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Ballistic Resistance of Composite Materials Tested by Taylor Anvil Test

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This study is focused on testing the ballistic resistance of composite materials to define their limit thicknesses according to the US STANDARD NIJ 0101.06, level III. The materials Twaron CT 747, Twaron CT 747 TH110 and Endumax Shield XF33, which are widely used in the manufacture of the ballistic protection systems, were tested. A method known as the Taylor Anvil Test (TAT) was used to verify their ballistic resistance. The missile 7.62 mm M80 was used to test the ballistic resistance of these materials. Within the experimental part, the deformation processes of composite materials were examined after impact by this missile. The value of the traumatic effect according to the US STANDARD NIJ 0101.06 was also measured. The results of the experiment provide an idea of the ballistic resistance of selected materials. Based on the results, TAT proved to be the perspective measurement method for further development and optimalization of the multilayer composite armor.

Keywords: Taylor Anvil Test, ballistic resistance, material penetration, Twaron, Endumax

1 Introduction

In the military industry, the development of firearms is associated with the development of ballistic protective equipment. The purpose of this equipment is to protect against ballistic threats. In view of the current situation due to increasing of the ballistic threats and local conflicts, there is a constant need to improve this equipment. One of the requirements for the construction of military equipment is to ensure its mobility on the battlefield with sufficient ballistic resistance. Light military vehicles are exposed to the effects of ammunition from small arms weapons. The most commonly used micro-caliber ammunition includes the 5.56 x 45 mm NATO cartridge (American design) and the 5.45 x 39 mm cartridge (Russian design). For small-caliber ammunition, the most commonly used cartridges are 7.62 x 51 mm NATO (American design) and 7.62 x 39 mm (Russian design) [1, 2, 3, 4].

Currently, the development of ballistic equipment is moving towards composite multilayer armors. The purpose of the combination of several types of ballistic materials is to deform the missile or its penetrating core so that the armor does not penetrate [3, 4, 5, 6].

The composite multilayer armors are composed of the strike face layer and back composite layer. The strike face layer is characterized by high hardness, which must be higher than the hardness of the missile to destabilize the missile and reduce its penetrating ability. For the impact layer, ballistic ceramics are most often used. These materials are characterized by high hardness, tensile strength, chemical resistance, low thermal and electrical conductivity. The main disadvantage is its fragility and sensitivity to internal defects, therefore ballistic ceramics are composed of segments into a mosaic. The purpose of the back composite layer is the absorption of kinetic energy of the missile or their fragments. For the manufacture of back composite layer, para-aramid fibers and ultra-high molecular weight polyethylene (UHMWPE) are used. To stop the missile, these fibers are required to have high strength, toughness and high modulus of elasticity. [5, 7, 8, 9, 10, 11].

One of the possibilities to determine the mechanical properties of materials depending on the deformation rate is to use dynamic test methods. The most commonly used dynamic method is the Taylor test (Taylor Anvil Test). It is the method that examines the behavior of materials at high deformation rates [12, 13].

In this article, the ballistic resistance of samples made of Twaron CT 747, Twaron CT 747 TH110 and Endumax Shield XF33 was tested. These samples were tested by the missiles 7.62 mm M80, which were delaborated from the cartridges 7.62 x 51 mm NATO FMJ M80. The aim of the TAT measuring method was to find the limit thickness at which the manufactured samples will not be penetrated. With regard to the development of ballistic protection equipment, the TAT method can be used in testing suitable combinations of ballistic materials to create the composite multilayer armors.

2 Materials and methods

The examined materials were Twaron CT 747, Twaron CT 747 TH110 impregnated with thermoplastic resin and Endumax Shield XF33. The parameters of the examined materials are given in Tab. 1.

***Tab. 1** Parameters of the examined materials*

Materials	Thickness [mm]	Area density [g/m²]	Tensile strength module [GPa]	Composite density [kg/m³]
Twaron CT 747	0.62	410	115	1450
Endumax Shield XF33	0.16	146	170	970

2.1 Manufacture of composite materials for Taylor test

In order to determine the limit thicknesses, samples of different thicknesses and with different number of layers were manufactured. The parameters of the manufactured samples are given in Tab. 2.

