Research article

The mechanical behaviours of polyurethanes hybrid polymer composites embedded with Nickel-Titanium (NiTi) shape memory alloys

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Abstract:

In this study, polyurethanes embedded with Nickel-Titanium (NiTi) SMAs is investigated by experimental methods to understand the mechanical properties of the embedded SMAs with the aim of using them as active and passive surfaces in various applications. A matrix composite was utilized for the production of the silicone moulds and casting of the specimens. The implanted NiTi SMA wires were cut into required lengths using and aged at 250^{0C} and pre-strained by 3%. to ensure homogeneous behaviour. For each of the SMA/polyurethane composites, the treated NiTi SMA wire was properly located in the groove created in one half of the silicone mould the polyurethane resin was poured and cool to room temperature in vacuum casting machine. The result shows that the mechanical properties embedded SMA increased in of the SMA/polyurethane composite. The improvements in the properties cannot be sustained at high temperature owing to degradation of interfacial strength between the SMA and polyurethane

interface due to high recovery stress generated by the SMA upon activation. This work will help in integrating SMAs into matrix materials will improved understanding of the performance characteristics and application potentials of composites in terms of innovative and cost-effective manufacturing processes and provides an alternative to the traditional metals.

Keywords: Shape memory alloys; composite; smart materials; Nickel-Titanium

1. INTRODUCTION

Shape memory alloys (SMAs) are metals possess sensing and actuating functions which exhibit an exceptional thermo-mechanical behavior which allowing them to completely recover a pre-imposed shape after significant deformations, either upon a temperature change or simply by removing the applied load (Yang, et al.(2016); Karimi Mahabadi et al.(2016) ; Tang et al.(2015). These novel materials also have the ability to return to a predetermined shape when heated (Ochonski (2010); Braunovic et al. (2006); Song et al. (2006) ; Çakır et al.(2013). When this material is cold, or below its transformation temperature, it has a very low yield strength and can be deformed quite easily into any new shape which it will retain and it heated above its transformation temperature, it undergoes a change in crystal structure which causes it to return to its original shape (Song et al.(2000); Song(2006); Ni et al.(2007); Patoor et al.(2006); Paine et al. (1993).The materials can undergo martensitic phase transformations as a result of applied thermo-mechanical loads and are capable of recovering permanent strains when heated above a certain transformation temperature (Patoor et al. (2006) ; Huang et al.(2015). (See Figure1). SMAs possess sensing and actuating functions and have the potential to control the mechanical properties and responses of their hosts due to their inherent unique characteristics of shape memory effect and pseudo-elasticity (Ni et al. (2007). A composite is a hybrid of two or more constituent materials with significantly different physical or chemical properties and which remain discrete on a macroscopic level within the finished structure and it designed to display a combination of the best characteristics of each of the constituent materials (Williams (Jr). (2003). The SMAs have been applied in different forms such as spring, thin films, and tendon and they have been utilized as wires or patches to consolidate many types of structures. Researches related to the application of SMAs for advanced structures are ongoing (Abdollahi et al. (2015). Consequently, a composite performance is superior to those of its constituents acting independently and despite the good characteristics displayed by composites, but there are some drawbacks associated with them (Groover (2002). Many important composites are anisotropic and many polymer-based composites are susceptible to chemical or solvent attacks. Some of the manufacturing methods for shaping composite materials are slow and costly. Smart materials are used in adaptive structures to perform multi-functional tasks. The potential use of shape memory alloys as active fibres, embedded in a composite lamina is one such application to develop SMA embedded composite actuators (Jarali et al. (2008). SMA-Composite materials are created by embedding SMA elements in the forms of wires, ribbons or particles into matrix materials such as polymers, fibres-reinforced polymers, metals, or ceramics (Paine et al. (1993).When integrated into structural components, they perform sensing, diagnosing, actuating and repair or healing functions, thereby enhancing improved performance characteristics of their hosts (Ni et al.(2007). Embedding SMAs into composite materials can create smart or intelligent composites and controlling the structural properties and this are now attracting much attention and there is a growing demand to improve on composite materials to have “smart" capabilities so as to be able to sense, actuate and respond to the surrounding environment (Sanusi et al.(2014). Amongst the commercially available SMAs, NiTi (Nickel-Titanium) alloys are the most widely used because of their excellent mechanical properties and superior material characteristics: of shape-memory performance, good process-ability, good corrosion resistance, cyclic stability, fatigue resistance and wear resistance and biocompatibility, which enable them to be used in the biomedical field (Wei et al.(1998); Qidwai et al.(1999).The thermo-mechanical properties of SMAs have been investigated by many researchers (Song et al.(2006); Tsoi et al.(2002); Liang et al.(1991); Ikedia (2015); Yang et al. (2016). However, the concept of smart hybrid composites with embedded elements emerged in the late 1980s and attracted a worldwide research interest in the last decade (Sittner et al.(2000) ; Aurrekoetxea et al.(2011) ; Fathollah et al. (2011) ; Kim et al. (2011); Raghavan et al. (2010); Kang et al. (2009) ; Ni et al. (2007) ; Murasawa (2004) . The aim of this research work is to investigate the improvement in the mechanical properties of 60D polyurethane embedded with NiTi shape memory alloy. The elastic modulus, tensile strength and bending stiffness of the virgin polyurethane (without SMA implant) as well as that of SMA/polyurethane composites were investigated at both room temperature and at an elevated temperature.

