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Control of Crack Propagation in Composite Fiberglass-Polyester Laminates Using Nitinol Wire

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Abstract. The experimental analysis presents the control of cracked composite fiberglass-polyester by using reinforced Shape Memory Alloy (SMA). SMA wires were used to control and close the crack gap in the composite. The experimental analysis was conducted for one and two SMA wires, whereby these SMA wires were heat treated and trained before being embedded into the fiberglass matrix strip. The composite reinforced strips were pre-notched as a criterion for crack initiation and propagation under gradual tensile loading. It was observed, a complete separation into two pieces of the strip was hindered by the existence of the SMA wires. The control of cracked composite is based on the changing of resistance of the SMA wire during the deformation phase. The variation of the resistance in the stretched SMA wire acts as a feedback to the on-off controller. It was observed during the experimental analysis that when the electric current of 2 Amps is switched on, the wires temperature will be increased until 60℃ to produce a contraction effect, hence this effect will close the cracks that occurred under loading condition.

Introduction

The usage of smart materials in the automotive industry has expanded in the recent years. Outstanding thermo-mechanical properties of some of these materials such as SMA has been attracted the attentions of many researchers. Due to the thermo-mechanical behaviors of SMA, the usage of this kind of material in the industry is popular. Unique behavior of shape memory alloy comes from phase transformation. There are two main phases of austenite and martensite that helps the material to have unique performance. Once nitinol wire goes under strain the phase of material changes from austenite to martensite. The reverse cycle can be completed by heating up the wire [1]. There are many researchers in the literature that have been trying to formulate the constitutive behavior of SMA [1-3]. Initial studies in this area were done by Tanaka [1] in order to find an appropriate solution. Nitinol has two characteristics that make it important; it is Superelasticity and Shape Memory Effect (SME). Superelasticity allows nitinol wire to be deformed higher than conventional materials; this ability causes nitinol wire to be strained near 11% in comparison with other materials which is typically around 1%. On the other hand shape memory effect is another property of SMA that remembers its initial shape upon heating. Liang and Rogers [2] refined the proposed constitutive model of Tanaka; the model of Tanaka is based on exponential form however Liang and Rogers presented their model in cosine form. Burton et al. [3] used finite element simulation in the metal matrix composite which is reinforced by self–healing SMA wires. In their case study, the matrix was brittle and mode I cracking was allowed to propagate in the specimen [3]. Similar work, was done by Sharma et al. [4]. They applied Variational Asymptotic Method (VAM) to analyze the reinforced composite shell structure using SMA wires. The shell was pre-notched and the SMA wire was pre-strained. Upon longitudinal loading, the composite longates and SMA wires are heated to recover the initial shape and repair the cracks. Repairing of cracked

composite are presented in another study by Wang [5]. Polymer patches are applied to repair and close the crack.

In this study, composite notched fiberglass-polyester strip is reinforced by nitinol wire; from the tip of notch location crack propagates under a tensional force. After complete propagation of crack through the entire width of the nitinolstrip wire, it causes a bridge in the crack gap (Fig. 3). Meanwhile the control system closes the current and brings back the cross sections area together. The performance of controller is based on changing of resistance. As resistance increases due to elongation of nitinol wire, the controller closes the circuit and current resistance heats up the wire by 60℃. As soon as temperature ascends more than 48.75℃(A_s), wire starts to remember its initial shape. Crack closes completely once temperature increases higher than A_f (Table 1).

