prof. dr hab. inż. Adam WIŚNIEWSKI
Wojskowy Instytut Techniczny Uzbrojenia

THE POSSIBILITY OF USE OF THE MAGNETO-RHEOLOGICAL FLUIDS IN ARMOURS

Abstract: The possibility of use of the Magneto-Rheological Fluids (MRFs) in armours, particularly in bullet-proof vests, is presented in this paper. The requirements for the MRFs to be applied for this specific use, the factors which influence on their properties and the behaviour of the MRFs under a magnetic field are described. The comparison of three LORD MRFs with different mass concentration of the ferromagnetic particles: 72%, 80.98% and 85.44% is made. Based on the behaviour of the Shear Thickening Fluids (STFs) one of these MRFs has been chosen as the best for the bullet-proof vests, and the ways of its application are proposed. As the source of the magnetic field it has been selected a solenoid supplied by the Li-Po battery.

THE POSSIBILITY OF USE OF THE MAGNETO-RHEOLOGICAL FLUIDS IN ARMOURS

Streszczenie. W pracy zaprezentowano możliwości wykorzystania cieczy magnetoreologicznych (MRF) w pancerzach, szczególnie w kamizelkach kuloodpornych. Przedstawione zostały wymagania stawiane cieczom magnetoreologicznym do zastosowania ich w kamizelkach kuloodpornych, a także czynniki wpływające na właściwości cieczy magnetoreologicznej oraz opisano jej zachowanie pod wpływem pola magnetycznego. Zostały porównane trzy ciecze LORD o różnych stężeniach wagowych cząsteczek magnetycznych: 72%, 80,98% i 85,44%. Na podstawie aplikacji cieczy zagęszczających się pod wpływem dużych szybkości ścinania (STF) wybrano jedną z cieczy magnetoreologicznych, która najbardziej nadaje się do stosowania w kamizelkach kuloodpornych i zaproponowano sposoby jej aplikacji. Zaproponowano baterię litowo-polimerową Li-Po jako źródło zasilania solenoidu do wytwarzania pola magnetycznego w kamizelkach z cieczą MRF.

1. Introduction

The armours are used for protection of bodies (mainly bullet-proof vests and helmets), land and flying vehicles and/or for objects against the influence of destruction agents. Their properties like resistance to penetration, ease of fixing, shelf life or ease of regeneration are constantly improved and their masses are diminished.

In case of the bullet-proof vests the main aim of research and development is to improve freedom of movement for its holder,keeping the resistance to perforation at least on the current level.

There are attempts undertaken fort he use of the shear thickening fluids (STFs) and the magneto-rheological fluids (MRFs) for this purpose.

The characteristic feature of the STF is thickening under influence of high shear rate, then adoption of properties of a solid body [1].In case of the MRF, the same properties are created under influence of the magnetic field [2]. These features allow for better absorption and dissipation of kinetic energy of a projectile on a larger area.

The MRFs for use in the bullet-proof vest shave to fulfil special requirements: they have to be non-toxic, able to operate in temperature of - 40÷50^{o}C and their rheological properties should significantly change in as low range of the magnetic field intensity as possible.

The non-toxicity of the MRF is a very important feature, particularly in case of the perforation of the bullet-proof vest. Any direct skin contact or the MRF penetrating into the blood stream shall not cause any disturbance in functions, disabilities or death of the human cells or organs. The ability to operate in the temperature of - 40÷50^{o}Callows for use of the bullet-proof vests in various atmospheric conditions.

The yield stress of the MRF should increase in the range of the magnetic field intensity as near zero as possible, to make the apparent viscosity of the fluid higher than it would be in case of high shear rates, without any influence of the magnetic field. This makes possible saving of the energy for producing of the magnetic field.

2. Properties of the MRF

Rheology is the science about materials showing very complicated mechanical properties of fluids and solids, which are defined by relationships between external influence (forces loading the body) and internal reactions of the material (deformation of the body). Rheology describes the processes of plastic deformation and material flow during changes in shear [1].

