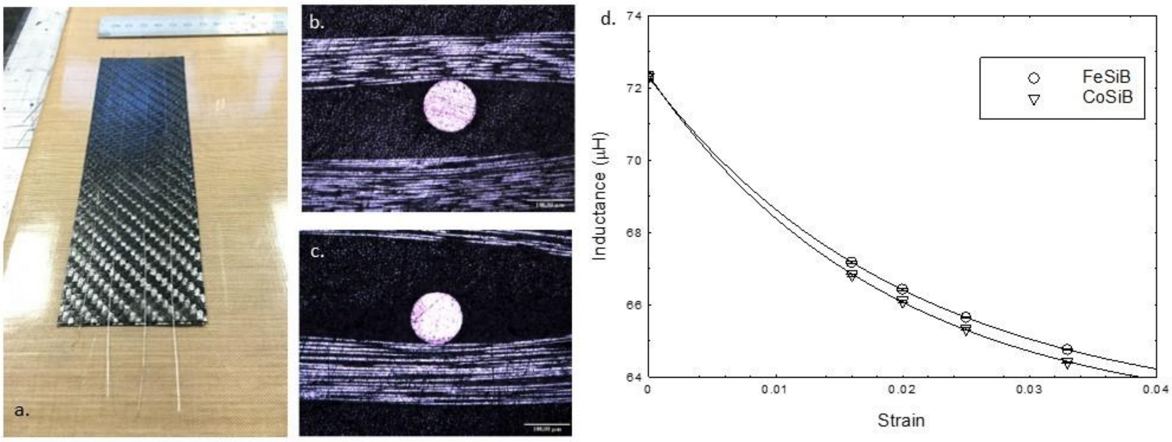

Figure 1a. Image of the magnetostrictive wires being placed within the composite. **1b&c.** Optical images of CoSiB wires within the composite at 50x magnification. **1d**. Inductance vs strain for two magnetostrictive wires epoxied to the composite surface. The lines are a guide for the eye.

To determine whether the embedded wires changed the structural integrity of the composite, static tensile testing using a Hounsfield machine with a 100 kN load cell was performed. Along with an interlaminar shear strength measurement using the short-beam method [10] for three sets of five samples. The samples were composite with no wires, composite with a wire along the sample length and composite with a wire perpendicular to the sample length. This test investigates the modes of failure due to external forces and whether they are acceptable (i.e. delamination) or not (tension or compression). The Young's modulus of the uncoated wires were also determined. Optical microscopy using a Nikon Eclipse LV150 microscope was used to image the embedded wires within the composite (Figs 1b&c). The strain sensitivity of the magnetostrictive wires in/on the composite was measured using an inductance method. A 112 turn pick-up coil connected to an Atlas LCR45 analyser was used to measure the inductance of the composite and the wires. To detect the response to strain, the composite was strained over a series of known bend radii (300, 400, 500, 600mm), which gave an uniform strain within the composite via the beam bending method. Using a 800 turn coil placed on the composite surface with the LCR45 analyser, the change in inductance was measured as a function of applied strain. This was repeated five times to check repeatability.

3. Results and Discussion

From the tensile tests, it was found that the ultimate tensile strength (UTS) increased with the number of wires within the composite, i.e. for 2 CoSiB wires UTS = 306 ± 1 MPa, while for 8 CoSiB wires UTS = 451 ± 1 MPa. All the composite samples with 4 or more wires embedded had a larger UTS than the composite only sample (UTS = 405 ± 1 MPa), suggesting that the wires helped to strengthen the composite. The CoSiB wires embedded in the composite gave higher UTS compared to the FeSiB wires, independent of whether they were glass-coated or uncoated. This is probably due to the CoFeSi wires having a smaller diameter and larger Young's modulus (E = 137 ± 2 GPa) than the FeSiB wires (E = 115 ± 5 GPa). For the interlaminar shear strength measurements, it was found that all three samples failed due to tension, with the composite failing at the centre of the underside. This was due to the manufacturing method of the samples. The breaking point for the samples with no wire was 920 ± 5 N compared to 860 ± 5 N for the wires parallel to the sample length and 830 ± 10 N for the wires perpendicular to the sample length. This is because the perpendicular wire is in the same direction as the loading force, so an increased volume of the wire lies in the same orientation as the induced load, which will increase the chances of failure.

