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Morphing and Control of a Smart Fibre Metal Laminate utilising Plastic Optical Fibre Sensor and Ni-Ti Sheet

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SUMMARY

This paper reports a study of the use of nickel-titanium shape memory alloy (Ni-Ti SMA) sheet and carbon fibre reinforced composite to produce a novel smart fibre-metal laminate (FML). Investigations into the morphing response and control using integrated heaters and plastic optical fibre sensors have shown the potential to accurately control the amount of deflection of the smart FML.

Keywords: shape memory alloy, fibre metal laminates, plastic optical fibre (POF), sensors, composites

INTRODUCTION

Fibre metal laminates comprised of an alternating layered arrangement of advanced composites such as glass fibre reinforced polymer and metallic alloy sheets such as aluminium or titanium alloy. This hybrid material system offers the combined features of outstanding specific strength, stiffness and fatigue properties associated with fibre composites and the machinability and toughness of metals [1]. Many studies have been carried out to show the excellent mechanical properties of FMLs highlighting their superiority in structural performance compared to conventional plain aluminium alloys [2]. For example, GLARE (glass-fibre aluminium reinforced epoxy), one of the best known grades of FML has been applied as fuselage skin material for the new flagship of Airbus, the Airbus A380. GLARE can also be applied for bulkheads, wing skin, flaps, floors and liners, providing substantial advantages over conventional materials. The unique concept of a layered arrangement of different fibre composites and metallic sheets allows for a wide range of applications in various industries. In view of the potential of such a hybrid material system for high performance applications, having added features such as integrated sensing and morphing capability would likely increase its survivability and functionality rendering it the ideal material system for use in many applications.

Indeed, there has been considerable interest in the morphing characteristics and geometry control of wings and other aircraft structures, with the aim being to achieve a change in wing twist during flight. In the area of noise reduction in jet engines, geometry control of the engine chevron has been proposed and shown that an active chevron design concept yields promising results [3]. The use of shape memory alloys (SMAs) has been proposed as a possible approach allowing conventional materials to be imbued with morphing capabilities. Due to their ability to undergo shape recovery while exhibiting large recovery stress, shape memory alloys are the actuation material of choice in many applications. The distinctive features of a SMA include their shape memory effect (SME) and superelasticity which result from a thermally-induced and stress-induced martensitic transformation respectively. For SME to occur, the SMA must be heated above its activation temperature at which point the martensitic will undergo a reverse transformation into its austenitic phase. To a large degree, the activation temperatures (austenite start and finish) depend on the relative amount of Ni-Ti constituent. Although typically composition of 50-50 Ni-Ti is used, different variations in the percentage are also adopted in its manufacture - a small variation in the percentage combination of Ni-Ti would change the phase transformation temperatures considerable.

The SMA wires, with typical diameters ranging from 0.02 mm to 12 mm, are available commercially and their integration into composite materials has received much attention. Very little work has been reported, however, on the use of SMA sheets as actuators and as a structural member in conjunction with advanced composites. The embedding of SMA wires for strain recovery applications where the diameters of the wires are typically that of 10-order of magnitude larger than the reinforcing fibres, may lead to degradation of the structural properties of the host composites. The use of an array of SMA wires to achieve the necessary recovery strain in order to create the twist or deflection of the composites further compounds the loss of structural integrity leading to a structurally compromised material system. Due to its greater degree of freedom compared to a rectangular sheet, placement and fixation of these wires to the host composite requires careful attention during specimen preparation and manufacture. The concept of using thin SMA sheets bonded to composite prepregs in the same fashion as conventional fibre metal laminates offers a viable alternative without the risk of degradation in structural properties in addition to the comparative ease of manufacture. The resulting material system termed as a smart FML, offers actuation capability in addition to superior structural characteristics compared to conventional materials.

