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EXPERIMENTAL EVALUATION OF THE IMPACT STRENGTH OF LAMINATED COMPOSITES WITH A THERMOPLASTIC MATRIX

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Tensile tests were performed to obtain the quasi-static mechanical properties of the aramid fabrics (Twaron®, RUSLAN®-SVM). The elastic modulus of filaments, pulled out from the fabrics was measured with compact testing machine INSTRON 5942. Filaments pull-out tests were carried out to compare the frictional forces in different aramid fabrics. Eight various types of ballistic panels with the thermoplastic matrix based on polyethylene were fabricated and two types ballistic panels based on UHMPE (Dyneema®).

Extensive ballistic tests have been carried out on various ballistic panels using 6.35 mm steel ball. Special powder gun stand for acceleration of projectiles with terminal velocity up to 900 m/s was developed The ballistic performance was assessed in terms V50 threshold as well as post V50 limit.

After the test, the comparison was produced of effectiveness between all of materials used in this work. Laminates based on UHMPE fibers are much better than others in respect to the values of on indicators of V50 (about 10 %) and of the absorbed energy (about 25 %) under high-velocity impact conditions. But their energy absorption capability can sharply drop down when projectile's velocity exceeds the ballistic limit. When selecting reinforcing aramid fabric for ballistic application, it is important to consider not only the mechanical properties of the fibers and the type of fabric construction, but also the material should have good results on all parameters of ballistic efficiency such as filaments width, etc. Best aramid fabric composite was SVM S125 with twill construction and LDPE films.

Keywords: high-velocity impact, fragment protective structure, UHMPE, aramid fabric, thermoplastic matrix.

Introduction

Protective structures on the basis of durable composite materials are widely used for protecting manpower and vehicles against fire arms bullets and explosives fragmentations [1]. Typically they have low surface density, high ballistic efficiency, and can be used as main element of protective structure, or as support material for metallic or ceramic face armor layer.

Most commonly used for manufacturing ballistic composites are aramid fibers (RUSLAN®-SVM, Kevlar®, Twaron®, Rusar®, Teksar®), ultra-high molecular polyethylene fibers (UHMPE), such as Dyneema®, Spectra®, glass and carbon fibers [2–6]. Composite materials, based on PBO (Zylon®), basalt and organic fibers, are less common, as later are relatively less strong [7], and PBO fibers have a tendency to aging, that can lead to sharp decreasing of ballistic features [5].

Composites with low resin content (less than 20 % per weight) are also very attractive for using in armor structures. Different thermoplastics with high flexibility are usually used as matrix for such composites.

Using of such materials has some advantages:

- low adhesion between matrix and fibers allows later to face maximum deformations and elongate in the impact point [8];
- additional energy dissipation mechanisms, related to stratifying and cracking [9, 10];
- fibers, not contacting directly with the projectile, are loaded [9–11];
- decreasing blunt trauma if to compare with soft armor [9, 12];
- sufficient bending stiffness for using as support.

Protective structures ballistic effectiveness is determined by several parameters. Ballistic limit (V_{50}) – one of the main parameters, determined as speed of the striker, leading to material penetrating with 50 % possibility [13]. Fragmentations simulating devices of different shapes and weights are used during testing protective structures [13, 14]. There is a special standard in Russian Federation, regulating armor structures testing [15]. According to this, standard tests should implement steel spherical ball 6.35 mm in diameter with weight of 1.05 g, manufactured of ShKh15 steel.

Composites on the basis of aramid and UHMPE fibers assure high ballistic effectiveness [5, 16]. UHMPE fibers based composites behavior under ballistic loads was widely studied in theory and experimentally [17–21].

There are several works, dedicated to ballistic composites with thermoplastics matrix (polypropylene, polyvinilbutyral, and vinilester), based on aramid fiber [9, 22, 23]. There is no information in literature sources on ballistic features of the polyethylene matrix composites. Low pressure polyethylene (HDPE) is a cheap, easy melting material, binding aramid fibers with each other, which has appropriate viscosity, not allowing full filaments saturation. That is why HDPE is used as light and thin binding agent for aramid layers.

This work includes analysis of laminated composites on the basis of aramid fabrics with HDPE matrix. Pressed panels have passed ballistic tests with a striker, presented by fragmentation simulating device according to GOST R 50744-95. In order to compare ballistic efficiency parameters same tests were performed for panels, based on UHMPE fibers. In order to determine ballistic limit, experiments data were processed using Lambert-Jonas empirical-formula dependence. All manufactured laminated panels have got similar surface density (4.2 ± 0.2 kg/m^2). Aramid fibers mechanical properties under quasistatic load are also presented in this work.

