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Influence of Chemical Surface Modification of Woven Fabrics on Ballistic and Stab Protection of Multilayer Packets

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In order to achieve enhanced protective and wear (flexibility, less bulkiness) properties of ballistic and stab protecting panels the investigation of chemical surface modification of woven p-aramid fabrics was performed applying different chemical composition shear thickening fluid (*STF*) which improves friction inside fabric structure. For the chemical treatment silicic acid and acrylic dispersion water solutions were used and influence of their different concentrations on panels' protective properties were investigated. Results of ballistic tests of multilayer protective panel have revealed that shear thickening effect was negligible when shooting at high energy range (E > 440 J). Determination of stab resistance of p-aramid panels has shown that different chemical composition of *STF*s had different influence on protective properties of the panels. Application of low concentrations of silicic acid determined higher stab resistance values comparing to higher concentrations of acrylic dispersion water solutions. At this stage of research stab tests results as ballistic ones determined that *STF* application for multilayer p-aramid fabrics protective panels is more efficient at low strike energy levels.

Keywords: bullet proof vest, shear thickening fluid, aramid fiber, ballistic resistance, stab resistance.

1. INTRODUCTION

Soft body armour, which protects from ballistic and stab threats, is usually bulky, stiff and heavy, thus limiting the mobility and strength of the wearer. In order to produce lightweight, comfortable, low cost and with advanced protective performance body armour a lot of research is needed. Contemporary body armour is made of a number of plies of fabrics having different structure and composition (woven, unidirectional, nonwoven, knitted, etc.). Such fabrics can be processed with different surface treatment or finishing technologies and have very different characteristics of wearing comfort.

Analysing protective mechanism of body armour Cunniff [1] stated that the energy absorption characteristics of ballistic panels under impact depend on material parameters such as material failure criteria and constitutive properties; construction parameters such as fabric type, number of fabric plies, and system areal density; and impact conditions such as projectile mass, striking velocity, striking obliquity, and geometry.

When a projectile impacts a fabric target, momentum and energy are transferred from a projectile to a fabric. The energy of the projectile goes, mainly, into kinetic and strain energy of the fabric, although other possible "sinks" of energy could be friction (layer/layer, yarn/yarn, projectile / yarn), generation of free surfaces (failure of yarns), plastic deformation of the projectile (heat), etc. [2, 3].

In order to increase friction between yarns though limiting yarns displacement in the system during impact, investigations of different chemical fabric surface treatment methods are performed. One of such methods is based on a shear thickening phenomenon. Shear thickening is a non-Newtonian flow behaviour often observed in concentrated colloidal dispersions characterized by significant, sometimes discontinuous increase in viscosity with increasing shear stress [4, 5]. Treatment of textiles with shear thickening fluid (*STF*) reduces yarn mobility due to increase of resistance to yarn displacement. Thus the energy portion (during impact) absorbed in the process related to yarn displacement inside the textile increases [6]. This reduces the rate of longitudinal waves' propagation in yarn system and consequently the ultimate perforation velocity. The advantage of *STF* treatment of ballistic panel is that at low strain rates, when a wearer makes natural movements, the fluid will make no significant influence on flexure of the panel, and agility of the wearer. At the moment of ballistic (or stab) attack when energy level crucially increases *STF* will thicken, hereby improving protective properties of the armour [5, 7].

Research results of other investigators showed that woven fabrics impregnation with *STF* determines improved ballistic protection under certain conditions [4, 6, 7]. The tests of ballistic resistance are performed using lower energy projectiles: fragment simulation projectiles, small calibre bullets. These tests are performed in order to evaluate protective properties of light body armour systems (small number of layers) which are basically used for protection of separate body parts (arms, legs, throat) from injuries caused by fragments and other objects with lower energy [4, 6].

It is lack of information and publications in an open literature aiming to evaluate ballistic response of high kinetic energy bullets to the protective mechanism of multilayer ballistic panels treated with *STF*. Results of Park *et al.* [3, 8, 9] of real ballistic experiment of body armour revealed that protective performance of *STF* treated

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p-aramid fabrics enhanced, still in combination with untreated fabric layers.

In parallel with ballistic tests investigations of stab resistance to *STF* treated body armour panels are carried out. In their research Rao *et al.* [10] and Park *et al.* [11] determined a significant influence of *STF* impregnation on p-aramid fabrics' protective properties. The treatment was especially efficient for spike protection panels.

