Characterizations of STF-treated aramid fabrics using picture frame test

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Abstract. Shear thickening fluid (STF) is a non-Newtonian fluid featuring the increased viscosity upon high strain rate applied. Recently, STF-treated aramid fabrics have been researched to enhance the bulletproof efficiency maintaining the lightweight, however their shear properties including tow shearing, which significantly contribute to the bulletproof properties, have not been characterized, in particular under high shear strain rates. In this study, the shear properties of STF-treated aramid fabrics are characterized using a picture frame test. For this purpose, STF is prepared using polyethylene glycol and silica colloids and coated onto aramid fabrics. Varying the shear strain rate by controlling the pulling speed of the picture frame, the effect of STF on the shear properties of the aramid fabric is investigated. Finally, the shear properties of STF-treated aramid fabrics are predicted a multi-scale energy model and compared with the experiments. This prediction is then extended to cover such a high strain-rate situation as the bullet impacts, enabling to determine the mechanism behind the improved bulletproof performance of the STF-treated fabric.

Introduction

High performance woven fabrics such as Kevlar® and Spectra® have been used in various protective applications including ballistic and stab armors. The advantages of the woven fabrics compared to metallic or ceramic bulletproof armors are lightweight, flexibility, and thin thickness. In addition, woven fabrics are reported to disperse the energy effectively through the mechanisms of the rotation, lateral sliding, and translation of yarns, let alone their plastic deformation and fracture [1]. There have been significant improvements in the performance and functionalities of body armors, however body armors still require enhanced mobility and agility of wearer, especially in military application. As such, the improvement of performance-to-weight or performance-to-thickness ratio is demanded, for which woven fabrics are important and essential material structure.

Many studies have reported that the ballistic and stab performance of materials can be enhanced when impregnated with shear thickening fluid (STF) [2-4]. Since the shear thickening phenomenon is a non-Newtonian behavior widely observed in concentrated colloidal suspensions, STF is prepared by making the colloidal suspension of solid particles in a liquid. Accordingly, the fluidic behavior of STF can be tailored by the particle shape, size and concentration [2]. Generally, dense suspensions show more shear thickening effects. The dispersed colloidal particles form clusters, often denoted by the term 'hydroclusters' [3], leading to increased viscosity (i.e., shear thickening). Most previous studies on STF-treated fabrics have been focused on STF containing spherical silica particles because the suspension of silica particle in poly (ethylene glycol) (PEG) shows discontinuous shear thickening at low volume fraction about 0.5 [4]. Enhanced ballistic performance and stab resistance of STF-treated aramid fabrics have been demonstrated empirically, maintaining high performance-to-weight ratio. However, their shear properties including tow shearing and jamming have not been characterized, in particular under high shear strain rates, even though these properties are important parameters to investigate the mechanisms behind such improved ballistic performance and stab resistance of STF-treated aramid fabrics.

In this study, the shear properties of STF-treated aramid fabrics were investigated using the picture frame test at various strain rate (controlled by the pulling speed of the picture frame up to 15,000 mm/min). In addition, the rheological property of STF was measured to interpret the shear properties dependent on the shear strain rate.

Experimental STF used in this study is made using poly (ethylene glycol) and silica colloids and coated on aramid fabrics.

Materials and sample preparation All specimens were using Heracron HT840 woven aramid fabric (840 denier, 26.2 yarns per inch, Kolon Corporation) with an areal density of 200 g/m^2. STF was prepared using silica particles dispersed in poly (ethylene glycol) (PEG). The silica particles were supplied in sol form, the components of which were 30 wt% of silica particle and 70 wt% of methanol. The silica particles were in spherical shape with the diameter of 84 nm. PEG (MW 200) was used as a dispersant in this study because it was less volatile at low temperature and could minimize the aging. Silica sol was mixed with PEG using a homogenizer into 65 wt% of silica tin whole suspension (i.e., 65wt% of silica and 35 wt% of PEG after drying all methanol on vacuum oven). STF was then coated onto aramid fabrics. Due to low viscosity, STF penetrated into thefabric and wetted the fabrics. The fabric was cut into test specimens using a laser cutter (K2 laser system).