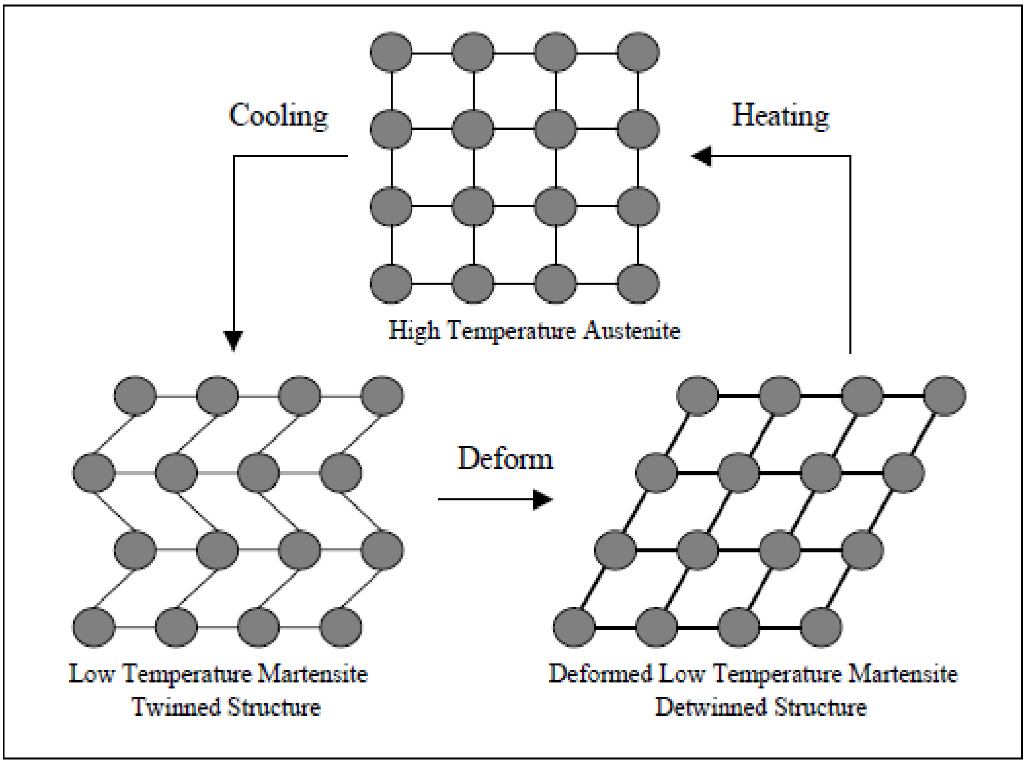

Figure 1: SMA microstructural behaviour.

2. Materials and methods

In this research work, a matrix composite was utilized for the production of the silicone moulds and casting of the specimens. The chemical composition of the NiTi SMA and the 60D polyurethane resin are as given in Tables 1 and 2 respectively. The implanted NiTi SMA wires were cut into required lengths using guillotine cutting machine were aged at 250^0C to ensure homogeneous behaviour (Sanusi et al. (2014). All the NiTi SMAs were pre-strained by 3%. For each of the SMA/polyurethane composites, the treated NiTi SMA wire was properly located in the groove created in one half of the silicone mould. The mould was placed inside the vacuum chamber of the vacuum casting machine where the polyurethane resin was poured and cool to room temperature. Figures.2-3 tensile specimens and rectangular beams used for the pullout and the four point bending tests.

Table 1: Chemical composition of NiTi SMA

Ni (%)	Ti (%)	C (%)	O (%)	Others (%)	Active A_f (0^C)
55.32	44.67	0.05	0.05	0.20	60.7

Table 2: Technical Data for 60D polyurethane resin

Mix Ratio (pbv)	Pot Life (mins)	De-mould Time (mins)	Mixed viscosity (cps)	Density g/cm^3)	UTS (psi)
1A:1B	5	20	1500	1.05	2200

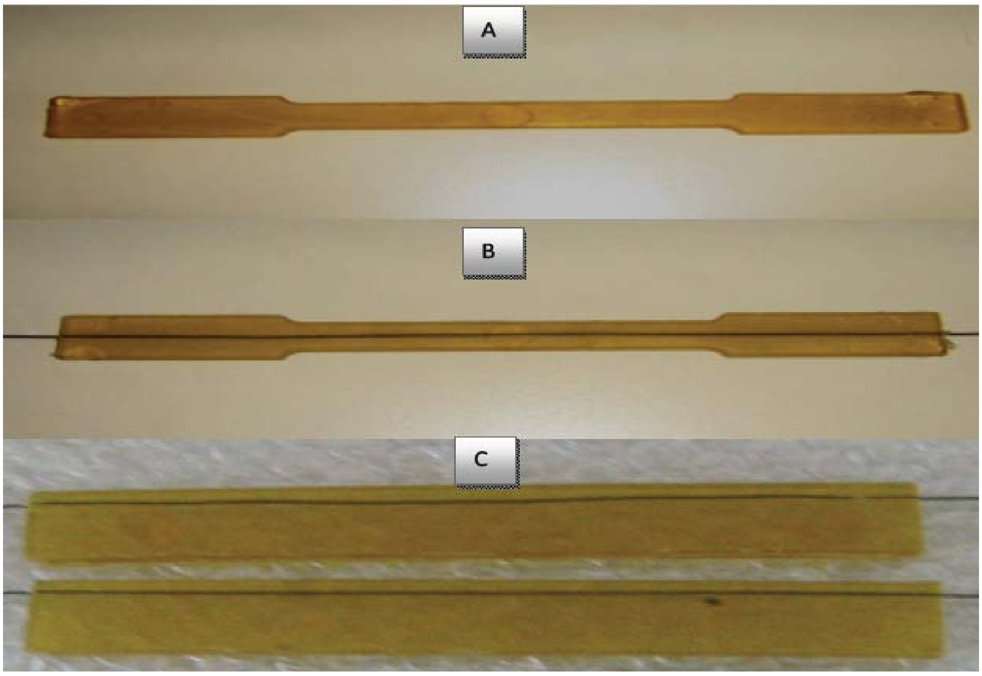

Figure 2: Polyurethane (A) without NiTi SMA Implant (B) with implanted NiTi SMA for tensile test (C) Polyurethane beams with implanted NiTi SMA for bending test