***Tab. 2** Parameters of the manufactured composite samples*

Testing order		Materials	Dimension [mm]	Number of layers	Thickness [mm]	Weight [g]
A	A1	Twaron CT 747 with matrix LG700	60 x 60	33	14.7	62.8
	A2			21	9.9	43.3
B	B1	Twaron CT 747 TH110 (thermoplastic)	60 x 60	38	15.2	70.9
	B2			25	10.4	44.7
C	C1	Endumax Shield XF33	60 x 60	95	15.1	51.4
	C2			65	10.3	33.1

A) Samples of Twaron CT 747 with matrix LG700

Tab. 2 shows that two composite samples were made of Twaron CT 747. For manufacture was used vacuum infusion technology (VARTM). The description of VARTM is given in the source [14, 15]. In the Fig.1 a), there is the preparation of the materials for vacuum infusion. The matrix used for the production was made of epoxy resin (LG700) and hardener (HG700). The weight ratio of epoxy resin and hardener was 100:30. The curing was performed at room temperature 22 °C for 24 hours. Fig. 1 b) shows two manufactured composite samples. After curing, the thickness of the 33-layer sample A1 was 14.7 mm and its weight was 62.8 g. The thickness of the 21-layer sample A2 was 9.9 mm and the weight was 43.3 g.

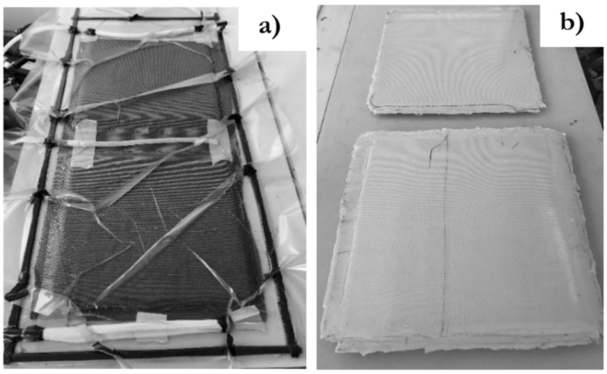

***Fig. 1** Vacuum infusion technology (VARTM) a) preparation of materials b) manufactured samples A*

B) Samples of Twaron CT 747 TH110

After cutting Twaron CT 747 TH110 to the required size, the hot pressing method was used to produce the composite samples. The pressing of the vacuumed material (Fig. 2) was performed on the testing machine ZD 40 (400 kN), which allows the loading of samples in tension, pressure and bending. To record and evaluate the tests the TIRAtest program was installed. The machine acted on layers with the force of 350 kN for 20 minutes and the curing temperature was 140 °C. Two composite samples B1 and B2 were manufactured by this method. The sample B1 was composed by 38 layers of Twaron CT 747 TH110. The thickness was 15.2 mm and its weight was 70.9 g. The sample B2 was composed by 25 layers of Twaron CT 747 TH110. The thickness was 10.4 mm and its weight was 44.7 g.

