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NANOTECHNOLOGY FOR INCREASE OF BODY PROTECTION CAPABILITY

Abstract: Below we would like to present the results of applied technological process of obtaining flexible vest proofs which contain SiO_2 nanoparticles. Multi-layered Kevlar impregnated with shear thickening fluid (STF) is presented. The behaviour of vest proof as a flexible during normal motion and as a rigid shield while impact of bullet, spike or knife-edge, is shown. Besides, penetration depth of Kevlar impregnated with STF in function of the type of impregnation of 4-Kevlar layers, is presented. Furthermore, the performance of impregnated Kevlar, like dissipation energy while impact, is determined.

1. Introduction

The threat posed by global terrorism, at home and abroad, often means that police and army personnel, journalists reporting from war zones and civilian rescue workers have to wear body armour capable of stopping high velocity projectiles such as bullets and bomb shrapnel.

Integral body armour has evolved a long way since the 1960s when the ability of alumina ceramics to withstand bullet impacts was discovered. Modern armour is now much more sophisticated, using advanced materials such as Kevlar and glass fibres together with ceramic and carbon epoxy. The current armour can take multiple hits, provides good fire and smoke resistance and has low toxicity characteristics, a vast improvement on that of the 1960s. However, modern armour generally relies on a ceramic layer to take almost all of the ballistic impact. The use of such materials compromises the weight and flexibility of armour in the field.

Research conducted by the CCLRC Daresbury Laboratory, Liverpool University, Tuskegee University (Alabama, USA) and Florida Atlantic University (USA) has validated the possibility of utilising nanotechnology in the design of new materials which will ultimately enable the production of flexible light-weight body armour.

There are several types of body armour:

- conventional - contains 20÷40 layers of neat Kevlar,
- rigid ceramic inserts - for high threat situations protect torso only,
- extremities protection: arms, legs, neck (battlefield statistics from WWII, Korea (Reister, 1973) ~ 16% of deaths due to trauma to extremities and ~ 70% of non-fatal injures to extremities [1]),
- flexible,
- low bulk,
- lightweight,
- protective with minimum level - fragments / shrapnel protection.

Currently there is no armour for extremities because conventional materials (i.e. neat Kevlar) are too bulky and stiff therefore they do not meet material requirements.

2. Shear Thickening Fluid STF

When materials such as Nylon 6, polyethylene, Polypropylene or Epoxy matrices are infused with spherical SiO_2 nanoparticles, or multi-walled carbon nanotubes, the new nano-composite material produced has significantly improved structural strength. For example, the tensile strength of Nylon 6 infused with carbon nanotubes, compared to Nylon 6 alone, was 220% higher 1. Ballistic testing of sandwiched composites, made from polyurethane foam dispersed with TiO_2 nanoparticles, at Tuskegee University [2], has shown that embedded nanoparticles successfully offer resistance to high-speed projectiles.

Although nanocomposites appear to offer improved structural and ballistic characteristics, the bonding involved between the core material molecules and the nanoparticles is unknown. Researchers are currently discovering the complex structure of the new materials through the CCLRC's high resolution X-ray photoelectron spectroscopy facility. Although still in development, these new materials are already catching the attention of security services and promise to have wide-ranging potential for protecting society [2], both at home and abroad (Fig. 1).

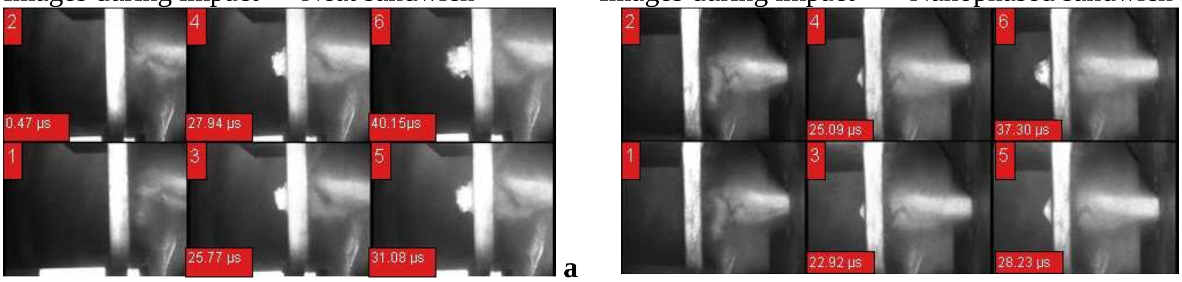


Fig. 1. High speed streak camera images of a bullet impacting on a neat polypropylene sandwich (a) and nanophased polypropylene sandwich layer (b) [2]

Measurement of the bulge height as a function of time shows that the nanocomposite resists the impact better.

