RAILGUN APPLICATION FOR HIGH ENERGY IMPACT TESTING OF NANO-REINFORCED KEVLAR-BASED COMPOSITE MATERIALS

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ABSTRACT

An advanced electromagnetic accelerator, called railgun, has been assembled and tuned in order to perform high energy impact test on layered structures. Different types of layered composite materials have been manufactured and characterized in terms of energy absorbing capability upon impact of metallic bullets fired at high velocity. The composite materials under testing are manufactured by integrating several layers of Kevlar fabric and carbon fiber ply within a polymeric matrix reinforced by carbon nanotubes at 1% of weight percentage. The experimental results show that the railgun-device is a good candidate to perform impact testing of materials in the space debris energy range, and that carbon nanotubes may enhance, when suitably coupled to the composite's matrix, the excellent antiballistic properties of the Kevlar fabrics.

1 INTRODUCTION

Carbon nanostructures (in particular nanotubes) are supposed to be ideal candidates as composite reinforcing filler, by means of their very low density (high surface area) joined to excellent mechanical properties. A scaled-up employment of such materials has been hindered so far by technical limitations related to their poor degree of bond to the macro-molecules of the conventional composites matrixes. Several chemical and morphological analyses have been carried out on the nano-reinforced composite materials before and after the ballistic characterization, in order to assess the effectiveness of the nano-filler in terms of impact resistance. In particular, viscosity and homogeneity of the enriched polymeric matrix are the main issues to be focused, as well as the physical coupling and the mechanism of the stress transfer to the Kevlar and carbon reinforcing fibers. In order to perform an high energy ballistic characterization of the manufactured composite samples an in-house built electromagnetic railgun was employed. A railgun is an electrically powered electromagnetic projectile launcher [1-4]. A railgun is made up of a pair of parallel conducting rails, along which a sliding metallic armature is accelerated by the electromagnetic effect (Lorentz force) of a current that flows down one rail, into the armature and then back along the other rail. The experimental results show that the railgun-device is a good candidate to perform impact testing of materials in the space debris energy range, and that carbon nanotubes may enhance, when suitably coupled to the composite's matrix, the excellent antiballistic properties of the Kevlar fabrics. Further investigations on such topic are needed in order to achieve a better knowledge of the complex mechanism that drives the physical/chemical interactions between the carbon nanostructures and the fiber/matrix substrate during an high energy sharp external stress. Nevertheless, this work promotes the carbon nanotube employment in composite materials for aerospace applications, where the cogent constraints of lightweight and high mechanical resistance must be simultaneously satisfied. The paper is organised in three main sections. The first one describes the experimental activity focused on the manufacturing of layered composite structures. The second one analyses the in-house built railgun. The last section reports some results about the firing tests carried out.

2 MANUFACTURING OF LAYERED COMPOSITE MATERIAL

The composite materials under testing are manufactured by integrating several layers of Kevlar fabrics and carbon fiber ply within a polymeric matrix (epoxy resin) also reinforced by carbon nanotubes at 1wt% versus the matrix. The polymeric matrix is the bi-component epoxy resin PrimeTM 20LV (density 1.123 g/cm^3) purchased at GURIT. The MWCNTs are the NC7000 (average diameter around 9.5 nm, average length 1.5 µm, purity 90%, surface area 250-300 m^2/g) supplied by NANOCYL. Fig.1 and Fig.2 show scanning electron microscope (SEM - TESCAN Vega 3LMH) pictures of the employed MWCNT. Four different kind of composite structures were manufactured: one by using only Kevlar fabric and epoxy resin, one by using only multiwall carbon nanotubes (MWCNTs) and epoxy resin, another one by using Kevlar fabric and carbon fiber embedded in the resin, and the last one by using

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Kevlar fabric, carbon fiber and by adding MWCNT as filler in the epoxy resin adopted to make the structure.

