Experimental analysis and numerical simulation of tensile behavior of Ti-Ni shape memory alloy fibres reinforced epoxy matrix composite at high temperatures

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Abstract - The shape memory alloys (SMA) possess both sensing and actuating functions due to their shape memory effect, pseudo-elasticity, high damping capability and other remarkable properties. Combining the SMA with other materials can create intelligent or smart composites. The epoxy resin composites filled with TiNi alloys fibres were fabricated and their mechanical properties have been investigated. In this study, stress/strain relationships for a composite with embedded shape memory materials (SMA) fibres are presented. The paper illustrates influence of the SMA fibres upon changes in mechanical behavior of a composite plate with the SMA components, firstly and secondly, the actuating ability and reliability of shape memory alloy hybrid composites.

Keywords: Smart material, shape memory alloys, composites, mechanicals properties.

1. Introduction

The shape Memory Alloys (SMA) with abilities to change their material properties such as Young's modulus [1] damping capacity [2] and the generation of large internal forces [3], when combined with other materials can create intelligent or smart composites by utilizing the unique properties of SMA, such as shape memory effect, pseudo-elasticity, high damping capability (Fig.1a). The principal characteristic of shape memory alloys (SMA) is the ability to memorize their original configuration after they have been deformed by heating the SMA above the characteristic transition temperatures. This phenomenon is caused by a phase transformation of the SMA microstructure from martensite to austenite when the transition temperature is reached. Shape memory alloy (SMA) reinforced composites are an extremely versatile class of materials. Indeed, the use shape memory alloys as fibre reinforcement gives structures numerous adaptive capabilities. One of them is the controlling of motion and the vibration of structures (active control of their static and dynamic behaviour). SMA has been utilized as actuators to successfully control the larger static deformation and vibration of various larger structures [4, 5]. Investigations concerning the design of shape memory hybrid polymer matrix composites have shown the influence of volume fraction [6], surface treatment [7], pre-strain of the shape memory components [6], and matrix curing process [8] on the properties of SMA hybrid composites. These contributions enabled the production of some prototypes of smart materials, but are not enough to produce a reliable composite.

This paper focuses on the integration of thin shape memory alloy wires into polymer plates with the goal to provide them with adaptive functional responses. A simple network consisting of only a single family of reinforcements is shown in Fig. 1b. In order to better understand the effect of the integrated SMA fibres reinforced layer on the reduction of the stress concentration in the hybrid structure, some numerical examples are presented and the integrity and efficiency of the SMA reinforced joint system is simulated. Moreover, the finite element analysis solutions presented in this work are compared and validated to those obtained from experimental results.

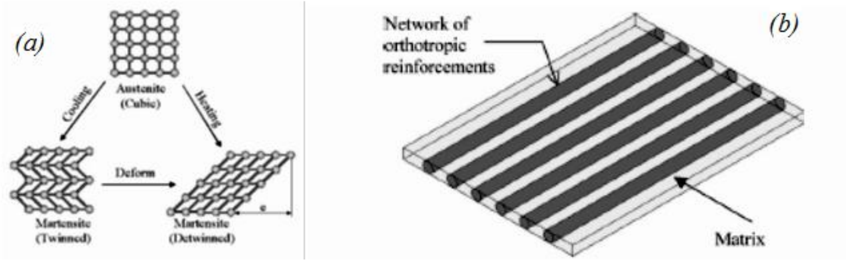

Figure 1: (a) The Shape Memory Effect Process (b) composite plate reinforced with a network of orthotropic bars.