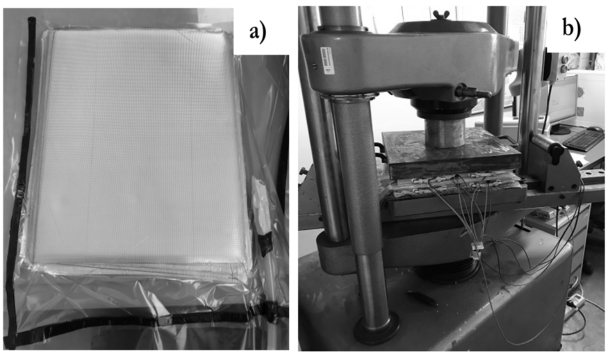

***Fig. 2** Composite panel B a) prepared materials b) manufacturing process of sample B*

C) Samples of Endumax Shield XF33

The Endumax Shield XF33 was vacuumed after cutting to the required size, Fig. 3 a). For the manufactory of these samples was also used the method of hot pressing by using the testing machine ZD 40 (400 kN). The manufacturing process is shown in Fig. 3 b). The machine applied with the force of 350 kN for 20 minutes and the curing was set to the temperature of 140 °C. Two samples C1 and C2 were manufactured by method of hot pressing, see Tab. 2. The sample C1 was composed by 95 layers of Endumax Shield XF33. After relieving the applied force, the thickness of this sample was 15.1 mm and its weight was 51.4 g. The sample C2 was composed by 65 layers of Endumax Shield XF33. After relieving the loading force, the thickness of the sample C2 was 10.3 mm and its weight was 33.1 g.

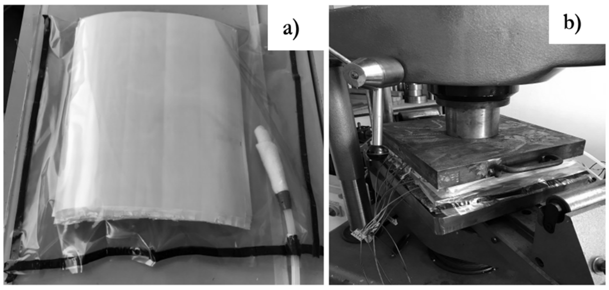

Fig. 3 *Composite panel C a) prepared materials b) manufacturing process of sample C*

2.2 Shooting experiment

To perform the shooting experiment was used the experimental device for the Taylor anvil test (Fig. 4), which is located in the Laboratory of High Strain Rates at the Faculty of Mechanical Engineering in Brno. Experimental device for the TAT is composed of the pneumatic cannon, the carrier with a test sample, the impact camera, the speed sensor, the oscilloscope with the amplifier and also contains the strain bar. The main components of the pneumatic cannon include the control and recording panel, the air chamber, the barrel, the breech, the compressor, the relief valve and the base.

Taylor Anvil Test (TAT) is the method that examines the behaviour of materials at high strain rates [13]. The missiles 7.62 mm M80 rifle were used to verify the ballistic resistance of the composite samples. These missiles were delaborated from the military cartridge 7.62 x 51 mm NATO FMJ. The principle of the shooting experiment consisted in the impact of the missile on the tested sample, which was located in the impact plate (Fig. 5). The missile inserted into the carrier (Fig. 6) was accelerated by compressed air from the pneumatic cannon towards the impact plate. Before impact, the missile was separated from the carrier and hit the sample in the impact plate.