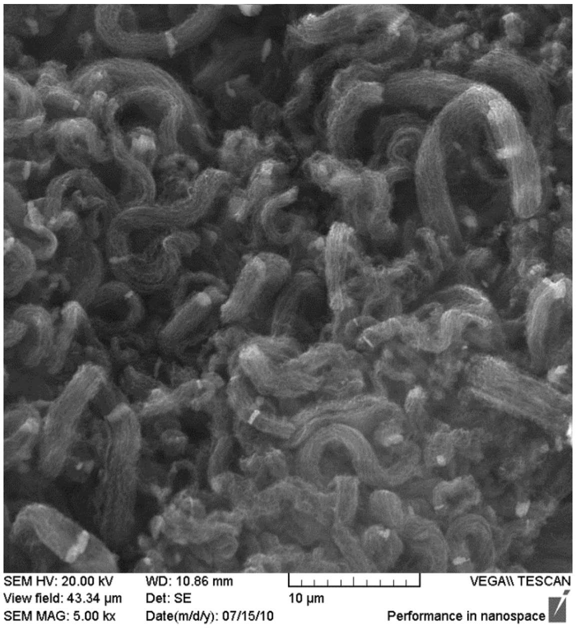

Figure 1. SEM pictures of MWCNT; pristine material.

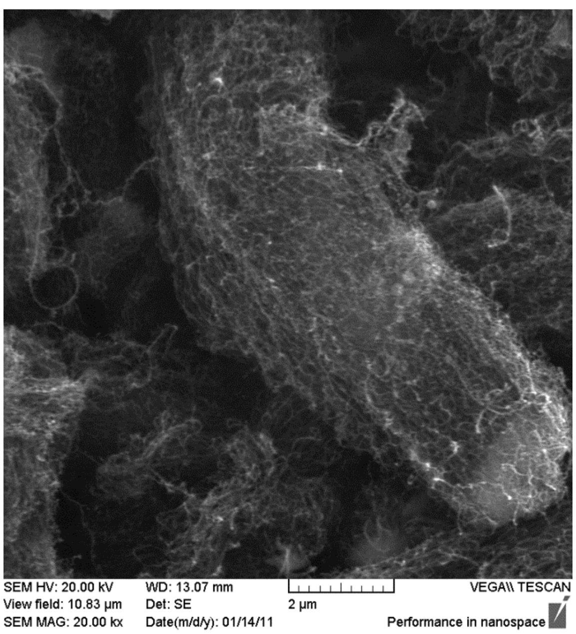

Figure 2. SEM pictures of MWCNT. Zoom of one bundle of multiwall carbon nanotube; pristine material.

For each kind of structures two different thickness of the layered composite material were considered, one of about 3mm, and the other one of about 6mm. The first layered carbon fiber reinforced polymer (CFRP)+Kevlar structure is made of three layers of carbon fiber (biaxial woven roving 0°-90°), taking care to overlap one layer upon the other by following the scheme (0°÷90°), (+45°÷−45°), (0°÷90°), two layers of biaxial Kevlar fabric, and again three layers of carbon fiber as above [5]. The second layered CFRP+Kevlar structure is made increasing the number of layers, exactly five layers of carbon fiber, three layers of biaxial Kevlar fabric, and again five layers of carbon fiber as above. In Fig.3, the first layered CFRP+Kevlar structure is shown. It can be observed the border parts of the manufactured structure before mechanical machining. In Fig.4, the first layered CFRP+Kevlar structure is shown after mechanical machining.

Figure 3. First kind of layered material. First layered CFRP+Kevlar structure before mechanical machining.

Figure 4. First kind of layered material. First layered CFRP+Kevlar structure after mechanical machining.

In Fig.5. a picture of both layered CFRP+Kevlar structures after mechanical machining is taken by showing one side of both sandwiches.

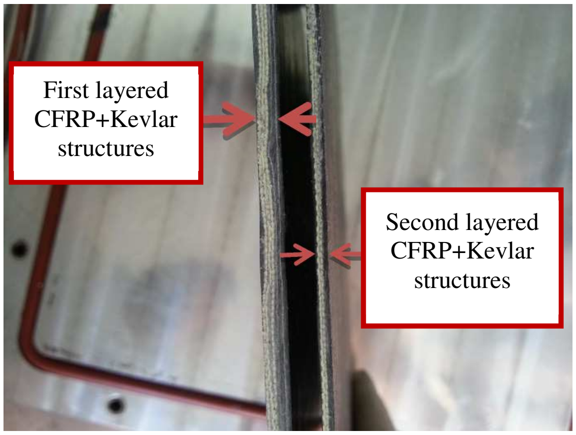

Figure 5. Picture of one side of the layered CFRP+Kevlar structures after mechanical machining.

