Karolina Olszewska,
Jadwiga Polak,
Dorota Zielińska,
Marcin H. Struszczyk,
Iwona Kucińska,
*Łukasz Wierzbicki,
*Joanna Kozłowska,
*Marcin Leonowicz,
**Adam Wiśniewski

Textile Multilayered Systems with Magnetorheological Fluids for Potential Application in Multi-Threat Protections. Preliminary Stab - Resistance Studies

Institute of Security Technology MORATEX,
ul. M. Sklodowskiej-Curie 3, 90-965 Lodz, Poland,
E-mail: itb@moratex.eu,

***Faculty of Materials Science and Engineering, Warsaw University of Technology,**
ul. Woloska 141, 02-507 Warsaw, Poland

****Military Institute of Armament Technology,**
ul. Wyszynskiego 7, 05-220 Zielonka, Poland

Abstract

The article presents the results of preliminary work carried out for flexible body armour systems designs which contained three types of magnetorheological fluid (MRFs). The stab resistance of the multilayered material systems with magnetorheological fluids were investigated. Tests were carried out on a newly built rig at the Faculty of Materials Science and Engineering, Warsaw University of Technology. Three different configurations of flexible body armour were made. It was found that samples of the multilayered material system containing MRF had lower depth of deformation by about 30% than the reference samples. The combination of MRFs with para-aramid woven fabrics in several usable forms and/or sheets of ultra-high molecular weight polyethylene fibres gives possibilities for obtaining new types of multi-layered systems protecting effectively against various kind of threats.

Key words: *ballistic insert, magnetorheological fluid (MRF), MRF/fabric composite, impact test, stab resistance.*

Introduction

Many scientific and R&D centres, all over the world carry out studies aimed at the development of new, innovative protective materials or the improvement of existing ones. Recently the shear thickening fluids (STFs) as well as magnetorheological fluids (MRFs) have been used for the modification of para-aramid woven fabrics in order to enhance the ballistic and stab resistance of the neat fabrics. STF is defined as a fluid that exhibits an increase in viscosity with an increasing shear rate [1, 2]. MRF is a colloidal suspension which exhibits a rapid and reversible change in flow properties when subjected to a sufficiently strong magnetic field[3]. Due to these special properties of these fluids, R&D centres attempt to use the fluids for developing multifunctional, flexible and lightweight materials potentially applicable for bullet, knife or spike-resistant protections [4 - 10].

The aim of current research, carried out at the Institute of Security Technologies "MORATEX" is aimed at adding STF or MRF with nano- or micro-particles to textile materials made of para-aramid and/or ultra-high molecular weight polyethylene fibres (UHMWPE).

The result of such technology is making flexible and lightweight, multi-layered composite structures which allow for moving, while getting thick and hard immediately upon a strong impact (knife, bullet) or exposed to a magnetic field.
Wagner, et al. developed the liquid body armour using shear thickening fluid and Kevlar® fabric [4 - 7]. They developed a flexible knife-resistant STF-Kevlar® target featuring an areal density comparable to a neat Kevlar® target, and with a lower number of layers [4]. The results of the quasistatic test showed that the addition of STF efficiently improves the stab resistance of Kevlar® fabrics. Layers of STF treated Kevlar® had the same strength as neat layers of Kevlar®, even though the STF-Kevlar® target indicated 20% fewer fabric layers [1]. The resistance of STF-impregnated fabrics (areal density of 132 g/m^2) to needle puncture was explored, the results of which demonstrated that STF-fabrics provide better needle puncture resistance than neat fabrics, except the needle with the smallest diameter [6].

The composite of STF-Kevlar® shows a marked increase in spike and needle resistance as well as a reduction in yarn pullout. The V50 velocity of single-layer STF-treated Kevlar® fabric, using 0.22 caliber spherical steel bullets, was found to be approx. 50% higher than that of neat Kevlar® fabric [7].

Hassan, et al. compared the properties of STF-impregnated fabrics, i.e.: Kevlar® (areal density of 180 g/m^2) and Nylon [8]. The results showed that the STF impregnated fabrics had a better stab resistance than the neat fabrics.

Only limited literature data is concerned with the use of MRFs in ballistic armour.

Kwon Joong Son [9] applied magnetorheological fluid for the impregnation of ballistic fabrics. He achieved a ballistic performance of impregnated Kevlar® fabric layers comparable to neat Kevlar® layers.