Magneto-rheology is a part of rheology focusing on flow and deformation of materials under influence of the magnetic field. The MRF is a suspension of small ferromagnetic particles (1÷5 μm) in the non-magnetic oil (Fig. 1). The ferromagnetic particles are covered by a film of oil, which prevents their agglomeration. Under the influence of the magnetic field the particles create a chain, which significantly changes the parameters of the fluid. Such behaviour is called a magneto-rheological effect.

Fig. 1. View of the MRF under a microscope[2]

The factors that influence on the properties of the MRF can be divided into internal and an external ones. The internal factors, such as type of the ferromagnetic particles, their magnetic saturation, concentration, size and distribution of the particles, viscosity and thermostability of the carrier fluid, and a kind of stabilizer, depend on a composition and a structure of the fluid. The external factors include magnetic field intensity, shear rate and thermodynamical parameters of the fluid, i.e. temperature and pressure.

The MRF shows high sensitivity to influence of the magnetic field. Without any magnetic field effect it behaves similarly to the Newtonian fluid, for which the dependence between the shear rate γ and the shear stress τ is linear. Under the influence of the magnetic field the MRF behaves like the Bingham fluid, which characterizes with the initial stress τ_f, depending on the magnetic field intensity H, which is the yield stress of the material. Below the initial stress τ_f the MRF behaves as a solid(Fig. 2) [2].

$$\tau = \tau_f(H) + \eta_B \gamma \quad (1)$$

where: τ – shear stress, τ_f – initial (yield) stress, H – magnetic field intensity, η_B – Bingham viscosity, γ – shear rate.

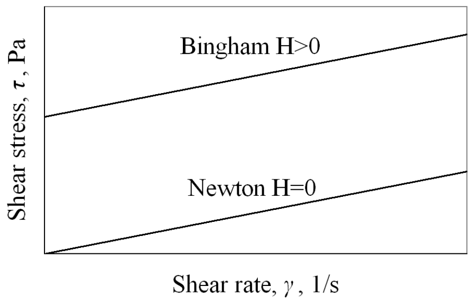

Fig. 2. Flow curve for the MRF with (*H*>0) and without (*H*=0) influence of the magnetic field [2]

The yield stress τ_f can be controlled by the change of the magnetic field *H*, which influences on the fluid, and its occurrence is caused by creating a chain of the ferromagnetic particles (Fig. 3).

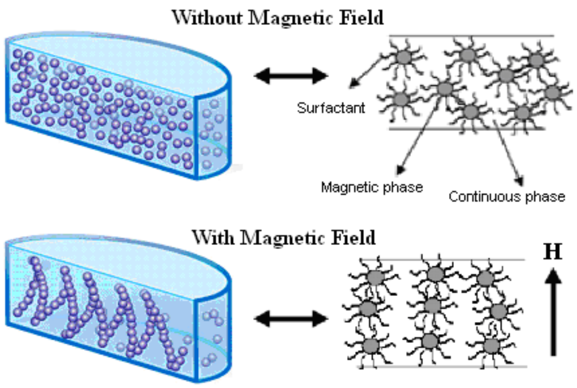

Fig. 3. Scheme of the chain of ferromagnetic particles, forming towards the magnetic field *H* [2, 3]

Each of the particles becomes a dipole and tends to create a chain with a neighbouring particle, which causes change of the apparent viscosity μ_{app}(2). The effect is fully reversible.

The apparent viscosity μ_{app}(2) is the ratio between the shear stress τ and the shear rate γ. It is the same relationship which can be used for counting viscosity of the Newtonian fluid, however it does not refer to the non-Newtonian fluid.

$$\mu_{app} = \tau/\gamma \tag{2}$$

where: μ_{app} - apparent viscosity, τ - shear stress, γ - shear rate.

The MRF is a two-phase fluid, so there is a friction between one phase (the ferromagnetic particles)and the second (the oil). The apparent viscosity is a super position of the both phases viscosity and also relations between the ferromagnetic particles under the magnetic field effect in the chain created by them [1].

If any external force influences on the chain created under the magnetic field [2]it will be deformed (Fig. 4). The external force may be created by a shift of the magnet (a), activation of the MRF flow (b) and bringing the magnets near each other (c).