2. Materials and Methods

2.1. Materials

The SMA wire used in this study is 0.2mm in diameter, made in China, with a composition of Ni-50.8 wt% Ti. Each wire has been heat treated at 650°C during 30 min and then quenched in water where it was kept for 2h. After heat treatment, the austenite-finish temperature is 79°C (the wires are fully martensitic at room temperature). The resulting micrograph is shown in Fig. 2a. The transformation temperatures of the alloy were determined by the method of tangents from the differential scanning calorimeter (DSC) data and the results were found to be A_s=50°C, A_f=79°C, M_s=58.4°C and M_f=32.4°C, as shown in Fig. 2b. The polymer used as a matrix was ER3 epoxy resin, and the hardening agent was EH208W produced by GHCRFT Co., Ltd., Japan. The ER3 epoxy resin had a high impact resistance property, and the glass transition temperature (T_g) was approximately 140°C. The engineering constants of TiNi alloy and ER3 epoxy resin were listed in Table 1.

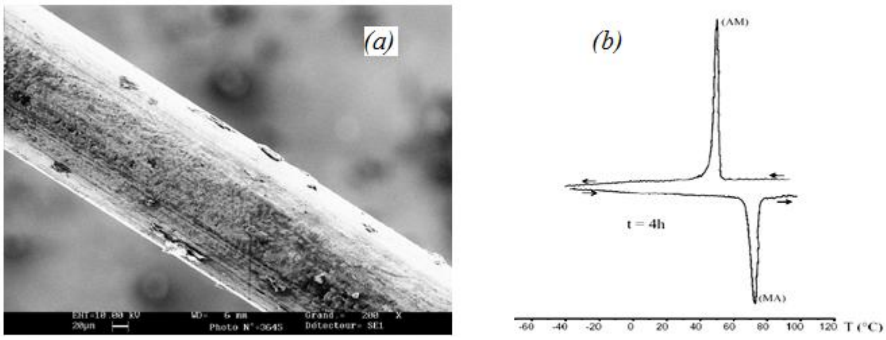

Figure 2: (a) Surface condition of SMA wire at room temperature (293 K), (b) DSC measurement of TiNi sample annealed at 650°C, 4h.

Table 1: Mechanical properties of constituents

Materials	Young's Modulus	Density	Yield stress at 90°C	Glass temperature
SMA - austenite	58400	6500	700	-
Epoxy	3500	1150	25	140

2.2. Experimental methods

The specimen is made of the TiNi fibres reinforced/epoxy composite developed by the authors having a thickness of about 0.4mm. The design concept for enhancing the mechanical properties of the SMA composite is schematically shown in Fig 3. These samples were produced in an autoclave, using a special frame designed to maintain the wires clamped during processing (Fig.4a). After the unreinforced epoxy resin and fibres reinforced composite was dried, it was cut using a saw cutter to get the dimension of specimen for mechanical testing. The resulting thin SMA composites have the dimension of 140x 30x0.4mm^3. The specimens were shortened to a length of 100mm and mounted in the clamps of the thermo-mechanical testing machine, as shown in Figure 5a.

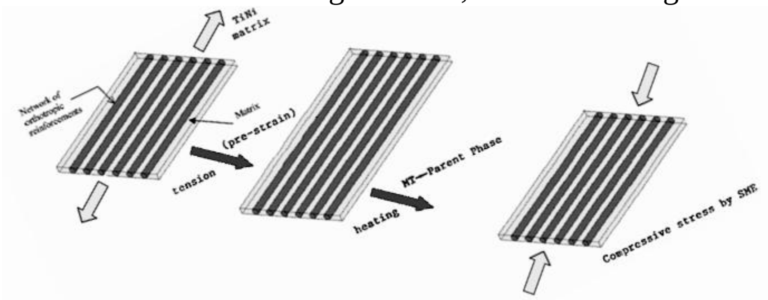

Figure 3: Basic design concept of intelligent composite material.