In order for an SMA to be used as an actuator, it is necessary to train the SMA sample to impart the desired memorized shape and degree of strain recovery by subjecting it to a training regime which involves holding the specimen at an elevated temperature (400-500^{o}C) for a short duration of time, from 3 – 30 minutes and subsequently quenching it in a bath, typically cool water. The training involves the reordering of the dislocation into stable position such that the shape memory alloy reverts to this position when it is heated to its austenitic temperature.

In control applications, the use of a suitable feedback sensor could lead to a significantly more accurate control of the parameter of interest. Optical fibre sensors have received much attention in recent years for measuring a variety of parameters which include strain, temperature, deflection, pressure and others. Plastic optical fibres (POF), being easier to handle than glass fibres due to their high resistance to breakage and lower cost than their glass-counterpart, have also been developed for structural monitoring applications [4]. In this work, an intensity-based plastic optical fibre sensor has been used to provide the feedback signal to the controller unit to control the amount of heating necessary to achieve the required deflection in the smart FML. To achieve better positional control of the deflection of the specimen, the feedback signal used is a direct measure of the physical state (deflection or position) of the beam instead of temperature via a thermocouple, which is the default feedback signal for the temperature controller unit used in the study. Although the temperature at which the SMA is subjected to is related to the deflection of the beam, this relationship may not be readily formulated due to the effects of both linear and non-linear thermomechanical response of the SMA. Temperature monitoring via a thermocouple provides an indirect measurement of the physical response of the SMA (e.g. the extent of deflection or twist) whereas deflection (or strain) monitoring using the POF sensor gives a direct real-time physical response of the beam.

This paper reports a study into the use of a nickel-titanium shape memory alloy sheet and fibre-reinforced composites to produce a novel smart fibre-metal laminate. A POF sensor was used to monitor the deflection of the specimen in addition to providing the feedback signal to the controller which in turn powers a thin-film silicon heater bonded to the SMA sheets. The voltage output of the intensity-based POF sensor allows ease of integration to the control unit and this enables the position of the smart FML to be effectively controlled.

EXPERIMENTAL PROGRAM

Specimen Fabrication

The study focused on the morphing response of a smart FML based on woven carbon fibre reinforced epoxy composite. The SMA sheet was 0.8 mm thick nickel-titanium (Ni-Ti) alloy type M, with an activation temperature (austenite finish), A_f of 65^oC (from Memory-Metalle GmbH). It was desired that the SMA sheet adopts a curved memorised shape upon activation and thus was partially rolled up and constrained within a steel tube with inner diameter of 120 mm. The Ni-Ti allow sheet (400 mm x 55 mm) was initially subjected to a training regime which involved holding the Ni-Ti at 500^oC in a furnace for 2 minutes before quenching in water in its constrained shape, although a training regime at lower temperatures (just above its A_f temperature) with a higher number of heating-quenching cycle was also found to be effective [5]. A longer holding duration in the furnace could be adopted to yield a higher strain recovery if required. In this study, the heating and quenching cycle was repeated 3 times and was found to be effective in imparting the desired strain recovery. The carbon fibre composite was initially cured and bonded to the Ni-Ti sheet using an epoxy-based adhesive. The thin-film silicon heater (0.4 mm x 250 mm x 55 mm) was attached to the Ni-Ti- surface using a room-temperature vulcanising adhesive (1430RED7871 *Innerbond* from Inland Inc).

POF Sensor Design and Construction

The POF sensor used in the study was modified from a previous design [6] to suit the present application and is shown schematically in Figure 1. The basic operating principle of the POF sensor used here relies on measuring the displacement of two cleaved fiber surfaces housed within the tube. The signal output of the sensor is directly related the separation of the two end faces. As the SMA deflects upon activation, the two cleaved surfaces of the POF sensor will approach each other resulting in an increased of light transmission. The photodetector will generate a corresponding increase in the output signal which will then be sent as a feedback signal to the control unit. In principle, the POF signal acquisition system consists of a set of four stable high-intensity light-emitting diodes (LEDs) and a narrow-band photo-detector which produces a proportional voltage of the intensity of the transmitted optical signals. The signal acquisition system was stable and did not exhibit power source fluctuation commonly associated with intensity-based system.