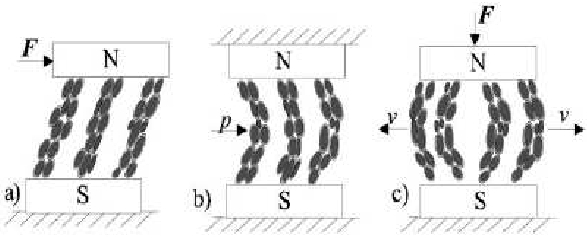

Fig. 4. Deformation of the ferromagnetic particle chain caused by the external force:
a -shift of the magnet,
b - activation of the MRF flow,
c -bringing the magnets near each other

The magnetic particles chain deformed by the influence of the external force returns to the previous state when the external force stops acting. It is applied in the automotive sector, e.g. in brakes as a liquid between brake discs, for sealing up the valves and may find application in the armament as a damper, which could be used in the armour designing for partial absorption of the kinetic energy of the projectile.

One kind of the magneto-rheological fluids is the LORD MRF, very popular and easily available. The basic physical properties of the types: LORD MRF-122EG, LORD MRF-132DG and LORD MRF-140CG are shown in Table 1.

Table 1. Basic physical properties of the LORD MRFs[4÷6]

Property	**LORD MRF-122EG**	**LORD MRF-132DG**	**LORD MRF-140CG**
Appearance	Dark gray liquid	Dark gray liquid	Dark gray liquid
Solids content byweight, %	72	80.98	85.44
Density, g/cm^3	2.28	2.98÷3.18	3.54÷3.74
Operating temperature,^{o}C	-40÷130	-40÷130	-40÷130
Apparent viscosity,Pa·s*	0.042±0.020**	0.092±0.015***	0.280±0.070***
Flash point,^{o}C	>150	>150	>150

*measured at 40^{o}C, **measured in the shear rates range of 500÷800 s^{-1}, *** measured in the shear rates range of 800÷1200 s^{-1}

These types of LORD MRFs differ by mass concentration of the ferromagnetic particles, what influences significantly on their density and apparent viscosity. The increase of mass concentration from 72% to 85.44% caused growth of the density of about half of the value, while the increase of mass concentration from 80.98% to 85.44% quadrupled the apparent viscosity. However, the change of concentration does not influence on the flash point, which is over 150^{o}C for all of them.

Table 2. Magneto-rheological properties of the LORD MRFs[4÷6]

Property	**LORD MRF-122EG**	**LORD MRF-132DG**	**LORD MRF-140CG**
Response to the magnetic field changes	Immediate and reversible	Immediate and reversible	Immediate and reversible
Shear stress under influence of the magnetic field	High	High	High
Shear stress without influence of the magnetic field	Very low	Very low	Very low
Control of the shear stress	Wide range	Wide range	Wide range
Causing abrasion	No	No	No

Although the properties of the MRFs significantly change when the concentration increases, they are suitable for application in the armours. All of the fluids compared in Table 2 show an immediate and reversible response to the magnetic field changes, high shear stress under influence of the magnetic field, wide range of the shear stress control by change of the magnetic field and non-abrasiveness, what can be important for use in the bullet-proof vests.

When the concentration of the magnetic particles in the MRF increases the shear stress τ is higher and it increases faster with increasing of the shear rate γ (Fig. 5).The distributions of the shear stresses τ increases linearly above the shear rate γ=50 1/s for all concentrations of the LORD MRF.