1. Materials and methods

Fig. 1 presents a photo of the surface of aramid fabrics, used in this work.

1.1. Fibers mechanical properties study

As composite materials properties depend, first of all, on the fibers' properties, elastic and strength filaments' characteristics were determined on compact testing machine INSTRON 5942 during filaments static elongation tests.

In order to exclude machine rigidity influence on determined elastic modulus, we used maximal possible filament length of 450 mm. Elastic modulus was measured *during unloading* from stress, equal to ~50 % of destructing (initial filament condition after pulling out of fabric is characterized by crimp).

In order to test filaments strength we used special clamps INSTRON SG-1, where filaments were rolled on drums 51 mm in diameter, and filaments ends were clamped in microgrips. Friction on drums allowed unloading clamping area and obtain destruction in operating range.

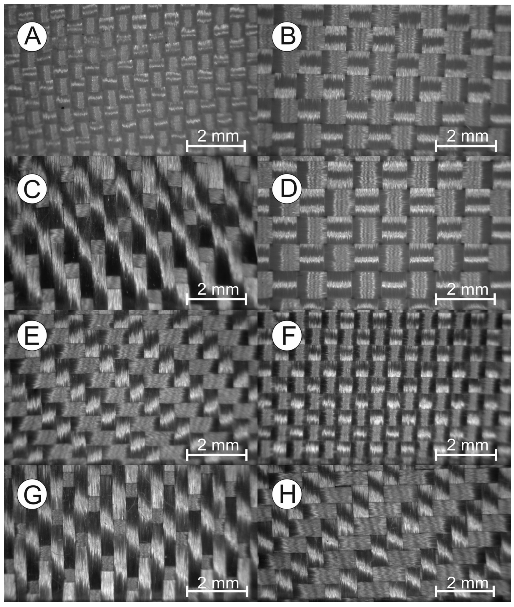

Fig. 1. Fabrics structure: A – Twaron® Microflex; Б – Twaron® 613; В – СВМ 56334; Г – Twaron® 709; Д – СВМ S-110; Е – СВМ Р-110; Ж – СВМ А-145; З – СВМ S-125

Table 1 includes results of testing separate filaments (series of 10 filaments along basis and woof) from all investigated woven fabrics. Where E, σ_v, ε_v – elastic modulus, breaking strength, and breaking deformation. Material density was assumed equal to 1.44 g/cm^3.

These data allow evaluating fibers quality and, subsequently, armor materials, manufactured of them: elastic moduli vary very slightly, in the range of 1–2 % (maximum of 5 % for Twaron® 613). Twaron® also has slight variation of strength properties – not more than 8 %. Same time CBM strength properties demonstrate variation coefficients of 13 % (along basis direction). CBM 56334 fibers have highest strength – about 3.5 GPa. Russian aramid filaments CBM are generally more durable than foreign filaments, so sound speed in them is about 20 % higher. This gives advantages under impact loading.

Table 1

Aramid filaments mechanical properties

Filaments from fabric	Cross section area, mm^2	Average E, GPa	E variation coefficient, %	Average σ_v, MPa	Variation coefficient σ_v, %	Average ε_v, %
CBM A 145 basis	0.021	129	0.45	2 980	2.9	2.31
CBM A 145 woof	0.021	131	0.55	3 350	3.8	2.55
CBM P 110 basis	0.021	132	0.76	2 700	11.0	1.96
CBM P 110 woof	0.021	124	0.93	3 510	2.6	2.81
CBM S 125 basis	0.021	133	0.47	3 080	10.0	2.31
CBM S 125 woof	0.021	133	0.83	3 460	9.4	2.61
CBM S110 basis	0.021	132	0.80	2 590	22.6	1.95
CBM S110 woof	0.021	132	0.70	3 490	5.5	2.65
CBM 56334 basis	0.021	136	0.91	3 420	3.9	2.52
CBM 56334 woof	0.021	136	0.70	3 600	2.3	2.65
Twaron® Microflex basis	0.038	103	4.21	1 470	4.2	1.43
Twaron® Microflex woof	0.038	103	5.11	1 675	5.9	1.63
Twaron® 613 basis	0.039	90	0.19	2 560	7.7	2.84
Twaron® 613 woof	0.039	96	3.70	2 840	2.7	2.97
Twaron® 709 basis	0.063	100	0.19	2 570	5.1	2.57
Twaron® 709 woof	0.063	99	3.70	2 640	3.3	2.68