The single-wire pull out test was conducted at room temperature (when SMA was not activated) and at an elevated temperature (when SMA was activated) using a Hounsfield tensile testing machine. The experimental set up is shown in Fig.3. The uniaxial tensile tests were performed at an ambient temperature of 24^0C. The cross head displacement speed was 5 mm/min. the experiments were conducted under essentially isothermal conditions. The four pull test was conducted with tensile testing machine. The cross-head displacement speed was 1 mm/min and the maximum deflection was limited to 5 mm to ensure accuracy of result. The activation of the implanted NiTi SMA was accomplished by direct heating method with a current of 3 amps from a DC source for the elevated temperature tests.

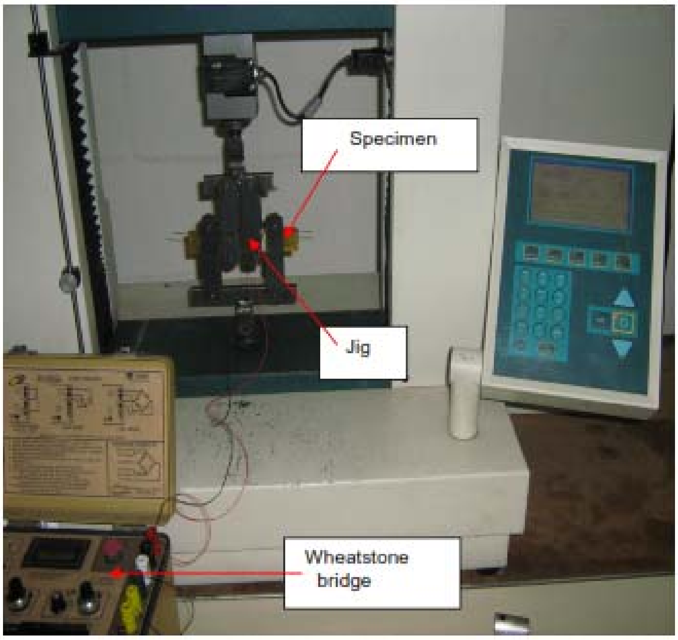

Figure 3: Experimental set up for pull-out and tensile tests

3. **Results and discussions**

From the results Fig. 4 shows the average of the stress versus strain curves for the un-aged (as obtained from the Manufacturer) and the aged NiTi SMA wires to show the effect of ageing on

NiTi SMA Wires. From the curves, it is evident that the quasi-plastic characteristic associated with NiTi SMAs was less pronounced in the un-aged wires and there is an improvement in the mechanical properties of the aged wires. Fig. 5 shows the average of the combined stress versus strain curves obtained at different ageing temperatures of 250^0C, 300^0C, 350^0C and 400^0C. The stress versus strain curves show the homogeneous behaviours of the aged wires and consistent elastic strain and ultimate tensile strength which are in conformity with the work of (Paine, et al., 1993).

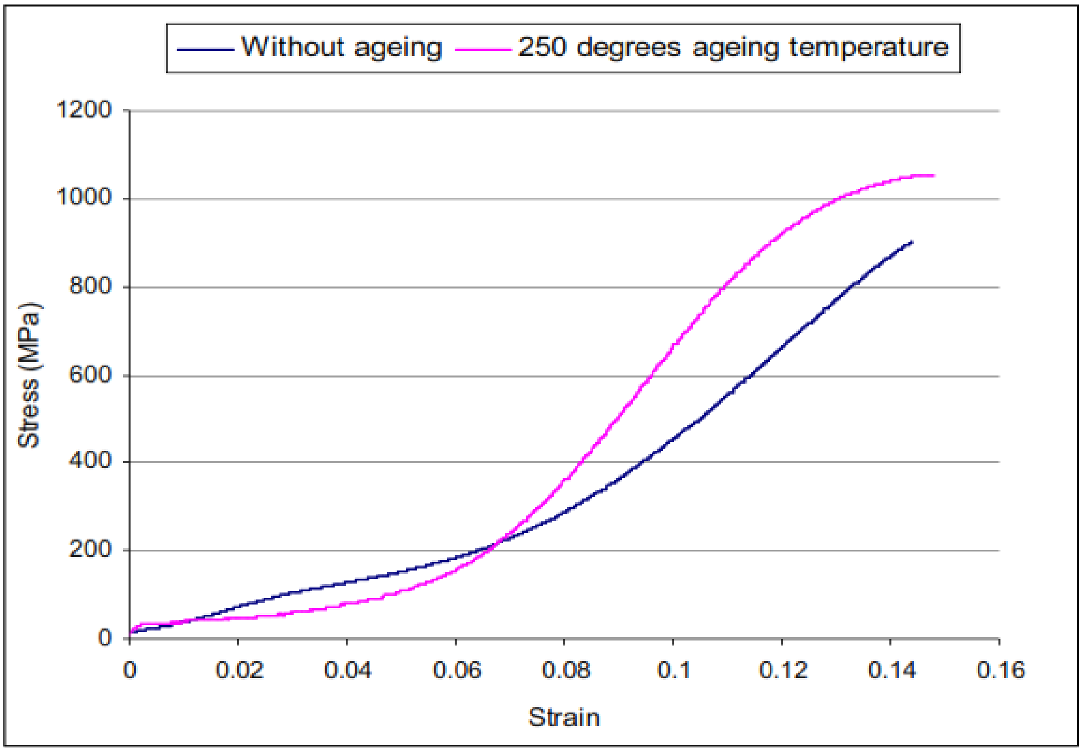

Figure 4: Effect of ageing on NiTi SMAs.

