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Dynamic stab resistance of ultra-high molecular weight polyethylene fabric impregnated with shear thickening fluid

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ABSTRACT

The dynamic stab resistance properties of ultra-high molecular weight polyethylene (UHMWPE) fabrics impregnated with shear thickening fluids (STFs) were investigated. The chemical composition of dispersing medium in STF was varied. The resistance mechanism of woven fabrics against knife and spike threats was discussed and the role of STF in stab resistance improvement of UHMWPE fabrics was analyzed in detail. To further improve the stab resistance performance, the influence of polyethylene glycol (PEG) additives with different concentrations and molecular chain lengths on the stab resistance of STF/UHMWPE composites was investigated. The results demonstrate that the dynamic stab resistance of UHMWPE fabric is significantly enhanced due to the presence of STF. STF effectively decreases the yarn mobility and accelerates the transverse response of UHMWPE fabric. With the molecular weight of dispersing medium increasing, the energy dissipated by STF/UHMWPE fabrics decreases. Further, the stab resistance properties of STF/UHMWPE composites, especially the spike resistance, are improved with the increase of the concentration and the molecular chain length of additive.

1. Introduction

Soft body armors are generally made of fabrics woven with high performance yarns [1]. However, conventional soft body armor is relatively bulky and inflexible since many layers of fabric are required. In order to improve the flexibility without reducing the effective protection, shear thickening fluids (STFs) are combined with high-performance fabrics to fabricate a new body protective material, which is also called liquid body armor [2]. STFs are non-Newtonian fluids, whose apparent viscosity increases dramatically when the shear rate reaches a critical value [3–5]. The shear thickening phenomenon is characterized by the formation and percolation of shear induced transient aggregates, or “hydroclusters”, which cause flow jamming and increase the viscosity dramatically [6,7]. STFs can transfer into a solid substance rapidly when countering a strike and turn back into liquid removal of the impact.

Efforts have been made by researchers in investigating the impact resistance of the advanced protective material which is composed of aramid fabrics and STFs. Lee et al. [2] found that the ballistic properties of aramid fabrics was improved by impregnating colloidal STFs. In addition, they demonstrated that the enhanced ballistic performance of impregnated fabric was due to the addition of STF to the fabric, not due to the increased target mass or solvent effects on the fabric weave. Egres et al. [8] reported that the stab resistance of STF-treated fabrics exhibited significant improvement over neat fabric targets with equivalent areal density. Majumdar et al. [9] demonstrated that the transformed STF acted as a bridging matrix which converted the network of Kevlar yarns in the fabric into a single structure during impact so that more yarns participated in load bearing and energy absorption in STF-treated fabrics than in untreated ones. Yurim et al. [10] conducted a numerical study of the impact energy absorption characteristics of STF-impregnated Kevlar fabric with a focus on minimal computational cost and friction. The results showed that the major factor behind the energy absorption mechanism was assumed to be the friction between the impactor, fabric, and yarns within the fabric during impact. Gong et al. [11] investigated the influence of the shear thickening fluid types on the knife stab and puncture resistance performance of STF/Kevlar composite. The results showed that the knife stab and puncture resistance of the shear thickening fluid-fabrics exhibited significant enhancement. The hardness of the particles was the dominant factor for the knife stab resistance, while the inter-yarn friction played a critical role for improving the puncture resistance. Feng et al. [12] studied the effects of fumed silica and submicron silica particles in shear thickening fluids on quasi-static stab resistance properties of Kevlar fabrics impregnated with shear thickening fluids. It was found that quasi-static stab resistant properties of treated fabrics containing submicron silica particles were better than that of treated fabrics containing fumed silica particles. Diana et al. [13] performed an investigation of chemical surface modification of woven p-aramid fabrics by applying different chemical composition shear thickening fluid. The results showed that the application of low concentrations of silicic acid determined higher stab resistance values comparing to higher concentrations of acrylic dispersion water solutions. Laha et al. [14] investigated the influence of STF in improving the dynamic impact resistance performance of p-aramid fabrics with

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different weave structures and thread densities. It was reported that the increase in impact energy absorption after STF treatment was more for infirm weaves (matt and satin) as compared to that for firm weave (plain) and it reduced with the increase in thread density of fabric. Majumdar et al. [15] studied the influence of process parameters like padding (squeezing) pressure and silica concentration in STF on dynamic impact performance of Kevlar/STF soft composite. It was found that higher padding pressure reduced the STF add-on% on Kevlar fabrics making the composite lighter. However, the impact energy absorption by the Kevlar/STF composite increased with the increase in padding pressure due to better and uniform distribution of STF within the fabric and yarn structures. Ahn et al. [16] characterized the shear properties of STF-treated aramid fabrics using a picture frame test. It was concluded that strong silica particles reinforced the fabric, in particular by increasing the frictional resistance.

Apart from aramid fabric, there have been other high-performance fabrics utilized in liquid armor. Hassan et al. [17] reported on the knife resistance of STF/Nylon composite and found that STF-treated target exhibited higher loading than neat Nylon target. Egres et al. [8] explored the stab resistance of STF/Nylon composites and reported that puncture resistance increased measurably as yarn denier of the Nylon fabric decreased. Yu et al. [18] investigated the quasi-static stab resistance of STF/glass fabric composites and found that STF-treated glass fabrics offered superior stab protection as compared to neat targets for knife threats.