One of the newest advantage of the vest proof is possibility to be flexible during normal using and to be stiff while projectile impact or for example stab. It is due to the use of reological fluid called share thickness fluid STF (Fig. 2) which is used with Kevlar fibre. STF, also called "dilatant" fluid, has unusual (that is, non-Newtonian) behaviour in response to a shearing force. Viscosity of this fluid radically increases while impact with the shear thickening transition at shear rate of ~ $10^1 \div 10^3\ s^{-1}$ (projectile velocity / projectile diameter is 244 m/s / 0.56 cm $=10^4 \div 10^5\ s^{-1}$). Shear rate during ballistic impact should transit fluid to rigid state (Fig. 3). Before impact, the particles in shear-thickening fluid are in a state of equilibrium, after impact, they clump together, forming solid structures.

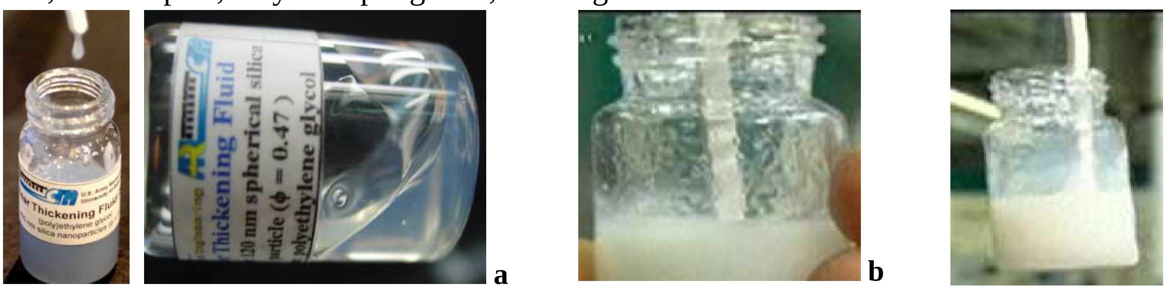


Fig. 2. Shear thickening fluid's behaviour: a - in a jar without motion, b - easily stirred with a plastic stick, - c after rapid forceful motion [3]

Preparation of engineering process of this type protection shield manufacture is the following [2]:

1. Preparation of shear thickening fluid which contains:
   - colloidal silica particles (average particle size: ~450 nm),
   - ethylene glycol (EG) or polyethylene glycol (PEG) carrier fluid. Their advantages over water carrier fluid are:
     – they wet Kevlar moderately,
     – they are environmentally stable,
     – their final particle concentration is: 55÷65 vol%.
2. Using of the Kevlar (Fig. 4) for instance KM-2 Kevlar® fabric or Style 706, 600 denier (180 g/m^2).
3. Preparation of Kevlar+STF composite: the Kevlar should be saturated with the diluted fluid and placed in an oven (80°C for 20 min) to evaporate the ethanol. The STF then permeates the Kevlar, and the Kevlar strands hold the particle-filled fluid in place. When an object strikes or stabs the Kevlar, the fluid immediately hardens, making the Kevlar stronger.