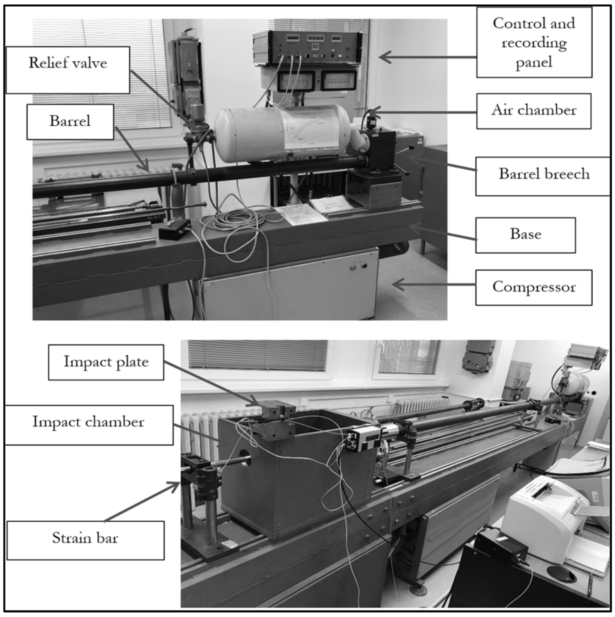

Fig. 4 *Arrangement of the experimental device*

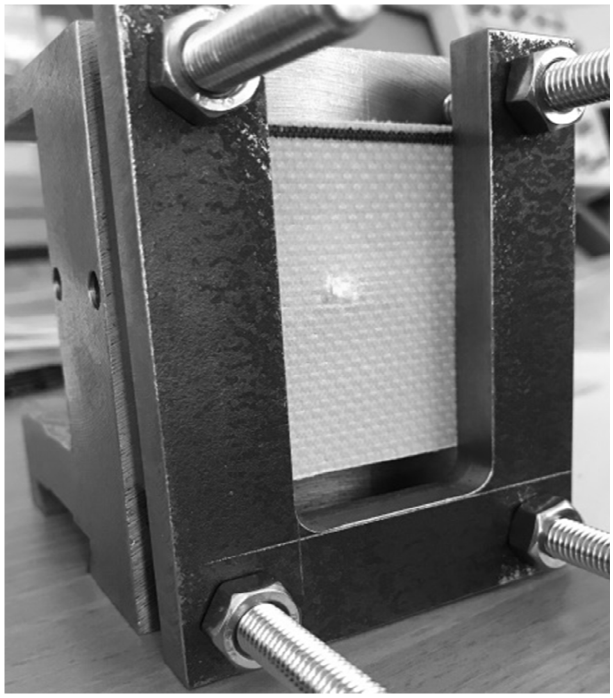

Fig. 5 *Located sample in the impact plate*

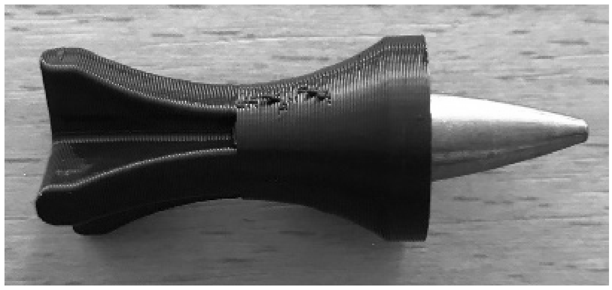

Fig. 6 *Missile 7.62 mm M80 inserted into the transparent carrier*

Tab. 3 shows the parameters of the military cartridge 7.62 x 51 mm NATO FMJ M80.

Tab. 3 *Parameters of the military cartridge 7.62 x 51 mm NATO FMJ M80*

Cartridge type	Missile type	Missile weight [g]	Serial number	Manufacturer
7.62 x 51 mm NATO	FMJ M80	9.55	1/82	S&B

3 Results and discussion

In order to verify the ballistic resistance, samples A to C were tested by the missiles 7.62 mm M80. The parameters of this missile are given in Chapter 3, see Tab. 2. Missiles were accelerated by expanding air from the pneumatic cannon, and missiles velocity ranged from 149.5 to 151.7 m/s. The kinetic energies of the missiles varied depending on the velocity of the missiles. They ranged from 106.7 to 109.9 J. The aim of the shooting experiment using the TAT method was to find the limit thicknesses of selected materials.

3.1 Twaron CT 747 with matrix LG700

The first tested sample A1 was the Twaron CT 747 with matrix LG 700 of 33 layers, the thickness of 14.7 mm and the weight of 62.8 g. The sample was tested by the missile 7.62 mm M80. The strike and back face of the tested sample Twaron CT 747 with matrix LG700 is shown in Fig. 7. There was no perforation of the sample. Fig. 7 shows that the back face of the sample is not damaged and it was not possible to determine its limit thickness. The deformation of the missile after the impact is shown in Fig. 8.