Following construction of the POF sensor, it was attached to the compression side of the FML sample to monitor the morphing response of the beam. A schematic of the experimental set-up to study the morphing response and deflection control of the smart FML is shown in Figure 2.

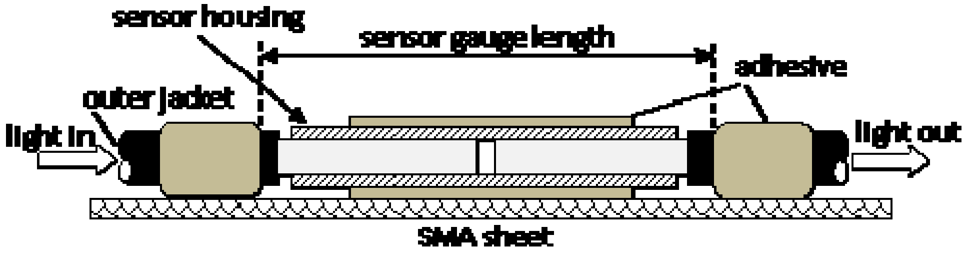

Figure 1 Schematic of POF sensor and location of adhesives used in the study.

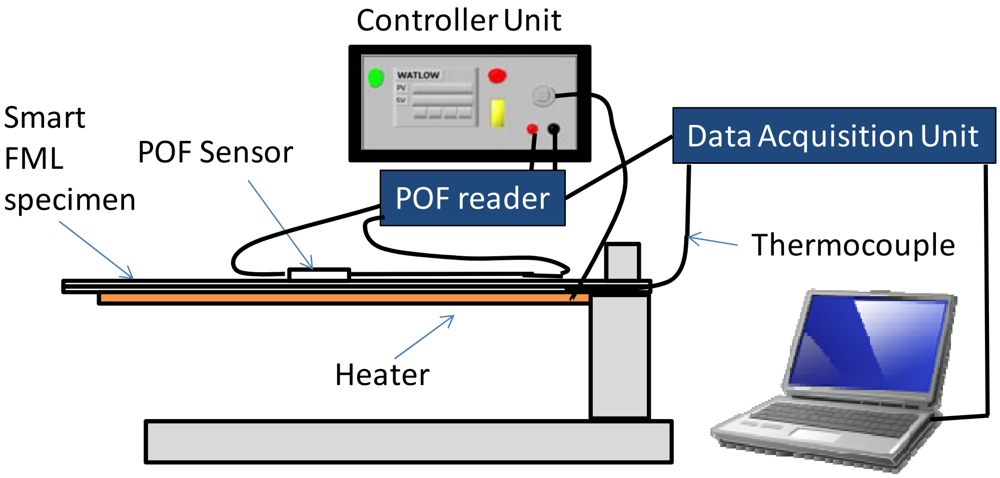

Figure 2 Schematic of POF experimental set-up.

RESULTS AND DISCUSSION

Three beam positions were programmed into the controller unit sequentially as indicated by (A) to (C) as illustrated in Figure 3. In each cycle, a steep climb in both the temperature and the deflection (as given by the POF sensor reading) can be observed as the silicon heater was powered by the controller unit to bring the specimen to the pre-programmed positions. The positions were arbitrarily chosen and could be re-programmed if desired to be at any position within the range of the recovery strain, the final memorized shape being the maximum possible deflection. Sensing the overshoot in the POF signal, an immediate reduction in heater temperature followed as the controller switches off automatically. This allowed the beam to relax as the heater cooled and subsequently achieving the steady state position accurately in all three cycles of the test.

