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Dynamic Tests on Polyurea-Based Hybrid Composites for Ballistic Protection

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Abstract: *Due to its chemical and mechanical properties, polyurea gains more and more interest in military applications. In this study, polyurea and carbon nanotubes were processed as coating polymer composites for ballistic plates and/or packages, in order to increase their protection potential, meanwhile maintaining an appropriate weight and an economic accessibility. In this respect, the composite material was layered on various commercially-available materials and various thicknesses and further, the performances of the products obtained were tested in order to assess their behavior against traumas produced by shockwave, blunt, shooting and fragment.*

Keywords*: attenuation, blunt trauma, shooting trauma, ballistic package*

1. Introduction

Both during training and combat situations, military are submitted to a wide range of stress factors. In the view of increasing their combat potential and trust, both in theatres of operations or unconventional events, tests and research are continuously bringing important data to update the gadgets, and, nonetheless, the individual protective equipment (IPE) they use.

Since it is regarding land, air and naval troop's endowment, such equipment requires to fulfill specific demands. On the one hand, the weight of the IPE should not overcome a certain limit, since otherwise it might conduct to limitations in movements of the individuals and to transportation vehicle overloading. On the other hand, the product obtained should not be expensive and the raw materials should be available on the market.

In previous studies, there was shown the importance of polymers in various military protection applications [1-4], and was demonstrated that the reinforcement of such polymers conducts to better composite materials, which possess higher strength and higher modulus [2,5-10], in order to, e.g., reduce blunt trauma [10].

Functionalized multi-wall carbon nanotubes (MWCNTs) reinforcing a polyurea matrix and added to standard ballistic plates have shown a significant improvement in armor piercing resistance against .44 cal. Magnum and 7.62x51 cal. armor piercing bullets [10].

Thus, the aim of the present study was to continue previous studies performed by the laboratory in order to investigate deeper the high potential of these composite in the field of ballistic protection, more specifically against dynamic impacts, from explosives, ammunition and fragments.

2. Materials and methods

2.1. Materials

The materials tested pursued the fabrication conditions detailed in [10, 11]. Since the best results in terms of ballistic resistance were obtained by one specific composition of polyurea-based composite, that same composition was employed in the appropriate tests performed during the present study. In brief, the MWCNT–OH was obtained from MWCNT (from Sigma Aldrich) using the method described in [12] and, further, the MWCNT-OH-polyurea derivative (PUC) was prepared using 0.75% MWCNT–OH reinforcing agent, 49.625% polyurea (PU) prepolymer and 49.625% polyamines from EUROPOL®.

The polymer obtained was applied through a pressurized container at 150 bar and 65°C by direct continuous - layer spraying. The ballistic package included an extruded polystyrene plate (40 kg/m^3

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density and 9 mm thickness), and the polymeric composite was layered in 1 mm-thickness on each side of the plate and allowed to dry. As explosive materials, 100 g-TNT cylindrical blocks (CN ROMARM SA, Romania) and RIODET electric detonators (Maxam, Romania) were employed. Prior experiments, the ballistic packages were conditioned for 2 h at the experiment environment temperature and humidity. The tests were repeated five times, for accuracy and reliability of results.

2.2. Determination of resistance against explosion effects, i.e. shockwave overpressure

The test was performed using a multichannel system for analog-digital acquisition of the explosive devices functional parameters, consisting in: an oscilloscope type PICOSCOPE 6404, a signal conditioner, a low-noise coaxial cable with BNC connectors and two freshly calibrated piezoelectric pressure transducers type 102B04.

In order to determine the attenuation of the overpressure through the protection plate studied, a testing assembly was used, so that one transducer measure the explosion pressure side-on the sample at 1 m away (13.939 bar/V sensitivity), and the second transducer behind the sample (13.576 bar/V sensitivity), according to Figure 1 a. The system TNT – electric detonator was mounted and placed in the air at 1 m away from the sample, to avoid as much as possible interferences and the formation of compound waves resulting from the interaction with the ground (Figure 1 b). The acquisition accuracy provided by the manufacturer was over 99%. The explosion was triggered by electrical blaster.