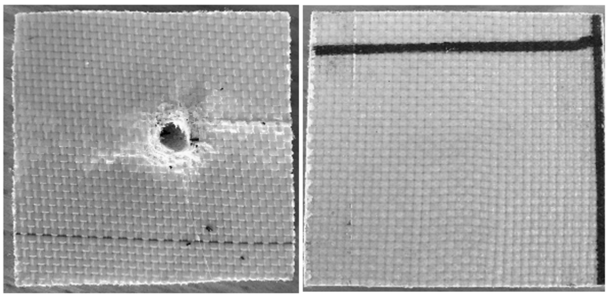

Fig. 7 *Sample A1 a) strike face b) back face c) missile deformation*

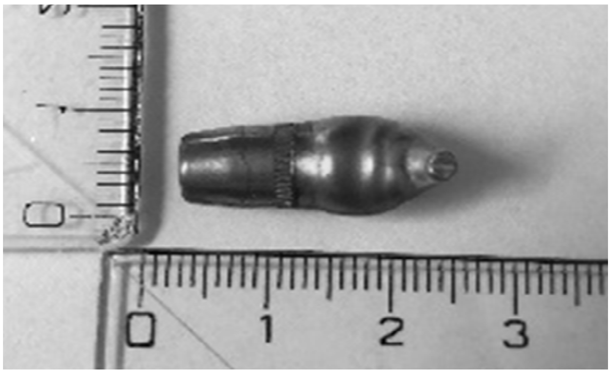

Fig. 8 *Missile deformation*

The sample A2 Twaron CT 747 with matrix LG 700 of 21 layers, the thickness of 9.9 mm and the weight of 43.3 g was used to determine the limit thickness. Fig. 9 shows the strike and back face of the sample after impact of the missile 7.62 mm M80. After the impact of the missile, the plastic deformation formed on the back face of the sample, which indicates the traumatic effect. The deformation of the missile after the impact is shown in Fig. 10. The size of the trauma effect is 12.7 mm. The maximum value of the trauma effect according to US STANDARD NIJ 0101.06 is 44 mm [16]. The back face of the sample was also damaged.

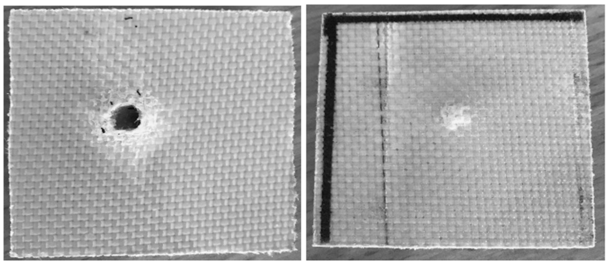

Fig. 9 *Strike and back face of the sample A2*

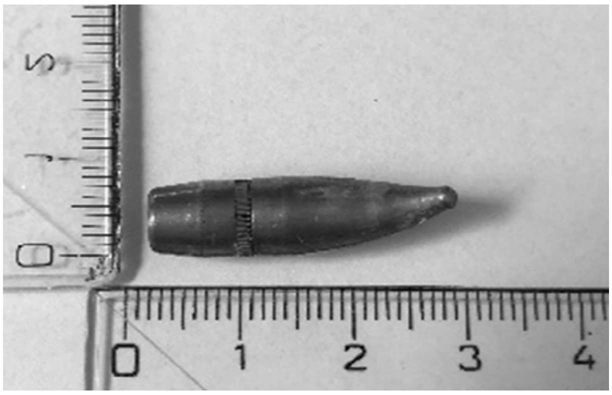

Fig. 10 *Missile deformation*

3.2 Twaron CT 747 TH110 (thermoplastic)

In addition, the sample B1 of Twaron CT 747 TH110 impregnated with thermoplastic resin of 38 layers, the thickness of 15.2 mm and the weight of 70.9 g was tested. Fig. 11 shows the strike and back face of the sample after impact by the missile 7.62 mm M80. There was no penetration of the sample, but the missile caught in the sample. The traumatic effect is visible on the back face of the sample. The size of the traumatic effect is 8.1 mm.

