Mechanical Behavior of a Carbon Fiber Composite Material Reinforced with Titanium Nickelide Wire

D Gusev¹, E Lukina¹, R Vinogradov¹

¹Department of Materials Science and Technologies of Materials Treatment, Moscow Aviation Institute (National Research University), 125993, Moscow, Russia

E-mail: GusevDE@mai.ru; lukinaea@mati.ru

Abstract. A composite material of a carbon fiber matrix and reinforcing elements in the form of a wire made of titanium nickelide (PC-SMA) has been studied. The obtained PC-SMA material demonstrated improved elastic and strength characteristics compared to those of traditional carbon fiber composite material upon static three-point bending tests.

1. Introduction

The application of fiber reinforced composite materials consisting of a polymer matrix with various reinforcing fillers has widened recently in construction and other industries [1]. Most of these composite materials are based on a matrix of thermosetting polymers (epoxy, polyester, phenol-formaldehyde, and organosilicon resins). Glass, carbon, and polymer fibers are normally used as fillers [2-4]. In particular, carbon fibers have high strength and chemical resistance, and low density, temperature coefficient of linear expansion and coefficient of friction. However, the disadvantages of carbon fiber composites are the lower specific impact strength, insufficient crack resistance, and higher sensitivity to stress concentration compared with other reinforced plastics.

A promising way to increase the mechanical properties of polymer materials, as well as to provide them with new functional characteristics, is reinforcement with elements made of materials possessing shape memory effect and superelasticity (shape memory alloys – SMA), in particular, titanium nickelide (TiNi) [5-9]. This alloy is capable to restore up to 1-8% of deformation upon unloading (superelasticity) or additional heating (shape memory effect) due to the occurrence of thermoelastic martensitic transformation. The first attempt to create an “SMA composite” was made in the late 1980s [10] when Rogers and Robertshaw embedded NiTiNOL (titanium nickelide based alloy) wires in a laminated polymer matrix composite (PMC). However, even now the widespread use of such composites has been restrained due to the complexity of controlling their mechanical and functional properties.

An analysis of literature shows that the introduction of TiNi into various polymer matrices makes it possible to increase their crack resistance and durability [11], improve damping ability and resistance to vibrations [12], and also gives the shape memory effect [13-14] and characteristics of superelasticity [15-18]. Composite polymer materials with TiNi are sometimes referred to as SMA hybrid composites (SMAHCs). At the same time, polymer matrix composites reinforced by SMAs are referred to as “PC-SMA” [5]. This term will be used further in our work.

An improvement in the mechanical properties of carbon fiber composite may be expected in case of its reinforcement with TiNi wire being in an austenitic state. In this state titanium nickelide is
capable of recovering significant deformations (up to 6-8%) due to the development of an austenite-martensite transformation (figure 1, a). The presence of such deformation mechanism in the alloy minimizes the role of dislocation slip which is accompanied by the accumulation of irreversible deformation resulting in microcracks formation. Thus, realization of deformation via austenitemartensite transformation provides titanium nickelide with high elastic, damping, and fatigue properties [19-22].

For comparison, reversible elastic deformation in traditional structural metallic materials (for example, 12Kh18N10T stainless steel, titanium alloys) does not exceed 1-2% (see the linear intervals of the deformation curves in figure 1, b). Higher deformations can only be accumulated by the dislocation slip mechanism (non-linear intervals of the deformation curves in figure 1, b), which quickly leads to the formation of dislocation networks, the formation of microcracks and their growth. Therefore, carbon fiber reinforcement with elements made of traditional metallic materials will not allow to increase the elastic and fatigue properties of the hybrid composite material.

At the same time, titanium nickelide in the superelastic state can be reversibly deformed to significant values which are characteristic for the elastic deformation of the carbon fiber matrix. In this case, an increase in the stiffness of the PC-SMA material while maintaining its elastic properties may be expected. This should positively influence the PC-SMA fatigue characteristics and the durability of products made from such material.

