Ballistic Performance of Textile Armor Treated with Shear Thickening Fluid

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Laminated textile armor packages made of high-strength ballistic fabrics are widely used as armor panels in body armor to stop bullets of short-barrel small arms and fragments of artillery ammunition and mines [1].

One of recently most-widely discussed ways of increasing the ballistic resistance of textile armor is its impregnation with shear thickening fluid (STF). Newspapermen named the STF-treated textile armor "liquid armor", and the name stuck.

The main idea of upgrading the ballistic performance of the textile armor package by impregnating it with high-dispersive suspension is based on the following: at standard conditions the STF-impregnated textile armor package remains soft and flexible and does not impede movement; but when hit by a bullet or a fragment, the armor STF-content hardens thus improving the protective performance of the textile package.

Most often in ballistic applications such suspensions are used for STF as high-concentrated sub-micron suspension of inexpensive SiO_2 in ethylene glycol or in polyethylene glycol [1–4].

An important special feature of shear flow of the suspension is that the particles which are moving at an average speed of the carrying gradient flow of the dispersion medium rotate, which is caused by the difference of the flow speeds in the direction perpendicular to its direction. The rotating particles entrain the dispersion medium adjoining their surface, thus generating so-called adjoint mass.

As the concentration of the suspension increases, the layers of fluid adjoined to the particles begin to overlap, and their interaction becomes more significant. At some critical shear rate the rotation of individual particles decelerates to such extent that they adhere to each other and form a kind of undeformed clusters confining a portion of dispersion medium, and the rotation of particles is transferred to the clusters.

When the shear strain rate reaches some extremal value, the interaction forces among the clusters lead to their rupture which shows itself as reduction of effective viscosity and shear stress reaching the horizontal asymptote – it does not depend any more on the shear strain rate. On the contrary, reduction of the shear strain rate results in rupture of clusters due to Brownian movement of the dispersed phase particles; the effective viscosity of the mixture decreases, it shifts to the initial state of homogeneous dispersed medium in the form of suspension.

Particular dependences of viscosity factors of sub-micron suspensions of SiO_2 in ethylene glycol on the shear rate are presented in Fig. 1 [11].

For proper understanding of the mechanisms of STF effect on ballistic resistance of textile armor an adequate model of bullet/textile armor interaction is required in the first place. We succeeded in developing such a model which is described in papers [1, 5]. According to this model, at high-velocity impact the ballistic resistance of the textile armor package is determined mainly by its ability to transform the kinetic energy of the bullet into work for yarn stretching without their breaking. The analytical dependence of the ultimate penetration velocity of a laminated textile armor package v_{ult} on its structural characteristics and physical-and-mechanical properties of the textile,

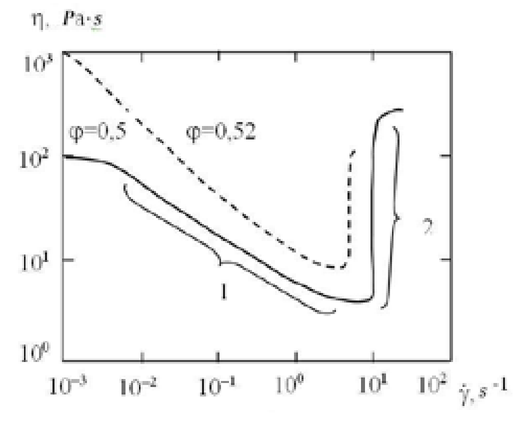


Fig. 1: Viscosity dependence of suspension of SiO_2 – particles with an average diameter of 446nm in ethylene glycol (φ - volume fraction of particles in the suspension, η - viscosity factor, γ - shear rate); 1- viscosity decrease branch; 2 – drastic viscosity increase branch

obtained on the basis of this concept, looks as follows [1, 5]:

$$v_{ult} = K c_y \varepsilon_p \sqrt[3]{\frac{m_{m} d_b^2}{m}} \quad (1)$$

where K is the factor depending on the textile type; c_y is the rate of elastic wave spreading in the textile yarns; ε_p is the ultimate deformation of yarn elongation; d_b and m are bullet diameter and weight.