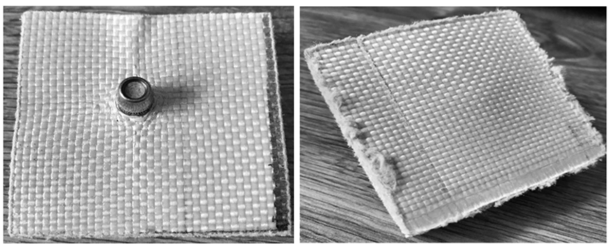

Fig. 11 *Strike and back face of the sample B1*

To evaluate the ballistic resistance of Twaron CT 747 TH110 and the size of the traumatic effect, the sample B2 of 25 layers, the thickness of 10.4 mm and the weight was 44.7 g was used. Fig. 12 shows the strike and back face of the sample after the impact. After the impact, the missile 7.62 mm M80 was caught in the sample and there was also the back layer damage. The size of the traumatic effect reached 15.8 mm. This value indicates that this is the limit thickness of the sample B2.

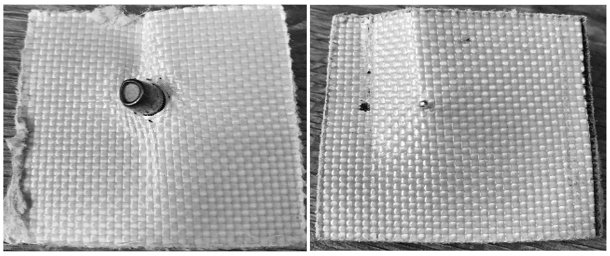

Fig. 12 *Strike and back face of the sample B2*

3.3 Endumax Shield XF33

The last tested material was Endumax Shield XF33. First, the sample C1 of 95 layers, the thickness of 15.1 mm and the weight of 51.4 g was selected. The missile 7.62 mm M80 was shot into this sample. The strike and back face of the sample is shown in Fig. 13. The missile was caught in the sample. Due to the absorption of the kinetic energy of the missile, the traumatic effect was created on the back face and its size reached 9.4 mm.

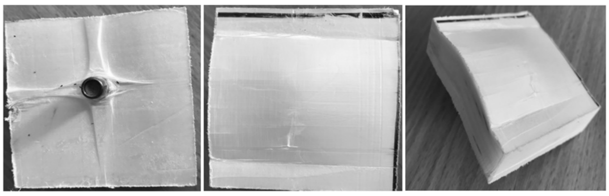

Fig. 13 *Strike and back face of the sample C1*

To evaluate the ballistic resistance, another sample C2 of material Endumax Shield XF33 of 65 layers, the thickness of 10.3 mm and the weight of 33.1 g was used. After the impact by the missile 7.62 mm M80, the sample was penetrated, which is visible in Fig. 14. In terms of visual evaluation, the fibres were broken and pulled out (Fig. 15). The size of trauma effect is 22.6 mm.

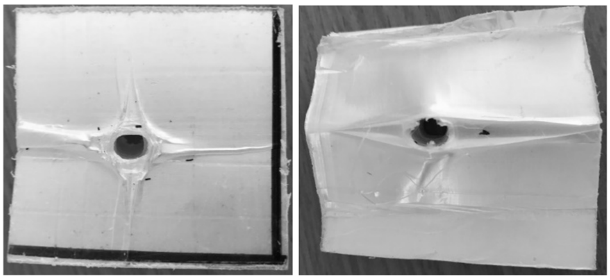

Fig. 14 *Strike and back face of the sample C2*

Fig. 15 *Delamination of the sample C2*

For the tested samples A to C of Twaron CT 747 with matrix LG 700, Twaron CT 747 TH110 and Endumax Shield XF33, the damage to the back faces of these samples after the impact of the missiles 7.62 mm M80 was more extensive by comparison with strike faces of the samples.

In order for the tested sample to be effective in terms of ballistic protection in accordance with the US STANDARD NIJ 0101.06, the value of the traumatic effect must not exceed 44 mm. Figure 16 shows the sizes of trauma effect for the tested samples A to C.