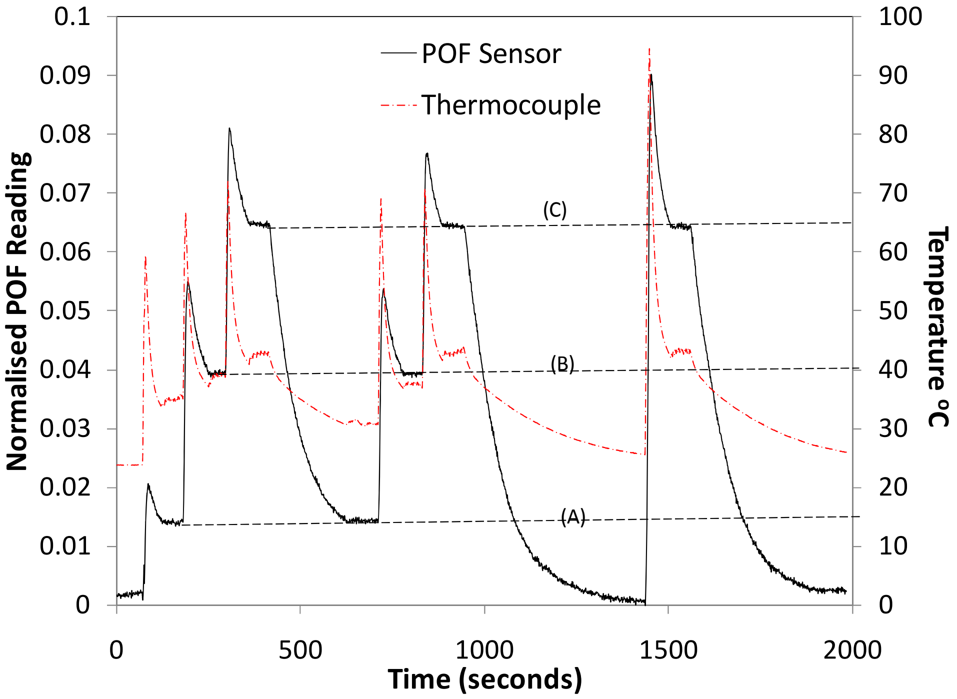

Figure 3 Plot showing the controllability of the smart FML beam using POF sensor

For the last cycle of the test, the beam was activated from room temperature. The rise time, defined as the time required for the response to rise from 0% to 100% of the steady state value, was calculated to be approximately 10 seconds at a heating rate of 6.5^{o}C/sec. The recovery rate was computed to be approximately 0.1% strain/sec demonstrating the responsiveness of the SMA to the heating mode applied in the study.

A plot of the thermocouple reading versus the POF sensor reading (beam deflection) of the same test is shown in Figure 4 clearly showing the presence of a linear and non-linear thermomechanical response of the smart FML. The large hysteresis is evident from the plot highlighting the inaccuracy that would accompany attempts at position control using temperature measurements as feedback signals. It is clear from this analysis that deflection measurement would be the preferred alternative to achieve an accurate control of the amount of deflection desired.

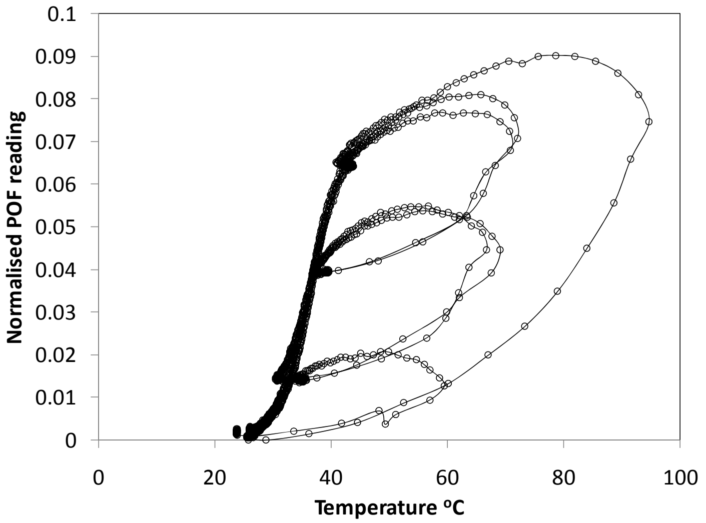

Figure 4 Plot showing the linear and non-linear thermomechanical response of the smart FML.

