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Stabbing resistance of body armour panels impregnated with shear thickening fluid

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ABSTRACT

This paper presents an investigation on the use of shear thickening fluid (STF) to improve stabbing resistance of soft ballistic body armour. STFs were produced from polyethylene glycol and silica nanoparticles. The effects of silica nanoparticle sizes and silica nanoparticle weight fraction were studied and STFs made with the different compositions were used to impregnate the Twaron® woven fabrics. Systemic investigations into rheological behaviour of STF were carried out experimentally on STFs with different compositions. STF impregnated woven fabric panels were created and tested for stabbing resistance. Stabbing impact tests were conducted on 6 different types of STF impregnated fabric panels against 2 untreated fabric panels, and the results were studied against the benchmark fabrics without STF impregnation. Based on the same number of layers of fabric, the STF impregnation improves the stabbing resistance notably. For same panel areal density, the STF impregnated panels outperform the untreated fabric panel. The results of this research indicate the possibility of lighter ballistic panel materials for higher stabbing protection. It was also found that higher nanoparticle weight fraction and larger nanoparticle size of silica leads to better stabbing resistance performance among the STF impregnated panels.

1. Introduction

Body armour for the military is designed to provide protection from the impact of high velocity projectiles such as bullets or bombshell fragments. High performance fibres such as aramid (e.g. Kevlar® and Twaron®), and ultra high molecular weight polyethylene (e.g. Spectra® and Dyneema®) have been used for engineering soft ballistic body armours [1]. These high strength, high modulus, high tenacity fibres have resulted in significant improvements in the performance of body armours against ballistic threats [2]. However, it seems that not sufficient attention was paid to the engineering of ballistic body armour for the anti-stabbing performance, which is obviously a serious concern for the body armour users. Anti-terrorist actions and regional conflicts necessitate the further development of protective and flexible armour systems with additional stab-resistant capabilities. Stab threats encountered by the body armour users include direct attacks from knives and sharpened instruments, as well as physical contact with debris, broken glass, and razor wire. The demand for improved protection against stabbing has also been motivated by civilian police forces, particularly in Europe, where restrictions on gun ownership have led to an increase in the proportion of assaults which are committed with knives [3].

Body armour designed with anti-ballistic function is not necessarily resistant to penetration of blades and armour specifically designed to withstand blade penetration is prohibitively bulky and heavy [4]. Hence, fabrication of body armour that provides protection against ballistic and stabbing impacts represents a meaningful effort. The major difficulty in improving stabbing resistance of ballistic body armour is that the stabbing resistance mechanisms differ from that for ballistic protection, because of the different impact velocities and different sharpness of the impactors [3,5]. Compared with ballistic impact, stabbing impact is more likely to cause stress concentration because of the sharp point and cutting edge of the impactor in the stabbing situation, whilst the material failure against ballistic impact is mostly caused by shear and tensile loading at high strain rate. In most cases, the stabbing impact velocity is in the range of 1–20 m/s, whereas that for ballistic impact 200–1000 m/s.

Much effort was to improve the stab resistance of ballistic fabrics. Thermal-sprayed hard ceramic coatings were applied to

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aramid fabrics to enhance stabbing protection [6]. The resulted material demonstrated increased energy absorption during the quasi-static stabbing test, but also added to fabric weight significantly the same time. Aramid fabrics with high yarn count were also developed to provide stabbing (puncture) resistance. However, these high yarn count fabrics were expensive to manufacture and typically resulted in decreases in ballistic protection efficiency of the fabrics [7]. One of approaches to enhance the stabbing resistance is to roughen the surface of fibres or yarns by sanding or corona treatment to achieve higher coefficient of friction. However, such roughening is believed to have limited utility due to the resultant degradation in the fibre [8].

Shear thickening fluid (STF) has attracted attention for impact protection due to its unique viscosity variation subject to impact. STF is a non-Newtonian fluid and shear thickening behaviour is triggered by sudden increase of shear rate to the STF, which causes the colloidal dispersions to be concentrated exhibiting abrupt increase in viscosity. This transforms a liquid dispersion into a solid-like material state [9–11]. Barnes [9] and Brown [12] reported that the shear thickening behaviour of an STF is influenced by many factors including the particle size and size distribution, particle shape, polydispersity of the particles, particle concentration, and interactions among particles, as well as the properties of the dispersion medium. The shear rate triggering shear thickening transition is referred to as the critical shear rate, which can be determined by using experimental and theoretical methods. Van der Werff and De Kruif [13] studied the methods to manipulate the critical shear rate and the viscosity increase of STF, and confirmed that lower critical shear rate and amplified severity shear thickening viscosity of STFs can be achieved by using larger particle size and higher particle volume fraction.