In present research the object of investigation is the protective system of multifunctional soft body armour which defends from ballistic and stab threats. Such security remedies are efficient for street police officers, riot, and prison gear. *STF* application to multifunctional p-aramid panel should gain in decreasing the total bulkiness of the body armour.

The objective of this work was to investigate the influence of shear thickening fluid on protective properties of multilayer panels for soft body armour and to determine the efficiency of fabrics chemical modification applying different strike energies.

2. MATERIALS AND METHODS

For this work two types of ballistic and stab resistant *Twaron* p-aramid plain woven fabrics made of high tenacity microfilament yarn were selected. Ballistic tests were performed with 200 g/m^2 fabric (930/1000 dtex), fiber density 105/105 dm^{-1} (warp and weft) directions. Stab resistance was investigated of fabric 220 g/m^2 (550/500 dtex) with special densification treatment, fiber density 185/185 dm^{-1} (warp and weft) directions.

Also two types of commercially available different chemical composition (silicic acid and acrylic dispersion water solutions) *STF* for fabric impregnation were investigated.

Chemical treatment for ballistic resistance. Specimens for ballistic protection of p-aramid fabric were treated with silicic acid (*F*) and water based acrylic (*A*) dispersions which concentrations were 50 g/l.

For ballistic p-aramid fabric surface treatment a low-pressure "Junior Plasma System SN 004/123" (Europlasma) was applied. Plasma treatment was conducted using a RF-Generator (600 W; 2.45 GHz). One side of fabric samples was treated with the use of nitrogen as the plasma gas under conditions of output power 100 W, flux of nitrogen gas 0.06 standard litre per minute (Slm) and system pressure 40 Pa for 120 s. After this treatment all samples were placed in a standard atmosphere conditions (temperature 20 °C ±2 °C and relative humidity 65 % ±5 %) for 24 h to enable both plasma and post-plasma reactions.

Plasma pre-treated and non-treated p-aramid fabric samples were immersed into 50 g/l *F* and 50 g/l *A* solutions, respectively using Laboratory Padder EVP-350 (Roaches International). Chemical treatment was performed in laboratory padder which parameters: fabric moving speed 2 m/min, padding rolls pressure – 81 Pa. After this all samples were dried and curried in Laboratory oven and steamer TFOS IM 350 (Roaches International) machine at 150 °C for 4 min.

Chemical treatment for stab resistance. In order to improve stab resistance of p-aramid fabrics, the samples were treated with low (50 g/l) and higher concentrations (150 g/l) of *F* and *A* agents applying the same technology as described above. In order to achieve a hard film after thermal treatment on the surface of p-aramid fabric acrylic dispersion *A* was applied using an oxalic acid (10 g/l) as a catalyst.

Ballistic tests. For ballistic tests samples of multilayer p-aramid panels which protect from 9 mm FMJ RN bullets with nominal masses of 8.0 g impacting at a velocity of (436 ±9) m/s and (341 ±9) m/s were selected. The tests were performed using the ballistic range, presented in Fig. 1.

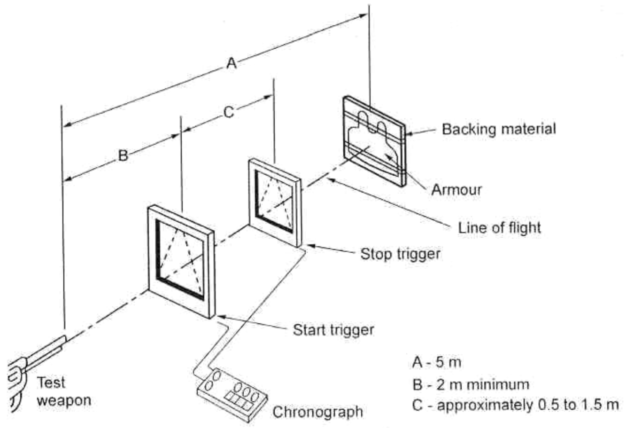


Fig. 1. Scheme of ballistic test range [12]

10 types of specimens of ballistic protection panels were prepared. Structural and technical parameters of test objects are presented in Table 1.

Table 1. Structural and technical parameters of ballistic panels' test objects

Fabric code	Structure	Area density, g/m^2
1C	Reference p-aramid fabric	6210
1A	p-aramid fabric treated with *A*	
1F	p-aramid fabric treated with *F*	
1P-A	p-aramid fabric treated with plasma and *A*	
1P-F	p-aramid fabric treated with plasma and *F*	
2C	Reference p-aramid fabric	4660
2A	p-aramid fabric treated with *A*	
2F	p-aramid fabric treated with *F*	
2C-2F	Reference p-aramid fabric (1/2 of panel) p-aramid fabric treated with *F* (1/2 of panel)	
2C-2A	Reference p-aramid fabric (1/2 of panel) p-aramid fabric treated with *A* (1/2 of panel)	

Each specimen was arranged of multilayer p-aramid fabric panel; measurements of specimens were 15 cm×22 cm; all specimens were stitched at their edges.