The attenuation was calculated by equation (1):

$$A = (1 - pT2/pT1) \times 100, \quad (1)$$

where: A – attenuation (%); pT2 – pressure acquired by transducer 2 (bar); pT1 – pressure acquired by transducer 1 (bar).

Figure 1. a) Testing assembly; b) setup containing the explosive charge

2.3. Determination of blunt trauma imprints

Another very important parameter when considering individual protection equipment is the trauma inflicted by non-penetrating factors, such as blunt objects or surfaces. The weight-testing equipment consisted in a steel sphere included in a wooden support that was launched from various heights perpendicular on the test plate samples. For reference, test samples of ballistic Roma Plastilina No. 1 clay were used. In order not to obtain refractions from rough surfaces, both types of samples were placed on batches consisting in single layer polyethylene foil, a neoprene sponge and rubber.

The impact energy was calculated using equation (2):

$$E = m \times g \times h, \quad (2)$$

where: E - impact energy (J), m - weight of the test sample (kg),
g - gravitational acceleration, 9.81 m/s^2, and h - height of test sample launching (m).

2.4. Determination of shooting trauma imprints

To assess the comparative behavior of the standard and the novel composite ballistic package, 9x19mm FMJ cal. bullets were shot against ballistic packages using a ballistic barrel at 390-400 m/s average bullet velocity. The ballistic barrel was mounted perpendicularly at 5 m away from the ballistic packages. The measurement of the traumatic imprint was made in ballistic Roma Plastilina No. 1 clay, very frequently used as backing material in ballistic tests [13], and conditioned accordingly to [14]. In terms of test packages, various types of materials were employed: 50 kg/m^3 density and 3 mm thickness extruded polystyrene, 40 kg/m^3 density and 6 mm thickness extruded polystyrene, 40 kg/m^3 density and 9 mm thickness extruded polystyrene, 217 kg/m^3 density and 4 mm thickness cork board, and 33 mm thickness polyurethane sponge, while a 1 mm-layer polymeric composite was added to coat each side of the main material.

2.5. Determination of fragment trauma imprints

Two ballistic packages were tested: a) a ballistic package made of glued Kevlar sheets (50 cm x 50 cm x 3.3 mm prepreg) with 2 mm-layer polymeric composite material on both sides and b) a ballistic package made of glued Kevlar sheets (50 cm x 50 cm x 3.3 mm prepreg) with 2 mm-layer polymeric composite material on one side. In order to be able to assess the fragments impact on the novel ballistic plates, tests were performed with batches of 100 g RDX-based plastic explosive with a TNT-equivalent of 1.2 (purchased from CN ROMARM SA, Romania) and 30 pcs. M8-hexagonal steel screw nuts. The explosive devices were put 0.2 m away from the ballistic packages.

3. Results and discussions

Polymeric composites and nanocomposites were widely studied even since the excellent properties of aramid fibers and Kevlar® proved to be applicable in ballistic protection. Moreover, the reinforcement of such composites with different fillers/nanofillers proved to enhance their mechanical performances, making these materials serious candidates to replace standard ceramic plates. Due to the fact that these materials achieve the two-fold requirement, of low density and high strength, an important number of studies on epoxy-, vinyl esters-, phenolic resins-, polyesters-, polyureas- and urethanes-based materials for employment in ballistic protection field were performed [15-16]. The rationale of the present study was to focus on continuing previous tests of the research team [10-11], in correlation with state-of-the-art findings regarding the dynamic behavior of polyurea [17-18].

3.1. Shockwave attenuation

The results obtained for the determination of the shockwave overpressure and its attenuation are illustrated in Table 1.

