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COMPOSITES THEORY AND PRACTICE

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MAGNETORHEOLOGICAL FLUIDS AS A PROSPECTIVE COMPONENT OF COMPOSITE ARMOURS

Magnetorheological characterization of a synthesized MRF and ballistic performance of a MRF-composite material with high-strength textiles as Kevlar and Dyneema, are presented. The ballistic performance of the investigated structures under a Parabellum 9 mm projectile with a velocity of 360 m/s, on the basis of deformation depth in backing clay and number of pierced layers was determined. The targets with MRF demonstrate a 30% reduction in depth of deformation when comparing to the neat samples. On the other hand, implementation of the MRF to the structures of the high-strength materials caused a twofold increase in the overall target weight. At the same time, the inherence of the MRF in the structure of the composite samples does not affect the number of damaged layers. This result indicates that the absorbing mechanism of the MRF is rather limited to residual energy absorption under the impacting projectile.

Keywords: **smart armour, smart magnetic materials, magnetorheological fluids, ballistic performance**

CIECZE MAGNETOREOLOGICZNE JAKO POTENCJALNY SKŁADNIK KOMPOZYTOWYCH PANCERZY OCHRONNYCH

Wytworzono i przebadano ciecz magnetoreologiczną na bazie oleju syntetycznego i żelaza karbonylkowego. Opracowanej cieczy magnetoreologicznej użyto w konstrukcjach kompozytowych pancerzy ochronnych. Wytworzone pakiety poddano badaniom odporności na przebicie pociskiem Parabellum 9 mm o prędkości 360 m/s, w celu określenia możliwości ich wykorzystania w obszarze kompozytowych ochron balistycznych. Obecność cieczy MR w hybrydowych pancerzach z warstwami wysokowytrzymałych materiałów typu Kevlar lub Dyneema wykazała redukcję głębokości deformacji podłoża balistycznego o 30% w porównaniu do konstrukcji próbek bez cieczy. Z drugiej jednak strony zwiększenie odporności balistycznej kompozytowych konstrukcji z cieczą MR nastąpiło przy dwukrotnym wzroście masy całkowitej układu. Jednocześnie, obecność cieczy MR nie wpłynęła na zmianę liczby warstw przebitych w konstrukcjach próbek kompozytowych. Uzyskane wyniki świadczą o tym, że rola cieczy MR w absorbowaniu energii wytworzonych próbek ogranicza się w zasadzie do pochłaniania i rozpraszania resztkowej energii podczas oddziaływania pocisku z pancerzem.

Słowa kluczowe: **inteligentny pancerz, magnetyczne materiały typu „smart”, ciecze magnetoreologiczne, odporność balistyczna**

INTRODUCTION

Smart materials, with their characteristic properties of reacting to specific stimulus and responding by producing a useful effect, is a prospective group of materials for the so-called “smart armour” [1]. The application of such a group of materials could lead to innovative systems incorporating multifunctional features as enhanced ballistic performance, improved biological and chemical protection or/and specific camouflage properties. Additionally, a protective system could provide improved situational awareness and comfort for the user [2].

One of the potential materials, whose usage may comprise variable-stiffness armours in the field of military or civil protection are magnetorheological fluids (MRFs). MRFs belong to the group of smart magnetic materials with characteristics of reacting to a magnetic field with noticeable and reversible changes in their properties. MRFs are suspensions of micrometric-size, magnetic particles dispersed in a non-magnetic carrier liquid. Under the application of a magnetic field, MRFs demonstrate a significant and reversible change in their rheological properties as a consequence of a dramatic transition in the microstructure. The resulting phenomenon, called the magnetorheological effect, corresponds to a significant increase in the shear stress with a magnetically variable yield stress [3]. MRFs can exhibit a yield stress of 10÷100 kPa in a magnetic field in the range of 150÷280 kA/m [3, 4]. Due to their characteristic properties, MRFs have been successfully employed in a wide range of engineering applications as shock absorbers, damping devices, clutches, brakes, artificial joints and in magnetorheological polishing systems [5-8]. The concept of MRF application in smart protective armours arises from their characteristic ability to absorb and dissipate energy in a wide spectrum, by varying the magnetic field intensity [9]. At present, there are only a few literature studies (ref. [10, 11]) on the subject of potential MRF application as a smart armour composite component. One group of scientists explored the ballistic performance of saturated Kevlar fabric with commercial MRF-140CG (LORD). The preliminary experiments in this area, indicate that MRF augmentation is not likely to enhance the ballistic performance of aramid soft body armours, and even reduces the energy absorption capability, as compared to neat Kevlar. The authors associated these poor results with the lubricating effect of the hydrocarbon carrier. However, the results indicate slight improvement in energy dissipation of the augmented fabric under the application of a magnetic field, the energy absorption was, thereinafter, inferior to the neat Kevlar fabric [10].