Experimental method

There are 4 important temperatures where the phase transformation of SMA is defined according to Table 1:

Table1: Phase transformation temperatures

Temperature	Value	Description
M_f	15.6 ℃	Martensite phase finishes at this temperature
M_s	29.9 ℃	Martensite phase starts at this temperature
A_s	48.75 ℃	Austenite phase starts at this temperature
A_f	59.4 ℃	Austenite phase finishes at this temperature

The working temperature for nitinol was studied by Mohamed et al. [6] for heat treatment temperature at around 750 ℃. Stress-strain diagram of nitinol wire for temperature $T > A_f$ is given in Fig. 1[3]. At point Amaterial is in austenite phase; then SMA wire goes under stress (between points A and B). The modulus of elasticity in this interval is E_A and the phase of material is austenite. Upon stress exceeding, the phase changes gradually to martensite (between points B and C) and the slope of diagram decreases considerably. After point C, the material is in complete martensitic phase and the modulus of elasticity at this interval (between point C and D) is E_M. Upon unloading, the stress-strain diagram moves from point D to E but the phase remains martensite. Heating up the wire, removes all the residual stresses and material transforms from martensite to austenite. Before applying SMA wire, it should be prepared appropriately [6]. In this study, the nitinol wire with a total length of 20 cm and thickness of 0.7 cm was used. Annealing process is the first step to ensure an appropriate transformation temperature is achieved and applicable at room temperature. After constraining the wire in the fixture, it is heated in the furnace for about 30 minutes at a temperature of 750 ℃. This temperature was chosen as it is derived in the literature [6] as an appropriate temperature. Heat treatment was completed by quenching the nitinol wire in air at room temperature. In order to program the wire, it is fastened to a tensile machine and the process of tension and heating implemented several times. The programmed nitinol wire was embedded in the fiberglass-polyester laminated composite like in Fig. 2. Two notches were placed at each sides of the composite strip. In order to initiate the crack, the tension force is induced until crack propagation occurs and causes the specimen to be separated in two pieces. The programmed nitinol wires restrict complete separation of the composite pieces. Specimens before and after tensile force are shown in Fig. 2 and 3. After inducing tensile force, the nitinol wires elongate by 4 mm (Fig. 3).

The control process was implemented via power supply, data acquisition and computer (Fig. 4). In order to apply the control system on the nitinol, Simulink part in MATLAB program software was used. Computer, power supply and sample are connected to data acquisition unit. All data were transferred from sample to data acquisition unit and monitored by computer. Before closing the circuit, the measured resistance of the wire in the elongated form was in the range of 0.56 Ω - 0.58

Ω while before elongation resistance was 0.54 – 0.56 Ω. It shows resistance value increases by elongation of nitinol wire. An On-Off controller was programmed to close the circuit as soon as resistance value crosses 0.57Ω. By closing the circuit, resistance increases significantly. The increase of resistance is the function of applied current value. The current heats up the nitinol wire and gradually the process of phase transformation from martensite to austenite occurs. By reducing the length of the wire about 3.5 mm as it is warming up, the resistance of the wire starts decreasing 10Ω. The controller system checks the current value in every step; upon the resistance value meets the predefined value 790Ωit opens the circuit. The Matlabprogram was able to control the crack gap and close it. This cycle can be repeated several times without any restriction. The program of opening and closing of circuit is given in Fig. 5.

