FABRICATION AND CHARACTERIZATION OF CARBON FIBER REINFORCED POLYMERS WITH EMBEDDED NiTi SHAPE MEMORY WIRES

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Abstract. *In this work, unidirectional carbon fiber reinforced plastics (CFRP) with embedded NiTi shape memory alloy (SMA) wire actuators were developed using a universal testing machine equipped with a thermally controlled chamber. Beam specimens containing cold-worked, annealed and pre-trained NiTi SMA wires distributed along its neutral plane were fabricated. Several tests in a three point bending mode at different constant temperatures were performed. To verify thermal buckling effects, electrical activation of the specimens were realized in a cantilevered beam mode and the influence of the SMA wires are discussed.*

Keywords: *Carbon fiber reinforced plastics, Active composites, Nitinol wires, Smart materials.*

1. INTRODUCTION

Carbon Fiber Reinforced Plastics (CFRP) are especially important because of its wide potential application in aeronautic technologies. Because of their inherent high specific stiffness and strength, use of laminated composite materials has increased in the design of thin-walled structural components for aerospace vehicles, such as high-speed aircraft, rockets and spacecraft, all of which are subjected to thermal loads due to aerodynamic and/or radiation heating. Such thin walled laminated composite structures may become unstable at a relatively low temperature change and thus cause buckling in the elastic region (Lee & Choi, 1999; Choi *et al*, 2000). When CFRP is combined with shape memory alloy (SMA) fibers, smart hybrid composites are developed with many objectives, like improve creep and fatigue properties, or strengthen the composite, improve damping capacity, control the shape or vibration property of composite (Xu *et al*, 2003). However, few studies on the thermal buckling and post-buckling of a composite laminated structure with embedded SMA wire actuators exist in the literature. Two methods have been proposed for integrating SMA actuators into a composite; bonding the actuators within the composite matrix as a constituent and embedding the actuators within sleeves through the laminate. The work presented by Turner *et al* (2001) focuses on the former method, where prestrained actuators are bonded within the composite matrix and the boundaries of the structure serve also as mechanical restraints for the actuators. Thus, an inherently elevated thermal environment in service will activate the actuators, which act against the mechanical boundaries to adaptively stiffen the structure without control electronics or auxiliary power.

In this work, an alternative route for production of CFRP – NiTi SMA laminated composites is proposed. For this one, a universal testing machine equipped with a thermally controlled chamber was mechanically adapted. Thermal buckling effects were verified by electrical activation of the specimens in a cantilevered beam mode and the influence of the NiTi SMA wires in three different states (cold-worked, annealed and trained) was analyzed.

2. EXPERIMENTAL PROCEDURE

2.1. Fabrication of the active beam specimens

The CFRP-NiTi active composite in the form of small beams (125 x 24 x 1 mm^3) were manufactured using an Instron universal testing machine (model 5582) equipped with a thermal chamber. It was employed the high performance tough epoxy matrix HexPly® 8552 unidirectional carbon prepregs from Hexcel Composites Inc. (England). The selected NiTi binary SMA wire of 0.29 mm in diameter, named alloy M, was supplied by Memory-Metalle Inc. (Germany) in a cold-worked state, without martensitic transformation. Firstly, the as-received NiTi wire was annealed at 400 ^oC for 900 s. Before fabrication of the active composite beams, a part of the NiTi SMA wires were stabilized by training using a thermal cycling under constant load procedure. Two meters of the heat-treated NiTi wire under a dead weight corresponding to a tensile stress of 200 MPa was submitted to 1000 heating and cooling cycles (contraction and expansion) using electrical resistive heating.

In fact, the designed active composite beam specimens incorporate the NiTi SMA wires in three different states: as-received (cold-worked), annealed and trained. The actuator wires are evenly distributed along the neutral plane of the beam samples.

To fabricate the CFRP-NiTi active composites in a hot pressure sandwich way, the universal testing machine was mechanically adapted as indicated in Fig. 1. In this design, the force produced in the machine parts (1) is transmitted by a pressure disk (2) to the stainless steel plate (3) and base (6). The NiTi actuator wires are equally spaced and oriented by two guides (5) and installed between the plate (3) and base (6).