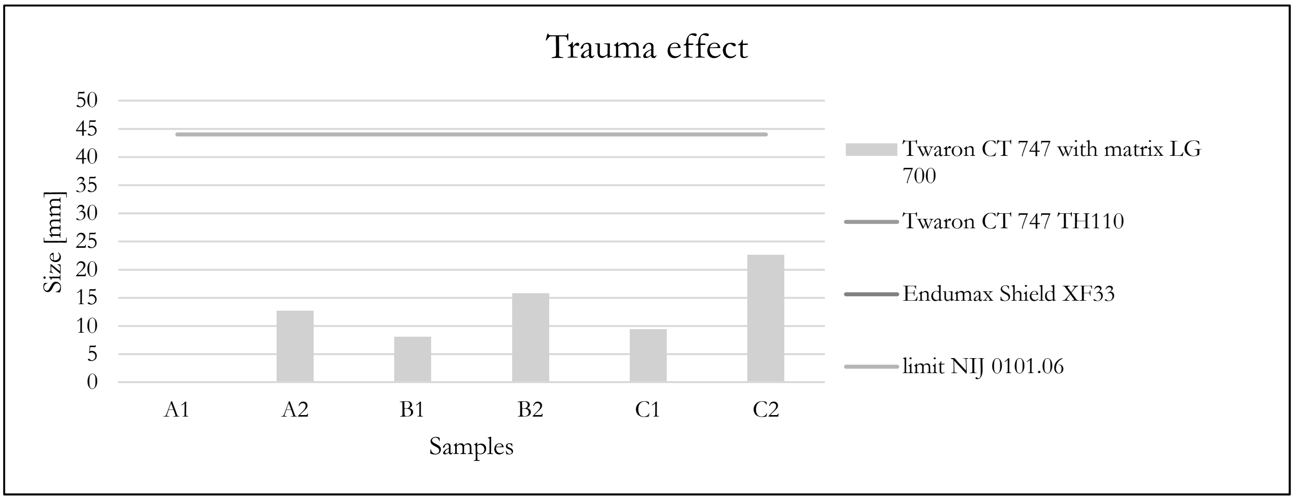

Fig. 16 *Size of trauma effect*

Fig. 16 shows that the values of the trauma effect of these samples are below the US STANDARD NIJ 0101.06 limit.

The key results from the shooting experiment are presented in Tab. 4. Here are the parameters of the tested sample, the velocities of the missiles before impact, the kinetic energies of these missiles and the values of the trauma effect.

Tab. 4 *Results of the shooting experiment*

Sample	Materials	Thickness [mm]	Weight [g]	Missile velocity [m/s]	Kinetic energy [J]	Trauma effect [mm]
A1	Twaron CT 747 with matrix LG700	14.7	62.8	149.5	106.7	0.0
A2		9.9	43.3	149.8	107.2	12.7
B1	Twaron CT 747 TH110 (thermoplastic)	15.2	70.9	150.2	107.7	8.1
B2		10.4	44.7	150.6	108.3	15.8
C1	Endumax Shield XF33	15.1	51.4	149.9	107.3	9.4
C2		10.3	33.1	151.7	109.9	22.6

The only sample that is not sufficient for ballistic protection is the 10.3 mm thick sample C2, which has been penetrated by the missile 7.62 mm M80. Other tested samples are evaluated as effective ballistic protection.

4 Conclusion

In this article, the ballistic resistance of samples A to C made of Twaron CT 747 with matrix LG 700, Twaron CT 747 TH110 and Endumax Shield XF33, which are used for ballistic protection, was examined. The Taylor Anvil Test was used to verify ballistic resistance and the samples were tested by the missiles 7.62 mm M80. The aim of this study was to determine the limit thicknesses of the manufactured samples.

The results from the experimental part (Table 4) show that the Taylor Anvil Test represents perspective method for examining the behavior of ballistic resistant materials at high strain rates. This table shows the impact velocities of the missiles, the kinetic energies of these missiles and the values of the trauma effect. The mechanisms of damage to the samples during the impact by the missiles 7.62 mm M80 were related to the rupture, elongation, stretching and delamination of the fibers. All samples, except sample C2, comply with ballistic resistance according to NIJ 0101.06.

Selected materials that were used in the shooting experiment represent perspective materials for the future development of ballistic protection. In order to increase this resistance, we will deal with composite multilayer armor, which will combine UHMWPE fibers, para-aramid fabric and ballistic ceramics.

Acknowledgements

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