Table 1. Results of the shockwave attenuation

Parameter	No. of measurement					Average
	Test 1	Test 2	Test 3	Test 4	Test 5	
p_{T1} (bar)	6.930	6.932	6.897	6.930	6.963	6.930±0.023
p_{T2} (bar)	0.610	0.568	0.593	0.585	0.602	0.592±0.016
Attenuation (%)	91.198	91.806	91.402	91.558	91.354	91.464±0.230

The five experimental tests and the results average demonstrate that the attenuation obtained using the ballistic plate including the polymer composite is very important, over 90%, and reliable in case of open-air energetic events (Figure 2), not bringing mechanical damages to the test plate. Moreover, this result is very encouraging from an ergonomic viewpoint, especially when considering the fact that the modified ballistic package used weighed only 674 g.

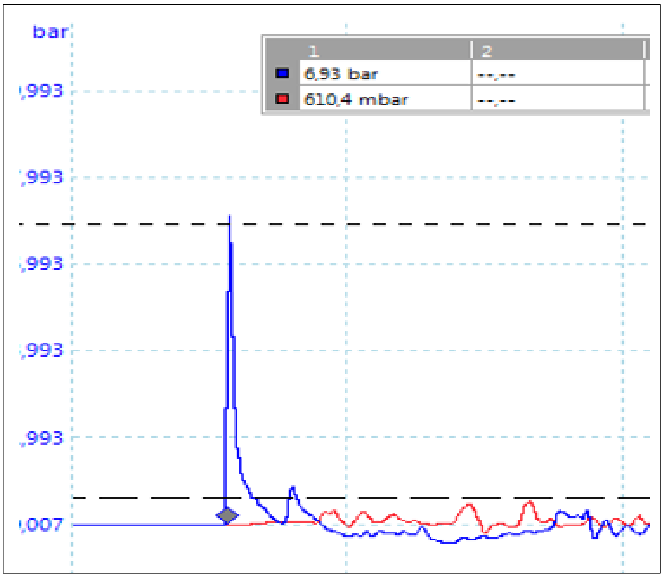

Figure 2. Attenuation results obtained in case of Test 1

3.2. Blunt trauma imprints

The comparative results of the tests performed (Figure 3) to obtain a certification of the fact that the addition of polymer composite increases the protection performances, revealed that the imprint, calculated as average imprint in the test plate versus imprint in clay reference, for E_{1-10}=90.7 J, is reduced by ca. 34% versus reference, while for E_{11-20}=36.3 J, the gain is of ca. 28% (Table 2).

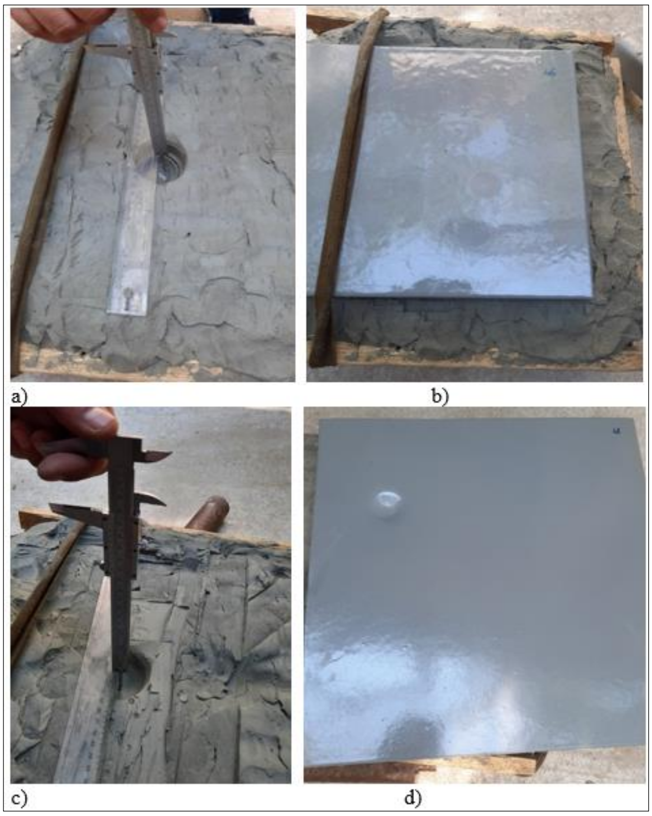

Figure 3. Blunt trauma test results on:
a) reference – 5 kg-dropping weight;
b) test plate – 5 kg-dropping weight;
c) reference – 2 kg-dropping weight;
d) test plate – 2 kg-dropping weight