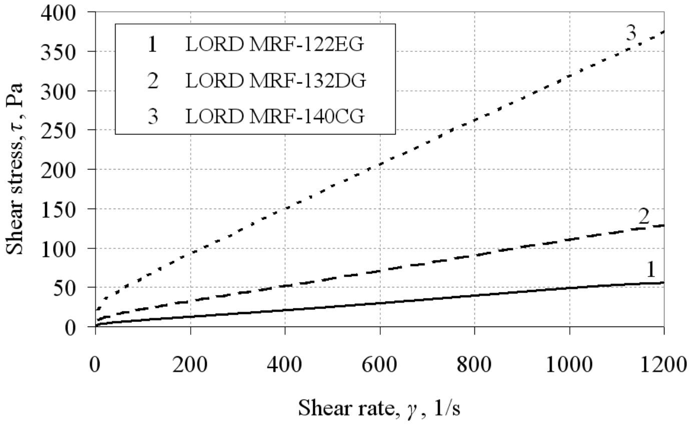

Fig. 5. Flow curve for the LORD MRFs [4÷6]

When the concentration of the magnetic particles in the MRF increases the yield stress $\tau_f$for a given value of the magnetic field *H*also increases (Fig. 6).

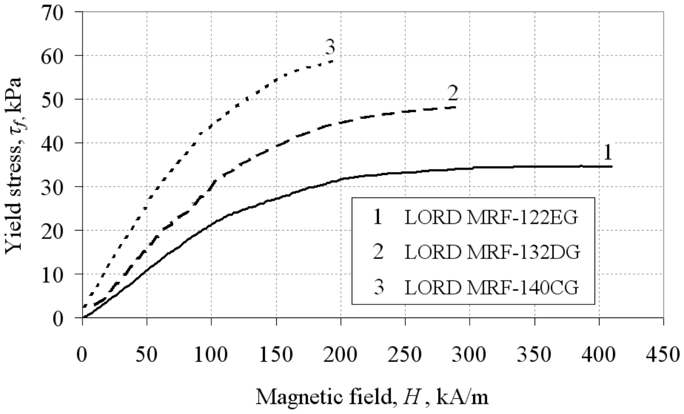

Fig. 6. Yield stress τ_f under the different magnetic field intensity *H* for the LORD MRFs [4÷6]

The biggest increment of value of the yield stress τ_f for all concentrations of the LORD MRFs is visible in the range of magnetic field *H*=0÷100 kA/m, and it changes linearly. For *H*=100 kA/m the yield stress $\tau_f$of the LORD MRFs reaches about 60% of maximum value, for *H*>100 kA/m the influence on the yield stress $\tau_f$decreases, but for *H*=300 kA/m it is insignificant.

The magnetic field has much more influence on the yield stress τ_f than the shear rate γ. In the range of *H*=0÷100 kA/m the yield stress of the LORD MRF-140CG,havingmass concentration of 85.44%, is twice more than the yield stress of the LORD MRF-122EG, having mass concentration of 72%. Taking into consideration these features the LORD MRF-140CG should be the best for use in the bullet-proof vests.

The LORD MRFs may cause irritation of skin and alimentary or respiratory systems in case of long contact with skin, accidental swallowing of the fluid or breathing in its vapours. The non-toxicity of the MRFs is a very important feature, particularly in case of the bullet-proof vest perforation. However, the producer of the LORD MRFs does not inform about any effects of their contact with blood or penetrating in to the bloodstream.

3. Application of the MRFs in the armours

The application of the MRFs is still developed. The MRFs are used in different parts of science, e.g. in the engineering and armament technology. In the armament the MRFs may be used for construction of the smart bullet-proof vests and in the armours of the armoured vehicles.

The bullet-proof vests are built from layers of material made of the aramid polymer fibres, adjoining to each other. The most popular aramid polymers are Kevlar, Twaron and Spectra, which are characterized by the high strength of the fibres. In the layer the fibres interact between each other, which in turn effects on the other layers absorbing the projectile energy on a large area, and the same protecting these layers against penetration. This also enables the bullet-proof vests to prevent trauma of the internal organs, caused by the after-hit shock, the so-called "blunt trauma".

In order to improve quality of the bullet-proof vests there are undertaken some attempts for the STFs and MRFs use for their construction. The consecutive layers of Kevlar one can impregnate by these fluids, or the fluids can be inserted into plastic bags, placed between the layers of Kevlar, properly saturated by the MRF. In case of the STF, the Kevlar should be saturated with the diluted fluid, then warmed in the temperature of 80^{o}C for 20 minutes, in order to evaporate ethanol[8].