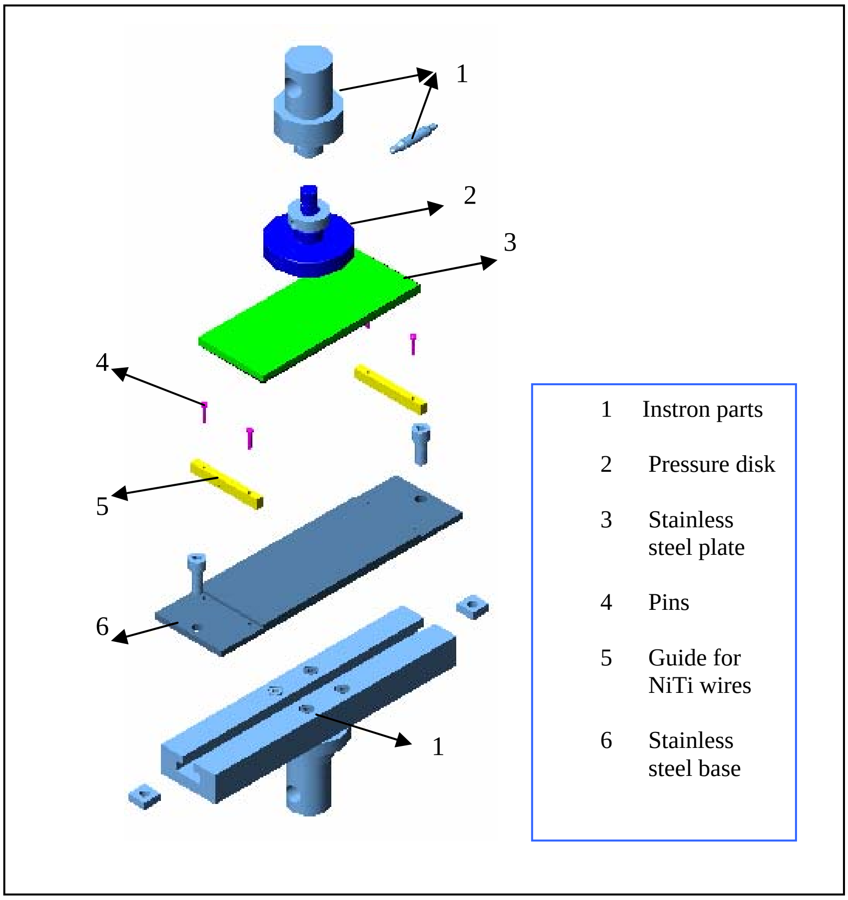

Figure 1. Design of the pressure molding system adapted in the 5582 Instron machine.

Figure 2 show the preparation of the CFRP-NiTi composite specimen and installation of the pressure mold illustrated in Fig. 1 into the thermal chamber of the testing machine.