Table 2. Blunt trauma test results

Test no.	Weight (kg)	Height (m)	Imprint in clay reference (mm)	Imprint in test plate (mm)
1-5	5	1.85	52±2.60	-
6-10	5	1.85	-	17.8±0.89
11-15	2	1.85	35±1.75	-
16-20	2	1.85	-	9.6±0.48

3.3. Shooting trauma imprints

The results obtained for the traumatic imprint are illustrated in Table 3, while in Figure 4 there are provided representative pictures from the experimental process. Firstly, the results obtained in case of the reference, which consisted in ballistic Roma Plastilina No. 1 clay, were between 18 and 21 mm, with an average of 19.5 mm (Figure 4 b). Secondly, in terms of test packages, various types of materials were employed to obtain higher performances than the state-of-the-art bulletproof vests. Here, the ballistic package included several types of commercially-available polymers and, next to them, a 1 mm-layer of PU-composite on each side of the plate.

The results of the tests performed revealed an important reduction of the traumatic imprint, of ca. 60%, from 19.5 mm to 7.8 mm in the case of bulletproof vest with additional package (3 mm-extruded polystyrene and polymeric composite layer), which appears to be optimal in terms of overall dimensions and weight versus the bulletproof vest only.

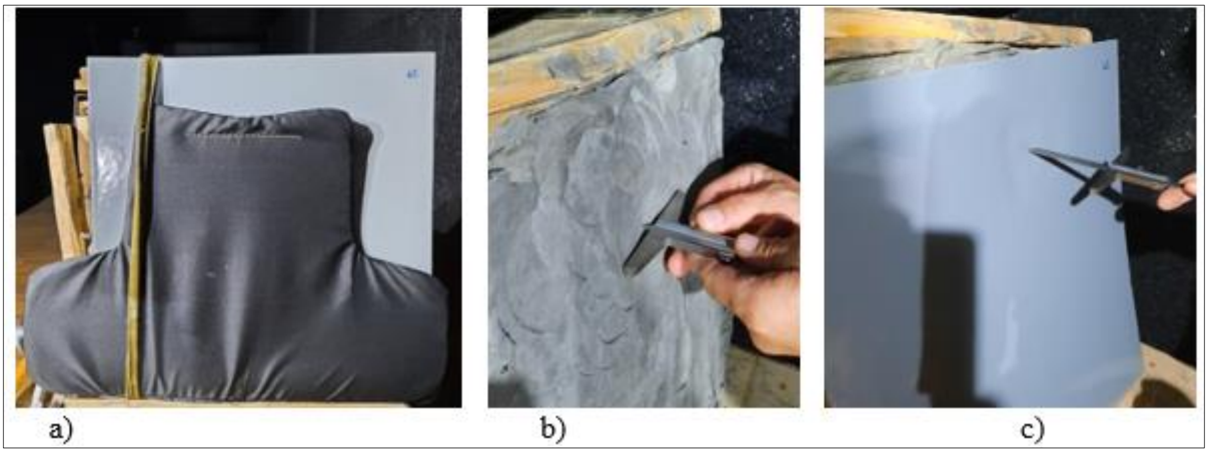

Figure 4. a) Shooting test setup, and results on b) reference; c) 3 mm-extruded polystyrene and polymer composite layer

Table 3. Shooting trauma imprint results

No.	Material	Density (kg/m^3)	Thickness (mm)	Traumatic imprint (mm)
0	clay (reference)	n/a	200	19.5±0.98
1	+extruded polystyrene	50	3	7.8±0.39
2	+extruded polystyrene	40	6	9.6±0.48
3	+extruded polystyrene	40	9	10.4±0.52
4	+cork board	217	4	6.2±0.31
5	+polyurethane sponge	n/a	33	0.6±0.03

3.4. Fragment trauma imprints

Even if the mechanism of high energy trauma events, such as those occurring from explosions, is not completely understood, the effects are certainly complex in terms of injuries [19]. In order to counter the ballistic traumas, it was mandatory to study the fragment impact versus the PUC.