It can be observed the different thickness of sandwiches: 3 mm and 6 mm respectively. In the second kind of layered materials MWCNT were homogeneously dispersed in the epoxy resin and such enriched resin was adopted to build Kevlar and carbon fiber layered composite materials. A critical issue of the nano-reinforced composite manufacturing is to perform the mixing of the nanoparticles within the matrix in such a way to obtain an homogeneous and isotropic distribution. Such requirement, needful for any kind of application, is critically hindered by the Van Der Walls forces that tend to aggregate the nanoparticles to each other [6-10]. Before mixing within the polymer matrix, the carbon nanomaterial was treated by sonication at room temperature in excess of ethanol. The sonication is carried out at 20 kHz for about 6 hours by means of Sonics Ultrasonicator (VCX750 model), setting 20% amplitude with respect to the full-scale oscillation magnitude of the ultrasonic processor. After this preliminary step, the resin is added to the alcoholic solution in such amount to have the desired MWCNT concentration in the final composite. The composite mixtures realized and analyzed consist in epoxy-resin with inclusion of MWCNT at 1wt% versus the matrix The obtained mixture is stirred for about 1h at room temperature, and then put in oven at ~60°C till the total evaporation of the solvent (typically it takes ~48h), finally an aminic hardener is added and mixed. To prepare the composite tiles, each layer is soaked within the mixture, then a pressure supplied by a load of about 50kg is applied over a square zone ($20\times20cm^2$) of the multilayer. Finally, the resin curing process is applied in oven at a constant temperature (50°C for 16 hours).

In Fig.6, Fig.7 and Fig.8 the manufacturing of the MWCNT-reinforced layered structures is illustrated.

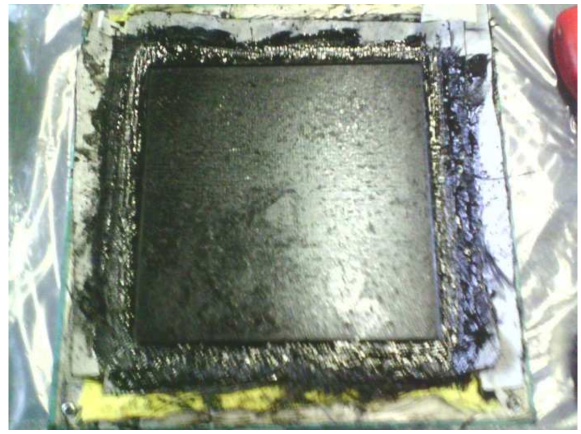

Figure 6. Manufacturing of nanostructured reinforced layered structures.

Figure 7. Top view of a nanostructured reinforced layered structures.

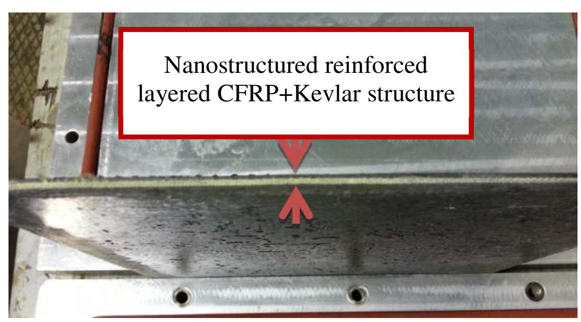

Figure 8. Picture of one side of layered CFRP+Kevlar structure after mechanical machining.

3 RAILGUN ANALISYS

In addition to military applications, railguns have been proposed to launch spacecraft into orbit [11-14]; however, unless the launching track was particularly long, and the acceleration required spread over a much longer time, such launches would necessarily be restricted to unmanned spacecraft. In the present work an electromagnetic launcher and in particular a railgun has been designed and manufactured. In Fig.9 the basic scheme of railgun is shown. The inner part made of two parallel barrel are the rails, while the remaining part are the mechanical assembly and the electrodes deputed to the energy supply.