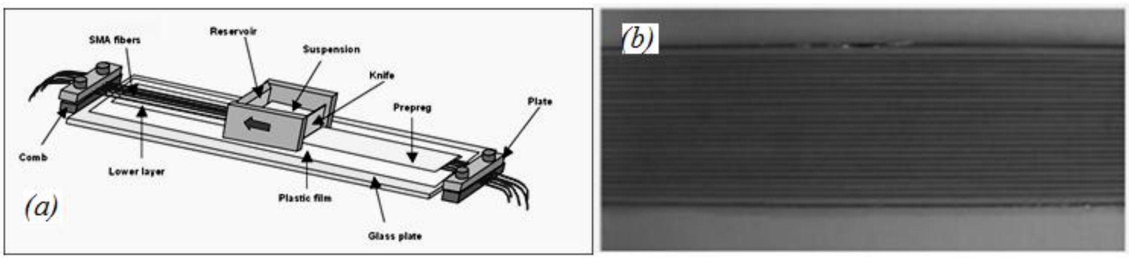

Figure 4: (a) Schematic presentation of the fabrication of smart composite, (b) photograph of SMA composite with 30 embedded TiNi wires

After manufacturing of these hybrid composite specimens, an experimental investigation for determined the mechanical properties subjected to tensile tests was conducted by using the Instron 6025 testing electrical machine operating in axial speed control (1mm/min). This machine was equipped with a load cell for measuring load and a capacitance sensor for measuring displacement between grips. These tests were carried out at various temperatures ($T<M_f$ or $T>A_f$) in order to observe various types of stress/strain curves showing strain behaviour associated with stress-induced martensitic transformation. Finally, the experimental results were used to validate the finite element model.

3. Experimental results and discussions

The tensile test results in the longitudinal direction are shown in Table 3, and the typical stress/strain curves for the glass/epoxy composites and SMA/epoxy composites are shown in Fig.5b. From these it is observed that the Young's modulus of the composites changes very little with temperature.

However the difference between the Young's modulus isn't large, due to the volume fraction of the wires in the specimen not being large enough for there to be a noticeable difference. Table 2 shows the differences in the Young's modulus found at different temperatures. It should be noted that the epoxy matrix has the effect of increasing the Young's modulus slightly, as shown by the small increase in the Young's modulus with temperature, in Figure 5b, which isn't obvious in Table 2 due to the averaging of the Young's modulus over the different pre-strains. Figure 6 shows different micrographic observations of the fibres/matrix interface after loading the appropriate material up to 12% deformation. We can note a separation of the matrix around some fibres, delamination often accompanies a matrix cracking.

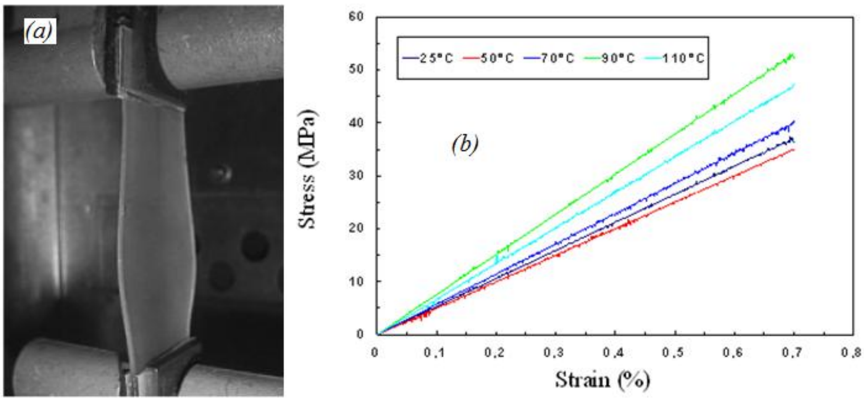

Figure 5: (a) SMA wire/epoxy matrix composite clamped in the tensile testing machine, (b) Stress versus strain charts for SMA-composite specimens heated at 25, 50, 70, 90 and 110°C.