Both ballistic packages, with one side and, respectively, both sides coated with PUC, withstood the test (Figure 5). None of the fragments resulting from the blast at 0.2 m penetrated the ballistic plate.

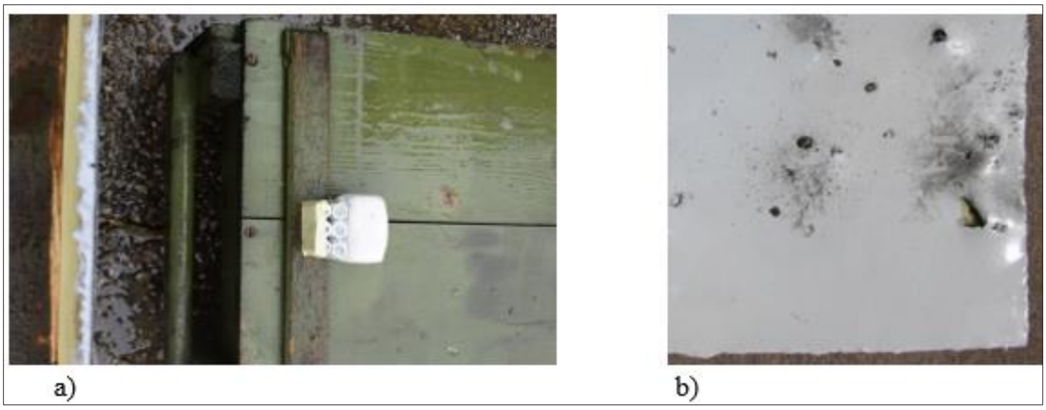

Figure 5. a) Explosive device – ballistic package setup; b) Fragment trauma imprints

4. Conclusions

The aim of the present study was to investigate the possibility to develop novel composite materials with a real potential to be applied in ballistic protection equipment area. Since polyurea and its MWCNT-OH derivatives were already tested for physical and chemical properties, experiments in dynamic environment were mandatory. In this regard, the composite material was applied by direct continuous-layer spraying on ballistic packages on each side of the plate.

The tests performed consisted in determination of resistance against dynamic impacts. In case of explosion effects, the attenuation of the shockwave overpressure was over 91%, which conducts to the conclusion that such material could be successfully used in protection panels against blasting. The determination of blunt trauma imprints conducted to very good results also, with an imprint reduction of over 28% versus a standard reference material, while the traumatic imprints consequently to shooting were reduced by over 60% and those caused by fragments were eliminated.

Thus, the dynamic tests performed conducted to very important results, which give a real positive option for implementing such polymer composites in ballistic protection equipment.

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References

1.MAGALHÃES, M.J., DE MAGALHÃES, S.T., REVETT, K., JAHANKHANI, H., *Cham International Conference on Global Security, Safety, and Sustainability,* 2016, 331-341.
2.ZHANG, M., ZHAI, Z., LI, M., CHENG, T., WANG, C., JIANG, D., CHEN, L., WU, Z., GUO, Z., Epoxy nanocomposites with carbon nanotubes and montmorillonite: Mechanical properties and electrical insulation, *J. Compos. Mater.*, **50**(24), 2015, 3363-3372.
3.BENZAIT, Z., TRABZON, L., A review of recent research on materials used in polymer–matrix composites for body armor application, *J. Compos. Mater.*, **52**(3), 2018, 3241-3263.
4.CAO, S., PANG, H., ZHAO, C., XUAN, S., GONG, X, The CNT/PSt-EA/Kevlar composite with excellent ballistic performance, *Composites Part B: Engineering*, **185**, 2020, 107793.
5.KAYMAKCI, A., AYRILMIS, N., GULEC, T., TUFAN, M., Preparation and characterization of high-performance wood polymer nanocomposites using multi-walled carbon nanotubes, *J. Compos. Mater.*, **51**(9), 2016, 1187-1195.
6.PITCHAN, M.K., BHOWMIK, S., BALACHANDRAN, M., ABRAHAM, M., Effect of surface functionalization on mechanical properties and decomposition kinetics of high performance polyetherimide/MWCNT nano composites, *Composites Part A: Appl. Sci. Manufact.*, **90**, 2016, 147-160.
7.DAI, L.H., WU, C., AN, F.J., LIAO, S.S., Experimental Investigation of Polyurea-Coated Steel Plates at Underwater Explosive Loading, *Adv. Mater. Sci. Engineering*, 2018, 1264276.