A group of researchers led by McKinley worked on the application of MRFs for materials used for manufacturing bulletproof vests. The aim of this research was to develop a fabric composite with MRF which will form an effective protection against fragments. The author explored the possibility of using very small magnets as valves to turn these fluids on and off.

Innovative techniques for superparamagnetic core/sheath composite nanofibres were obtained with MRF and poly(ethylene terephthalate) (PET) solution via a coaxial electrospinning technique [10]. The nanostructures are potentially useful for application in ultra-

Olszewska K, Polak J, Zielińska D, Struszczyk MH, Kucińska I, Wierzbicki L, Kozłowska J, Leonowicz M, Wiśniewski A. Textile Multilayered Systems with Magnetorheological Fluids for Potential Application in Multi-Threat Protections. Preliminary Stab - Resistance Studies. *FIBRES & TEXTILES in Eastern Europe* 2013; 21, 5(101): 112-116.

high-density data storages, sensors and bulletproof vests.

The article presents the results of preliminary work carried out within the project „Smart Passive Body Armour with Application of Rheological and Magnetorheological Fluids".

The aim of this research was to develop material systems with MFRs having knife-resistant properties. The results of impact tests on the composites developed (flexible armours) are presented.

Experimental research

Materials

The following materials were used for designing impregnates and flexible multi-layered systems with MRFs:

- woven fabric of various surface mass: Kevlar® Correctional (surface mass of 125 ± 5 g/m^2, DuPont, USA; material with proven stab and ballistic resistance), Twaron® CT 709 WRT (surface mass of 200 ± 5 g/m^2, Teijin, The Netherlands; material with proven ballistic resistance), Twaron® T 750 (surface mass of 470 ± 20 g/m^2, Teijin; material with proven ballistic resistance);
- material with polyethylene fibres of ultra-high molecular weight: Dyneema® SB 21 (surface mass of 145 ± 5 g/m^2, DSM, The Netherlands; material with proven ballistic resistance);
- other auxiliary materials: polyurethane foams (Eurofoam/Poland), pouch of polyethylene foil (Plast/Poland).

The following MFRs were applied:

- OM75.320.1A200, consisting of: 10 μm iron particles, OKS 352 synthetic oil, Areosil 200 stabiliser developed by the Faculty of Materials Science and Engineering, Warsaw University of Technology;
- OM45+HQ20.100, consisting of 10 μm and 1 μm iron particles, OKS 3760 synthetic oil, developed by the Faculty of Materials Science and Engineering, Warsaw University of Technology;
- 132-DG LORD by LORD Corporation, USA, hydrocarbon carrier fluid (commercially available MRF).

Methods

The institute of Security Technologies "MORATEX" developed its own procedure for designing impregnates with MFRs. According to this procedure, MFRs were carefully mixed before applying, then textile and synthetic materials were cut into pieces of 100 × 100 mm, single layers of fabrics and foam were subsequently immersed in homogenised MFR, and the excess was removed. The samples were closed in pouches made of polyethylene foil.
The flexible armours produced consisted of:

- a layer of fabric impregnated with the fluid, arranged in a laminar manner and closed inside a pouch made of polyethylene foil. The samples varied in the number of material layers;
- layers of fabric, combined with foam between them, soaked with MFR;
- layers of the given fabric, combined with a pouch between them, filled with 20 ml of MFR.

The samples were tested in a drop tower at the Faculty of Materials Science and Engineering, Warsaw University of Technology (***Figure 1***).

Stab tests were performed according to procedure No. PBB-06/ITB:2008 "Determining the resistance of a set of samples to puncture with cold steel" under a constant ambient temperature of 21 °C. In order to perform the stab test, the titanium knife was dropped with an impact energy of Ek = 24 J. In the case of samples with the MFRs, a titanium knife was dropped down into a magnetic field of H = 600 mT. The magnetic field lines were directed towards the plane of the sample.

After dropping down the knife, the following parameters were measured:

- the depth of deformation (D_{def}), defined as the highest extent of indentation in the baking material caused by the non-penetrated knife;
- in the case of system puncture: total depth of penetration (Dp), defined as the length of the knife penetrating the system tested. Additionally the number of knife penetrated (broken) layers was determined for samples partially punctured.