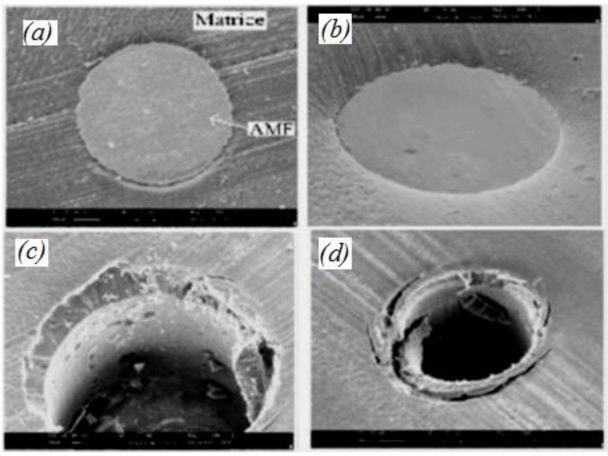

Figure 6: Scanning electron micrograph of a transverse section of the fibre/matrix interface: (a) initial state, (b) localised deformation around the fibres after a pre-stretching of 8%, (c) start tearing fibres SMA after a pre-stretching of 10%, (d) complete deterioration of the Interface after 12% pre-stretch.

Table 2: Young's modulus values of SMA-composites at different temperatures

Temperatures [°C]	50	70	90	110
Young's modulus [GPa]	4.4±0.8	5.9±0.8	7.1±0.8	6.9±0.8

4. Numerical simulation and discusions

4.1. Numerical methods

Numerical simulations were performed using LsDyna® code, based on finite elements method. These simulations were performed using a superelastic behaviour for a shape memory material available in the calculation codes LsDyna®. The material parameters of the models are represented in Fig. 7a. These physical parameters of the SMA wires are registered during the tensile test make it possible to derive the stress/strain relations. Table 3 summarizes results in terms of average engineering uniaxial stress/strain. The dimensions of the work-piece are: 30x100x0.4mm^3 for a matrix fine plate and 30 wires of diameter 0.2mm and length 100mm, which was then subjected to a longitudinal load of 10N at one end while the other end was fully fixed. The geometry, the boundary conditions and loading of the plate are shown in Fig. 7c. The 3D FE mesh, with a total element numbers for the matrix is 1554200, and the total element numbers for the thirty fibres is 192000. The solid element SOLID45 is employed for meshing the matrix and fibres tows respectively. The mesh refinement was chosen in order to guarantee a good estimation of the contact area between matrix/fibres which can undergo a causing delamination at an interface, as depicted in Fig. 7. This section presents some numerical simulations developed in order to show the qualitative behaviour of SMA/epoxy composite responses.

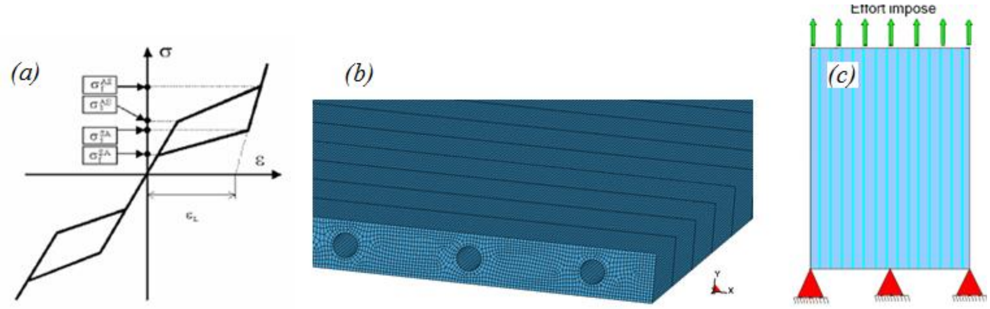

Figure 7: (a) Pictorial representation of superelastic behaviour for a shape memory material, (b) example of a mesh using LsDyna commercial package, (c) geometry and boundary conditions of the SMA/epoxy plate.

Table 3: Mechanical properties of the materials for modelling

Materials	Young's Modulus	σ^f_{AS} [MPa]	σ^s_{AS} [MPa]	σ^f_{SA} [MPa]	σ^s_{SA} [MPa]	ε_L [%]
100% austenitic	58334	350	475	250	175	0.06
100% martensitic	25000	175	100	60	25	0.06

4.2. Numerical results

Figure 8 shows the isovalues of von-Misses effective stress of the plates during tensile test. The difference in behaviour was observed on the values of the displacement field in the direction of loading fibres according to their phase (martensitic or austenitic). These results confirm that an adaptable structure with active fibres in the austenitic state remains the best choice to improve the system overall behaviour of TiNi/epoxy structure.