The aim of this paper was to study the possibility of increasing the elastic and strength characteristics of carbon fiber matrix reinforced with titanium nickelide wires.

![Figure 1](image.png)

**Figure 1.** Comparison of the mechanical behavior of carbon fiber composite and Superelastic Nitinol (titanium nickelide based material in the austenitic state) (a) with the behavior of structural metal materials (b): stainless steel 12Kh18N10T, commercially pure titanium, titanium alloy Ti6Al4V. Upon three-point bending tests.

**2. Materials and methods**

A wire with a diameter of 1 mm made of titanium nickelide Ti – 55.7 wt % Ni was used as a reinforcing element for the PC-SMA material manufacturing. The wire was obtained by warm drawing (500-600°C), which provides the formation of a deformed structure of the B2 phase with a high concentration of defects in the crystal structure. Such structure ensures superelastic behavior of titanium nickelide over a wide temperature range [23].

PC-SMA samples in the form of flat plates 25 × 200 mm in size were manufactured using two inner layers of directional carbon fiber and two outer layers of carbon prepreg (braided carbon fabric). Titanium nickelide wires in the amount of 6 or 12 pieces were placed in the middle layer of the composite material. PC-SMA samples were prepared on a gypsum positive with low humidity coated with a polyvinylchloride film. The specimens were autoclaved in vacuum at a temperature of 140°C for 2 hours. The photos of the prepared PC-SMA samples are demonstrated in figure 2, a.
Static tests of the samples were carried out at room temperature using three-point bending scheme with a base of 100 mm on a TIRAtest 2300 testing machine (figure 2, b). The samples were subjected to cyclic loading and unloading with a gradual increase in the deflection by 1-2 mm in each cycle. The test was terminated in case of destruction of the sample or in case of formation of defects (delamination, etc.), which were accompanied by a sharp decrease in the load on the sample. In addition, loading parameters corresponding to crackling sound were also noted since it indicates the appearance of internal defects in the sample.

Based on the testing results, the ultimate forces and deflection at which the sample had elastic behavior ($P_{el}$ and $f_{el}$, respectively) were determined. Maximum $P_{max}$ and $f_{max}$ values were also recorded. In addition, the stiffness of the samples ($K$) was calculated from the linear interval of the stress-strain curve.

![Figure 2. Appearance of PC-SMA samples (a) and their three-point bending tests (b).](image)

### 3. Results

Testing of the samples was carried out in groups, each containing a certain number of titanium nickelide reinforcing wires. It should be noted that, depending on the number of wires, the cross-section shape of the samples changed, affecting, among other reasons, the characteristics of mechanical behavior.

Linear elastic behavior characterized by the coincidence of loading and unloading curves was typical for carbon fiber samples without reinforcement up to a deflection of 11–12 mm (figure 3, a). Further increasing of the strain resulted in a deviation from the linear dependence of the load vs. deflection curves, and a hysteresis appeared between the loading and unloading curves. Upon reaching the maximum level of the applied load corresponding to a deflection of 26±2 mm, the deforming forces gradually decrease until the destruction of the samples. It should be noted that during the tests of carbon fiber samples without reinforcement, upon reaching the maximum load, a sound of cracking was heard, indicating the ongoing processes of violation of the material integrity.

The samples reinforced with titanium nickelide wire demonstrated higher rigidity and deformation forces, and deviations from linear behavior is observed upon smaller deflections, which indicates the manifestation of superelastic properties (figure 3, b and c). Samples reinforced by titanium nickelide wires also produced crackling sound at the moment of reaching the maximum load values, indicating internal cracking of carbon fiber layers. Apparently, the appearance of these cracks occurs at the boundary between the matrix and the titanium nickelide wire in the longitudinal direction without cracks reaching the sample surface. After exceeding the maximum load the carbon fiber matrix is destroyed, characterized by its significant stratification and the presence of longitudinal secondary cracks. In this case, the destruction of the reinforcing fibers was not observed and the overall integrity of the PC-SMA material was not violated.
4. Discussion