In order to study the phenomenon of the titanium knife impact affect on the samples, a video camera with a registration rate of 30 frames per second (fps) or a fast speed camera recording 3000 fps were used.

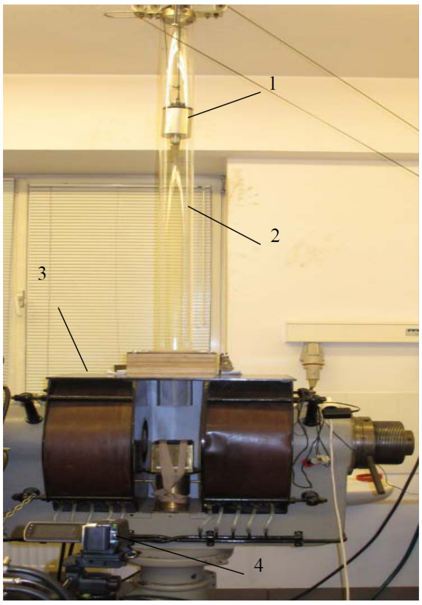

Figure 1. *Resistance testing drop tower for puncturing the samples: 1 - drop mass consisting of knife, knife holder; 2 - drop tube; 3 - electromagnet; 4 – camera.*

In order to investigate the infusion of MRF in the fabric sheets, microscopic observations with a scanning electron microscope - S-3500/Hitachi (Japan) were made.

The surface mass of initial (native) woven fabrics, fabrics after MRFs impregnation as well as multi-layered systems containing MFRs was determined according to Standard PN-ISO 3801:1993, whereas the thickness of the materials tested was estimated according to Standard PN-EN ISO 5084:1999.

Results and discussion

Various variants of sample design using textile and plastic raw materials with MFRs were made. Impregnation tests for different materials of para-aramid fibers were done. For the designing of multilayered systems containing MRFs, several types of materials were used, most of which have proven ballistic properties (woven fabrics: Twaron® T 750, Twaron® CT 709 WRT, Kevlar® Correctional and sheets of UHMWPE: Dyneema® SB 21) or stab resistance (only Kevlar® Correctional). The main idea of the research was to determine the stab resistance of newly-designed systems containing MRFs implemented into them in several ways in materials having, or not, proven stab resistance.

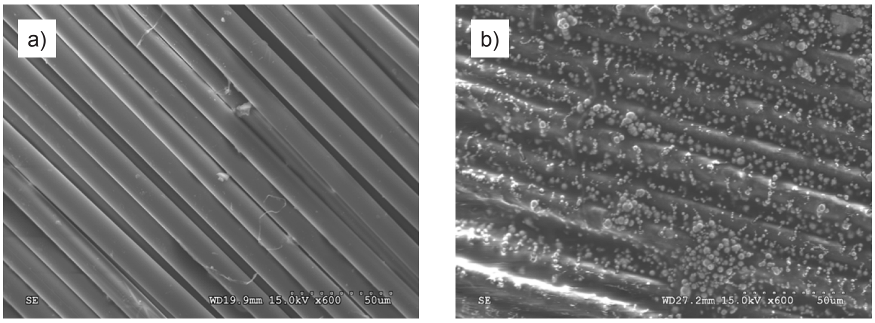

Figure 2. *SEM microphotographs of Twaron® T 750 fabric surfaces: a) without impregnation, 600× magnification, b) impregnated with MRF, 600× magnification.*

Figure 2 presents examples of SEM microphotographs of native Twaron® T 750, while ***Figure 2.b*** shows Twaron® T 750 impregnated with MFR.

MRF particles penetrated the fabric structure and filled the empty spaces between fibers (***Figure 2.b***). The SEM microphotograph shows that all the Twaron® fibers are coated with the MRF.

Table 1 shows the stab resistance behaviour of multilayered flexible armours designed consisting in layers of Twaron® T 750 impregnated with three types of MFRs: 132-DG LORD, OM45+HQ30.100 or OM75.320.1A200. Stab resistance results obtained for non-impregnated (native) systems containing only Twaron® T 750 fabrics are also given.

The highest increase in the surface mass of a single layer was obtained in the case of fabrics impregnated with 132-DG LORD fluid (***Table 1***; sample No. 2). The application of OM45+HQ30.100 and OM75.320.1A200 fluids gave very comparable values between multi-layered systems containing the MFRs mentioned above (***Table 1***; samples No. 4, 5).

