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Synthesis and Stab Resistance of Shear Thickening Fluid (STF) Impregnated Glass Fabric Composites

Abstract
A shear thickening fluid (STF) was prepared successfully and its rheological behavior was investigated. Glass fabrics were soaked in STF/ethanol solution to prepare STF-glass fabric composites. The morphologies of the STF-glass fabric composites were observed by SEM. Quasi-static stab-resistant tests were carried out on both the neat glass fabrics and STF-glass fabric composites using a knife based on the areal density. The corresponding puncture and strengthen mechanisms were also investigated.

Key words: *shear thickening fluid, rheological property, glass fabrics, composites, impact behavior.*

Introduction

Shear thickening fluid (STF) exhibits non-Newtonian flow behaviour defined as an increase in viscosity with an increasing shear rate or applied stress [1 - 3]. It has been demonstrated that the shear thickening behavior is due to the formation of jamming clusters resulting from hydrodynamic lubrication forces between particles, often denoted by the term ‘hydroclusters’ [4 - 6]. It means that the shear thickening phenomenon can induce dramatic changes in the suspension microstructure, such as particle aggregation, which results in poor fluid and coating qualities [7, 8]. Motivated by recent developments in liquid body armor technology, fabricating fabrics from STF has been attempted [9]. Wagner’s group and the United States Army research lab investigated the ballistic properties of woven Kevlar fabrics impregnated with shear thickening fluids [10, 11]. These research results showed that the ballistic penetration performance of STF/Kevlar fabric composites was a significant improvement over neat Kevlar fabric targets of equivalent areal density. In the latest research paper, it was reported that STF could be synthesised using the sonochemical method, and explored this shear thickening phenomenon successfully to enhance the stab protection afforded by woven nylon fabrics [12]. The results showed that the penetration resistance of STF/Nylon fabric composite targets were increased greatly as compared to neat Nylon fabric targets for both spike and knife threats.

It is well-known that glass fibres are widely used in the textile industry. And with the development of science and technology, glass fibres have begun to appear in the body armour area. Compared to aramid fabric, the manufacturing processes are much simpler and the costs of glass fabrics much lower. Thus in this study glass fabrics were used to replace aramid fabrics in hope of getting useful data in the application of glass fibres in the protection of the body armour area.

The objective of this study was to synthesise the shear thickening fluid using silica nanoparticles directly under regular stirring and attempt to explore this shear thickening phenomena to enhance the stab protection afforded by woven glass fabrics. The puncture mechanisms were also investigated.

Experimental

The STF was prepared by adding 22 g of silica nanoparticles (d = 12 nm, 200 ± 5 $m^2 \cdot g^{-1}$) directly into 78 mL of polyethylene glycol (PEG) at a speed of 800 r.p.m. and stirring for about 5 hours. The preparation of the STF/glass fabric composites were as follows: The STF was first diluted in ethanol at a 3:1 volume ratio of ethanol:STF. The glass fabrics were then soaked in the ethanol/STF mixtures for 2 minutes, squeezed to remove excess fluid and dried at 65 °C for 2 h. The glass fabrics were of plain woven construction of 40 × 30 yarns per inch with an areal density of 194 g/m^2.

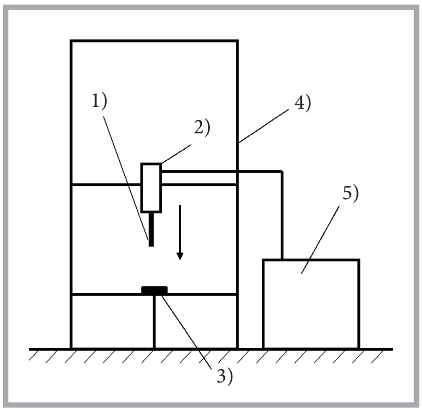

Figure 1. Quasi-static stab experimental device; 1) standard test tool, 2) sensor, 3) ring clamp, 4) backer, 5) stab-proof recorder.