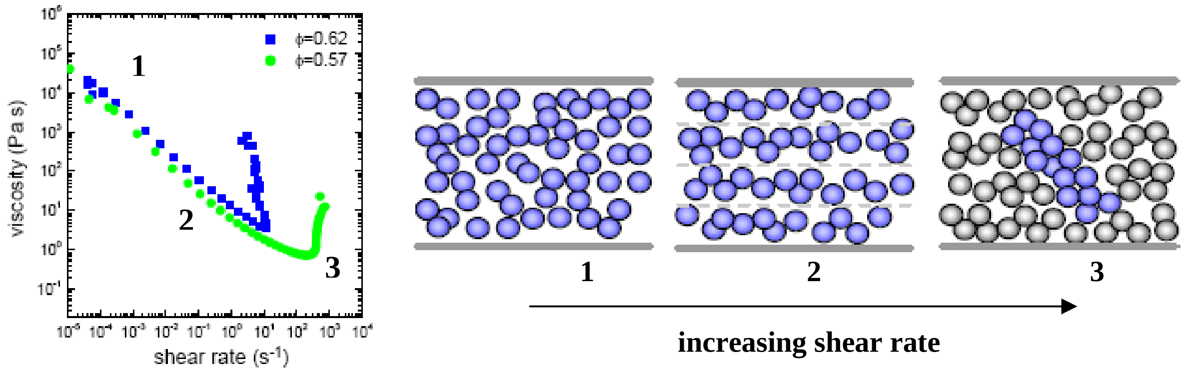


Fig. 3. Behaviour of reological fluid STF depending on shear rate: 1 - equilibrium, 2 - rarefaction by shear, 3 - shear thickening fluid [1]

Fig. 4. Interceptor Vest Kevlar® KM2 (a) and PASGT Vest Kevlar® 29 (b) [1]

Silica particles are suspended in polyethylene glycol or ethylene glycol. Silica is a component of sand and quartz, and polyethylene glycol is a polymer commonly used in laxatives and lubricants. The silica particles are only a few nanometers in diameter, so this fluid can be described as a form of nanotechnology.

Liquid phase is highly filled with rigid, colloidal particles (Fig. 5), at high shear rates hydrodynamic forces overcome repulsive interparticles forces and hydroclusters form, so particles collide, material becomes macroscopically rigid.

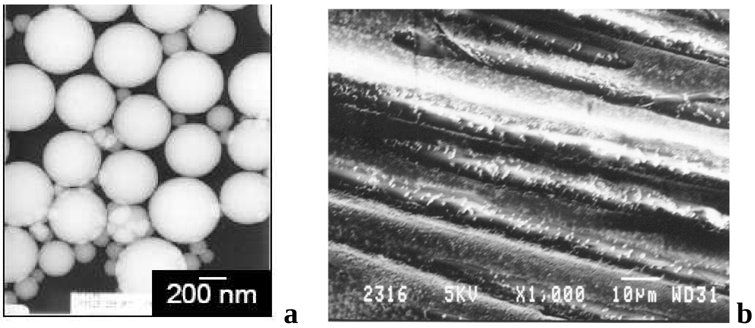


Fig. 5. Transmission electron microscopy of silica particles of Nissan Chemicals MP4540 (enlargement 40,000) (a) and scanning electron microscopy of Kevlar fabric impregnated with colloidal silica particles (b) [1]

Kevlar fabric impregnated with shear thickening fluid used as body armour is characterized by the following:

- at low shear rates (normal motion) - STF behaves like a liquid with high flexibility, little or no impediment to motion,
- at high shear rates (object strikes or stabs the Kevlar) - relative motion of yarns / fibers within fabric deforms STF at high rate and STF transits to rigid phase in a few milliseconds (immediately hardens), making the Kevlar stronger so enhances ballistic protection of fabric (Fig. 6),
- body armour becomes flexible again afterward when strikes or stabs disappear.

The STF is a colloid, made of tiny particles suspended in a liquid (silica particles generally stay in suspension) and the particles repel each other slightly, so they float easily throughout the liquid without clumping together or settling to the bottom. But the energy of a sudden impact overwhelms the repulsive forces between the particles - they stick together, forming masses called hydroclusters. When the energy from the impact dissipates, the particles begin to repel one another again. The hydroclusters fall apart, and the apparently solid substance reverts to a liquid.