1.2. Pulling fibers out of the ballistic materials

It is known that friction between filaments has major effect on efficiency energy absorption by multilayer fabric protective structures under high speed impact [8]. Experiments on filaments pulling out were performed for comparing friction forces between filaments in different aramid fabrics. Testing machine INSTRON 5942 with pneumatic rubber-covered grip INSTRON 2712-019 is used for tests performing. This grip clamps one central fiber of the 50 × 50 mm specimen. Four specimens for each ballistic material were tested (two along basis direction and two along woof direction). Typical results of testing by pulling fibers out for Twaron® 613 material are presented on Fig. 2. For this material maximum pulling out force is equal to 2.25 N for basis and 1.15 N for woof.

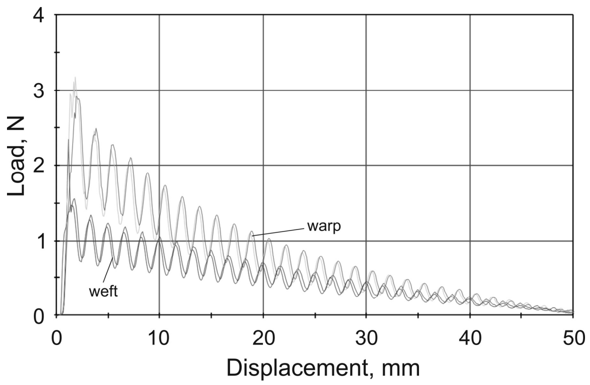

Fig. 2. Filament pulling out diagram for Twaron® 613 fabric

Averaged maximum friction forces values for different materials are indicated in Table 2. Measurements demonstrate that in all materials, except CBM 56334, friction force along woof is higher than along basis. Twaron® Microflex has highest friction forces in both directions. Lowest friction forces were obtained for materials CBM 56334 and CBM A145. Both materials have sateen construction.

Table 2

Results of fibers pulling out tests

Fabric type	Woof/basis F, H
CBM A145	0.4/0.3
CBM P110	4.5/1.7
CBM S125	1.3/1.1
CBM S110	0.85/0.65
CBM 56334	0.29/0.45
Twaron® Microflex	13.5/5.05
Twaron® 613	2.25/1.15
Twaron® 709	1.8/1.6

1.3. Manufacturing pressed ballistic panels

When performing this work we've used ballistic panels 85 × 85 mm with surface density of about 4 kg/m^2, manufactured of aramid fabrics and ballistic polyethylene. Intermediate layers are presented by thermoplastic films – low density polyethylene (HDPE) – with initial thickness of 40 µm, that were placed between aramid fabric layers. Panels of ballistic polyethylene HB2 and HB80 were pressed without additional intermediate layers. Table 3 presents data on used materials.

Table 3

Data on used materials

Fabric type	Surface density, g/cm^2	Layer thickness, mm	Number of layers	Panel thickness, mm	Construction type
Twaron® Microflex	218	0.275	17	3.63	Linen
Twaron® 709	195	0.255	17	3.50	Linen
Twaron® 613	137	0.175	23	3.49	Linen
CBM 56334	145	0.190	23	4.36	Satin
CBM A-145	145	0.220	22	4.21	Satin
CBM P-110	110	0.170	27	3.72	Linen
CBM S-110	110	0.160	27	4.03	Twill
CBM S-125	125	0.170	25	4.12	Twill
Dyneema® HB2	257	0.320	16	4.43	Four unidirectional UHMPE fibers layers with laying them 0/90/0/90 and with thermoplastic matrix
Dyneema® HB80	145	0.235	30	4.70	Four unidirectional UHMPE fibers layers with laying them 0/90/0/90 and with thermoplastic matrix

Set of aramid filaments was heated in an oven up to 145 ± 5 °C during 2 hours up to reaching uniform temperature distribution over the set height. Temperature monitoring was performed with a thermocouple, installed in the middle part of the set. Sets from ballistic polyethylene were heated up to temperature of 120 ± 5 °C during 2 hours. When pressing pressure has reached 100 ± 10 bar, exposure time was equal to 10 minutes, set was cooled down to 60 °C, after which the set was disassembled and cooled down under air.

This has resulted in manufacturing 10 different variants of ballistic panels, 6 specimens for each type.

2. Ballistic tests

Ballistic tests were performed according to GOST R 50744-95 by spherical striker 6.35 mm in diameter (1.05 g) of tempered ball bearing steel. We've used SUSU ballistic test bench, Fig. 3 [24].