During the stab resistance tests, the knife did not puncture any sample tested. The samples with 14 layers of Twaron® T 750 impregnated with MRFs had a lower D_{def} in comparison to the reference sample (non-impregnated). Particularly D_{def} was lower by approx. 30% as compared with data obtained for the sample containing 14 layers of woven fabrics without MRF impregnation (***Table 1***; sample No. 1).

The crucial disadvantage of the multilayered systems tested containing MRF is the large mass and thickness compared with the reference sample. Therefore the sample with a lower number of impregnated layers (***Table 1***; sample No. 3) was prepared to reduce the mass of the final system. In this case, a higher D_{def} was observed compared to the non-impregnated system. The sample above also had a lower mass and thickness as compared with the MRF impregnated samples containing 14 layers (***Table 1***; sample No. 2).

The 22 layered systems of Twaron® CT 709 WRT fabric were made with the same MRFs, each of which was placed in a plastic pouch.

Selected parameters of the samples prepared are shown in ***Table 2***. The parameters of the reference sample, i.e. without the pouch, are also included as a reference (***Table 2***; sample No. 6).

Each multilayered system tested, consisting in 22 layers of woven fabric and a pouch filled with 20 cm³ of each MRF placed between them, were not punctured during the stab resistance test. A lower value of D_{def} was obtained for all the MRF impregnated systems as compared with reference. Regardless of the MRF type, the systems tested showed a D_{def} at a similar level.

Table 1. *Stab resistance results for Twaron® T 750 fabric with or without MFR impregnation and final multi-layered system; * - reference sample, i.e. consisting in minimum number of layers to provide protection required against knife impact.*

Sample No.	Description	Surface mass of single layer before/after impregnation, g/m²	Surface mass of multi-layered system, g/m²	Thickness of sample, mm	Depth of deformation, D_{def}, mm
*1	14 layers of fabric	470/-	6194	8.8	19
2	14 layers of fabric impregnated with 132-DG LORD fluid	470/1106	16334	14.0	11
3	10 layers of fabric impregnated with 132-DG LORD fluid	470/1137	10882	10.0	18
4	14 layers of fabric impregnated with OM45+HQ30.100 fluid	470/795	11777	12.0	13
5	14 layers of fabric impregnated with OM75.320.1A200 fluid	470/798	11438	10.0	13

Table 2. *Stab resistance results for Twaron® CT 709 WRT fabric with or without pouches filled with MFRs; * - reference sample, i.e. consisting of minimum layer number to provide protection required against knife impact.*

Sample No.	Description	Volume of MRF applied, cm³	Surface mass of multi-layered system, g/m²	Thickness of sample, mm	Depth of deformation, D_{def}, mm
*6	22 layers of fabric	0	4440	6.7	22
7	A pouch filled with 132-DG LORD fluid located below 11 layers of fabric, next 11 layers below the pouch	20	9158	6.8	15
8	A pouch filled with OM45+HQ30.100 fluid located below 11 layers of fabric, next 11 layers below the pouch	20	9242	6.9	16
9	A pouch filled with OM75.320.1A200 fluid located below 11 layers of fabric, next 11 layers below the pouch	20	8441	6.9	15

Table 3. *Stab resistance results for Twaron® T 750 fabric with or without pouches filled with 132-DG LORD fluid.*

Sample No.	Description	Volume of MRF applied, cm^3	Surface mass of multi-layered system, g/m^2	Depth of deformation, D_{def}, mm	Total depth of penetration, D_p, mm
10	8 layers of fabric	0	3670	26	26
11	A pouch filled with MRF located below 8 layers of fabric	20	8000	26	30
12	A pouch filled with MRF located below 6 layers of fabric and next 2 layers below the pouch	20	8309	21	23
13	A pouch filled with MRF located below 2 layers of fabric and next 6 layers below the pouch	20	8274	20	34

Table 4. *Stab resistance results for Kevlar® Correctional fabric and hybrid samples with 132-DG LORD fluid.*