2 gunshots were performed per one specimen, indicating Backface Signature (*BFS*) – the depth of the depression made in the backing material, created by a non-penetrating projectile impact, measured from the plain defined by the front edge of the backing material fixture [12]. Each object was tested for 6 gunshots.

Stab tests. For stab tests samples of multilayer p-aramid panels which protect from NIJ spike [13] at energy levels "$E1$" = 24 J ±0.50 J and "$E2$" = 36 J ±0.60 J were selected.

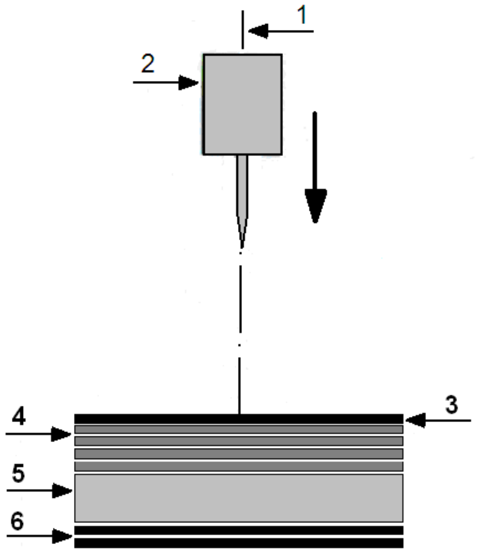


Fig. 2. Schematic of armour and spike arrangement: 1 – line of flight of drop mass; 2 – drop mass with spike; 3 – armour (specimen); 4 – neoprene sponge; 5 – polyethylene foam; 6 – rubber

Table 2. Structural and technical parameters of stab resistant panels' test objects

Fabric code	Structure	Area density, g/m^2
1S	Reference p-aramid fabric	1448
SA	p-aramid fabric treated with *A* (50 g/l)	
SF	p-aramid fabric treated with *F* (50 g/l)	
2S	Reference p-aramid fabric	413
2A_50	p-aramid fabric treated with *A* (50 g/l)	
2F_50	p-aramid fabric treated with *F* (50 g/l)	
2A_150	p-aramid fabric treated with *A* (150 g/l)	
2F_150	p-aramid fabric treated with *F* (150 g/l)	
2AO	p-aramid fabric treated with *A* (150 g/l) and oxalic acid	

The tests were performed when 1960 g drop mass (Fig. 2) moving in a vertical plastic tube drops freely under its own weight to strike the armour panel at a specified energy. The energy is determined according to the position (height) of drop mass in the tube.

For the initial investigation of stab resistance 3 types of test objects were prepared (1S, SA, SF), and their structural and technical parameters are presented in Table 2.

In order to investigate limiting conditions of the influence of *STF* on stab resistance of p-aramid fabric, additional tests were performed on the range of low strike energies (not exceeding 2 J) and testing samples of 2 fabric layers (6 test objects) (Table 2).

3. RESULTS AND DISCUSSION

Ballistic tests results. Results of ballistic tests performed with higher protective level samples (6210 g/m^2) at bullet velocity 436 m/s ±9 m/s (Table 3) showed that chemical treatment had no significant influence on protective properties of p-aramid panels.

Table 3. Results of ballistic tests

Fabric code	Energy, J	*BFS*, mm	No. of layers penetrated
1C	777	37.0	8
1A	732	36.2	5
1F	782	39.2	9
1P-A	739	35.6	7
1P-F	764	38.6	9
2C	472	25.9	1
2A	460	30.4	2
2F	441	27.0	2
2C-2F	442	27.1	2
2C-2A	451	27.9	2

Application of low temperature plasma was an option to achieve more efficient fabric surface modification. Notwithstanding the tests results of samples 1P-A and 1P-F showed no significant difference of panels' ballistic resistance (Table 3). In all cases performing shots at 436 m/s ±9 m/s velocity number of perforated layers didn't decrease comparing to reference sample 1C.

Further research was performed with lower area density protective panels (4660 g/m^2) at bullet velocity 341 m/s ±9 m/s. Such tests were based on analysis of other researchers works [4, 6, 7] where ballistic protection of *STF* treated fabrics has been investigated in a lower energy range. Nevertheless strike velocity has been declined, no significant influence of chemical treatment on ballistic results was determined comparing to reference sample 2C (Table 3).