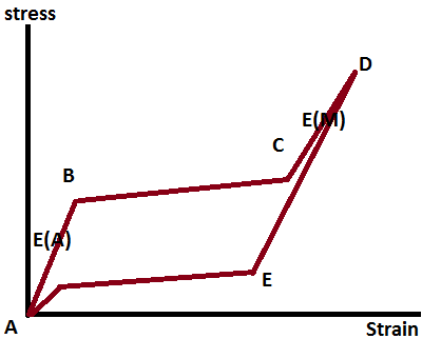


Fig. 1: Stress-strain diagram of SMA

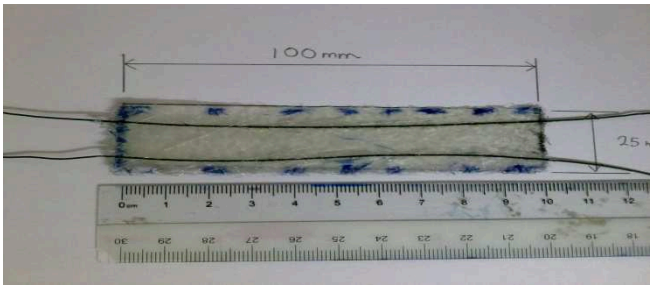


Fig. 2: Reinforced composite strip before inducing tensile force

Results and Discussion

By closing the circuit in the two nitinol wires, the changing resistance and temperature versus current can be plotted as in Fig. 6 and 7 respectively. The resistance of the wire after the circuit closes increases with increasing current (Fig. 6). There is14% difference between wire 1 and wire 2 which was attributed to the programming process. The results of contraction of wire 2 are so near to the results of Mohamed et al. [6]. The response of the wires to the different current value was illustrated in Table 2. Below a current value 1.4 Amps, the nitinol wire doesn't response. As the current increase slightly, nitinol wire gradually starts going back to the original shape. At a current value of 2 Amps, the distance between the two pieces reaches a minimum value of 1 mm. However by persisting for a longer period of time, this gap difference approaches to zero. It can be concluded that using a current value of 2 Amps provides a faster time for the nitinol to be recovered.