Dissipating mechanisms of energy absorption (friction work at yarn displacement) belong to "slow" mechanisms of energy absorption which are effective at the final phase of bullet deceleration or at low-velocity impacts of penetrators.

As treatment of textiles with STF reduces yarn mobility due to increase of resistance to yarn displacement, the energy portion absorbed in the processes related to yarn displacement inside the textile, increases. Hence we can expect increase of resistance of textile armor packages to penetrators which usually perforate textile armor due to stretching and separating the yarns in the fabric (like it takes place at puncturing laminated textile armor packages with a needle or an awl).

At the same time the presence of STF in inter-yarn and inter-filament space of the yarns (Fig. 2) increases their linear density ρ_y

$$\rho_y = \rho(1+\xi)$$

where ρ is the density of the dry yarn, ξ is a mass fraction of STF (with respect to the mass of the dry yarn). As the modulus of elasticity of SVM ballistic fabric yarns is much higher than that of STF we can assume that impregnation of the yarn with STF actually doesn't affect its modulus of elasticity. As a result of increase of the yarn inertia, the velocity of elastic wave propagation c_y in STF-impregnated yarn decreases according to relation (2).

$$c_y = \sqrt{\frac{E}{\rho_y}} = \sqrt{\frac{E}{\rho(1+\xi)}} = \frac{c}{\sqrt{1+\xi}} \quad (2)$$

where $c = \sqrt{E/\rho}$ is the velocity of longitudinal elastic wave propagation in a dry yarn.

Decrease of c_y results in reduction of the deformed volume, and consequently, in reduction of the energy