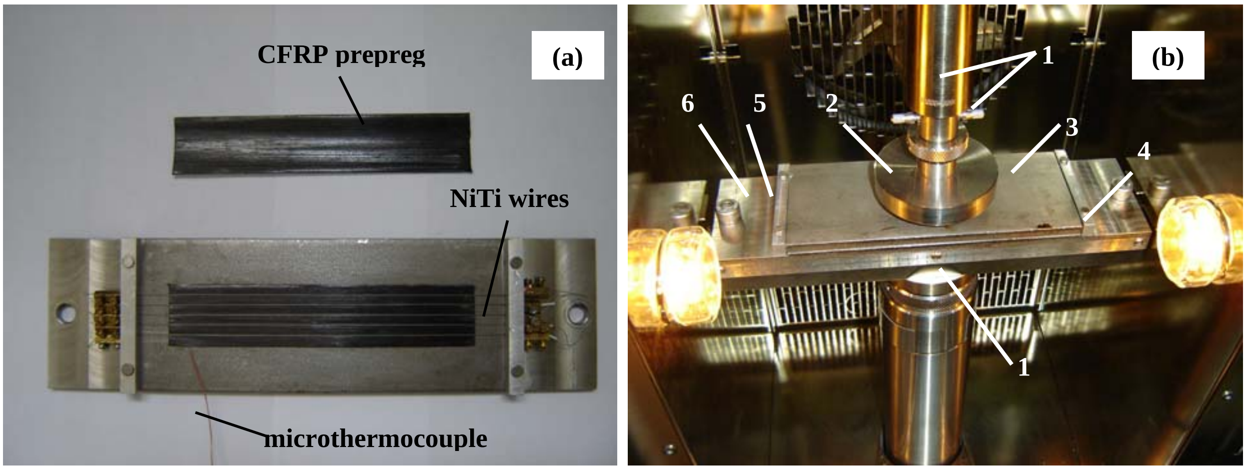

Figure 2. Pressure mold for manufacturing of sandwich CFRP-NiTi composite specimens. (a) Preparation for hot pressure molding. (b) Installation of the mold into the thermal chamber of the testing machine.

Two layers of the CFRP prepreg are put below and above the NiTi wires as indicated in Fig. 2(a). In this system, the carbon fibers are aligned with the NiTi ones. After assembly between the plate and the base, the CFRP-NiTi system is installed in the thermal chamber of the testing machine to the hot pressure molding (Fig. 2b). Temperature evolution during the curing cycle is measured by a micro-thermocouple (type K, 80 μm in diameter) soldered on the base (Fig. 2a).

Figure 3 show the cure cycle and CFRP-NiTi specimens fabricated with the system of Fig. 2. The molding by uniaxial hot pressure was realized at 110 °C for 4 h under approximately 0.32 MPa followed by natural cooling into the thermal chamber, as can be noted in Fig. 3(a). Figure 3(b) show the four specimens fabricated by this procedure: without NiTi wires and embedding as-received, annealed and trained NiTi wires.

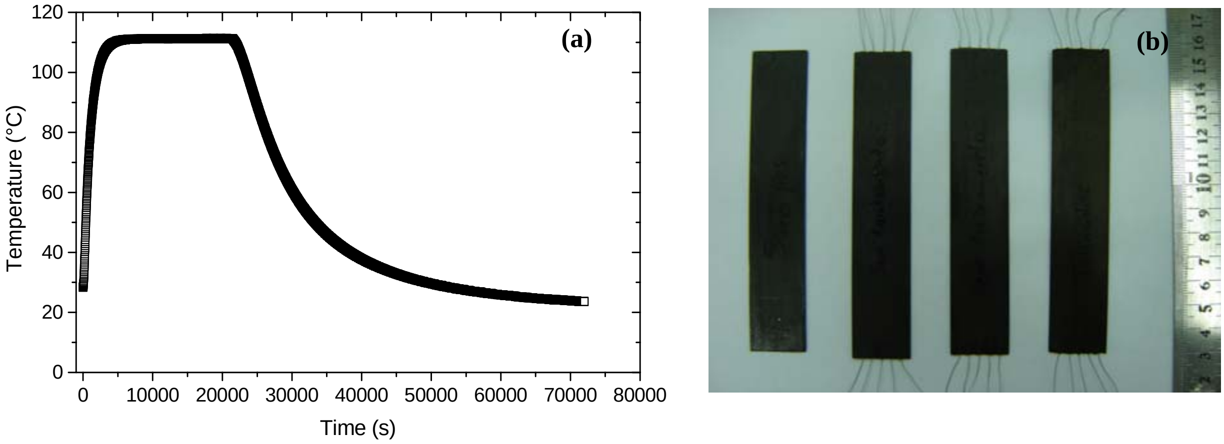

Figure 3. Fabrication of the CFRP-NiTi composites. (a) Temperature curing cycle. (b) Active composite beam specimens.

2.2. Static characterization of the active beam specimens

Specimens shown in Fig. 3(b) were tested in a three point bending mode and thermal buckling by resistive heating in a cantilevered beam mode, as indicated in Fig. 4. The bending tests were carried out at different constant temperatures between 30 and 90 °C, in steps of 10 °C, using the 5582 Instron machine and a distance among supports of 80 mm (Fig. 4b). In these tests a central deflection of 3 mm was imposed to the specimens at a constant extension rate of 1 mm/min. For each temperature, ten force (F) – deflection (y) cycles were performed.