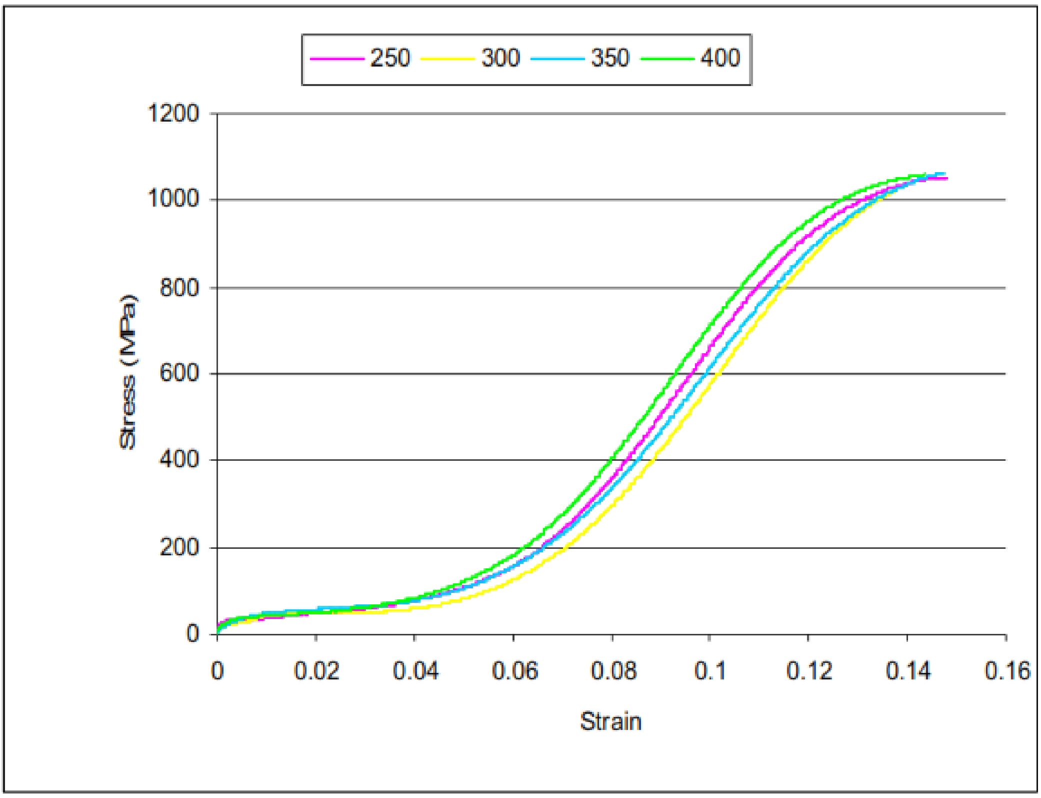

Figure 5: Stress vs. strain curves at different ageing temperatures

Fig. 6 illustrates the average pullout load versus displacement curves for the tests conducted at room temperature and at an elevated temperature to show the effect of temperature on the SMA/polyurethane composite. De-bonding is characterized by the sudden drop in the steadily increasing tensile load that was pulling the embedded SMA wire out of the SMA/polyurethane composite. The load which initiated the separation of the wire from the polymeric host is known as the pullout or de-bonding load. The loads at which the de-bonding occurred at room and elevated temperatures were 128.5 N and 70 N respectively. From the load displacement graph, it is evident that the separation of the wire from the polymeric host did not occur at once but rather in stages. In the case of the test at room temperature, initiation of the separation of the SMA wire from its polymeric host was accompanied by the sudden drop in the load from 128.5 N (point A) to 117 N. However, the subsequent increase of the pulling load above 117 N was due to the constraint offered by the matrix to the remaining portion of the embedded NiTi SMA wire. As the pulling of the wire continued, the shear stress increased to reduce the interfacial bond strength, and this led to the eventual separation of the wire from host matrix (point B). This final separation was accompanied by an abrupt drop in the pulling load. And for the test at an elevated temperature, the de-bonding process was also a gradual one however, the initial de-bonding occurred at a comparatively smaller load (70 N) and the final separation of the SMA wire from the polyurethane occurred over a relatively prolonged displacement as shown in the encircled region.