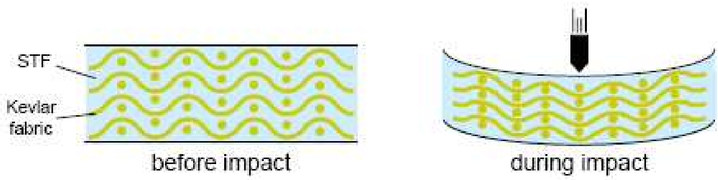


Fig. 6. Behaviour of Kevlar fabric impregnated with STF before and during impact of projectile [1]

3. The results of tests

Effect of STF impregnation into Kevlar is critical to enhance ballistic performance of neat fabric depending on type of impregnation (Fig. 7).

For targets of equal weight, STF-impregnated Kevlar demonstrates similar ballistic performance to neat Kevlar (Fig. 8).

Energy dissipation in above-mentioned figure is understood as absorbed energy divided by initial impact energy during impact projectile or stab.

The next parameter which is taken into account in this matter is the influence of volume of STF-impregnated 4-Kevlar layers on its protection ability. It is shown in Figure 9.

The results of this tests can be evaluated in the following: the adding more STF increases energy absorption in target, and adding neat ethylene glycol (EG) or dry silica powder of equal mass has less effect on energy absorption.

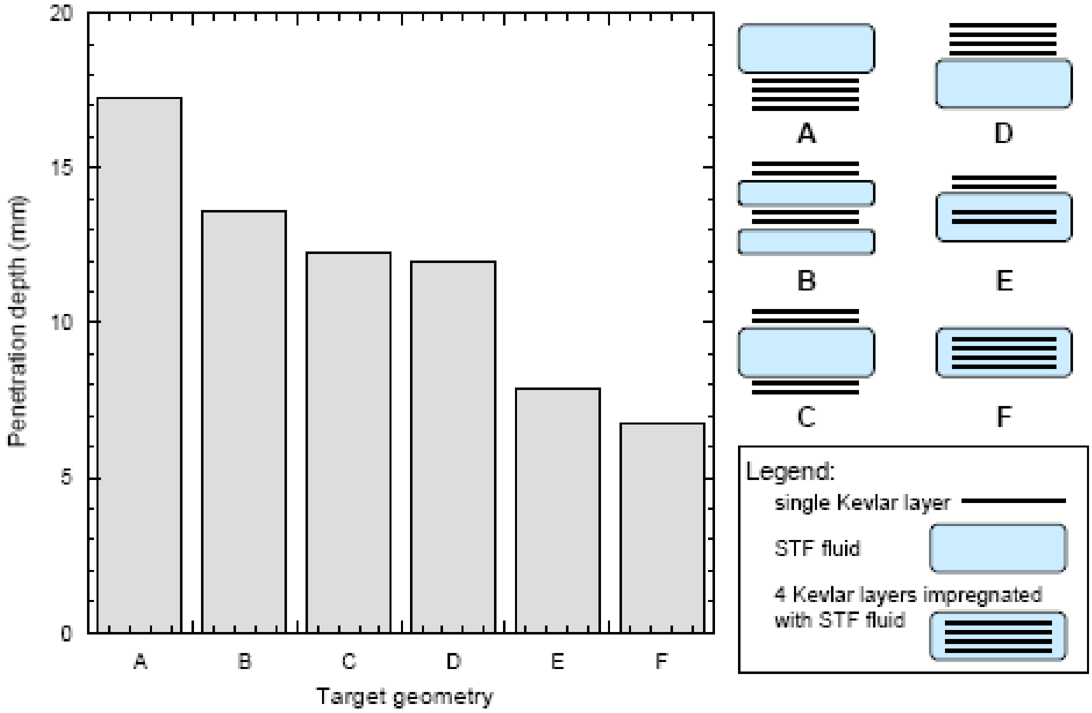


Fig. 7. Penetration depth of Kevlar impregnated with STF in function of the type of impregnation (A÷F) of 4 Kevlar layers [1]