Fig. 3. General view of the ballistic test bench

Fig. 4 demonstrates photos of composite panels after ballistic tests. Panels deflection and delaminating area increase as ball speed decreases. Left part of Figure 4 shows panel deflection in the impact spot (1.85 mm). Right part of the Figure shows deflection of 6.44 mm. Initial speeds and ball speed after penetration are presented in Table 4.

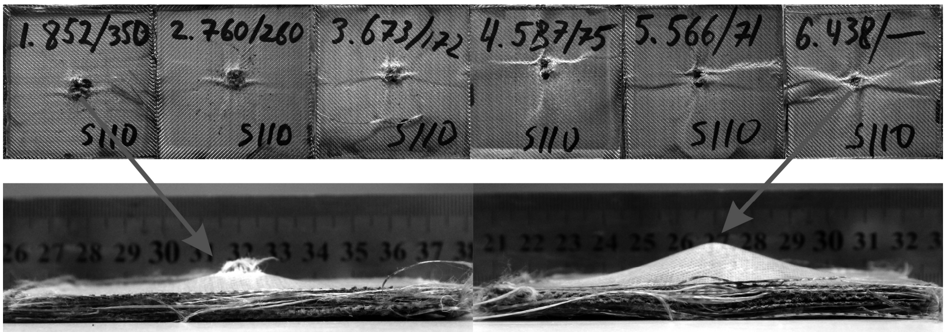

Fig. 4. Photos of samples from CBM S110 material after penetration

Table 4

Initial/final striker speeds

Specimens numbers	1	2	3	4	5	6
Twaron® 613	444/0	490/206	589/446	636/504	725/602	785/702
Twaron® Microflex	455/0	489/223	591/456	700/632	725/645	865/806
Twaron® 709	401/0	497/265	578/396	713/522	768/694	776/698
CBM 56334	442/0	498/113	559/321	600/376	770/660	865/756
CBM A145	525/0	603/338	671/462	785/670	850/763	855/773
CBM S110	430/0	566/362	587/372	673/563	760/692	852/803
CBM S125	508/0	570/309	608/438	649/500	758/655	837/746
CBM P110	503/0	543/306	648/524	720/639	774/688	874/822
Dyneema® HB2	457/0	526/0	571/0	619/391	811/680	865/732
Dyneema® HB80	595/0	608/0	690/418	771/558	800/639	888/715

3. Ballistic tests results

During damage of composite panels we've noticed fibers rupture, filaments major separation and pulling out. Separation was observed in all panels without exclusions (on the basis of aramid filaments and UHMPE). Low binding between matrix and fibers allowed pulling out filaments, directly contacting the striker (Fig. 5).

Fig. 5. Fibers pulling out of the composite panel on the basis of CBM 56334

Experiment data on impact with a fragmentation simulating device were processed using classical Lambert-Jonas dependence [25]

$$V_r = \begin{cases} 0 \; if \; V_i < V_{50} \\ A \cdot (V_i^m - V_{50}^m)^{1/m} \; if \; V_i \geq V_{50} \end{cases},$$

where A, V_{50}, and m – are parameters, determined from condition of calculated residual penetration speeds best corresponding with experimental data (least squares technique). V_{50} – speed, at each 50 % of strikers penetrate through the material. This parameter, as well, as surface density, is used when designing protection system, as well, as when comparing different armor structures. V_r and V_i – residual and initial striker speeds accordingly. This dependence should be used with care, as parameters, determined from it, will depend from material and geometry. Nevertheless, it helps analyzing behavior of different materials under ballistic load from the energy balance point of view. Lambert dependency parameters values and composite panels surface density are presented in Table 5.

Table 5

Lambert dependency parameters values and composite panels surface density

Fabric type	V_{50}, m/s	A	m	Surface density, kg/cm^2
Dyneema® HB80	656	0.87	4.401	4.35
Dyneema® HB2	604	0.861	6.322	4.11
CBM S125	555	0.933	4.168	4.09
CBM A145	525	1.162	1.941	4.04
CBM P110	511	1.003	3.089	4.01
CBM S110	505	1.082	2.471	4.01
Twaron® 613	476	0.954	3.004	4.04
CBM 56334	490	1.023	2.25	4.23
Twaron® 709	450	1.066	2.185	3.98
Twaron® Microflex	473	0.994	3.027	4.37

3.1. Ballistic effectiveness

Table 6 includes summary on ballistic properties of homogeneous and hybrid composite panels, faced high speed impact load. Two values: $\Delta = V_{50}/\rho$ and $\Psi = (m_p \cdot (V_{50})^2) / 2\rho$ (where m_p = 1.05 g – weight of the striker, ρ – panel surface density) were used for comparing ballistic effectiveness of different composites.