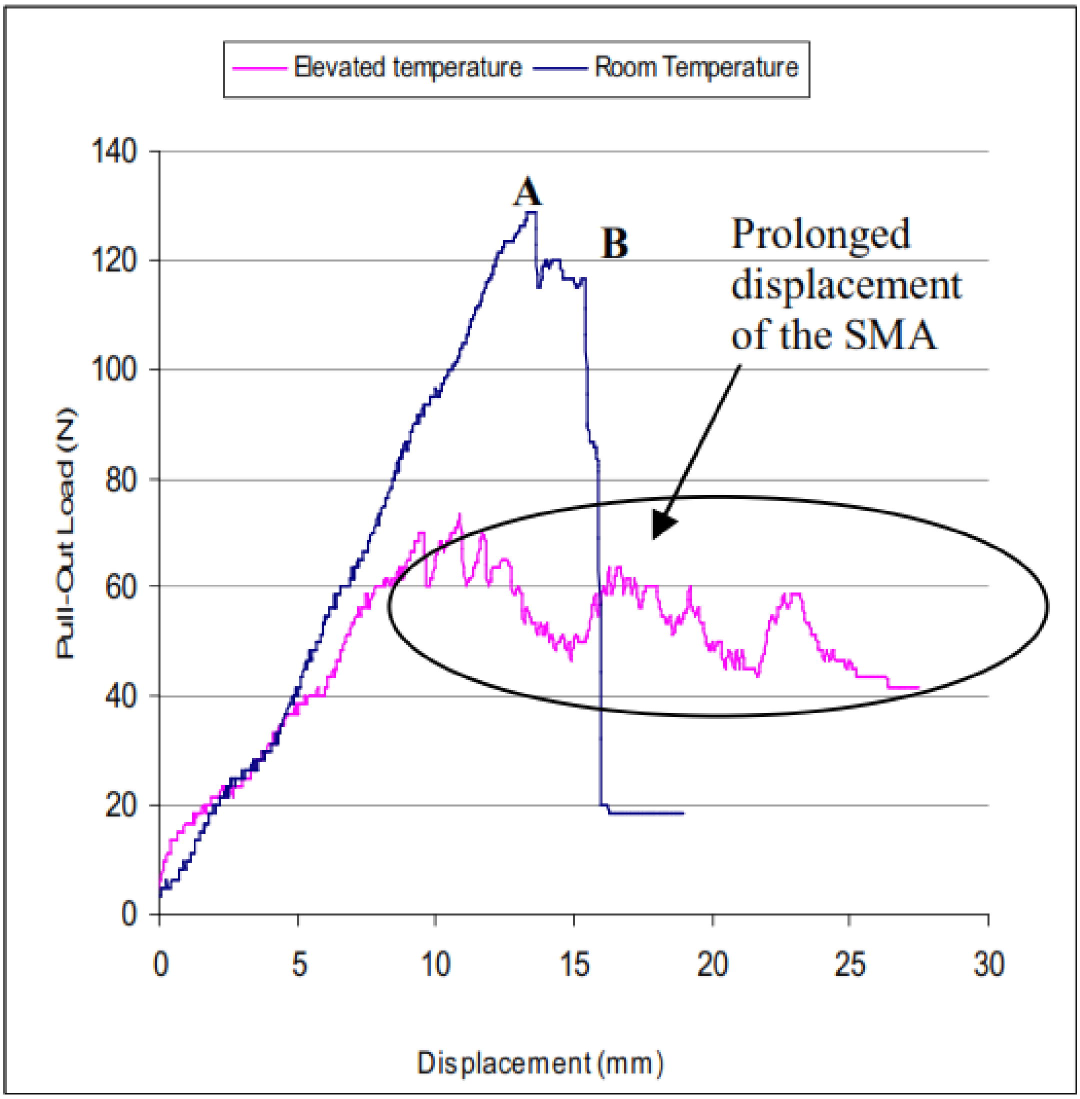

Figure 6: Pull out load vs. displacement at room and elevated temperatures.

This result was anticipated due to the shape memory effect (SME) of the activated SMA. Upon activating the embedded wire, a relatively larger interfacial shear stress will be generated at the SMA/polyurethane interface due to the SME. The generated interfacial shear stress resulted to interfacial failure between the SMA wire and the host matrix. Owing to initiation of de-bonding, only frictional resistance between the SMA and the composite will hinder shape memory recovery. This development led to the reduction of the pulling load. Increasing pulling load led to increase in the shear stress at the SMA/polyurethane interface and eventual separation of the SMA wire from the polyurethane matrix. A complete breakdown of the interface led to cessation of shape memory adaptation.

The average stress versus strain curves obtained from the tensile tests conducted on virgin polyurethane and the NiTi SMA/polyurethane composite without activating the SMA wire are illustrated in Fig. 7. It show the effect of embedding NiTi SMA Wire into 60D polyurethane It could be seen that the failure of the specimens was brittle in nature as there was no considerable plastic deformation before fracture occurred. This shows that the presence of the NiTi SMA wire which although possesses high ductility, did not affect the brittle nature of the thermosetting plastic polyurethane (Zhang, et al., 2007; Mirzaeifar, et al., 2014). However, it is obvious from the curves that the NiTi SMA/polyurethane composite offers more resistance to load than virgin polyurethane.