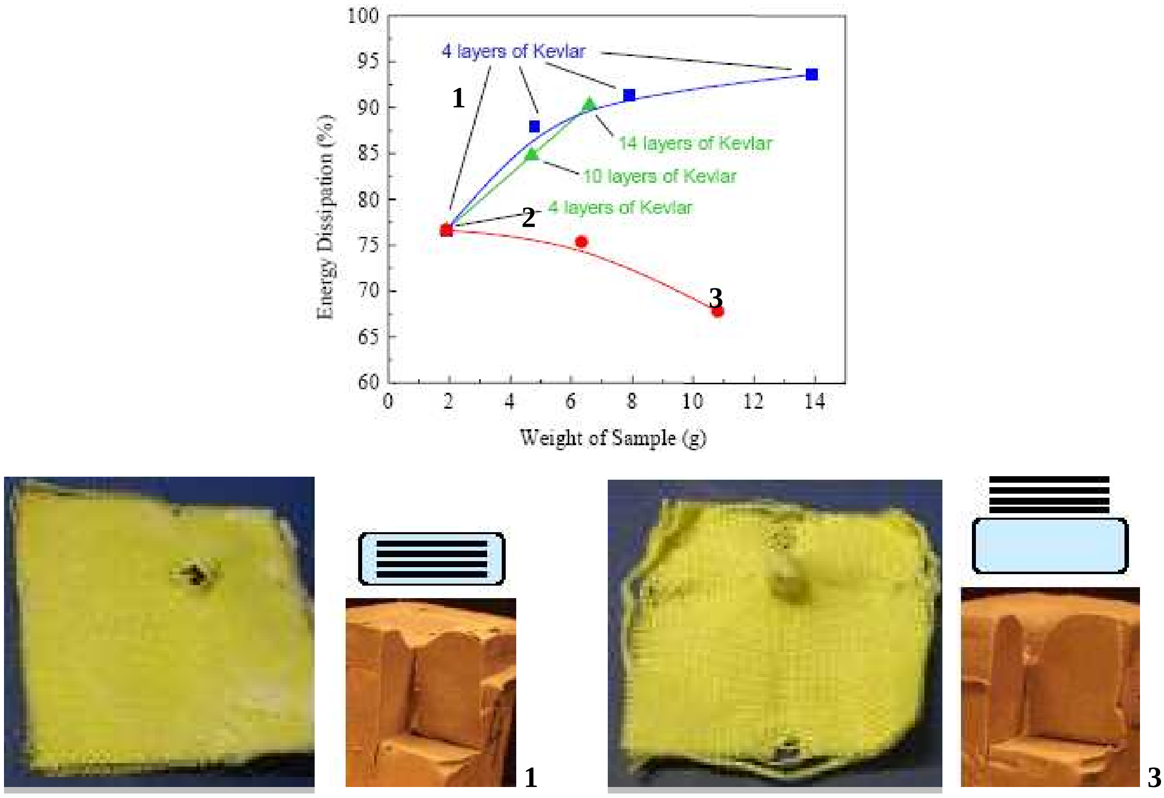


Fig. 8. Energy dissipation of the different layers of Kevlar impregnated with STF: 1 - 4 layers of Kevlar - first layer of Kevlar (back three layers show little pullout, no fracture), 2 - EG-impregnated 4 layers of Kevlar, 3 - neat Kevlar - first layer of Kevlar (back three layers show comparable pullout) [1]