It was of interest to assess the ability of the POF to detect external disturbance which changes the deflection of the specimen and to self-correct its shape to its predetermined position. A weight was added to the free end of the specimen as a perturbation. The result is shown in Figure 5. At the time when the perturbation was introduced, the POF sensor detects the change in the deflection and subsequently triggered the controller to power the heater. The SMA was promptly activated and the predetermined beam position was restored as evidenced by the steady state values corresponding to the controlled position of the beam. When the original perturbation was removed, the temperature of the heater cooled further allowing the beam to settle to the controlled position as evidenced by the POF trace in plot.

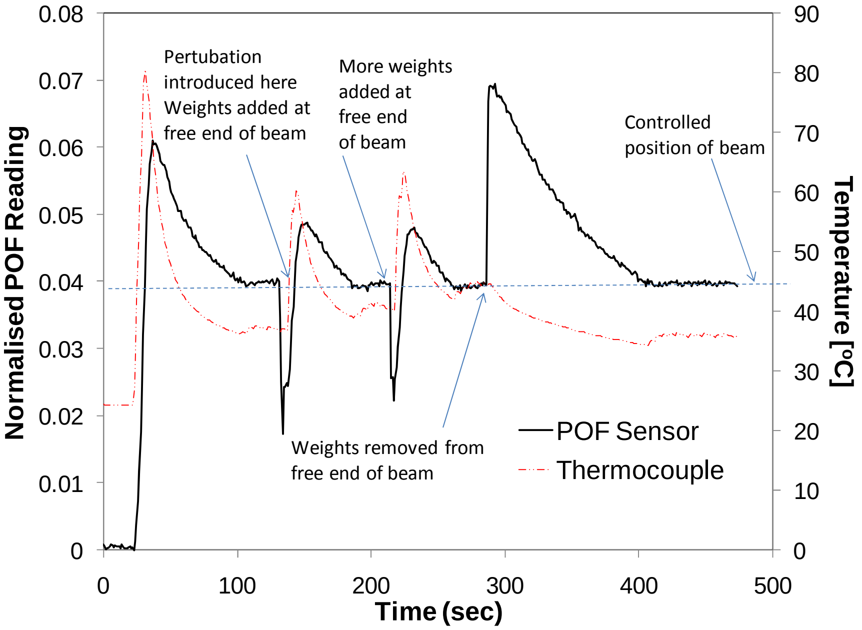

Figure 5 Plot showing the self-correcting response of the SMA beam based on the POF sensor signal

In order to eliminate or reduce the amount of overshoot observed in Figure 3, a tuning of the proportional-integral-derivative (PID) setting of the controller unit was carried out via a trial-and-error approach. The same heating and cooling sequence was adopted as previously carried out for ease of comparison. Earlier settings were restricted to only proportional control hence the large overshoot observed. It can be seen from Figure 6 that, with suitable settings of the integral and derivative control values it was possible to eliminate the large overshoot although it was also observed that this had led to a somewhat oscillatory response. Further tuning of the PID settings could result in a more stable response and is presently being explored.