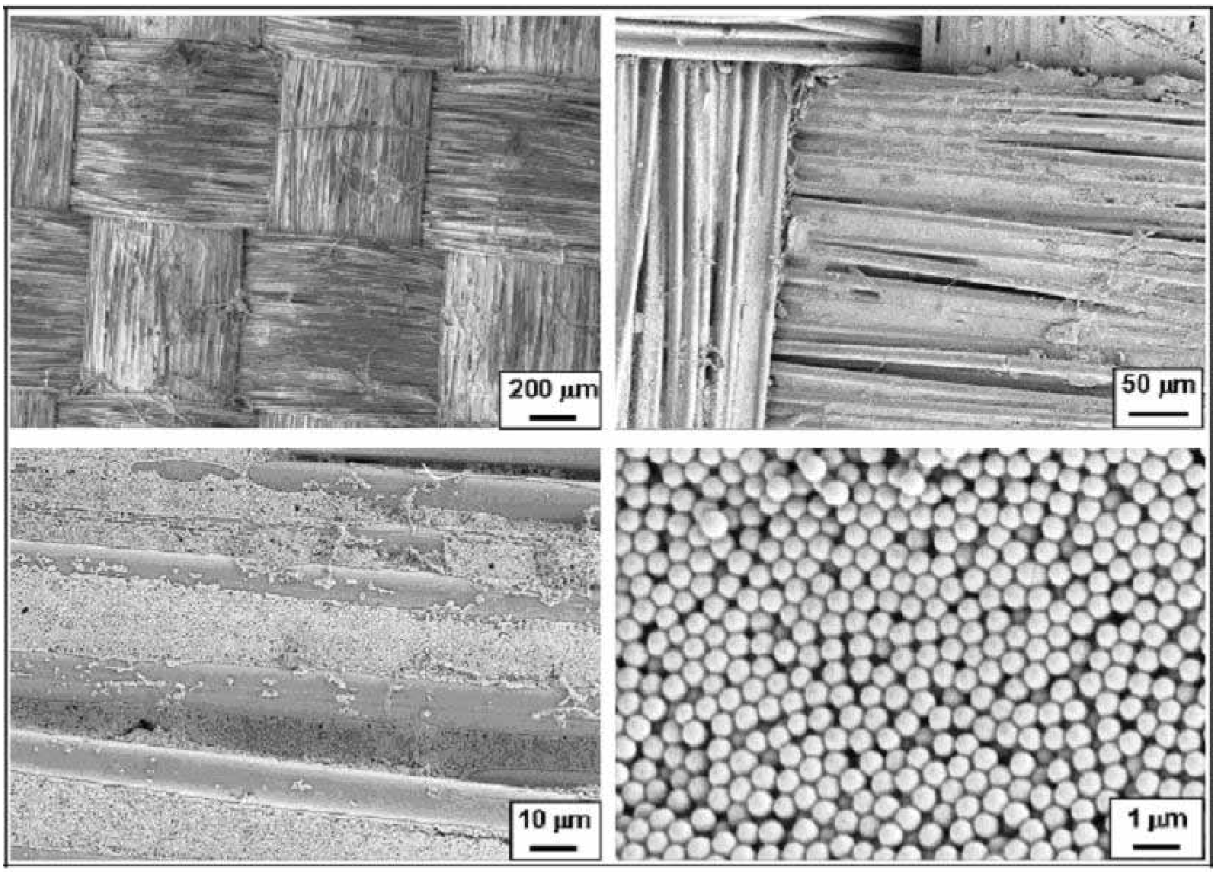


Fig.2 Microphotographs of Kevlar 706 fabric treated with STF based on polyethylene glycol and sub-micron SiO_2 particles. The particles are present both between the yarns and between the filaments [9].

absorbed by the armor package due to elastic stretching at their ultimate elongation. Thus, the ultimate velocity of STF-treated textile armor package perforation is reduced as in (3),

$$v_{\text{perf}}^{\text{STF}} = \frac{v_{\text{perf}}}{\sqrt{1+\xi}} \qquad (3)$$

where $v_{\text{perf}}, v_{\text{perf}}^{\text{STF}}$ are ultimate perforation velocities of the dry and STF-treated textile armor packages accordingly. The resulted formula qualitatively corresponds to the well-known facts: ballistic performance of textile armor decreases with introduction of any fillers, water (when armor packages get wet) or a polymer binder when making organic plastics.

In paper [7] the ballistic limits of perforation of single layers of ballistic fabric made of Kevlar yarns with linear density of 600 den (67 tex) and density of 34x34 yarns per inch were determined. The armor was tested with 5.59mm-diameter steel balls weighing 0.63g. For the dry fabric 50% ballistic limit was 100 m/s, and for the impregnated one it was 240 m/s.

In paper [6] the ballistic performance of Twaron CT615 textile armor packages impregnated with water suspension of SiO_2 particles with different concentrations was investigated. The target consisting of two layers of STF-treated fabric showed almost 100% increase of the specific ballistic energy capacity. However, this index of ballistic efficiency for STF-impregnated textile armor packages consisting of four and six fabric layers turned out to be much lower than for the dry fabric.

We also conducted a number of experiments for evaluation of the ballistic limit of 4-layer armor packages of Russian ballistic fabric Grade 56319A backed with plasticine. In these tests V_{50} of STF-treated armor packages was 20% higher as compared to dry packages.

These facts which look contradictory at first sight, can be explained as follows: it is known from experience that perforation of one- and two-layer textile targets is mainly caused not by yarn breaking in the deformation cupola, but by their separation and stretching. Prevention of yarn separation and stretching thanks to STF impregnation increases the ballistic limit due to changing the penetration mechanism. Such increase is limited by the breaking strength of the yarns correlated with the maximum velocity of the bullet or fragment v_p, which equals to [1]

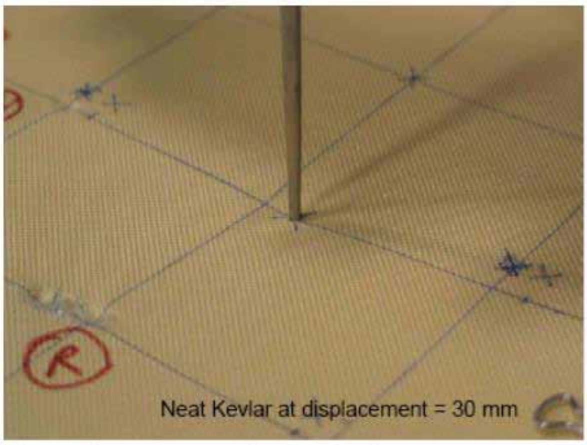
$$v_p \approx 1.41 c_y \varepsilon_p$$

For a wide range of dry para-aramid yarns v_p = 300-380 m/s. Impregnation of the yarns with STF reduces the rate of longitudinal waves propagation c_y (2) in them, and, consequently, according to relation (3), also the ultimate perforation velocity v_p to 250-300 m/s.