Work has been done to investigate impact properties of fabrics impregnated with STFs. It has been reported that STF enhanced fabrics were able to take advantages of STF properties for the enhancement of ballistic performance and stabbing resistance [14–17]. Work on ballistic and stabbing performance of body armour showed that improved impact resistance of STF-impregnated fabrics could be attributed to the shear thickening behaviour [18–19]. The deformation and energy absorption modes of STF impregnated and untreated Kevlar® woven fabrics upon impact was analysed by Majumdar et al. [20], and they reported that in the untreated Kevlar® fabrics, only the primary yarns, directly engaged by the impactor, participated the load sharing and energy absorption, leading to low energy absorption. In case of STF impregnated fabrics, the STF was transformed into a solid-like material upon impact and the transformed STF acts like a bridging matrix that converted the network of yarns in the fabric into a single structure. In this case, the entire fabric rather than only the primary yarns participated in load bearing and energy absorption. The failure of the STF impregnated structure is by rupture of fibres and yarns rather than their slippage. Some other studies showed that the enhancement of impact resistance was due to higher inter-yarn friction in the fabric brought by STF with constraining the pull-out of yarns [18,21–23].

It seems to be clear that STF is able to enhance the performance of the panels against low velocity impact such as stabbing, but the STF impregnation would definitely add weight to the panel. The research described in this paper aimed to investigate the feasibility of lightweight armour panels impregnated with STF. STFs with different constructional parameters were studied for impact behaviour and STF impregnated fabrics and panels were evaluated based on practical experiments for stabbing protection with respect to the areal density of the panels.

2. Materials and experiments

2.1. Experimental materials

2.1.1. Woven ballistic panel materials

Aramid fibres are popularly used as protective materials for ballistic and stabbing protection. In the chemical construction, aramid has aromatic rings between the amide groups that contribute to the high tensile strength and thermal resistance of the fibres. According to the different orientated chemical linkages, there are *meta*-aramid (e.g. Nomex®) and *para*-aramid (e.g. Kevlar® and Twaron®), the chemical structure of which are shown in Fig. 1. Because of the structural differences, *para*-aramid fibres demonstrate higher mechanical properties than the *meta*-aramid fibres.

In this research, a Twaron® filament yarn was used for producing the plain woven fabric, and the fabric specifications are described in Table 1.

It is necessary to mention that the thread density 8 picks/cm was the optimal results from previous studies with the given yarn count, leading to best ballistic performance [24].

2.1.2. Preparation of shear thickening fluids

The STF colloidal dispersions employed in this research were made from silica nanoparticles and PEG (Polyethylene Glycol). In order to explore the performance of shear thickening fluid upon shear load, different particle sizes and different particle weight fractions (concentrations) were taken into consideration during the STF preparation.

Two different silica nanoparticle sizes (650 nm and 12 nm), supplied by Sigma-Aldrich (Germany), were used in STF preparation. The specific density of the nanoparticles is 36.8 kg/m^3 at 25 °C. For both 12 nm and 650 nm particles, three silica weight fractions, 20%, 25% and 30%, were used in making the STFs. 30% particle weight fraction was the maximum concentration that was able to achieve for the 12 nm silica STF because of the higher free surface energy of the 12 nm silica particles. The same particle weight fractions were adopted for making STFs from the 650 nm silica particles for comparison purposes. A previous research [13] on critical shear rate showed that high silica particle fraction led to lower critical shear rate and greater increase of shear thickening viscosity, and vice versa.

The STFs were synthesised by intensive mixing of silica nanoparticles in polyethylene glycol (PEG). PEG was chosen as a solvent due to its non-toxicity, low volatility, thermal stability and its ability to form hydrogen bond with the aramid fibres [25]. PEG can be made to have different molecular weight, such as PEG200, PEG400 and PEG600. Park et al. [22] found the molecular weight of PEG would not affect the STF performance significantly, and accordingly only PEG200 was chosen for the current research for the investigation into the nanoparticle size and particle weight fraction. Additionally, PEG200 has the lowest viscosity and is easier for production of STFs. The volume density of PEG200 is 1.127 g/cm^3 [26].

A high speed homogenizer (Silverson L4R homogenizer emulsifier) was used with the speed of 6000 rpm to stir the solution while adding silica powder into the PEG so as to achieve even distribution of particles in the STFs. Ultrasonic wave vibration also was used to improve STF quality. The STFs were placed in a vacuum chamber at room temperature for 24 h to remove the air bubbles prior to rheological measurement.

2.1.3. Fabrication of STF-Twaron® composites

This task aimed to impregnate the Twaron® fabric with the produced STFs. Due to the high viscosity of the STFs, they were diluted with ethanol at a 3:1 vol ratio between ethanol to STF to reduce the