In case of the fluid insertion into the plastic bag it is important to focus on its construction and closure. The plastic bag, as well as the weld of its closure, should be strong enough to avoid spilling out of the fluid during normal use of the bullet-proof vest. Also, in case of a gunshot both the bag and the weld should have maximum resistance to puncture. For cracking of the bag it is important to check which place of the bag is much advantageous in case of a very high pressure impact: the weld of the bag’s closure or somewhere else. The found solution one can verify by impairment of the bag's construction in the relevant place.

It has been made a comparison of methods of the STFs use in the Kevlar layers and for different configurations (Fig. 7) [8].There is no such comparison for the MRFs in the literature.

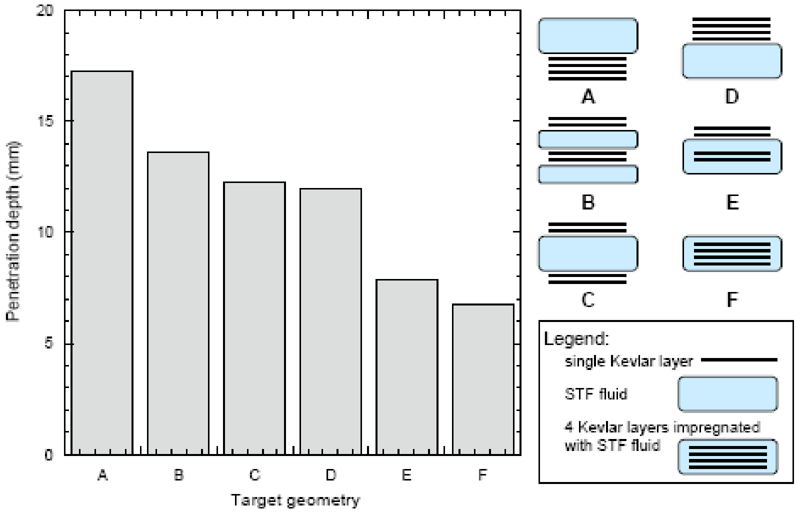

Fig. 7. Comparison of penetration depth of different Kevlar layers with the use of the STFs in different configurations[8]

In order to obtain the least penetration depth the most advantageous is the impregnation with the STF of all the Kevlar layers (Fig. 7f), or a part of them (Fig. 7e).In case of the use of the STF in plastic bags, it is important to place them behind the maximum number of the Kevlar layers (Fig. 7d), as the penetration depth is the least and the resistance of the bullet-proof vest is the best. Four layers of Kevlar impregnated with the STF can dissipate the same amount of energy as 14 Kevlar layers without any impregnation [8]. It is caused by lower stretchability of the impregnated fibres, consequently the penetration depth is also smaller. The Kevlar layers should be impregnated with the MRF in the same way.

The application of the MRF in the bullet-proof vests is much complicated than the use of the STF. In the propitious moment one has to turn on the magnetic field, generated e.g. by a solenoid, and to deliver a source of energy for it. The solenoid is used for generation of the homogenous magnetic field, which intensity H is proportional to the number of the solenoid coils N and to the current intensity I, and is in inverse proportion to the length of the solenoid l.

$$H=NI/l \tag{3}$$

where: H - magnetic field intensity, N -number of the solenoid coils, I - current intensity, l - length of the solenoid.

In case of the flat solenoid the number of the coils N=1, so the magnetic field intensity H depends on the current intensity I and the length of the solenoid l.

For generation of the magnetic field the solenoid needs a source of energy. The comparison of available batteries is shown in Table 3.