Following investigations of ballistic panels' layering [3, 6, 9], further tests were performed arranging panels of different fabric layers (2C-2F and 2C-2A). The idea of such layering system is based on formation of a hybrid panel, where different fabric layers with different properties (modulus, mass density, etc.) are composed. According to results obtained by other researchers [3] the strike face of the panel was composed of layers of untreated p-aramid fabric, and the back face of layers of *STF* treated ones. Using such a system constrain of bullet penetration in transverse deflection had to be achieved, conditioning a superior overall ballistic performance. However in our tests such systems provided no significant results.

Following results of ballistic investigation it comes to the conclusion that *STF* treatment of p-aramides is not efficient enough at high strike energies ($E > 440$ J). This can be explained by damage mechanism of the fabric. At the initial contact moment the bullet penetrates the target and breaks fibers. When energy of the bullet decreases (the shape of the bullet changes – it's point flattens) fibers are slipped in the system, and at this stage application of *STF* would be purposeful.

Stab tests results. Initial stab tests were performed on multilayer stab protective panel at energy ranges "$E1$" = 24 J ±0.50 J and "$E2$" = 36 J ±0.60 J. The aim of the experiment was to determine the influence of energy level (strike velocity) on the efficiency of *STF* application on multilayer fabric panel. It was determined that stab penetration values of samples 1S, SA and SF at energy level "*E*2" balanced in between 2 mm limits, i. e. negligible differences were obtained comparing samples with and without *STF* treatment. Additionally, no stab perforation of multilayer panels was obtained at energy level "*E*1".

In accordance to the results presented by other researchers [11], who showed that more precise analysis of protective mechanism could be obtained evaluating the influence of *STF* treatment in a low energy range (<5 J), additional tests of p-aramid layers were performed applying lower strike energy (<2 J). Tests results are presented in Figure 3.

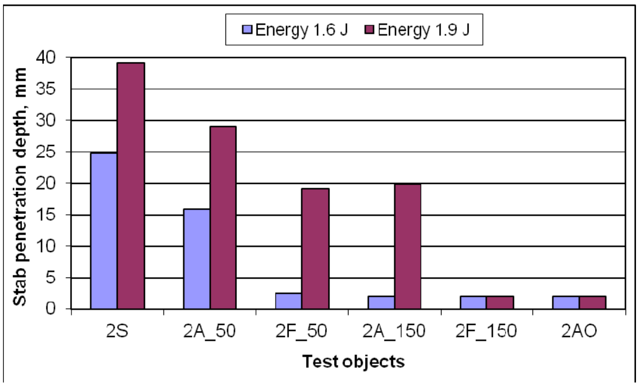


Fig. 3. Influence of chemical composition and different concentrations of *STF*s on stab penetration of p-aramides

Analysing the influence of the same concentration but different chemical composition *STF*s it was determined that fabrics treated with *A* (50 g/l) showed better resistance to puncture comparing to reference and samples treated with *A*. In energy range of 1.6 J the difference between *F* treated fabrics and reference ones reached 9.8 times, and comparing to *A* treated fabrics the difference was 6.4 times. Comparing results it was also obtained that acrylic base agent also had influence on puncture resistance of p-aramid fabrics, still the difference was minor – 1.5 times.

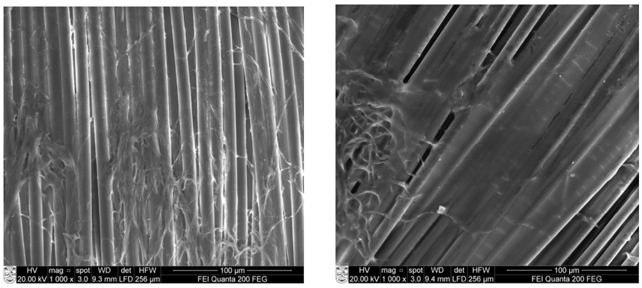
Test results of strike resistance in energy range of 1.9 J revealed less significant values: spike penetration depth was reduced from 1.4 (*A*) to 2.0 (*F*) times comparing to reference sample.

Further experiment was based on analysis how concentration of different chemical agents influenced a puncture resistance (Fig. 3). It was determined that applying higher concentrations of *A* and *F* (150 g/l) puncture resistance of p-aramid fabrics significantly increased, especially with treatment of agent *A*. Increasing concentration of the agent for 3 times led to decreasing of spike penetration to 7.6 times comparing to 50 g/l. Still, no differences were obtained for silicic acid (*F*) treated samples, nevertheless puncture resistance of these samples remained the highest.