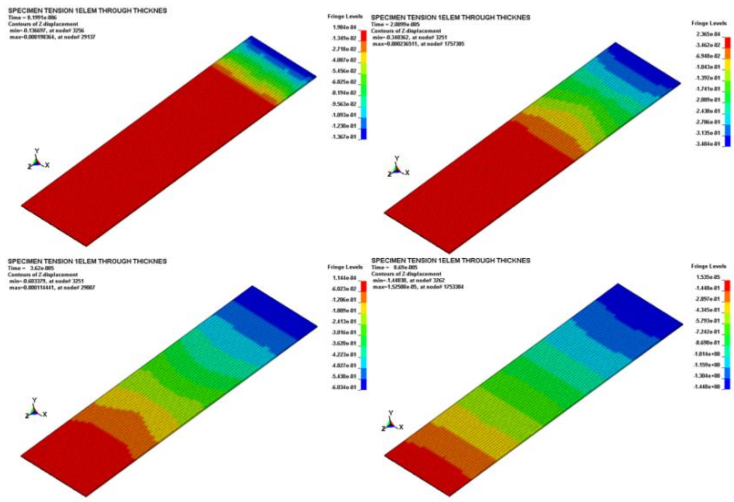

Figure 8: Displacement field along the direction z-z, of TiNi wires (austenitic)/epoxy.

4.3. Experimental validations

This section presents some numerical simulations developed in order to show the qualitative behaviour of SMA composite responses. To validate the model analysed, a series of simulations were conducted in which the constitutive parameters were those indicated in Table 1 and 3. In Fig. 9, stress/strain correlations between experimental results and their simulations are shown for different materials. Results show a good agreement between the experimental and the numerical model and the model is close to experimental results.

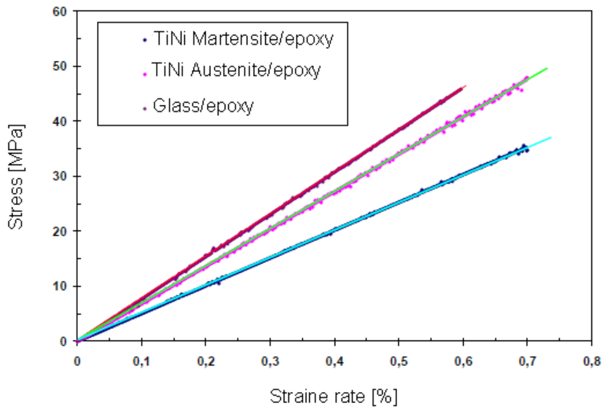

Figure 9: Comparative results of the experimental and numerical curves for the tensile tests performed on thin structures in materials suitable to active fibres and folds composite glass/epoxy.

5. Conclusion

The main objectives of this work were to investigate numerically the mechanical behaviour of smart composite plates embedded with super-elastic shape memory alloys wires. In the work a general description of the problem is introduced. The finite element formulation to predict changes in mechanical behaviour of composite plate with the SMA fibres has also been shown. The stress/strain relationships for a plate of composite material with embedded SMA fibres are also presented. In this article, the design concept has been proposed for developing the composite material that has the high mechanical properties. The smart composite samples with different various levels of wires pre-strain were successfully produced. The modelling approach and experimental data lead to the following conclusions: Based on the results of the SMA wire tests it was determined that the TiNi (austenitic phase) wires have the best characteristics for embedding into fibre reinforced composite materials. Moreover, the recovery stress is generated by shape memory effect of the TiNi fibres along the temperature rise. The results of the above research also demonstrated that using of the SMA wires within the traditional composite plates improves the global behaviour of the structure. The finite element analysis results presented in this work are compared to those obtained from the experimental results. The results of the simulation are in good agreement with the experimental resulting from the tensile tests.

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