Table 3. The comparison of available batteries [9]

Type of battery	**Nickel-Cadmium**	**Nickel-Metal-Hydride**	**Lithium-Ionic**	**Lithium-Polymer**
Symbol	NiCd	NiMH	Li-Ion	Li-Po
Intensity of individual cell, V	1.2	1.2	3.6	3.7
Energy density, Wh/kg	40	80	150	150
Capacity, Ah	33	66	41	40
Self-discharge rate,%/month	10	20	2÷5	2÷5

The basic criterion for selection of the source of supply is its power. The Nickel-Cadmium(Ni-Cd) and the Nickel-Metal-Hydride (NiMH) batteries are the obsolete devices, which capacity is getting lower in case of start up re-charging before their total discharge. The Lithium-Ionic (Li-Ion) and Lithium-Polymer (Li-Po)batteries give the biggest concentration of energy, even twice more than the NiMH battery of the same mass. The Li-Po battery is the modernized type of the Li-Ion battery and can have any shape. For this kind of battery it is possible to build cells in a shape of the 1 mm thick foil, supplying devices of the credit card size. With regard to it such cells would be the best source of energy for the use in the bullet-proof vests. Additionally, the Li-Po batteries contain only solids and gels, without any liquid chemicals. It eliminates the danger of spilling out and thus housing this battery into a metal casing is not necessary.

In case of the armoured vehicles one can use the MRFs for construction of the armours or as a damper in the additional armour of the vehicle. The MRF would be placed between two sheets of the armour steel (Fig. 4c). The elastic strain of the MRF would damp a part of the projectile kinetic energy, causing less deformation of the additional armour. The MRF could be placed in the plastic bags and the armour should adjoin them on both sides.

4. Conclusions

On the basis of the analysis of the literature there can be drawn the following conclusions:

1. It is necessary to check if the LORD MRFs meet the requirement of non-toxicity.
2. The increase of concentration of the LORD MRF from 72% to 85.44% causes twice more increase of the yield stress in the range of magnetic field H=0÷100 kA/m.

3. The yield stress of the LORD MRF changes linearly in the range of magnetic field H=0÷100 kA/m, independently from the concentration, and it reaches 60% of maximum value for H=100 kA/m.
4. The maximum yield stress for the LORD MRF under influence of the magnetic field ($H \geq 300$ kA/m) may increase even about 200-fold.
5. Four layers of Kevlar impregnated with the STF may dissipate the same amount of energy as fourteen layers of Kevlar without any impregnation. It is necessary to check whether impregnation of the Kevlar layers with the MRF gives the similar effect.
6. A solenoid, Lithium-Polymer (Li-Po) battery-powered, may be used for the magnetic field generation.
7. The cells of the Li-Po batteries can occur in a shape of 1 mm thick foil, suitable for the devices with the size of e.g. a credit card.

This work was co-financed by European Fund for Regional Development in Poland (Project "Smart passive body armours with the use of rheological fluids with nanostructures" under the Contract No.UDA-POIG.01.03.01-00-060/08-00) and carried out in co-operation between the Institute of Security Technology "MORATEX" (Instytut Bezpieczeństwa "MORATEX"), Warsaw University of Technology (Politechnika Warszawska) and the Military Institute of Armament Technology (Wojskowy Instytut Techniczny Uzbrojenia).

5. References

[1] Wilczyński K.: *Rheology in plastic processing*, Scientific and Technical Publishing, Warsaw, 2001.

[2] Zipser L., RichterL., LangeU.: *Magneto-rheological fluids for actuators*, Sensors and Actuators A, 92, 2001, pp. 318÷325.

[3] *How liquid armour works*, www.science.howstuffworks.com/liquid-body-armor 2.htm

[4] *MRF-122EG Magneto-Rheological Fluid*, LORD Technical Data, LORD Corporation OD DS7027 (Rev. 1 7/08).

[5] *MRF-132DG Magneto-Rheological Fluid*, LORD Technical Data, LORD Corporation OD DS7027 (Rev. 1 7/08).

[6] *MRF-140CG Magneto-Rheological Fluid*, LORD Technical Data, LORD Corporation OD DS7027 (Rev. 1 7/08).

[7] *How does a bullet-proof vest work?*,www.bodyarmornews.com/bullet-proof-vest.htm

[8] Wiśniewski A.: *Nanotechnology for increase of body protection*. Problems of Armament Technology (Problemy Techniki Uzbrojenia), Military Institute of Armament Technology, Zielonka, Poland, Vol. **107**, 3/2008, pp. 7÷14.

[9] *How does a battery work*, www.komputerswiat.pl/jak-to-dziala/2010/01/jak-dziala-akumulator.aspx