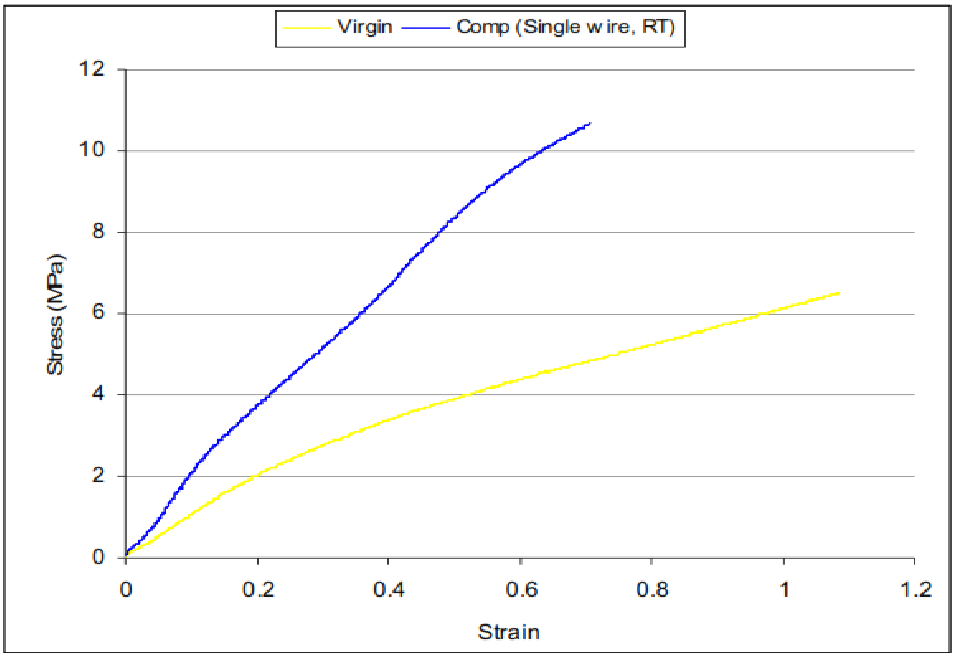

Figure 7: Effect of the embedded NiTi on Polyurethane.

The elastic modulus for the virgin polyurethane was 10 MPa and for the SMA composite in which the embedded SMA wire was not activated, the elastic modulus was 30 MPa. This result shows the contribution of the embedded NiTi SMA to increasing the stiffness of the beam. This result indicates the effectiveness of SMA for passive applications and it conforms to what was reported by (Turner, 2001).

Fig. 8 illustrates the effect of temperature on the NiTi SMA/Polyurethane composite to show the effect of activation of the NiTi SMA wire embedded in the SMA/polyurethane composite. RT refers to inactivated SMA while ET refers to activated SMA in the SMA/polyurethane composites. It could be seen from the curves that the relative advantage of activating the SMA was only manifested at the initial stage of loading, but as the loading progressed, the resistance of the SMA/polyurethane which had its implanted SMA wire activated reduced. Upon activating the SMA wire, the constraint provided by the host matrix will prevent the SMA from reverting to its un-deformed length. This hindrance to recovery of the recoverable deformation led to the generation of recovery force which produces shear stress at the SMA wire – polyurethane interface. The generated shear stress reduced the interfacial cohesion and eventually resulted in de-bonding.