In the present study, the precursory ballistic resistance results of an MRF composite material with high-strength textiles as Kevlar and Dyneema, are presented. The MRF was implemented in the sample structures as a separate material between multiply targets with the same number of layers as the neat samples. The ballistic performance of the investigated structures under a Parabellum 9 mm projectile on the basis of deformation depth in backing clay and number of pierced layers was determined.

EXPERIMENTAL PROCEDURE

Two different, high-strength materials were chosen for the antiballistic targets with the MRF compound. The first one was the para-aramid, Kevlar® XP S102 woven textile based on 1100 dtex yarn and the areal density of 510±2 g/m^2. The second material comprised the ultra-high-molecular-weight polyethylene, non-woven textile Dyneema®SB 71 with the areal density of 185÷195 g/m^2. The textiles were cut into 100x100 mm layers and placed into an appropriate target structure. The one of them consisted of 8 Kevlar XP layers. Additionally, hybrid composite structures incorporating 8 layers of Dyneema and 3 Kevlar layers were prepared.

The MRF was synthesized from a carbonyl iron (CI) powder (OM, BASF) with a mean particle size of 5 μm and spherical shape. The iron powder constituted 75 wt.% of the MRF composition. Synthetic oil, polyalpahaolefins (PAO), with a density of 0.9 g/cm^3 and kinematic viscosity of 100 mm^2/s at 40°C, was applied as the carrier fluid. Additionally, a stabilizer (1 wt.%) was added to the MRF to inhibit the sedimentation process of the solid particles. The MRF was prepared by mixing appropriate constituent component amounts by a mechanical stirrer until a homogeneous composition was obtained.

The synthesized MRF was used in the structures of the composite armour samples with the Kevlar® fabric and in the hybrid structure based on Kevlar and Dyneema, based on the same number of layers (Table 1). A polyethylene bag was filled with 50 g of MRF and implemented to the target structures between fabric layers.

TABLE 1. **Structure of prepared samples targets for ballistic testing**

TABELA 1. **Konstrukcja próbek wytworzonych do badań balistycznych**

Sample structure	Sample areal density g/m^2	Weight of MR fluid g
8 layers Kevlar XP	4 473	-
6 layers Kevlar XP / MRF/ 2 layers Kevlar XP	9 776	51.36
8 layers Dyneema SB/ 3 layers Kevlar XP	3 540	-
8 layers Dyneema SB/ MRF/ 3 layers Kevlar XP	7 876	43.36

The rheological characterization of the magnetorheological fluid used in the composite samples was conducted using a rotational Ares TA Instruments Rheometer, equipped with a magnetic coil. A plate-plate geometry with a diameter of 20 and 1 mm gap was used. The rheological characterization of the MRFs was carried out in the steady shear and dynamic oscillatory modes. Steady shear tests were conducted in a shear rate range of 0.1-630 s^{-1} without a magnetic field and in a 159 and 318 kA/m field. In the oscillatory mode, two types of measurement tests were used. One type was the magneto-sweep mode, where the frequency of angular deformation was 1 Hz and the angular deformation was +/− 0.5% under a linear magnetic field increment from 0 to 230 kA/m. In addition, the strain sweep mode was applied without a magnetic field and under various magnetic strengths (80, 120, 160 kA/m). The strain amplitude was swept from 0.001 to 46% at a fixed driving frequency of 50 Hz.