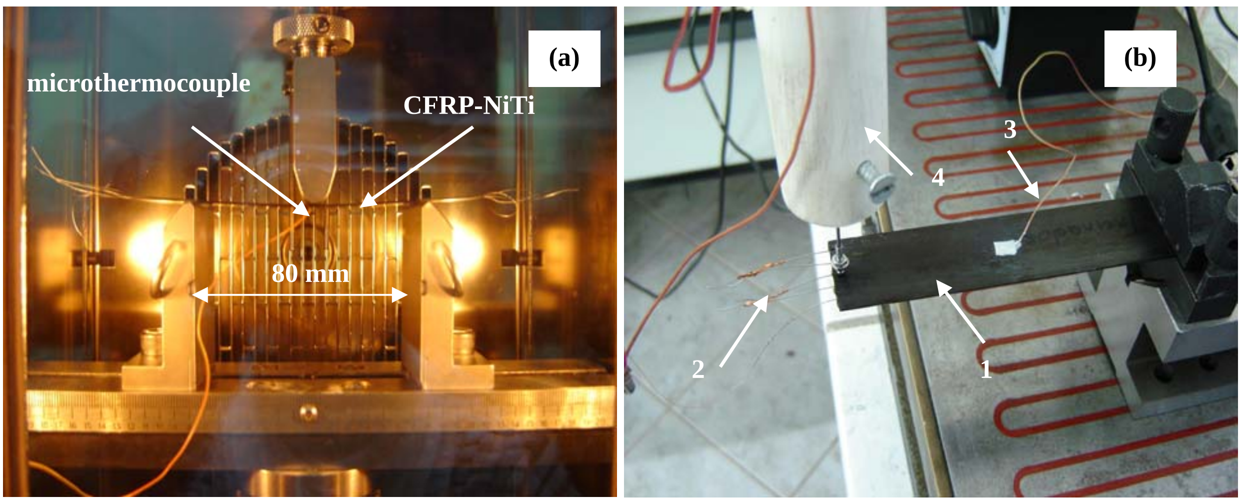

Figure 4. Assembly for testing the CFRP-NiTi active composites. (a) Three point bending tests. (b) Thermal buckling in cantilevered beam mode.

The smartness of the CFRP-NiTi composites was verified by detecting thermal buckling effects in the active beam specimens. For these tests, the CFRP-NiTi specimens were assembled as observed in Fig. 4(b). Activation of the composite (1) is done by electrical resistive heating of all NiTi SMA wires (2) using a programmable DC power supply from Agilent, E3633A model. The temperature of the composite surface is measured using a K type micro-thermocouple with 80 μm in diameter (3) while tip deflection of the beam is accompanied by a LVDT displacement sensor from Solartron, DF5.0 model (4), installed at 100 mm from the clamped extremity. The tip deflection and temperature of the active beam as well as the electrical resistance of the NiTi SMA wires are stored in a data acquisition system from Agilent, 34970A model.

3. RESULTS AND DISCUSSIONS

Transformation of the NiTi wires embedded into CFRP matrix was verified by electrical resistance (R) as a function of temperature using a thermocontrolled silicone oil bath (Reis *et al*, 2006). Figure 5(a) confirms that no transformation exist in the CFRP + cold-worked NiTi wire specimen. However, as observed in Fig. 5(b), transformation was detected in both, CFRP + annealed NiTi wire and CFRP + trained NiTi wire specimens. The annealed and trained NiTi wires present a two-step phase transformation during cooling, from austenite to R-phase and then to martensite (Otsuka & Ren, 2005). As expected from De Araújo *et al* (2001), Fig. 5(b) also shows that the training procedure increases the transformation temperatures (R_s, R_f, A_s e A_f).