Sample No.	Description	Volume of fluid applied, cm^3	Surface mass of multi-layered system, g/m^2	Thickness of sample, mm	Depth of deformation, D_{def}, mm	Total depth of penetration, D_p, mm
14	24 layers of Kevlar® Correctional fabric	0	3175	4.4	24	24
15	24 layers of Kevlar® Correctional impregnated with MRF	27	11672	6.7	9	23
16	24 layers of Kevlar® Correctional, a pouch with MRF between layers	20	8405	4.6	20	20
17	13 layers of Kevlar® Correctional, 18 layers of Dyneema, polyurethane foam soaked with MRF between layers	13	9060	19.2	12	12
18	10 layers of Kevlar® Correctional, 8 layers of Twaron T 750 impregnated with MRF	18	10518	9.8	15	15

In order to determine the optimal position of the pouch filled with MRF, the reference sample containing 8 layers of Twaron® T 750 fabric was used. The pouch was located in several positions below 8 layers of the non-impregnated woven fabric. A description of the systems and their parameters are summarised in ***Table 3***. Additionally the parameters of the reference sample, without the MRF, are also included.

The results in ***Table 3*** indicate that the position of the pouch containing MRF in the system tested has a significant influence on the value of D_p. Hypothetically the location of the pouch with the MRF affects the rate at which the knife penetrates the system tested and thus changes its flexibility and hardness gradually.

The lowest D_p was observed for sample No. 12 (***Table 3***), in which the pouch from the backing material was separated by two layers of the ballistic fabric. D_p showed a lower value than that obtained for the reference sample.

Another kind of multi-layered system was made of Kevlar® Correctional fabric and MRF by applying both the impregnation of fabric layers and the pouch containing MRF (***Table 4***).

The sample consisting of 24 impregnated layers (***Table 4***; sample No. 15) was punctured. For the same number of layers non-impregnated but containing a pouch with the MRF between them (***Table 4***; sample No.16), a similar D_p was obtained.

Samples No. 17 and 18 are multilayered hybrid systems composed of layers of Kevlar® Correctional fabrics and layers of UHMWPE sheets (Dyneema® SB 21), among which foam saturated with MRF or layers of para-aramid fibers impregnated with MRF were placed.

A lower D_p value was found for the multilayered hybrid systems as compared to the sample consisting in impregnated layers, or Kevlar® Correctional fabrics layers with a pouch filled with MRF between them.

Figure 3 shows the dependence of D_p on the surface mass of samples No. 14 - 18.

The lowest value of D_p was shown by sample No. 17. However, the disadvantage of the above design is high thickness During the research, optimisation of the design was carried out taking into account the final mass of the system as the general criterion. Finally the system consisting in 10 layers of Kevlar® Cor-

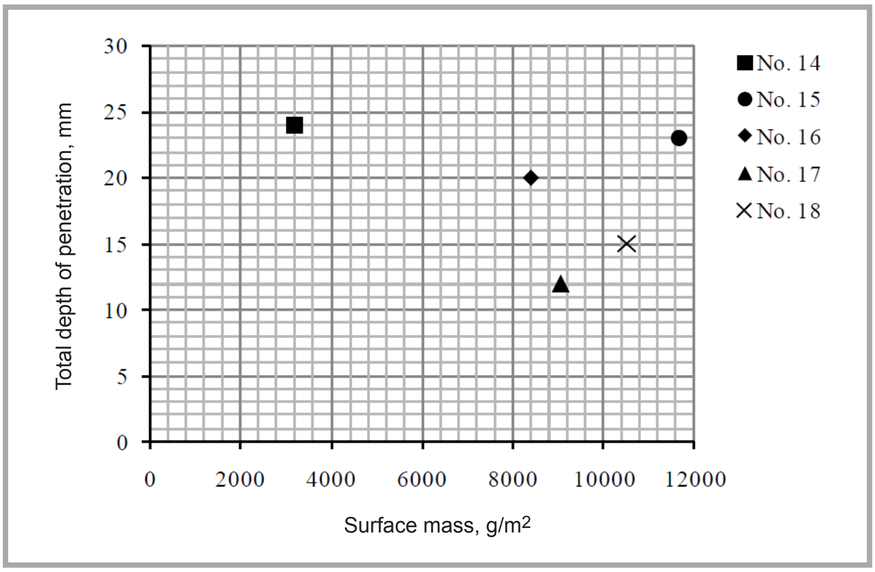

Figure 3. *Dependence between the total depth of penetration and surface mass of hybrid systems consisting in Kevlar® Correctional fabric. Description of sample system is presented in* ***Table 4***.

rectional, 8 layers of Twaron T 750 impregnated with MRF, was selected as optimal (***Table 4***; sample No. 18), indicating optimal safety parameters: low D_p and lower thickness.