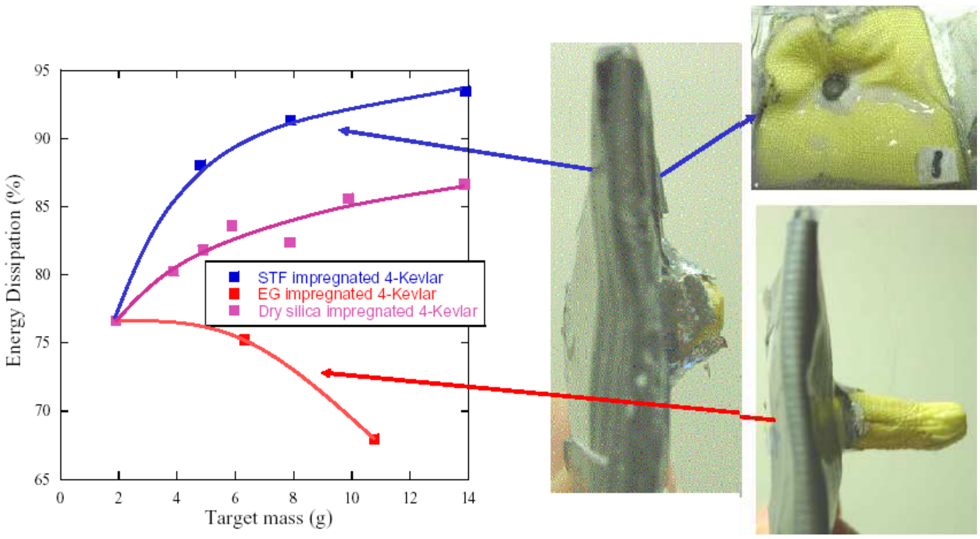
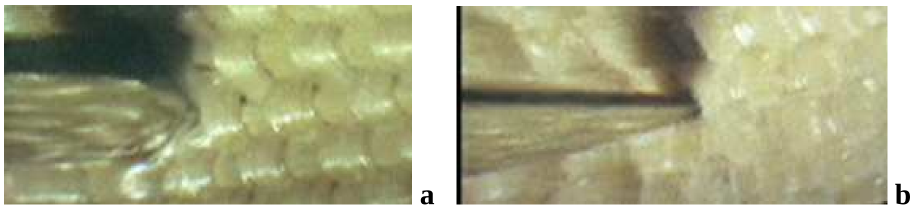


Fig. 9. Energy dissipation in target mass function for 4-Kevlar prepared in different way

Other examples of behaviour of impregnated Kevlar after impact ice pick are shown in Figure 10.



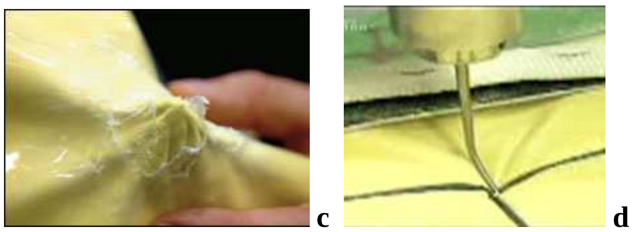


Fig. 10. Behaviour of an ice pick: distends the fibres of neat Kevlar fabric (a), does not distend the fibres of Kevlar treated with STF (b) and back side of Kevlar (c), bending of an ice pick after impact of force equal 120 kg-weigh-man force (d) [4]

The behaviour of flexible Kevlar impregnated with STF with the use of speed camera is presented in Figure 11.