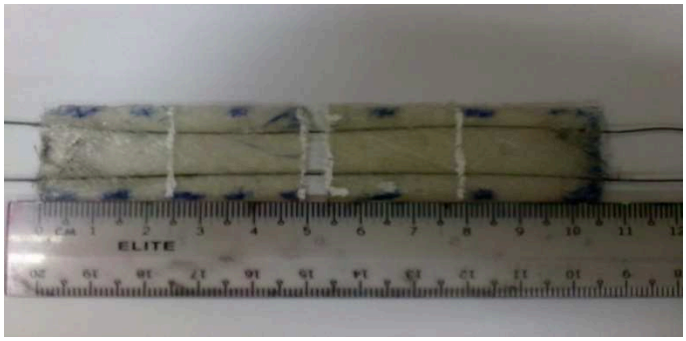


Fig. 3: Reinforced composite strip after induced tensile force

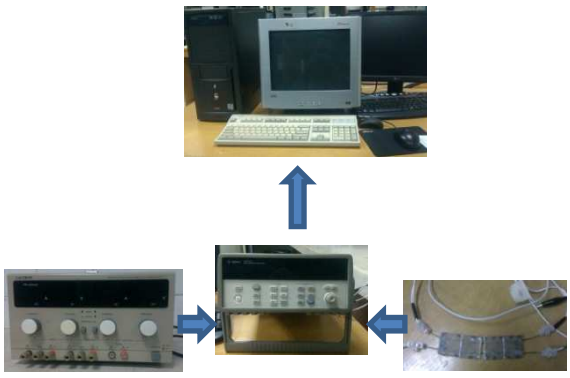


Fig. 4: Control instruments

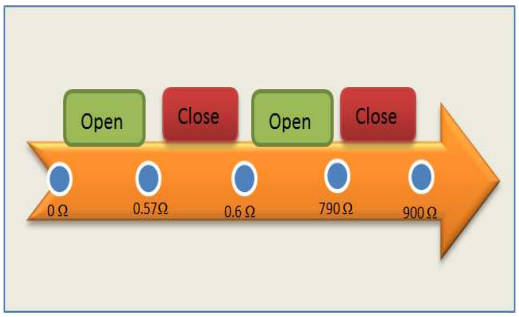


Fig. 5: Program of opening and closing of circuit

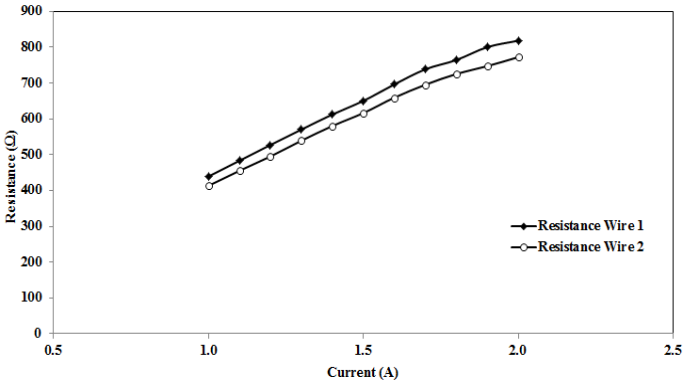
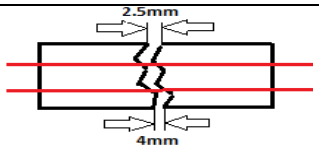
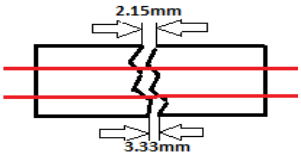
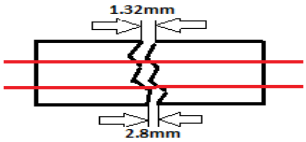
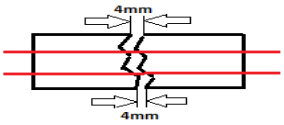
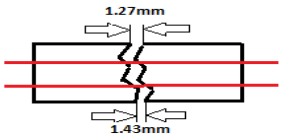
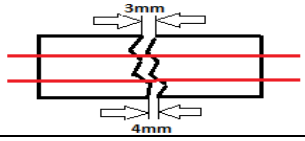
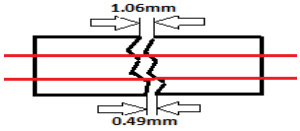


Fig. 6: Changing of resistance versus current

Table 2: Respond of sample to current value

Current (A)	Response of the Wires	Current (A)	Response of the Wires
1.1	No respond of sample	1.6	
1.2	No respond of sample	1.7	
1.3	No respond of sample	1.8	
1.4		1.9	
1.5		2	

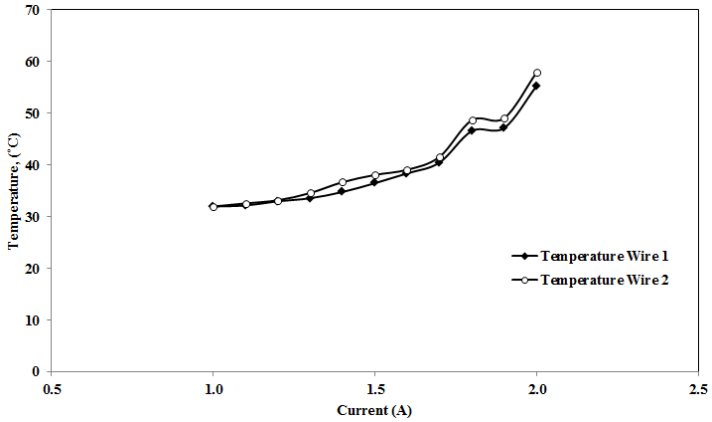


Fig. 7: Changing of temperature versus current

Conclusion

The composite cracked strip of fiberglass-polyester reinforced by nitinol wire was controlled by changing resistance. Initially, the specimen was notched at two sides and then under the tensile force, crack propagated through the entire strip. Once the sample was divided in two pieces ofnitinol wires avoid complete separation at crack location and makes the bridge in the crack gap. An On-Off control system was implemented in order to close the crack gap and recover the strip base on resistance variation. Optimum resistance variation was between 400 to 800 Ω whereas for current it was 1 to 2 Amps. It was observed that this method was reliable to use as a control method for crack propagation or recovering from cracks through reprogramming. Results of wire 2 are compatible with results from work done by N.A. Mohammed et al. [6].It was concluded that using a current of 2 Amps can be fast and reliable method to recover from crack propagation. At that current value, the temperature change between for wire 1 and 2 was 30 °C. Nitinol wire used in this study can be used as an effective means for crack propagation control in fiberglass-polyester laminates.

Acknowledgement

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