Value Ψ indicates maximum panel absorbed energy.

Table 6

Composite panels ballistic parameters comparison

Fabric type	Average σ_v, MPa	F, H	Construction type	Δ	$(\Delta/\Delta_{max})\times$ ×100 %	Ψ	$(\Psi/\Psi_{max})\times$ ×100 %	Rating
Dyneema® HB80	–	–	Unidirectionally oriented fibers	151	100	51.9	100	1
Dyneema® HB2	–	–	Unidirectionally oriented fibers	147	97	46.6	90	2
CBM S125	3270	1.2	Twill	137	91	39.5	76	3
CBM A145	3160	0.35	Satin	130	86	35.8	69	4
CBM P110	3100	3.1	Linen	128	85	34.2	66	4
CBM S110	3040	0.75	Twill	126	83	33.4	64	5
Twaron® 613	2700	1.7	Linen	118	78	29.4	57	6
CBM 56334	3510	0.37	Satin	116	77	29.8	57	7
Twaron® 709	2600	1.7	Linen	113	75	26.7	51	8
Twaron® Microflex	1570	9.25	Linen	108	72	26.9	52	9

3.2. Mechanisms, effecting the ballistic effectiveness

3.2.1. Materials

Above indicated results demonstrate that Dyneema® HB80 has the highest ballistic parameters among all tested composites. This is because this material has high quantity of unidirectionally oriented layers (120 in our case) of high strength UHMPE fibers. Fibers strength and elastic modulus can reach 2.8 GPa and 200 GPa accordingly [21]. This composite material absorbs 10 % more energy than Dyneema® HB2 and 50 % more energy than Twaron® 709 based composite. Best aramid fabric CBM S125 based composite absorbs approximately 25 % less energy than Dyneema® HB80. It should be noted that energy absorbing by UHMPE dramatically decreases when projectile speed exceeds the ballistic limit, see Fig. 6.

This can also be seen for composites on the aramid fabrics basis with linen and twill construction, see Fig. 7.

Dyneema® composite is twice more expensive than aramid fabrics based composites, therefore using aramid fabrics is more effective when there are no raised demands on protective structures weight.

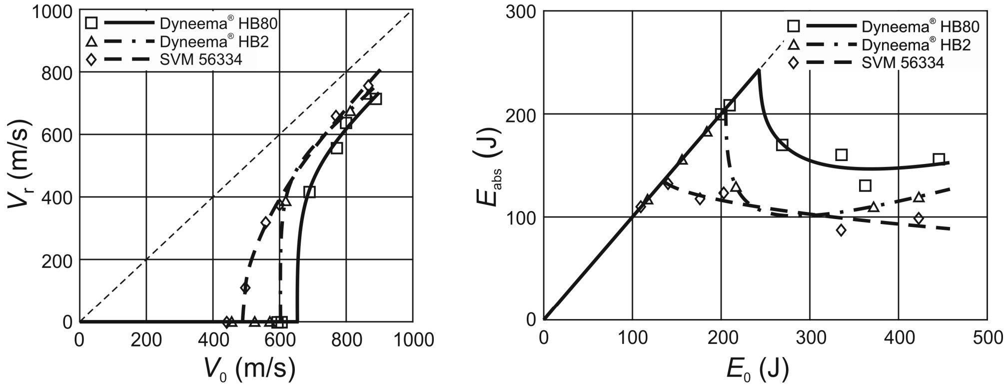

Fig. 6. Ballistic curve and absorbed energy – impact energy for composite sets Dyneema® and CBM 56334

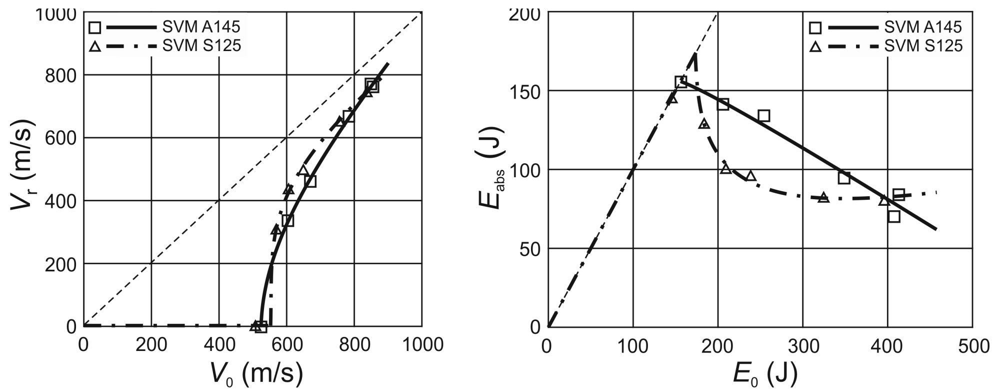

Fig. 7. Ballistic curve and absorbed energy – impact energy for composite sets CBM A145 and CBM S125