8.NASCIMENTO, L.F.C., LOURO, L.H.L., MONTEIRO, S.N., Ballistic performance of mallow and jute natural fabrics reinforced epoxy composites in multilayered armor, *Mater. Res.*, **20**(2), 2017, 1439–1516.
9.BUCUR, F., TRANĂ, E., ROTARIU, A., Numerical and Experimental Study on the Locally Blast Loaded Polyurea Coated Steel Plates, *Mater. Plast.,* **56**(3), 2019, 492-499.
10.PETRE, R., ZECHERU, T., PETREA, N., GINGHINĂ, R., SANDU, S., MUREȘAN, M., MATACHE, L.C., SAVA, A.C., NEAȚU, F., Synthesis and Mechanical Properties of Polyurea-Based Hybrid Composites for Ballistic Individual Protection, *Mater. Plast.*, **55**(3), 2018, 315-319.
11.PETRE, R., ZECHERU, T., PETREA, N., GINGHINĂ, R., BUGEAN, I., Polyurea-based Hybrid Composites for CBRN Protection, *Mater. Plast.*, **56**(4), 2019, 715-722.
12.VULCAN, M.A., DAMIAN, C., STANESCU, P.-O., VASILE, E., PETRE, R., HUBCA, G., Polymeric composites based on polyurea matrix reinforced with carbon nanotubes, *Mater. Plast.*, **54**(1), 2017, 41-44.
13.LI, Y.Q., GAO, X.-L., HALLS, V.A., ZHENG, J.Q., A new constitutive model for ballistic Roma Plastilina no. 1 clay, *Mechanics Adv. Mater. Struct.,* **27**(24), 2020, 2027-2034.
14.***NIJ Standard 0101.04/2000, *Ballistic Resistance of Personal Body Armor,* U.S. Department of Justice - National Institute of Justice.
15.LAXMAN, V., BALRAM, M., PIYUSH, V., PATEL, K., Review on polymer nanocomposite for ballistic & aerospace applications, Mater. *Today: Proceedings*, **26**(2), 2020, 3161-3166.
16.TAM, D.K.Y., RUAN, S., GAO, P., YU, T., 10 - High-performance ballistic protection using polymer nanocomposites, *Advances in Military Textiles and Personal Equipment*, Woodhead Publishing Series in Textiles, 2012, 213-237.
17.JIANG, Y., ZHANG, B., WEI, J., WANG, W., Study on the dynamic response of polyurea coated steel tank subjected to blast loadings, *J. Loss Prevention in the Process Industries*, **67**, 2020, 104234.
18.SUN, Y.-x., WANG, X., JI, C., ZHAO, C.-x., LIU, P.-l., MENG, L., ZHANG, K., JIANG, T., Experimental investigation on anti-penetration performance of polyurea-coated ASTM1045 steel plate subjected to projectile impact, *Defence Technol.,* online 2020.
19.NGUYEN, T.-T.N., TEAR, G.R., MASOUROS, S.D., PROUD., W.G., Fragment penetrating injury to long bones, *AIP Conference Proceedings* 1979, 2018, 090011.

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