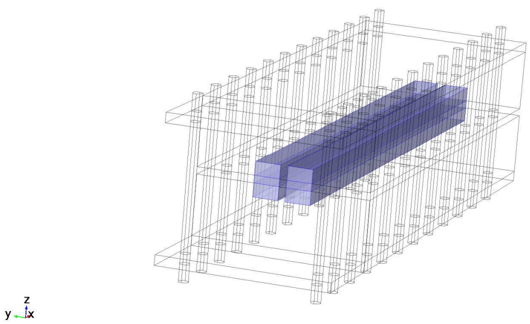

Figure 9. Railgun scheme, the couple of rails are in blue colour.

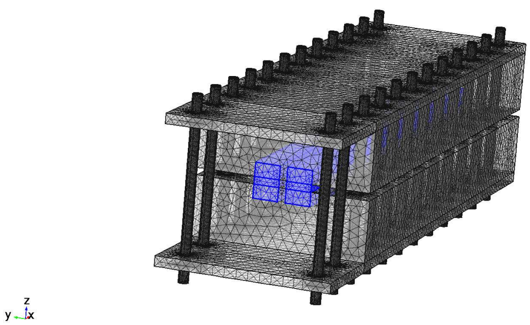

Figure 10. Mesh in numerical simulation of railgun by using finite element method.

The railgun length is 1m and the rails are electrically connected to a bank of 60 high voltage capacitors, for a total capacitance of about 5000 μF. The capacitors can be charged up to 6500 V for a theoretical overall stored energy of about 100 kJ. A great effort has been provided in order to achieve a reasonable high level of ballistic test reproducibility, mainly for what concerns the control of the railgun bias parameters and their influence on both values and statistical dispersion of the output energy. The armature may be an integral part of the projectile (commonly called bullet), and the moving armature are referred to the projectile. The metallic bullets adopted to test the layered material samples are shown in Fig.11. The bullet armature is made of aluminium while the upper part of the bullet is made of tungsten.

Figure 11. Bullets pictures: the armature is made of aluminium while the upper part of tungsten.

In Fig.12 the in-house built railgun is shown. It can be observed the bank of capacitors and the electrical connections to the railgun.

Figure 12. Bank of high voltage capacitors electrically connected to the railgun.

The railgun has been numerically simulated by COMSOL Multiphysics finite element method (FEM) software analysis [15]. Determination of the magnetic flux density and current density has been computed for a supply voltage of 6 kV.

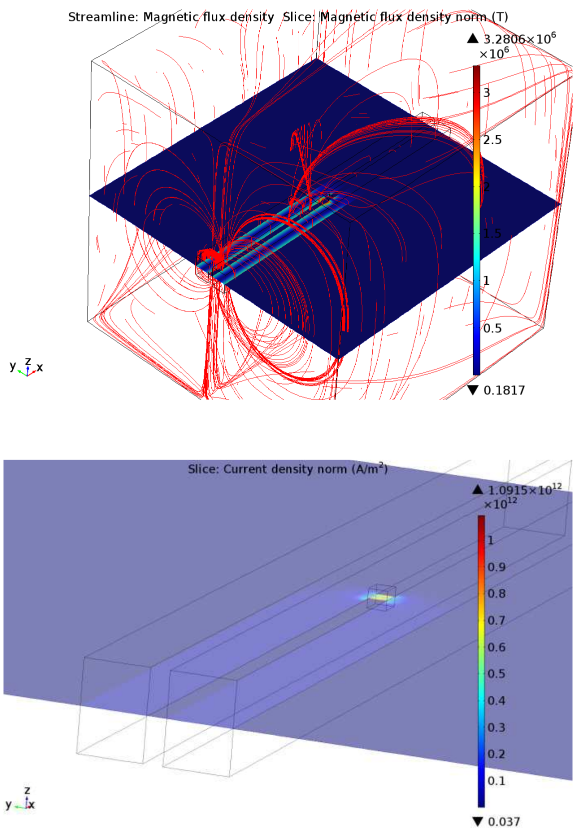

Figure 13. Railgun COMSOL simulation: computation of magnetic flux density (up), computation of current density (down).