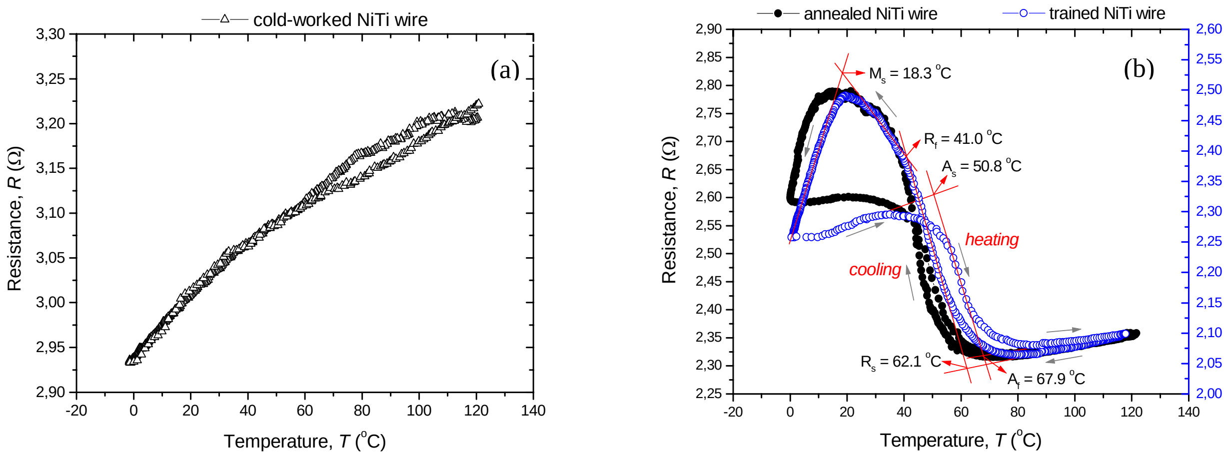

Figure 5. Phase transformation of the NiTi wires. (a) Cold-worked. (b) Annealed and trained.

Figure 6 show some results of the three point bending tests realized as indicated in Fig. 4(a). The characteristic slope (k) for each specimen tested at 30 °C and 80 °C are plotted in Figs. 6(a) and 6(b), respectively. These slopes were determined using data from the superposition of the ten load – unloading $F – y$ cycles.

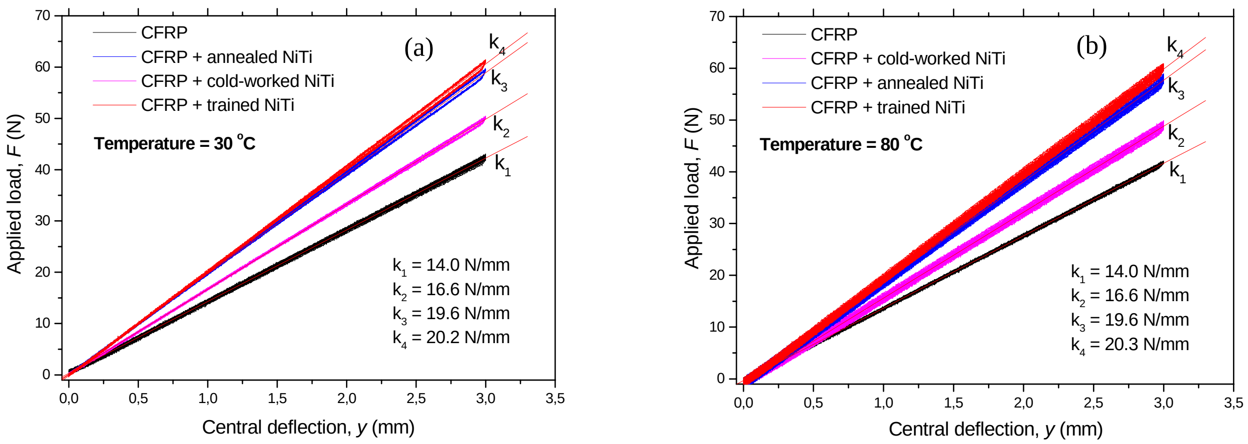

Figure 6. Thermomechanical behavior of the CFRP-NiTi active composites tested in a three point bending mode. Superposition of ten $F – y$ cycles. (a) Test at 30 °C. (b) Test at 80 °C.