Fig. 11. Flexible Kevlar treated STF before projectile impact

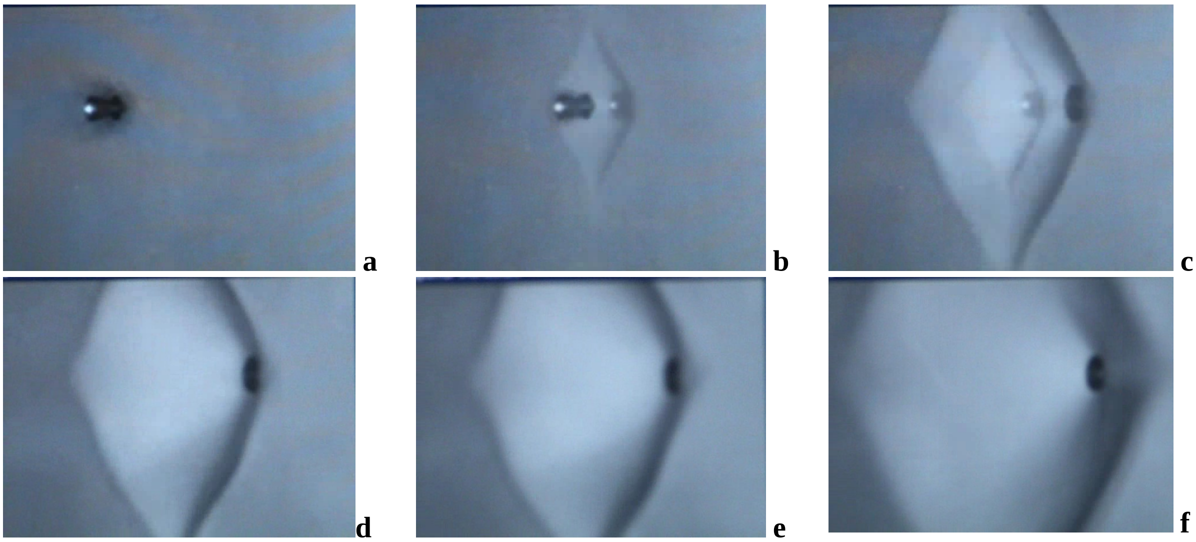


Fig. 12. Impact of projectile into Kevlar impregnated with STF (from Fig. 11) for the following time: a - 0 s, b - 0.08 s, c - 0.16 s, d - 0.24 s, e - 0.32 s, f - 0.48 s

4. Conclusions

The concluded tests provided following most important results related to the technology of impregnated Kevlar with shear thickening fluid:

- Four layers of STF-treated Kevlar can dissipate the same amount of energy as 14 layers of neat Kevlar, and in addition, STF-treated fibers do not stretch as far on impact as ordinary fibers, meaning that bullets do not penetrate as deeply into the armor or a person's tissue underneath. This is because it takes more energy for the bullet to stretch the STF-treated fibers.
- Only objects moving at slow speeds may penetrate this shield. Similarly, slowly-moving objects will sink through shear-thickening fluid without causing it to harden. In low-speed, or quasi-static, knife tests, a knife can penetrate both neat Kevlar and STF-treated Kevlar. The STF-treated Kevlar sustains slightly less damage, possibly because the fluid causes the fibers to stick together.

In comparison to neat Kevlar targets, the STF-impregnated targets have:

- significantly fewer layers,
- thinner bulks,
- more flexibility – in case of comparable ballistic performance.

Armour hardens almost instantly on impact and reversibly allowing thinner, lighter and more flexible.

The STF-treated Kevlar called sometimes “liquid armour” can be used in ballistic vests to protect torso, arms and legs, where many of these devastating and life-threatening injuries occur. It can be very useful to protect soldiers against shrapnel from roadside bombs.

The STF-treated Kevlar could be used in bomb blankets, to cover suspicious packages or unexploded ordnance, and be applied to jump boots, so that they would stiffen during impact to support soldiers' ankles.

Total features of the STF-treated Kevlar are especially important for prison guards, who are most often attacked with handmade sharp weapons, so the STF-treated Kevlar can be much better at reducing blunt trauma.

5. References

[1] Wetzel E. D., Wagner N. J.: *Advanced body armor utilizing shear thickening fluids*. 23rd Army Science Conference, Orlando, FL, 3 December, 2002.

[2] *Nanotechnology - Enabling Safer Body Armour for Real Life* http://www.srs.ac.uk/srs/news_extras/news06/nanotechnology.htm

[3] *Liquid Armor*: http://www.sciencentral.com/articles/view.php3?type=article&article_id=218392807

[4] *How Liquid Body Armor Works* http://science.howstuffworks.com/liquid-body-armor.htm

ZASTOSOWANIE NANOTECHNOLOGII W CELU ZWIĘKSZENIA ZDOLNOŚCI OCHRONNEJ CIAŁA CZŁOWIEKA

Streszczenie: Przedstawionorezultaty zastosowania procesu technologicznego w celu otrzymania elastycznej kamizelki kuloodpornej, która zawiera nanocząstki SiO_2. Zaprezentowano ciecz ulegającą zagęszczeniu podczas ścinania (Shear Thickening Fluid STF) impregnującą wielowarstwowy Kevlar. Pokazano zachowanie się kamizelki kuloodpornej elastycznej podczas normalnego użytkowania i jako sztywnej tarczy podczas uderzenia pocisku, szpikulca lub ostrza noża. Oprócz tego przedstawiono głębokość penetracji Kevlaru impregnowanego STF dla różnych typów impregnacji czterech warstw Kevlaru. Ponadto zaprezentowano wyniki rozproszenia energii w impregnowanej tkaninie Kevlar podczas uderzenia.