Ballistic performance tests were conducted in a specially designed and built workstation with a vertical structure, equipped with a magnetic coil. In this workstation, the distance between the barrel and the target was 0.6 m. The projectile, a 9x19 mm Parabellum was fired from the barrel after taking aim on the centre of the target by a laser positioner. All the tests were performed on target sizes of 100x100 mm with projectile velocities ranging between 350÷380 m/s. A magnetic field of 159 kA/m was applied under ballistic testing for the samples with the magnetorheological fluids. The lines of the magnetic field were perpendicular to the direction of the projectile motion axes and parallel to the target surface.

The methodology used in this study to determine the ballistic performance of the investigated samples consisted of establishing the depth of deformation in the ballistic clay and the number of damaged fabric layers. Each test for a given target structure was conducted a minimum of two times and the average results were taken into account.

RESULTS AND DISCUSSION

Magnetorheological investigation

The flow curves for the synthesized MRF under various magnetic field strengths are presented in Figure 1. As the results indicate, the MRF demonstrates magnetically controlled yield stress. In the off-state, the MRF demonstrates negligible yield stress, whereas under the magnetic field, the MRF exhibits substantial yield stress attributed to the formation of a chain-like structure induced by the magnetizable particles, parallel to the magnetic field lines. The yield stress in the magnetic field of 159 and 318 kA/m reaches values of 7.1 and 18 kPa, respectively.

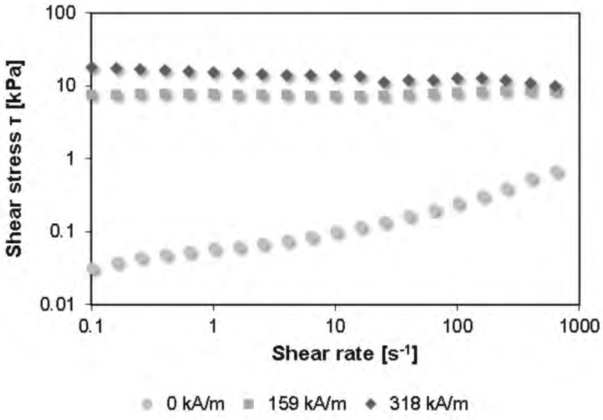

Fig. 1. Shear stress vs. shear rate (0.1-630 s^{-1}) for MRF under different magnetic fields

Rys. 1. Naprężenie ścinające wytworzonej cieczy (0.1-630 s^{-1}) MR w funkcji szybkości ścinania dla różnego natężenia pola magnetycznego

The dynamic shear modules obtained for the investigated MRF in a function of the magnetic field are presented in Figure 2. Complex modulus G* refers to the overall viscoelastic properties and quantifies the total resistance to the oscillatory flow. Storage module G' is a measure of the energy stored elastically during deformation, while loss modulus G" quantifies the energy dissipated into heat.

As can be noticed from Figure 2, increasing the magnetic field causes intense dynamic module appreciation for the examined MRF, due to the magnetically-induced aggregates. The complex and storage module G' rise up to three orders of magnitude under the applied magnetic field. The highest complex, storage and loss modules for the investigated MRF gain values of 1.04, 0.99 and 0.31 MPa, respectively, under the magnetic field of 238 kA/m. The dynamic characterization of the MRF in a function of applied magnetic field and strain can be seen in Figure 3.