A small hysteresis in the cyclic $F – y$ behavior was detected between 2 and 3 mm in the CFRP – NiTi specimens tested at 30 °C, as can be observed in Fig. 6(a). This behavior is amplified by the presence of the NiTi SMA wires because it was very limited in the CFRP pure specimen. Figure 6(b) show that for the test temperature of 80 ^{o}C, this $F - y$ hysteresis is not visualized in the cyclic $F - y$ behavior. However, the k slopes are unaffected by the test temperature indicating that transformation of the NiTi wires from R-phase (30 ^{o}C) to austenite (80 ^{o}C) does not change the stiffness of the active composite specimens. Figure 7 show the Young's modulus (E) of the CFRP-NiTi active composites measured at 30 ^{o}C after the cyclic $F - y$ tests (Fig. 6). It was verified that the modulus is larger in the specimens containing the NiTi wires, however that cannot simply be attributed to the SMA presence because of that volumetric fraction is quite small (about 1.4%). That difference is probably associated to the quick differences in the amount of epoxy resin added to each specimen during the fabrication. Table 1 summarizes the E values for each CFRP-NiTi specimen.

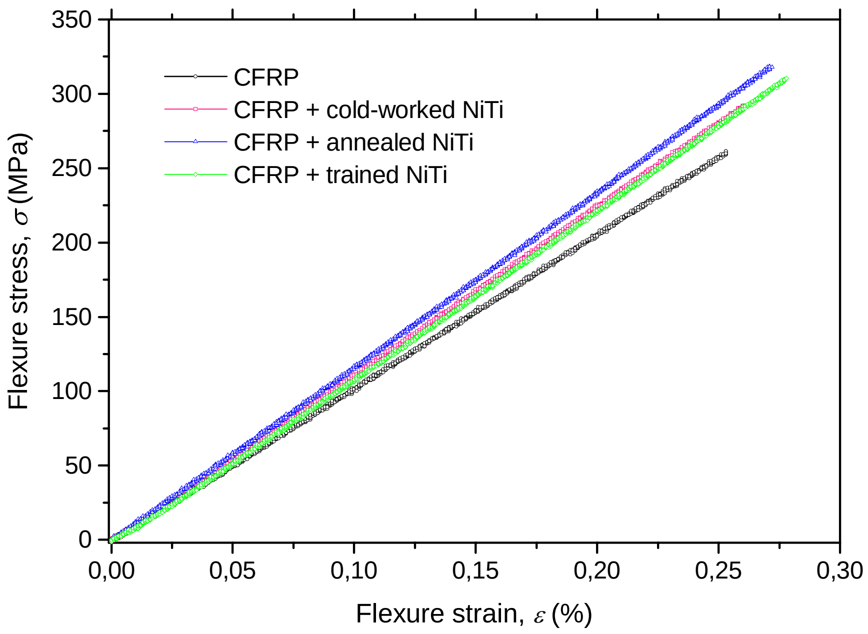

Figure 7. Mechanical behavior of the CFRP-NiTi specimens during three point bending tests at 30 ^{o}C.

Table 1. Young's modulus of the CFRP-NiTi active composites.

Specimen	***E* (GPa)**
CFRP	104.1
CFRP + cold-worked NiTi	113.9
CFRP + annealed NiTi	118.9
CFRP + trained NiTi	114.8

Figure 8 show the response of the CFRP-NiTi composites to a simple triangular current (I) wave from 0 to 1.5 A, with a heating – cooling rate of 0.4 A/min. For all composite specimens, superficial temperatures between 85 and 115 ^{o}C are reached. These temperatures are enough to transform the NiTi wires into the CFRP matrix, as indicated in Fig. 5(b).