3.2.2. Fibers parameters and fabric construction

Aramid fabrics based composites ballistic parameters depend on several factors, related to material features, on fabric construction, fiber thickness, interfibers friction force, etc. It is not possible to choose one main factor. It can be clearly seen when analyzing penetration results for aramid fabrics bases composite panels.

As we've indicated above, aramid fabric CBM S125 based multilayer material has the best ballistic parameters among all tested aramid composites. This fabric is characterized with not the best fibers strength, not the highest friction force in fibers pulling out tests, has middle fibers crimping structure (twill construction). But this material is one of the best per each of these parameters, which determines its ballistic effectiveness. Other fabrics have low values of one or several criteria.

For example, CBM A145 has high fibers strength and minimal fiber bending (satin construction), but has “loose” structure. If the projectile is relatively small, than it breaks only a few central fibers, moving the rest apart not breaking them. Loose fibers construction also leads to low fibers pulling out resistance, so, energy, absorbed by interfiber friction, is lower if to compare with twill or linen construction.

Aramid fabrics P110 and S110 based composites ballistic effectiveness is approximately the same. First material has construction with high crimping degree (linen construction), increasing stress from filaments bending. Second aramid fabric S110 resistance to fibers pulling out is lower if to compare with S125. Beside this, these fabrics have lower fibers strength than CBM S125 and A145.

CBM 56336 fabric filaments have maximum strength and elastic modulus among all. It should be noted, that CBM 56334 and CBM A145 constructions are the same (eight-harness satin), so it was expected, that ballistic limit for panels from CBM 56334 would be higher than for A145. But tests have demonstrated that it is not the case. We have interpreted these results as due to loose construction – CBM 56334 filaments are located approximately 25 % wider than filaments of A145. As the result, lower fibers quantity directly contacted with the striker.

All Twaron® fabrics have linen construction. Due to high filaments strength and their small diameter Twaron® 613 based composites have higher ballistic effectiveness than other Twaron® based panels. It should be noted that not depending from low fibers strength (1.5 times lower than for Twaron® 709 filaments), due to extremely dense fabric structure and due to maximum fibers pulling out resistance, Twaron® Microflex has ballistic effectiveness nearly equal to Twaron® 709 and only 10 % lower than Twaron® 613 has. Nevertheless, in case of panel penetration and fibers destruction, panel absorbed energy dramatically decreases for Twaron® Microflex, see Fig. 8.

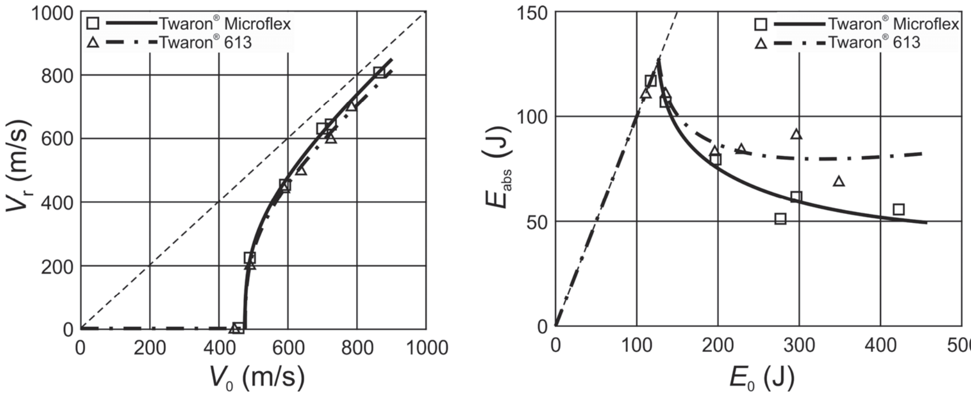

Fig. 8. Ballistic curve and absorbed energy — impact energy for composite sets from Twaron® 613 and Twaron® Microflex

Conclusion

This work deals with researching of ballistic effectiveness of thermoplastics on the basis of aramid fabrics (CBM and Twaron®) and ultra-high molecular polyethylene (UHMPE).