Rheological measurements were carried out on a stress-controlled rheometer (Rheometrics, AR2000, TA, America) at 25 °C, with the cone-plate geometry having a cone angle of 2 ° and a diameter of 40 mm. The morphologies of the STF/glass fabrics composites were characterised by means of a scanning electron microscope (SEM, Quanta-200, FEI, the Netherlands). According to the GA68-2008 standard of the People’s Republic of China and the NIJ standard 0115.00 (stab resistance of personal body armour), the quasi-static stab-resistant tests were performed on a modified electronic fabric strength tester (E-fabric Strength Tester, HD026H, Hongda, China), as shown in ***Figure*** 1.

Results and discussion

Figure 2 shows the steady apparent viscosity as a function of the shear stress and its corresponding schematic diagram. Both shear thinning and shear thickening behavior were clearly observed. By increasing the shear stress the viscosity began to plateau, followed by a transition to shear thickening behavior at high shear stress. A shear thickening transition was observed to occur at a shear stress of 29.91 Pa. At a high shear stress this shear thickening transition is assumed to be the result of a microstructural change, where the hydrodynamic forces overcome interparticle forces to create hydroclusters [4 - 6].

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The SEM micrographs presented in ***Figure 3*** show pictures of raw glass fabric and STF/glass fabric composite samples at different magnifications. Compared to the SEM images of raw glass fabric presented in ***Figure 3.a***, SEM images of the STF/glass fabric composite presented in ***Figure 3.b*** clearly show that STF was well dispersed over the entire surface of the glass sheet. It can be seen in ***Figure 3.c*** that STF was completely immersed into the fibre surface and incorporated between fibres, due to the capillary effect of glass fibres. Moreover, as shown in ***Figure 3.d***, the morphologies of silica nanoparticles could be clearly seen, and the dispersion was remarkably uniform. These images revealed that the shear thickening fluid infiltrated the glass fabrics very well, penetrating between fibres within the yarn. In other words, it meant that the STF/glass fabric composites were prepared successfully.

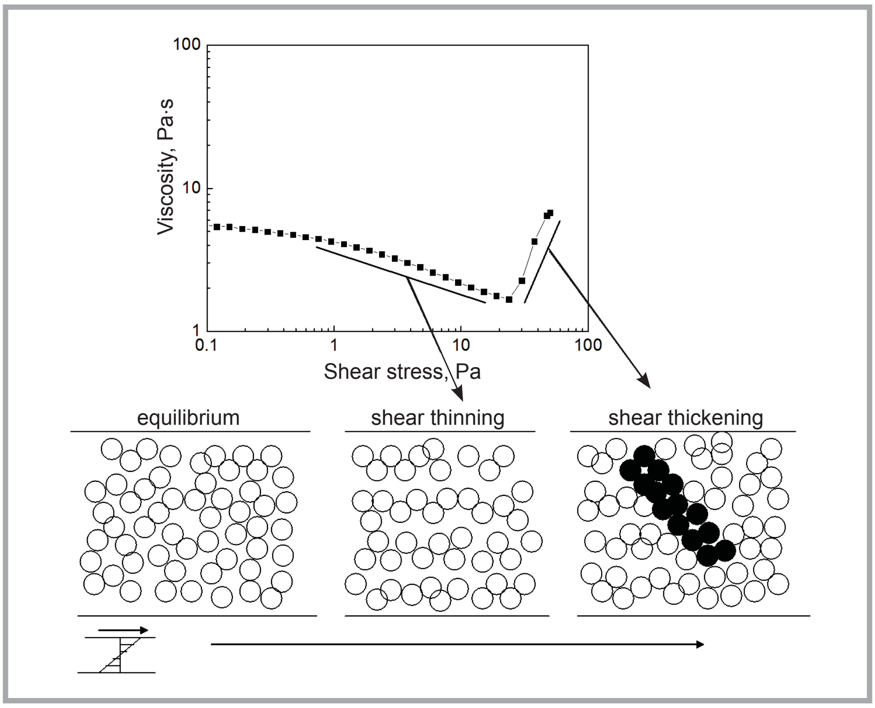

Figure 2. *Rheology graph and shear thickening schematic mechanism of STF prepared.*