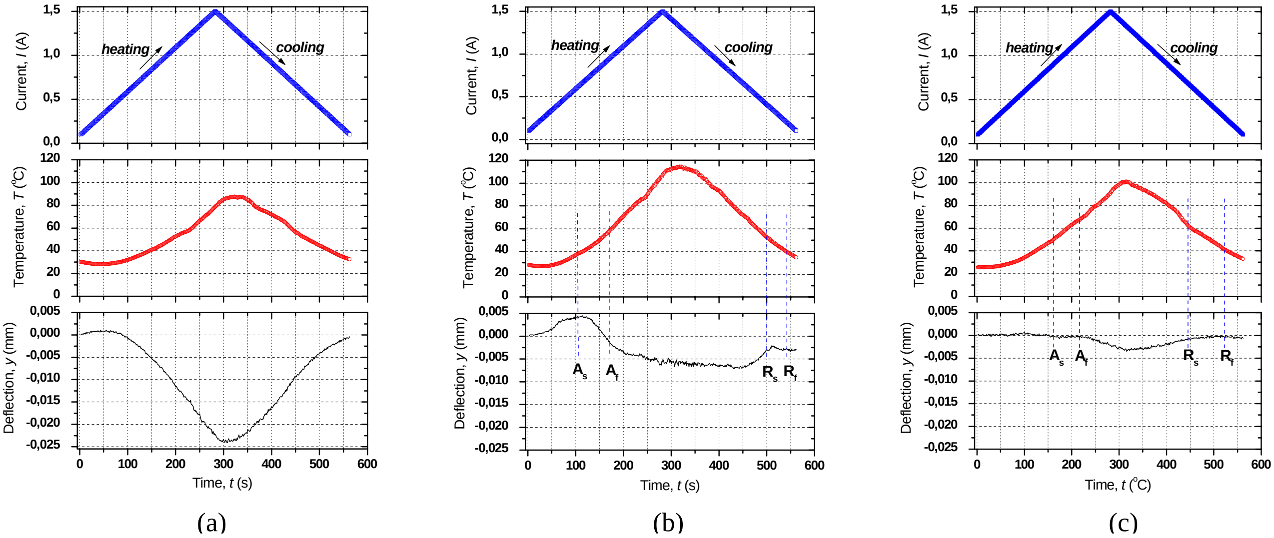

Figure 8. Thermal buckling of the CFRP-NiTi composites. (a) Cold-worked NiTi wires. (b) Annealed NiTi wires. (c) Trained NiTi wires.

Considering that cold-worked NiTi wires don't present transformation, the CFRP containing these wires can be considered a classical passive composite, similar to the GFRP-NiCr studied by Choi *et al* (2000). Figure 8(a) show that electrical resistive heating of the cold-worked NiTi wires cause a continuous and reversible thermal buckling (tip deflection) of the composite specimen. This behavior was attributed to a bimetal effect due the differences between the thermal expansions of the CFRP matrix and NiTi cold-worked wires. The annealed NiTi (untrained) wires into CFRP matrix present martensitic transformation that reduces thermal expansion without shape memory effect. Despite some deflection changes are observed in the transformation ranges (A_s – A_f and M_s – M_f), Fig. 8(b) shows that the activation of these wires reduces thermal buckling effects. In addition, Fig. 8(c) demonstrates that trained NiTi wires minimize thermal buckling effects. This behavior is attributed to the fact that transformation of the trained NiTi wires (Fig. 5b) is accompanied by generation internal forces due to the two-way memory effect occurring into CFRP matrix.

4. CONCLUSIONS

In this work a new fabrication procedure to manufacture CFRP-NiTi active composite specimens with a maximum length of 125 mm was presented. The manufacture process use an Instron universal testing machine equipped with a thermally controlled chamber to mold CFRP prepregs and NiTi wires by uniaxial hot pressure in a sandwich way. It was demonstrated that embedding stable (cold-worked) and transforming (annealed and trained) NiTi SMA wires into CFRP matrix cause different thermal buckling behaviors in a cantilevered beam mode. The CFRP containing NiTi cold-worked wires present a classical thermal buckling behavior which increases the tip deflection of the beam specimen during heating until temperatures as high as 100 ^{o}C. An important reduction, of the order of five times, in the tip deflection of CFRP-NiTi is obtained by embedding transforming wires that minimizes thermal expansion without present two-way memory effect (untrained). In the case of embedding NiTi SMA wires that present both, transformation and reversible memory effect (trained), a larger and stable reduction of thermal buckling phenomenon is observed.

5. ACKNOWLEDGEMENTS

The authors thank the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), Brazilian office for sponsoring the research (Universal grant 550325/2005-0 and PPP-Fapesq/PB grant 035/2004) during the course of these investigations. A special gratitude is dedicated to Mr. Edmundo Ortiz, Engineer of Hexcel Composites Inc., by the donation of CFRP prepregs and to Centrais Elétricas do Norte do Brasil (Eletronorte) for the financial support of the project Finatec 02850.

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