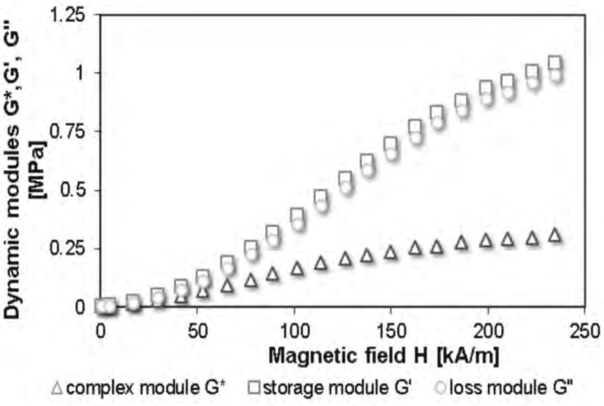

Fig. 2. Dynamic shear modules as function of magnetic field for MRF

Rys. 2. Dynamiczne moduły ścinania cieczy MR w funkcji pola magnetycznego

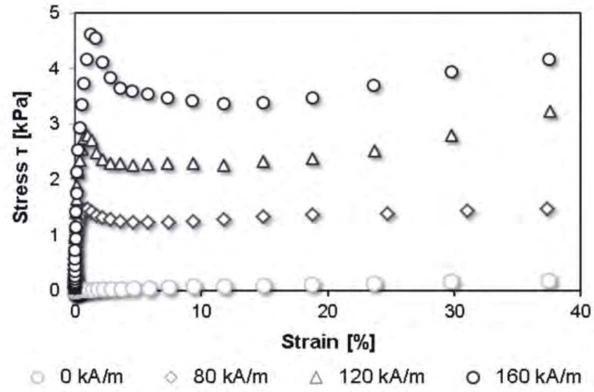

Fig. 3. Stress vs. strain in oscillatory mode for MRF, under different magnetic field.

Rys. 3. Naprężenie w funkcji odkształcenia wytworzonej cieczy MR dla różnego natężenia pola magnetycznego.

Clearly, under a magnetic field, the MRF demonstrates two characteristic regions, separated by the strain yield. In the pre-yield regime, stress is linearly related to strain and the MRF behaviour can be described as a linear viscoelastic solid. For the investigated MRF, a linear shear stress-strain relationship occurs below a 1.01% strain amplitude for the highest applied magnetic fields of 160 kA/m.

The results from rheological characterization can allow one to draw some conclusions. To exploit the MRF in the solid-like state, critical values of characteristic parameters as yield stress and critical strain should not be exceeded. Moreover the magnetic field strength should be high enough to provide the needed magnetorheological effect. In the aspect of ballistic application, it is worth emphasizing that the yield stress (kPa), and dynamic module (MPa) for the MRF can be three orders of magnitude inferior to high-strength materials as Kevlar, Dyneema or others. However, MRF performance can provide additional absorbing capacity in the composite materials due to the ability of storing (elastic portion) and dissipating energy (viscous portion). This conclusion may indicate that MRF can be applicable in enhancing the energy absorbing capacity as the subsidiary component of composite materials, but would not be able to attain ballistic performance as a separate material.

Ballistic tests

After impact of the projectile, deformation of the target occurred and created a conical area due to transverse wave propagation. The kinetic energy of the projectile was dissipated and absorbed by the material. Generally, there are various damage and energy absorbing mechanisms in the composites samples. Under ballistic impact, the kinetic energy of the projectile can be absorbed by: a moving cone, tensile failure of the primary yarns in the fabrics, elastic deformation of the secondary yarns, shear plugging and friction produced at the yarn crossover regions, yarn-projectile contact interfaces, and layer-to-layer interactions energy absorbed during penetration [12, 13]. Thus, the total energy of the projectile absorbed by the investigated target can be described as:

$$E_{TOTAL} = E_{KE} + E_{TF} + E_D + E_{SP} + E_F \qquad (1)$$

The schematic structures of the prepared targets with the MRF are presented in Figure 4.

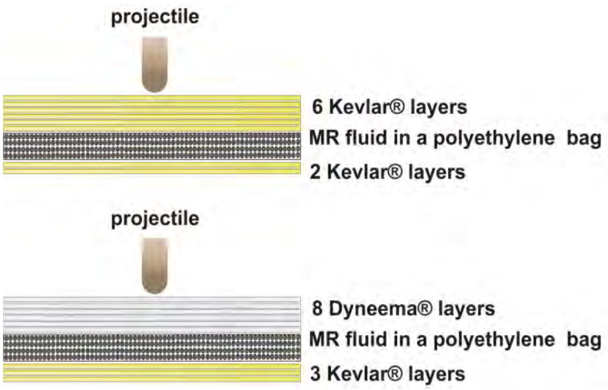

Fig. 4. Schematic illustration of composites structure target with MRF under magnetic field

Rys. 4. Schemat konstrukcji próbek z cieczą magnetoreologiczną w polu magnetycznym

Incorporation of MRF into textile structures can cause an additional mechanism of energy absorption in the form of viscous damping.