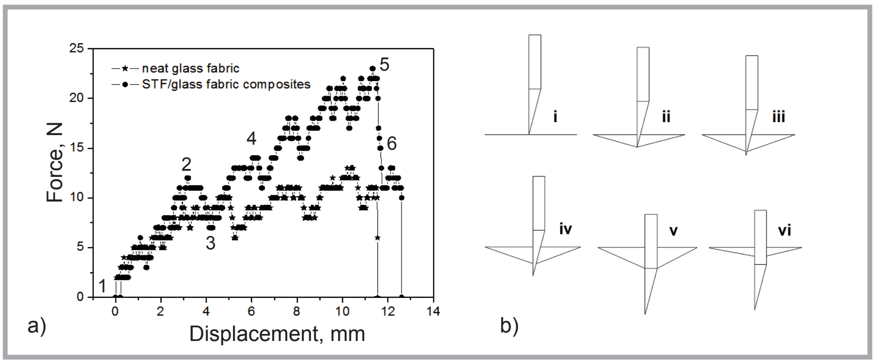

Figure 4. *(a) Quasi-static results of neat glass fabric and STF/glass fabric composite targets (b) Schematic of the puncture process.*

Figure 4.a shows the quasi-static load force versus displacement curves of the neat glass fabric and STF/glass fabric composite targets against the knife threat. The mechanisms of the impact resistance of woven fabrics have been analyzed by Termonia [13] for the case of a cylindrical penetrator with a conical tip. We applied many of the same basic mechanisms in our experiments, although the impact knife used in our quasi-static stab-resistant test is geometrically different from the conical tip. ***Figure 4.b*** illustrates the puncture mechanisms observed for our experiments, which were also labelled on the curves of ***Figure 4.a***. The stages of penetration could be summarised as follows: 1) initial contact, 2) loading the fabric prior to initial puncture, resulting in a load liner increase with displacements, 3) initial puncture, resulting in the first peak load and initiation of a fabric crack and cutting, 4) increasing loads as the impact knife contact area increased, widening the crack and cutting sizes, 5) the last peak load, when the fabric was cut and reached the maximum damage size, 6) relaxation in fabric loads, resulting in the load declining sharply. Our force versus displacement results agreed qualitatively with the modeling results of Termonia [13], showing a first peak force followed by a drop in force. Compared to the neat glass fabric target, the loads of the STF/glass fabric composite target were improved greatly after the initial puncture, which could be due to the shear thickening effects or the increase in viscosity with an increasing applied stress on the yarn pullout force. The quasi-static loading results showed a major improvement in the load resistance of the STF/glass fabric composite target

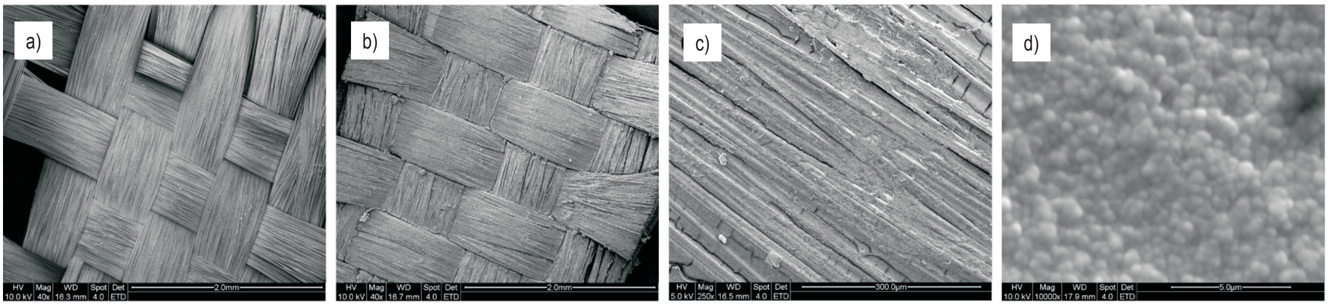

Figure 3. *SEM images of raw glass fabric (a) ×40 and STF/glass fabric composites (b) ×40 (c) ×250, (d) ×10000.*

as compared to the neat glass fabric target for knife threats.

Conclusions

A shear thickening fluid can be obtained by dispersing silica nanoparticles directly into polyethylene glycol under regular stirring. SEM results revealed that the glass fabrics were completely and uniformly coated with STF. The quasi-static stab-resistant tests results showed that the STF/glass fabric composites offer superior stab protection as compared to neat glass fabric targets for knife threats.

Acknowledgments

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