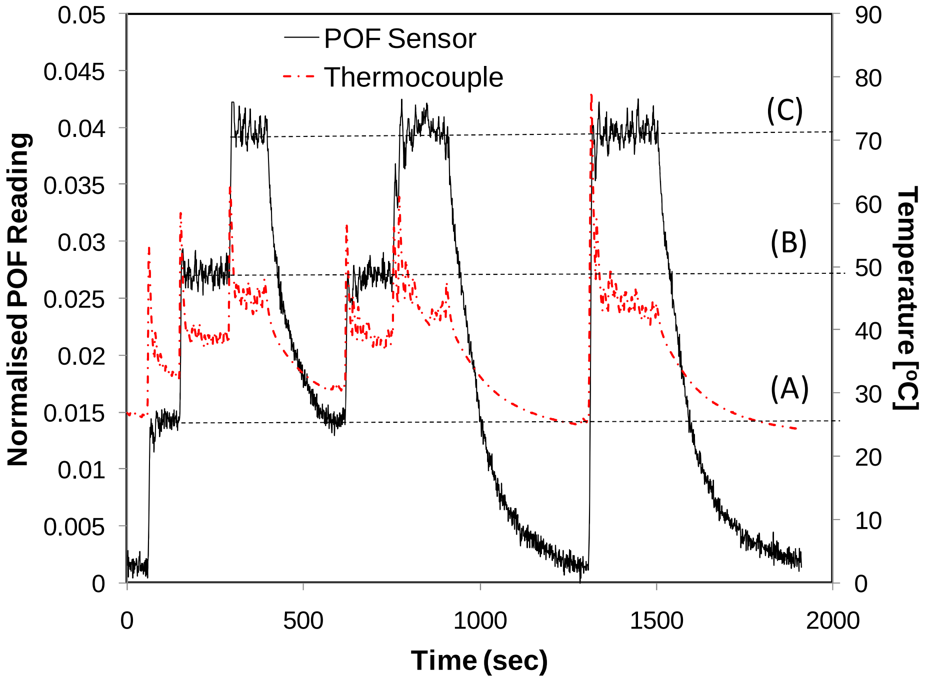

Figure 6 Plot showing the response of the beam using PID control to reduce the overshoot observed previously.

CONCLUSIONS

A novel fibre-metal laminate based on a nickel-titanium shape memory alloy has been developed and its activation capabilities have been investigated. The results have shown the controllability of the smart FML using POF sensor to monitor the deflection of the beam and using the signal as feedback to the controller unit. Test carried out also gave evidence of the self-correcting capability of set-up using the POF sensor signal. Tuning of the PID setting has shown that it was possible to eliminate the large overshoot initially observed resulting in a better control of the beam deflection for the entire duration of the test. It is expected that the oscillatory behaviour could be minimized following proper tuning of the PID control. The results have also highlighted that the incorporation of POF sensors into the laminates can successfully measure the out-of-plane response of these novel hybrid structures.

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References

1. A Vlot, LB Vogelesang and TJ De Vries, “Fibre Metal Laminates for High Capacity Aircraft”, in *The Proceedings of the 30th International SAMPE Technical Conference,* San Antonio, TX, October 20-24 (1998)
2. A Vlot and JW Gunnink (eds.) Fibre Metal Laminates: An Introduction, *Kluwer Academic Publishers,* The Netherlands, 2001.
3. TL Turner RD Buehrle, RJ Cano and GA Fleming, “Modeling, Fabrication, and Testing of a SMA Hybrid Composite Jet Engine Chevron Concept” *Journal of Intelligent Material Systems and Structures* Vol. 17, pp.483-497(2006).
4. KSC Kuang, M Maalej and ST Quek, “Hybrid optical fibre sensor system based on fiber Bragg gratings and plastic optical fibers for health monitoring of engineering structures’ *Proceedings of the SPIE* Vol.6174, pp.852-863 (2006).
5. KSC Kuang and WJ Cantwell, “ The use of plastic optical fibres and shape memory alloys for damage assessment and damping control in composite materials” *Measurement Science and Technology* Vol. 14, pp.1305-1313 (2003).
6. KSC Kuang, ST Quek and M Maalej, “Assessment of an extrinsic polymer-based optical fibre sensor for structural health monitoring” *Measurement Science and Technology* Vol.15, pp.2133-2141 (2004).

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