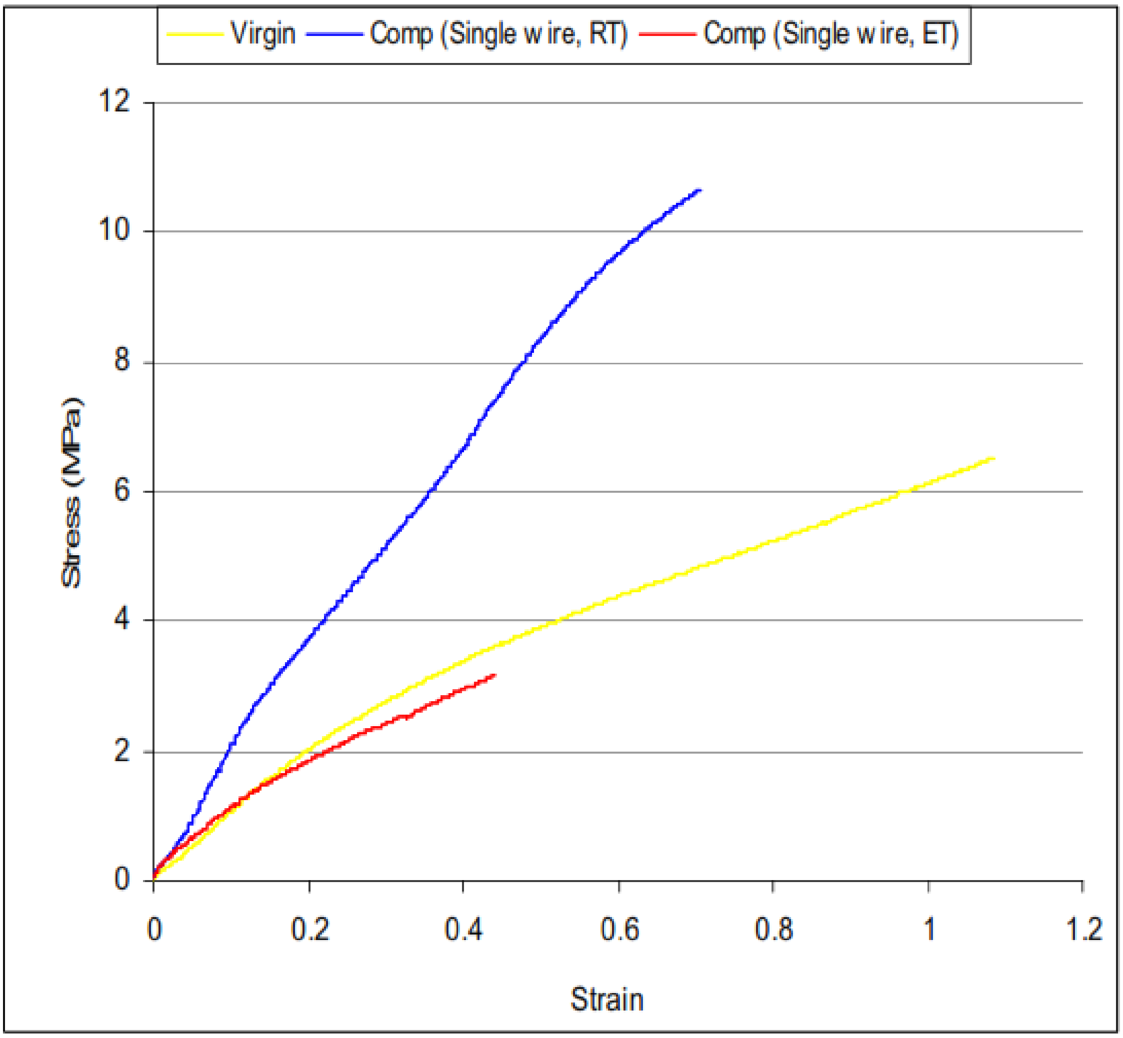

Figure 8: Effect of temperature on SMA/polyurethane composites.

Fig. 9 shows the curves of bending load versus strain for the virgin polyurethane beam, SMA/polyurethane beam with inactivated NiTi SMA Wire (RT) and SMA/polyurethane beam with activated NiTi SMA Wire (ET), this shows effectiveness of the shape memory effect of the embedded SMA on the SMA/polyurethane composite. It is evident from the curves that implanting NiTi SMA Wire into the polyurethane beam results in overall improved stiffness when the SMA is not activated. This result conforms to the result that was obtained from the tensile test. Also, it could be seen that the SMA/polyurethane beam with activated SMA wire offered more resistance to the bending load than the SMA/polyurethane beam without activation as well as virgin polyurethane beam but this trend was for a limited time frame (i.e. at the initial stage of loading). However, as the loading continued, the resistance to load decreased owing to the temperature sensitivity of the polyurethane host which resulted in the separation of the SMA wire from the matrix.

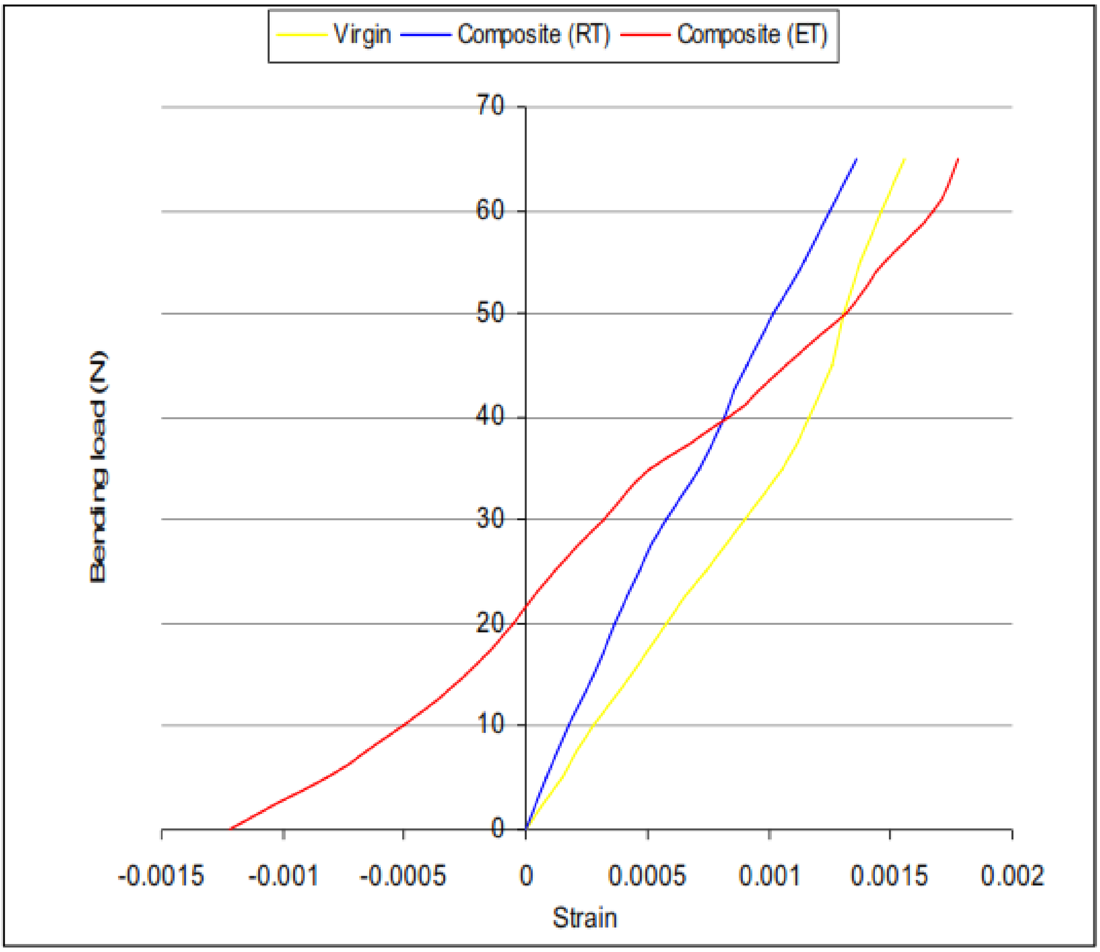

Figure 9: Effect of shape memory effect

The negative strain recorded at the initial stage of loading the SMA/polyurethane beam which had its SMA wire activated was due to the manifestation of the SME. Upon activation, the SMA contracted so as to revert to its initial un-deformed length. This brought about the generation of recovery stress owing to the constraint provided by the matrix and hence negative strain. This result demonstrates the ability of the SMA to gain control of composite structure behaviour when utilized for ASET (active strain energy tuning). As the loading continued, the merit of activating the embedded SMA was short-lived by de-bonding. This led to a drastic reduction in the resistance offered to the bending load. Figure 10 also shows the effectiveness of the embedded NiTi SMA upon activation, within a limited low range of bending load and before de-bonding occurred. Again, could be seen that as the test progressed, the property of the composite beam which had its SMA wire activated worsens drastically due to de-bonding.