In Fig.13, the simulation at the instant when the bullet is in the middle of its course between the rails is shown. Under these condition of magnetic flux density and current density the Lorentz force acting on the bullet is able to accelerate the bullet to values of velocity of thousands of m/s.

4 RESULT

In this last section some preliminary reports of the firing tests are illustrated. Three different test are shown, all for a capacitors charging voltage of 4kV: the first one on the material made by epoxy resin and Kevlar fabric, the second one on the material made by epoxy resin and MWCNTs, and the third one on the material made by Kevlar fabric and carbon fiber ply, by adding MWCNT as filler in the epoxy resin adopted to make the layered composite structures. In Fig.14 the velocity of the bullet is shown. This measurement of velocity was computed by using a ballistic chronograph (CHRONY, able to measure velocities of bullet up to 2500 m/S).

Figure 14. Bullets velocity of 1100 m/s at 4000 V of capacitors charging voltage.

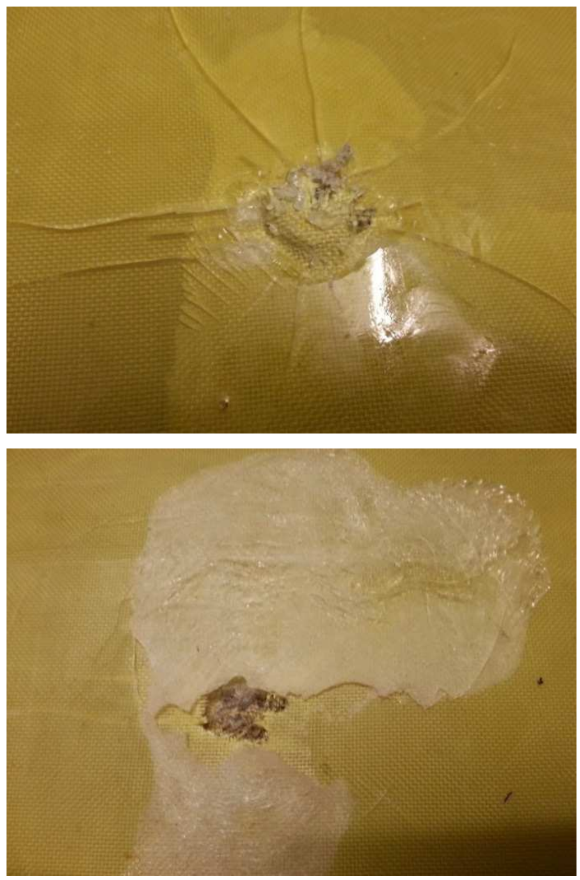

Figure 15. Damages of Kevlar based materials: sample front side (up), back side (down).

In Fig.15 the damage due to the impact on the material made exclusively by epoxy resin and Kevlar fabric is shown. In Fig.16 up to Fig.21 a sequence of pictures taken during the firing test on the nanostructured material made exclusively by epoxy resin and MWCNT is shown. It can be noticed the tile before firing in Fig.16 and the same after firing in Fig.21. In Fig.17-20 the plasma emission from the railgun in a 2ms of time-window and the intense flesh of light captured by the videocamera can be observed. The zero-instant photo is not reported, because at the start of the railgun fire the electromagnetic impulse (EMP) [16], generated by the extreme value of currents density, has induced some electromagnetic interference (EMI) [9] in the videocamera equipment affecting the quality of pictures.

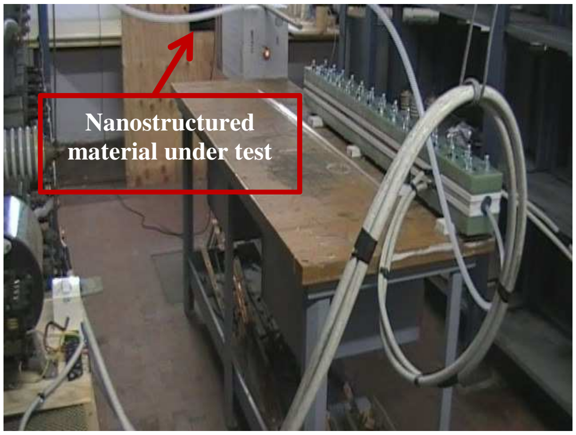

Figure 16. Railgun ready to fire and material to be tested.