Analysis of test results at 1.9 J energy range revealed significant improvement of stab resistance of samples treated with *F* (150 g/l) – penetration depth increased 9.6 times. But results of *A* treated fabrics showed a minor improvement – 1.5 times.

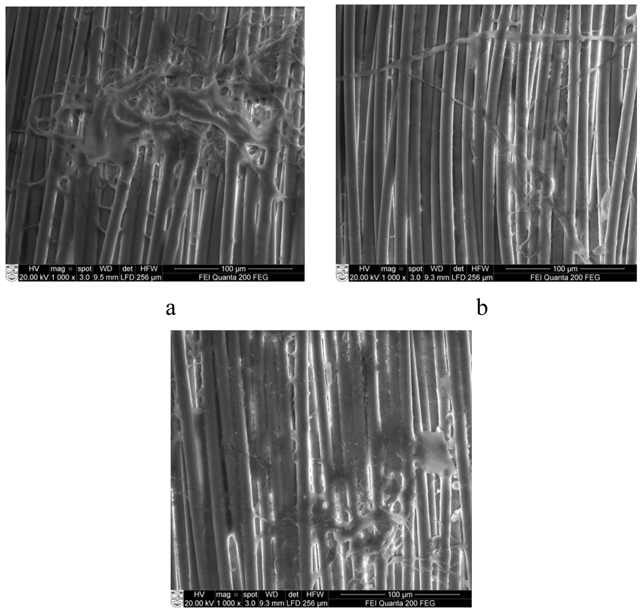
In order to improve protective properties of fabrics treated with acrylic dispersion (*A*), on the surface of p-aramid fabric oxalic acid (10 g/l) as catalyst was used. Hereby a hard film was created on the fabric surface. Test results of 2AO samples showed the improvement of their stab resistance and achievement of the same penetration values as using *F* (150 g/l) treatment, i. e. 2 mm depth (Fig. 3).

Figures 4 and 5 present SEM images of *F* and *A* agents application on the surface of p-aramid fabrics.



a b

Fig. 4. Influence of silicic acid (*F*) concentration on surface modification of the fabric: a – 50 g/l; b – 150 g/l



a b

c

Fig. 5. Influence of water based acrylic dispersion (*A*) concentration on surface modification of the fabric: a – 50 g/l; b – 150 g/l; c – 150 g/l + oxalic acid (10 g/l)

It can be clearly defined that low concentration (50 g/l) of silicic acid (*F*) (Fig. 4, a) modified the surface of the fabric at a similar level as high concentration (150 g/l) of water based acrylic dispersion (*A*) (Fig. 5, b) – the same tendency was determined analysing numeral values of test results of samples 2F_50 and 2A_150 (Fig. 3). Next it was noticed that after treatment with agent *F* (150 g/l) a strong binding film was formed on the fabric surface, and images of fabric surface in Fig. 4, b) can be compared to Fig. 5, c) (acrylic dispersion *A* (150 g/l) + oxalic acid (10 g/l)). Test results in Fig. 3 are coherent to results in Figs. 4 and 5: the binding film observed in SEM images described above led to higher resistance to spike penetration at both energy levels.

Hereby we can state that lower concentrations of silicic acid had significant influence on reducing of spike penetration depth. Comparable results can be obtained applying higher concentrations of water based acrylic dispersion, using oxalic acid as catalyst.

4. CONCLUSIONS

1. Results of ballistic investigation showed that treatment of p-aramid fabric with *STF* is not efficient at high strike energies ($E > 440$ J).
2. Analyzing the influence of different chemical composition of shear thickening fluids on stab resistance of p-aramid fabrics it was determined that silicic acid agent significantly improved friction between fibers (penetration depth was decreased approximately 10 times) in a low strike energy range.
3. It was determined that increase of *STF* concentration showed different results of panels stab resistance. Low concentration (50 g/l) of silicic acid determined the highest stab resistance, and increasing of concentration for 3 times gave no superior performance. Identical increasing of concentration of water based acrylic dispersion showed the improvement of stab penetration depth for 9.5 times.
4. Our research revealed that efficient stab protection in low energy range can be obtained using silicic acid agent (50 g/l). Application of water based acrylic dispersion (150 g/l) gives the same protection performance additionally using oxalic acid (10 g/l) as catalyst.

Acknowledgments

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