Figs 1b and 1c shows a CoSiB magnetostrictive wire within the composite laminate. It is observed that there are two scenarios, the first (Fig. 1b) shows that the longitudinal fibres surround the wire, so increasing the fibre volume fraction around the wire. The second scenario (Fig. 1c) shows that the fibres have not followed the curvature of the wire leaving a relatively large area of epoxy matrix. No voids were observed in the images, meaning that the epoxy formed a sound bond between the wire and the fibres, thus allowing the stress to dissipate through the laminate.

For the inductance measurements, it was found for the same number of wires in the composite the FeSiB wires had a higher inductance compared to the CoSiB wires, i.e. for 2 FeSiB glass coated wires, $L = 29\pm0.5$ µH, while for 2 CoSiB glass coated wires, $L = 27\pm0.5$ µH. As expected the more wires within the composite the higher the inductance measured, i.e for 2 CoSiB uncoated wires $L = 27.6\pm0.5$ µH, and for 8 CoSiB uncoated wires $L = 34.8\pm0.5$ µH. Thus as 8 wires embedded in the composite increased the UTS along with the inductance, this suggests that a spacing of 6.5 mm between the wires could be used for strain detection in composites, without being detrimental to the structural integrity. From Fig. 1d, it is observed that there is a decrease in inductance with an increase with strain, with a similar non-linear behaviour to that measured by Cristopolous [8]. The error bars (Fig. 1d) show the repeatability of the inductance measurement as a function of strain. The FeSiB wires gave a higher sensitivity compared to CoSiB wires, with the FeSiB wires able to detect a change strain of 500 µStrain, using a simple inductance technique. This demonstrates that the wires can measure a global strain to the composite. For structural health monitoring sensors, failure such as delamination produces a local strain within the composite. These local strains will change the magnetisation within the magnetostrictive wires, which will be detected using a handheld sensor such as a transducer [8]. Other structural health monitoring strain sensors, include surface mounted fibre optics, which can measure strains up to ±5000 µstrain with a resolution of ±1 µstrain [11], and surface mounted piezoelectric sensors, which have a measurement range of ±150 µstrain with a resolution of ±5 µstrain [12]. Thus further work has to be carried out to achieve magnetostrictive strain sensors with a resolution within the ±10 µstrain.

4. Conclusions

Magnetostrictive wires were embedded/epoxied onto composites to determine whether they could be used to measure the internal strain. It was found that the embedded wires improved the ultimate tensile strength of the composite with CoSiB wires increasing the UTS greater than the FeSiB wires. Thus the wires helped the structural integrity of the composite laminate. It was also found that there were no voids around the magnetostrictive wires, due to either the composite fibres or the epoxy matrix surrounding them. Measuring the inductance of the wires was found to be a reliable method to measure the strain within the composite, with the FeSiB wires having a higher inductance compared to CoSiB wires. A change of strain of 500 µStrain was measured using this technique for the FeSiB wires, making this a promising method to measure the internal strain in composites.

Acknowledgments

The results presented here have been partially supported by JTI-Cleansky2 project SHERLOC JTI-CS-2009-01-GRA-01-005

References

[1] Backman, B F, 2005, *Composite structures, design, safety and innovation*, (Amsterdam: Elsevier)
[2] Ristic R L R, 1994, *Sensor technology and devices*, (Boston: Artech House)
[3] Hashin Z, 1980 *J. Appl. Mech*, **47**, 329-334
[4] Duan Y, Zhang R, Zhao Y, Or S, Fan K and Tang Z, 2011, *J. Zhejiang Univ. Sci. A*, **12**, 12 895-901
[5] Abry J C, Choi Y K, Chateauminois A, Dalloz B, Giraud G and Salvia M, 2001, *Compos. Sci. Technol*. **61**, 855-864
[6] Fernando G F, 2005, *Reinf. Plast*, **49**, 12, 41-49
[7] Bowen C R, Dent A C E, Nelson L J, Stevens R, Cain M G and Stewart M, 2006, *Proc. Inst. Mech. Eng. Part C J. Mech. Eng. Sci*, 220, C11, 1655-1663
[8] Christoploulos A, Hristoforou E, Koulalis I and Tsamasphyros G, 2014, *Smart Mater. Struc*. 23, 8, 085035
[9] Ovari T-A, Lupu N and Chiriac H, 2015, *Magnetic Nano-and Microwires*, (Cambridge: Woodhead publishing)
[10] BS EN ISO14130 “Fibre-reinforced plastic composites determination of apparaent interlaminar shear strength by short beam mrthod”, 3, 1108, 1-9, 1998
[11] Di Sante R, 2015, *Sensors*, **15**, 18666-18713
[12] Sirohi J and Chopra I, 2000, *J. Int. Mat Sys. Struc*. **11**, 246-257