Thus,

$$E_{TOTAL} = E_{KE} + E_{TF} + E_D + E_{SP} + E_F + E_{MRF\ damping} \qquad (2)$$

The results of deformation in the backing clay for the investigated target samples are presented in Figure 5.

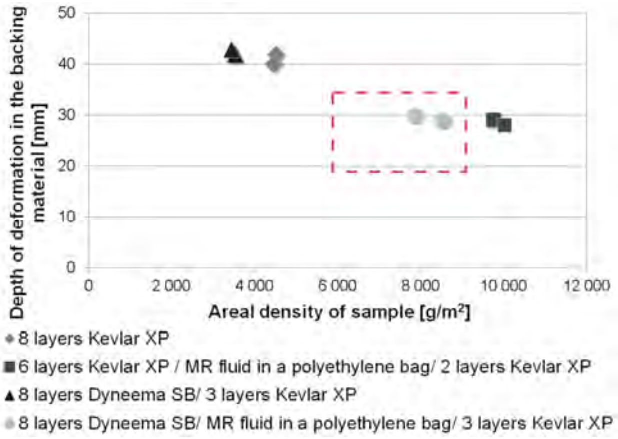

Fig. 5. Results of deformation in ballistic clay for investigated samples presented versus areal density of targets

Rys. 5. Wyniki deformacji podłoża balistycznego dla badanych próbek zestawione z ich masą powierzchniową

The maximum acceptable depth of deformation is 40 mm. As can be seen, the neat samples with the Kevlar and Dyneema layers do not attain the applicable level of ballistic resistance. By contrast, the structures with the MRF under a magnetic field illustrate the appropriate depth of deformation due to the additional absorbing mechanism. The targets with MRF demonstrate a 30% reduction in depth of deformation when comparing to the neat samples. On the other hand, implementation of the MRF to the structures of the high-strength materials caused a twofold increase in the overall target weight.

At the same time, inherence of the MRF in the structure of the composite samples does not affect the number of damaged layers (Table 2). This result indicates that the absorbing mechanism of the MRF is rather limited to residual energy absorption under the impacting projectile.

TABLE 2. **Results of fractured layers for investigated targets after ballistic testing under magnetic field of 159 kA/m (9 mm x 19 mm Parabellum projectile, velocity of 360 m/s)**

TABELA 2. **Wyniki przedstawiające liczbę warstw przebitych dla badanych próbek po testach odporności balistycznej w polu magnetycznym 159 kA/m (pocisk Parabellum 9 mm x 19 mm, prędkość 360 m/s)**

Sample structure	Sample areal density [g/m^2]	Magnetic field [kA/m]	Number of fractured layers
8 layers Kevlar XP	4473	0	3
6 layers Kevlar XP /MRF/ 2 layers Kevlar XP	9776	159	3
8 layers Dyneema SB / 3 layers Kevlar XP	3540	0	3
8 layers Dyneema SB /MRF/ 3 layers Kevlar XP	7876	159	3

CONCLUSIONS

Magnetorheological fluid based on carbonyl iron and synthetic oil was synthesized and exploited in composite structures with high-strength materials as Kevlar and Dyneema. The rheological measurement indicates that the MRF reveals magnetically controlled yield stress and viscoelastic properties. This performance can provide an additional absorbing capacity in the composite materials due to the ability of storing (elastic portion) and dissipating energy (viscous portion).

The ballistic tests results indicate that the application of MRFs with high-strength materials as Kevlar and Dyneema may cause some improvement in the composite targets ballistic performance and the overall energy dissipating process under projectile impacts. On one hand, MRF-Kevlar composites are characterized by a high areal density of targets. On the other hand, implementation of MRF components to the structure of high-strength ballistic materials can enhance the energy absorbing process and can be applicable in reducing the trauma blunt effect.

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