Ultra-high molecular weight polyethylene (UHMWPE) is a special type of thermoplastic fabric which shows great impact resistance performance due to its extremely long polymer chains. UHMWPE fibers retain high specific strength and low moisture absorption, which also have the lowest density (0.97 g/cm^3) of all fibers used for body armor [19]. Currently, there are few published studies on the stab resistance of UHMWPE fabrics impregnated with STFs. We had preliminarily synthesized STF/UHMWPE composites and found that the stab resistance of UHMWPE fabrics is greatly improved by impregnating STF [20]. In this paper, an effort has been made in further investigating the dynamic stab resistance properties of STF/UHMWPE composites. STF/UHMWPE fabrics with variations in the chemical composition of dispersing medium in STFs are fabricated and characterized. Analyzing the dynamic loads during stab process provides a better understanding of the role of STF in stab resistance improvement of UHMWPE fabrics. Additional results of dynamic stab test are included for STF/UHMWPE composites containing additives with different concentrations and molecular chain lengths (PEG6000 and PEG10000), which is considered as a means to further enhance the stab resistance.

2. Experimental details

2.1. Materials

Silica particles, which were selected as dispersing phase in STFs, were prepared through the catalyzing of tetraethylorthosilicate (TEOS) by ammonia solution and analyzed by X-ray diffractometer (D8ADVANCE0, Germany), Laser particle size analyzer (Mastersizer 2000e, Germany) and Scanning Electron Microscope. The results showed that the prepared particles were spherical in shape with an average particle diameter of about 500 nm. As the first step to fabricate STFs, a certain amount of silica particles were dispersed into ethylene glycol (EG) or polyethylene glycol (PEG, MW 200 or 400) by homogenization for several hours with a vortex hybrid device. Then the suspension was diluted with ethanol at a 1:1 volume ratio and irradiated by ultrasonic wave for about an hour. STF was obtained by placing the ethanol/suspension mixture in a vacuum drying oven at 60 °C for 24 h to evaporate ethanol. To synthesize STFs containing different additives, a certain amount of PEG (MW 6000 or 10000) was ground in an agate mortar and added into the STF during the stirring process.

Plain woven UHMWPE fabric with areal density of 120 g/m^2 was used in the research. The linear density of the high strength UHMWPE fibers is 400 denier, which are made in Jiangsu, China. The modulus of the fibers is 1300 g/d and the breaking elongation is 2.8%. To fabricate STF/UHMWPE composites, the UHMWPE fabrics were cut into 150 × 150 mm^2 layers and individually immersed in the ethanol/suspension mixture which had been mentioned in the preparation of STFs. Excess fluid was removed by squeezing each layer with a 2-roll mangle and then the fabrics were placed into the vacuum oven at 60 °C for 1 h to evaporate the ethanol. Eight layers of STF-treated fabrics were sealed together with polyethylene film as a specimen for the dynamic stab test. The parameters of the prepared STF/UHMWPE specimens are shown in Table 1. Moreover, a neat UHMWPE specimen was prepared as a contrast.

2.2. Rheological properties test of shear thickening fluids

The rheological properties of the as-prepared STFs based on different dispersing media were investigated by PhysicaMCR301. The test was carried out in a steady flowing mode at room temperature by using a cone plate of diameter 25 mm and angle 1° with the shear rate increasing from 1 s^{-1} to 100 s^{-1}. Prior to the rheological test, the STFs were placed in the vacuum drying oven on 25 °C for about 24 h to exclude the bubbles.

2.3. Dynamic stab resistance test

The dynamic stab resistance test against knife and spike threats was conducted on a homemade dynamic puncture tester based on NIJ standard [21]. The test equipment and stab impactors are shown in Fig. 1 and Fig. 2, respectively. During the stab, the specimens were placed on the top of the clay witness. The impact mass was mounted to a specific height and then released to puncture the specimens. The drop height was set 0.2 m, 0.4 m, 0.6 m for each sample and the weight of knife and spike impactors was both 2.38 kg. The dynamic resistance force was monitored and recorded by a load cell. The energy absorbed by the specimens during the penetration can be calculated from the initial velocity and penetration depth.

$$E_k = \frac{1}{2}\,\mathrm{m_k}\left(V_{ik}^{\,2} - V_{rk}^2\right) \tag{1}$$

$$E_s = \frac{1}{2}\,\mathrm{m_s}\left(V_{is}^2 - V_{rs}^2\right) \tag{2}$$

where E_k, E_s (J) represents the dissipated energy during the stab process for knife and spike threat, $\mathrm{m_k}$, $\mathrm{m_s}$ (kg) is the mass of knife and spike, V_{ik}, V_{is}(m/s) is the initial velocity of knife and spike, V_{rk}, V_{rs} (m/s) is the residual velocity after the impactors penetrate the specimens. To relate the penetration depth to the residual velocity, a series of experiments were carried out on the clay witness. The results show that the penetration depth as a function of velocity against knife and spike threats can be closely modeled by the linear relationship $Vr = 39.78436L\text{-}0.37405$ and

Table 1
Parameters of STF/UHMWPE specimens for stab test.

Sample	SiO$_2$ mass fraction (%)	Dispersing medium	Additive	
			Type	Concentration (%)
1	38	EG	/	/
2	38	PEG200	/	/
3	38	PEG400	/	/
4	38	EG	PEG6000	2%
5	38	EG	PEG6000	4%
6	38	EG	PEG10000	2%
7	38	EG	PEG10000	4%