Figure 4 shows an anticipated increase in PC-SMA stiffness and strength characteristics with an increase in the number of titanium nickelide wires. With an increase in the volume fraction of the reinforcing wire the rigidity of PC-SMA samples and the maximum load increase linearly, and the deflections corresponding to the maximal load and maximal elastic deformation decrease. A decrease in the elastic deflection $f_{el}$ suggests that the titanium nickelide wire provides the PC-SMA composite specimen superelastic properties. At the same time, a decrease in the deflection $f_{max}$ can be explained by a decrease in the distance between the wires with an increase in their number, which inhibits deformation in carbon fibers located between the wires and promotes the formation of the cracks at the interface between the carbon matrix and the titanium nickelide wire. In general, the mechanical behavior of the PC-SMA specimens is in line with the general trend for the structural materials, implying the decreasing of ductility ($f_{max}$) with the strength ($P_{max}$) increasing.

The analysis of mechanical behavior of the composite materials should also include the values of stresses and deformations arising in the material subjected to bending. However, such analysis for the PC-SMA specimens is hampered by their complex cross-sectional shape as well as by the complex structure of the carbon fiber matrix. For this reason it is useful to apply a simplified methodology for the assessment of the “effective” stresses and deformations. This methodology considers the cross section of a sample as a rectangle with the sides being equal to the thickness and width of the sample. In this case calculation of the maximum deformations and stresses at bending is possible using the method described in ASTM D7264 / D7264M-15 standard [24]. According to such calculations, in carbon fiber matrix without titanium nickelide wires the deflection $f_{el}$ being 11±12 mm corresponds to the effective deformation $\varepsilon_{el} = 0,7\pm0,8$ % and effective stress $\sigma_{el} = 180\pm190$ MPa, while $f_{max}$ corresponds to $\varepsilon_{max} = 1,6\pm1,7$ % и $\sigma_{max} = 260\pm270$ MPa, respectively. The incorporation of 6 or 12 titanium nickelide wires into the carbon fiber matrix leads to an increase of $\varepsilon_{el}$ up to 0,9±1,0 % and $\varepsilon_{max}$ up to 2,0±2,2 %. In this case the effective stresses increase to $\sigma_{el} = 230$ MPa and $\sigma_{max} = 345$ MPa for the samples with six wires and to $\sigma_{el} = 335$ MPa and $\sigma_{max} = 550$ MPa for the samples with twelve wires. Thus, the calculations demonstrate that the reinforcing of carbon fiber matrix with titanium nickelide wires results both in an increase in stiffness and strength and also in deformation characteristics [25].
Figure 4. Effect of the number of titanium nickelide wires on stiffness $K$, maximum elastic deflection $f_{el}$ and a deflection at maximum load $f_{max}$ (a), as well as the corresponding forces $P_{el}$ and $P_{max}$ (b) of the PC-SMA samples.

5. Conclusions
1. It has been demonstrated that the reinforcement of carbon fiber matrix with titanium nickelide wires results in an increase of the stiffness and strength of the obtained PC-SMA material in proportion to the volume fraction of the reinforcing component.
2. It has been revealed that while a slight decrease in the maximum elastic deflection ($f_{el}$) and a deflection corresponding to the maximal applied load ($f_{max}$) are observed for the PC-SMA specimens, the corresponding effective deformations $\varepsilon_{el}$ and $\varepsilon_{max}$ increase by approximately 30% compared to unreinforced carbon fiber samples.
3. The advantage of the PC-SMA specimens compared to unreinforced carbon fiber matrix is the absence of the complete destruction of the PC-SMA material when cracks appear, this being due to the reinforcing titanium nickelide wire. Such an approach provides the safety of the PC-SMA materials use.

6. References
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