UHMPE based composites have demonstrated best values of ballistics limit and absorbed energy if to compare with other materials. But their energy absorption capability dramatically drops down when projectile's velocity exceeds the ballistic limit. When selecting reinforcing aramid fabric for ballistic application, it is important to consider not only the mechanical properties of the fibers and the type of fabric construction, but also all parameters of ballistic efficiency such as filaments width, etc.

This article can form good basis for working out detail optimal model of protective structure (indicated in this work), taking into account all ballistic parameters.

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References

1. Wagner L. Introduction. In: Bhatnagar A, editor. Lightweight ballistic Composites Military and Law-Enforcement Applications. Abington Hall, Abington, Cambridge CB1 6AH, England, Woodhead Publishing Limited, 2006. p. 1–28.

2. Leszek A. Utracki. *Rigid Ballistic Composites* (Review of Literature). Available at: http://nparc.cisti-icist.nrc-cnrc.gc.ca/npsi/ctrl?action=rtdoc&an=16885314&lang=en(accessed 13.08.14).

3. *Hexcel, Technical Fabrics Handbook*. Available at: http://www.hexcel.com/Resources/DataSheets/Brochure-DataSheets/HexForce_Technical_Fabrics_Handbook.pdf (accessed 15.08.14).

4. *JSC "Kamenskvolokno"*. Available at: http://www.aramid.ru (accessed 15.09.14).

5. David N.V., Gao X-L., Zheng J.Q. Ballistic Resistant Body Armor: Contemporary and Prospective Materials and Related Protection Mechanisms. *Appl. Mech. Rev.*, 2009, vol. 62, no. 5, pp. 1–20. DOI: 10.1115/1.3124644

6. Kulkarni S.G., Gao X-L., Horner S.E., Zheng J.Q., David N.V. Ballistic Helmets – Their Design, Materials, and Performance Against Traumatic Brain Injury. *Compos. Struct.*, 2013, vol. 101, pp. 313–331. DOI: 10.1016/j.compstruct.2013.02.014

7. Wambua P., Vangrimde B., Lomov S., Verpoest I. The Response of Natural Fiber Composites

to Ballistic Impact by Fragment Simulating Projectiles. *Compos. Struct.*, 2007, vol. 77, pp. 232–240. DOI: 10.1016/j.compstruct.2005.07.006

8. Cheeseman B.A., Bogetti T.A. Ballistic Impact into Fabric and Compliant Composite Laminates. *Compos. Struct.*, 2003, vol. 61, pp. 161–173. DOI: 10.1016/S0263-8223(03)00029-1

9. Carrillo J.G., Gamboa R.A., Flores-Johnson E.A., Gonzalez-Chi P.I. Ballistic Performance of Thermoplastic composite Laminates Made from Aramid Woven Fabric and Polypropylene Matrix. *Polymer Testing*, 2012, vol. 31, pp. 512–519. DOI: 10.1016/j.polymertesting.2012.02.010

10. Iremonger M.J., Went A.C. Ballistic Impact of Fiber Composite Armors by Fragment-Simulating Projectiles. *Compos. Part A*, 1996, vol. 27A, pp. 575–581. DOI: 10.1016/1359-835X(96)00029-2

11. Lee B.L., Walsh T.F., Won S.T., Patts H.M., Song J.W., Mayer A.H. Penetration Failure Mechanisms of Armor-Grade Fiber Composites under Impact. *J. Compos. Mater.*, 2001, vol. 35(18), pp. 1605–1633. DOI: 10.1106/YRBH-JGT9-U6PT-L555

12. Gopinath G., Zheng J.Q., Batra R.C. Effect of Matrix on Ballistic Performance of Soft Body Armor. *Compos. Struct.*, 2012, vol. 94, pp. 2690–2696. DOI: 10.1016/j.compstruct.2012.03.038

13. NATO. Ballistic Test Method for Personal Armor Materials and Combat Clothing, STANAG 2920, 2st ed., July 2003.

14. Detail Specification. Projectile, Calibers .22, .30, .50, and 20 mm Fragment-Simulating, MIL-DTL-46593B (MR), July 2006.