Summary and conclusions

Preliminary variants of multilayered systems containing various types of MRFs and textile materials (showing proven ballistic or stab and ballistic behaviour) showed promising results with respect to stab resistance, confirming their usefulness for future designing of flexible body armour systems. A preliminary evaluation of their resistance to puncture with a knife in a magnetic field in accordance with the test procedure developed was made.

The implementation of MRF in the multilayered systems designed in the form of:

- impregnated layers of Twaron® T 750 fabric;
- layers of Twaron® CT 709 WRT or Kevlar® Correctional fabrics, with a pouch filled with MRF located between them;
- hybrid material

resulted in a reduction of up to 30% of the depth of deformation for the textile materials without MRF as compared to the reference sample.

All the samples consisting of Twaron® CT 709 WRT layers and pouches filled with MRFs had a depth of deformation at a similar level irrespective of the type of MRF used.

Apparently the location of the pouch with the MRF affects the rate at which the knife penetrates into the system, and thus changes its flexibility, making it more rigid. The lowest total depth of penetration was obtained for the sample in which the pouch containing the MRF was separated from the ballistic material by two layers of ballistic fabric.

The presence of MRF in the hybrid samples caused a reduction in the total depth of penetration as compared to the reference sample.

We expect that the incorporation of rheological fluids into para-aramid fabrics will enhance their ballistic resistance. The MRF/fabric composites will be arranged into multilayer targets and investigated against bullet threats in the future. We will also aim to reduce the weight of the MRF/fabric composites.

Acknowledgement

The Project "Smart passive body armour with application of rheological and magnetorheological fluids" is co-financed by the European Union, within the European Regional Development Fund, and Polish Government within the Innovative Economy Programme, priority 1, activity 1.3, subactivity 1.3.1, agreement with MSHE nr UDA-POIG.01.03.01-00-060/08-00, 25.02.2009 y.

References

1. Hoffman RL. *Journal of Colloid and Interface Science* 1974; 46: 491.
2. Barnes HA. *Journal of Rheology* 1989; 33: 32.
3. Rabinow J. *American Institute of Electrical Engineers* 1948; 67: 1308.
4. Egres Jr. RG, Decker MJ, Halbach CJ, Lee YS, Kirkwood JE, Kirkwood KM, Wagner NJ. Stab resistance of shear thickening fluid (STF)–Kevlar composites for body armor applications. In: *24th Army Science Conference*, Orlando, 2004.
5. Egres Jr. RG, Lee YS, Kirkwood JE, Kirkwood KM, Wetzel ED, Wagner NJ. Novel Flexible Body Armor Utilizing Shear Thickening Fluid (STF) Composites. In: *14th International Conference on Composite Materials*, San Diego, 2003.
6. Houghton JM, Schiffman BA, Kalman DP, Wetzel ED, Wagner NJ. Hypodermic needle puncture of shear thickening fluid (STF)-treated fabrics. In: *52nd International SAMPE Symposium and Exhibition*, Baltimore, 2007.
7. Rosen BA, Nam Laufer CH, Kalman DP, Wetzel ED, Wagner NJ. Multi-threat performance of kaolin-based shear thickening fluid (STF)-treated fabrics. In: *52nd International SAMPE Symposium and Exhibition*, Baltimore, 2007.
8. Tarig A. Hassan, Vijay K. Rangari, Shaik Jeelani. *Materials Science and Engineering A* 2010; 527: 2892.
9. Kwon Joong Son. *Impact Dynamics of Magnetorheological Fluid Saturated Kevlar and Magnetostrictive Composite Coated Kevlar*. The University of Texas, Austin, May 2009.
10. Sung YK, Ahn BW, Kang TJ. *Journal of Magnetism and Magnetic Materials* 2012; 324: 916.

Received 31.08.2011 Reviewed 25.02.2013

INNOVATIVE ECONOMY
NATIONAL COHESION STRATEGY

EUROPEAN UNION
EUROPEAN REGIONAL
DEVELOPMENT FUND