Another challenge for body armor designers is providing protection against different kinds of piercing weapons.

The results of an icepick impact on dry and STF-impregnated Kevlar packages with a backing plate of foamed elastomer are presented in Fig. 3 [10]. The dry 15-layer Kevlar package can be easily punctured by the icepick, whereas in the 12-layer STF-impregnated package even the outer layers cannot be pierced.

We also conducted a number of experiments on the effects of cold steel (bayonet and icepick) on dry and SiO_2-based STF-treated packages made of Russian ballistic fabric Article 56319A. The bayonet tests were conducted on a pendulous dynamic stand with the impact energy of 22.3 J. The acceptable outgoing depth of the bayonet behind the rear surface



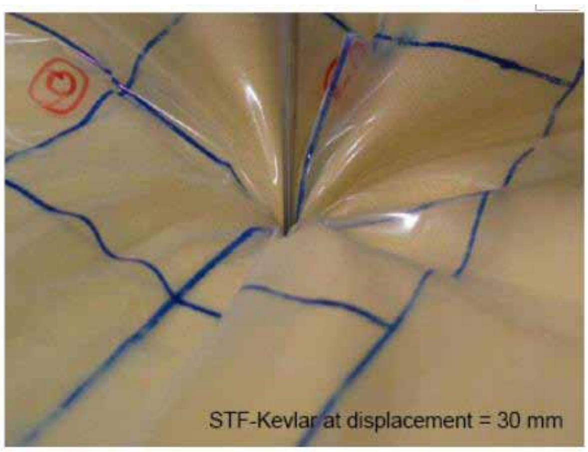


Fig.3 Impact effect of an icepick on 15-layer dry Kevlar package and 12-layer STF-treated Kevlar package [10]

of the target (5mm) was obtained on 16 layers of dry fabric and on 8 layers of fabric impregnated with SiO_2 water suspension. At the same time the weight of the impregnated armor package increased by a factor of 1.5, i.e. total gain by areal density was 25%. Fig. 3shows the photos of rear surfaces of the dry and impregnated 8-layer armor packages impacted by a bayonet.

A similar experiment was conducted with an icepick impacting dry and STF-treated armor packages made of Article 56319A ballistic fabric with the impact energy of 31 J. In this case non-perforation of the dry package was obtained on 32 layers, and of the STF-treated package – on 16 layers. Thus, in this case the gain by the areal density was also 25%. Fig.5 presents the photos of the rear surfaces of the dry and STF-treated 16-layer armor packages impacted by an ice-pick.

Camouflage as the Additional Form of Protection during Special Operations

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INNOVATIVE ECONOMY
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INTRODUCTION

The camouflaging materials used at present warrant a wide range of masking possibilities. They are found in two forms: as masking covers ensuring optical and radiolocation camouflage and anti-thermal sets. These sets are presently used for large objects, such as vessels, vehicles etc. It seems interesting to attempt designing materials that ensure the widest scope of camouflage possible. They should be made of raw materials of the newest generation and they should meet the requirements of the European standards.

A significant issue is introduction of camouflaging material in a wide range of personal protection devices, such as ponchos, tents, etc. and objects, such as curtains, tarpaulins etc. It is particularly significant due to the fact that at present, products of this kind are made of imported and very expensive raw materials.

THE OBJECTIVE OF CAMOUFLAGE

Ensuring of safety of soldiers and officers of services subordinate to the Ministry of Interior and Administration and the Ministry of Defense influences greatly their emotional shape during various operating activities and peacekeeping missions. The priority of the commanding officers must be to ensure protection of their staff throughout all stages of the operations carried out, which should be ensured thanks to the following undertakings: hiding, camouflage, dispersal of the forces, assets and activities and fortification development. Performance of the specific scope of camouflaging activities ensures such benefits as:

- Preventing recognition and identification of objects and people by the opponent;
- Limitation of own loss of life and equipment, and thus strengthening of the „fighting spirit" among the soldiers and officers;
- Ensuring of the proper conditions for effective use of the combat assets.

Camouflage and protection against detection are treated as components of threat prevention, which require substantially less financial expenditures than purchase of expensive equipment in the field of advanced technology.