15. Armor Clothes, Classification and General Technical Requirements, GOST R 50744-95, September 2013.

16. Iannucci L., Pope D. High Velocity Impact and Armor Design. *eXPRESS. Polymer Letters*, 2011, vol. 5(3), pp. 262–272. DOI: 10.3144/expresspolymlett.2011.26

17. Nguyen L.H., Ryan S., Cimpoeru S.J., Mouritz A.P., Orifici A.C. The Effect of Target Thickness on the Ballistic Performance of Ultra High Molecular Weight Polyethylene Composite. *International Journal of Impact Engineering*, 2015, vol. 75, pp. 174–183. DOI: 10.1016/j.ijimpeng.2014.07.008

18. Karthikeyan K., Russell B.P. Polyethylene Ballistic Laminates: Failure Mechanics and Interface Effect. *Materials and Design*, 2014, vol. 63, pp. 115–125. DOI: 10.1016/j.matdes.2014.05.069

19. Greenhalgh E.S., Bloodworth V.M., Iannucci L., Pope D. Fractographic Observations on Dyneema® Composites under Ballistic Impact. *Compos. Part A*, 2013, vol. 44, pp. 51–62. DOI: 10.1016/j.compositesa.2012.08.012

20. Grujicic M., Arakere G., He T., Bell W.C., Cheeseman B.A., Yen C.F. et al. A Ballistic Material Model for Cross-Plied Unidirectional Ultra-High Molecular-Weight Polyethylene Fiber-Reinforced Armor-Grade. *Compos. Mater. Sci. J.*, 2008, vol. 498, pp. 231–241. DOI: 10.1016/j.msea.2008.07.056

21. Utomo B.D. *High-Speed Impact Modeling and Testing of Dyneema Composite*. PhD thesis. Delft, 2011.

22. Soykasap O., Colakoglu M. Ballistic Performance of a Kevlar-29 Woven Fiber Composite under Varied Temperatures. *Mechanics of Composite Materials*, 2010, vol. 46 (1), pp. 35–42. DOI: 10.1007/s11029-010-9124-3

23. Park R., Jang J. Effect of Laminate Thickness on Impact Behavior of Aramid Fiber/Vinylester Composites. *Polymer Testing*, 2003, vol. 22, pp. 939–946. DOI: 10.1016/S0142-9418(03)00044-8

24. Sapozhnikov S.B., Kudriavtsev O.A. *Kompaktnyi razgonnyi stend dlia ballisticheskikh ispytanii* [Compact Accelerator for Ballistic Testing]. *Bulletin of the South Ural State University, Series Mechanical Engineering Industry*, 2012, vol. 20, no. 33 (292), pp. 139–143. (in Russ.)

25. Lambert J.P., Jonas G.H. Towards Standardization in Terminal Ballistics Testing: Velocity Representation, BRL Report No. 1852, U.S. Army Ballistic Research Laboratories, Aberdeen Proving Ground, MD. (1976).

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ЭКСПЕРИМЕНТАЛЬНАЯ ОЦЕНКА УДАРНОЙ ПРОЧНОСТИ СЛОИСТЫХ КОМПОЗИТОВ С ТЕРМОПЛАСТИЧНОЙ МАТРИЦЕЙ

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Проведены статические испытания нитей арамидных тканей (Twaron®, РУСЛАН®-СВМ) на растяжение для определения их упругих и прочностных характеристик на малогабаритной испытательной машине INSTRON 5942. Эксперименты по вытягиванию нитей были проведены для сравнения сил трения между нитями в различных арамидных тканях. Были изготовлены восемь различных вариантов баллистических панелей с термопластичной матрицей на основе полиэтилена и два вида баллистических панелей на основе сверхвысокомолекулярного полиэтилена (СВМПЭ марки Dyneema®).

Обширные баллистические испытания были проведены на изготовленных баллистических панелях, использовался стальной шарик диаметром 6,35 мм. Для разгона шарика до скоростей 900 м/с был использован баллистический стенд ЮУрГУ. Баллистические характеристики были оценены с точки зрения предельной характеристики материала – баллистического предела V_{50}.

После испытаний было произведено сравнение эффективности всех материалов, исследованных в данной работе. Композиты, основанные на СВМПЭ волокнах, оказались лучшими из всех рассмотренных материалов по значению баллистического предела (превышение на 10 % по сравнению с ближайшим конкурентом) и по значению поглощенной энергии (около 25 %). Но при превышении баллистического предела способность к поглощению энергии у СВМПЭ резко снижается. При выборе арамидной ткани для баллистических приложений важно учитывать не только механические свойства волокон и тип переплетения, но и все параметры баллистической эффективности такие, как ширина нитей и др. Лучшим баллистическим материалом на основе арамидных тканей стал СВМ S125 с саржевым переплетением и пленками из полиэтилена низкого давления.

Ключевые слова: высокоскоростной удар, защитная структура, СВМПЭ, арамидная ткань, термопластичная матрица.

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