The effectiveness of the embedded SMA on deflection on the SMA/polyurethane composite is show in Fig. 10 the figure which shows bending load versus deflection of the virgin polyurethane and SMA based composite beams. From this it shows that the activation of the embedded NiTi SMA wire considerably increased the stiffness of the composite beam at the initial stage of loading. That is, the SMA wire in its high temperature phase enhanced the resistance to the deflection of the SMA based composite material. This trend continued until a load of approximately 15 N when it becomes less stiff than the composite with inactivated SMA wire but still stiffer than the beam without SMA wire implant.

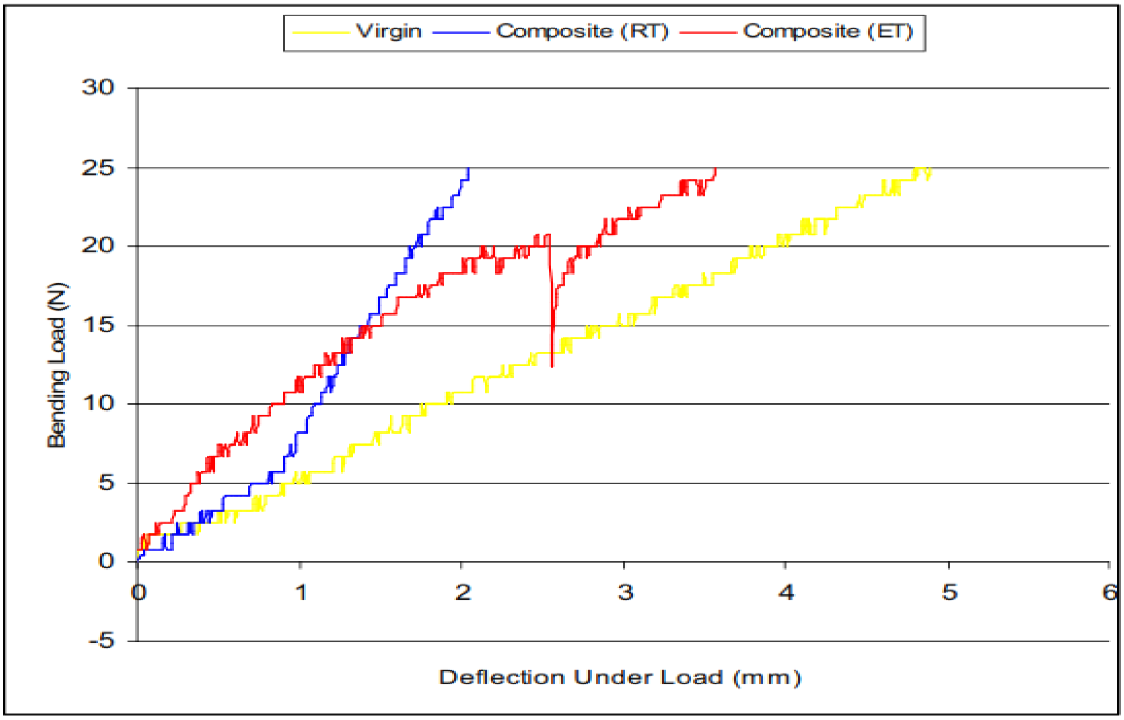

Figure 10: Bending load vs. deflection

From the result the deflection of the virgin beam varies linearly with the bending load. Regarding the SMA/polyurethane beams, their deflection deviated from linearity owing to the non-linearity in the behaviour of SMA wires, due to pseudoelasticity and SME. In the case of the beam which had its wire activated, the sudden drop in the bending load was due to the reduction of the interfacial strength between the SMA and the polymeric host. The reduction in the interfacial bond initiated de-bonding. However, despite the adverse effects of de-bonding and the temperature sensitivity of the polymeric host, the activated SMA based composite still offered more resistance to the bending load than the virgin polyurethane beam.

4. CONCLUSIONS

The improvement in the mechanical property and the behaviour of 60D polyurethane upon integration NiTi SMA Wires were investigated at room and elevated temperatures. Based on the results presented in this paper the following conclusions can be drawn:

- Ageing enhanced the properties of the embedded NiTi SMAs
- The pull out (or de-bonding) load when the SMA wire is inactivated is higher than when the SMA is activated
- The de-bonding load under an axial load is higher than the de-bonding load under transverse load
- Embedded NiTi SMA increases the elastic modulus, ultimate tensile strength and bending stiffness of the SMA/polyurethane composites
- High temperature degrades the interfacial adhesion between the NiTi SMA and the 60D polyurethane host matrix
- Embedded NiTi SMA wires gain structural control of the SMA/polyurethane composite beam upon activation of the NiTi SMA wire

From this the functional properties of SMA elements can be combined with the structural properties of matrix materials to create a novel materials with new enhanced properties

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