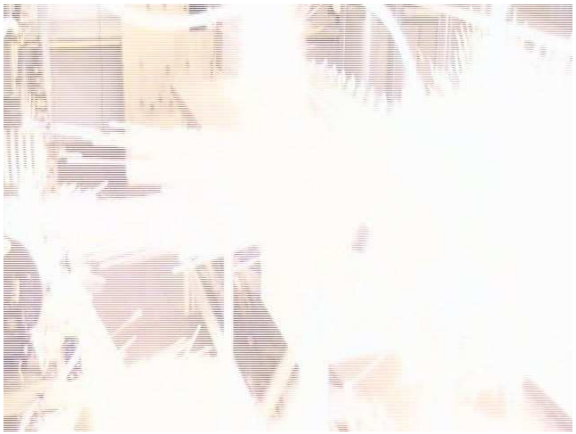

Figure 17. Railgun instants 1 of fire last 2ms.

Figure 18. Railgun instants 2 of fire last 2ms.

Figure 19. Railgun instants 4 of fire last 2ms.

Figure 20. Railgun instants 5 of fire last 2ms.

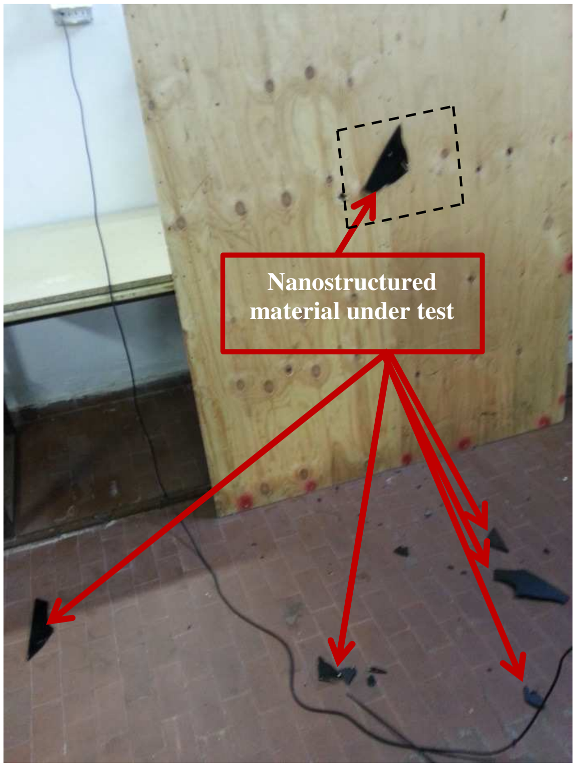

Figure 21. After the ballistic test the materials is completely destroyed.

In Fig.22 some bullets after firing tests are shown. It can be noticed the effect of currents. The mass of bullets decreases from about 19 to 14 g and from about 13 to about 9 g.

Figure 22. Two bullets after the firing test.

In Fig.23 and Fig.24 some pictures of the impact test on a tile made of Kevlar fabric, carbon fiber and MWCNT-reinforced epoxy resin are shown.

Figure 23. Damages of nanostructured Kevlar CFRP layered materials.

Figure 24. Damage of nanostructured Kevlar CFRP layered materials, zoom.

The results of this layered materials seems promising, since no extended damages has been discovered except of a little hole on the surface of structure. Further investigations, in order to achieve a better knowledge of the mechanism of the impact phenomena, as well as of the complex role of the carbon nanostructure in the load transfer to the carbon and the Kevlar fibers.

5 CONCLUSION

The paper analysed the effects of impact of metallic projectile on different type of composite materials. Tests were conducted by an in house railgun appositely manufactured for ballistic testing of materials at high energy of impact. Preliminary results show that the most promising materials able to resist to high velocity impact are nanostructured layered composite structures made by laminating several layer of carbon fiber, Kevlar fabric and by dispersing carbon nanotube in the epoxy resin adopted for the composite manufacturing.

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