Rheological characterization Rheological data of STF was experimentally obtained to identify its shear thickening region, based on which shear test results were discussed. Using a stress-controlled rheometer (AR 2000, TA Instruments) rheological data were obtained in steady-shear rate sweep mode at room temperature (from 1 to 10^4 s^{-1}). A cone (with 1° angle and 20mm diameter) and plate tool was used in this test.

Picture frame test A schematic diagram of the picture frame test is presented in Fig. 1. The specimen for the test was prepared using the laser cutter. The specimen was held by bolts on the picture frame. The upper crosshead in a universal tensile tester moved upward pulling the picture frame, resulting in the shape change of the specimen from the square shape to the rhombus one. Accordingly the specimen within the picture frame was sheared, ideally experiencing the pure shear deformation. The shear rate was controlled by the head speed of the machine, ranging from 100 mm/min to 15,000 mm/min. This methodology is well described in detail in [5-6]. The force and displacement of the crosshead were converted to the shear stress and shear strain respectively using the following equation.

$$F_s = \frac{F_{pf}}{2\cos\phi} \tag{1}$$

where ϕ is the frame angle, i.e. the angle between warp and weft, and F_{pf} is the measured axial picture frame force. The specimen surface was recorded using camera, which was coupled to the testing machine, to obtain the shear angle. The shear angle was then calculate using the following equation.

$$\theta = \frac{\pi}{2} - 2\phi \tag{2}$$

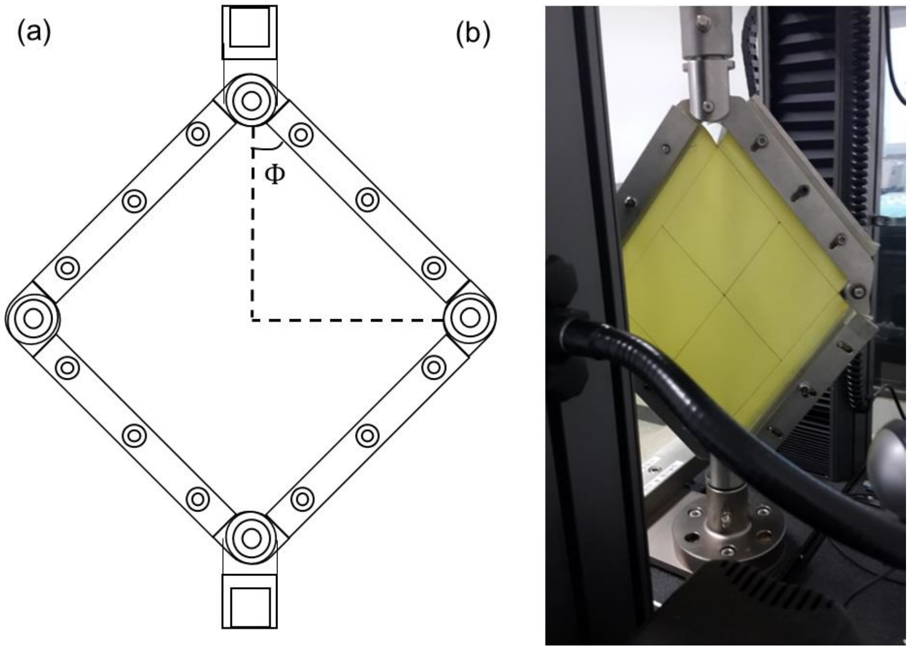

Figure 1 A schematic description of picture frame test of STF-treated aramid woven fabrics. (a) Four-bar linkage of picture frame and (b) installed specimen.

Results and discussion

Rheological properties of STF Fig. 2 shows the rheological data of STF, in particular the viscosity and the shear stress as a function of shear strain rate. From the data, the shear thickening behavior can be observed at low shear rate (1~10 s^{-1}), followed by shear thinning behavior at moderate from low to high shear strain rate. STF exhibits the shear thickening effect at high shear strain rate. The onset points of the shear thickening behavior were at 1 s^{-1} (low shear rate) and 376 s^{-1} (high shear rate), respectively. The shear thickening effect can be also confirmed by the shear stress, i.e., the slope of the shear stress is large in high shear rate region.

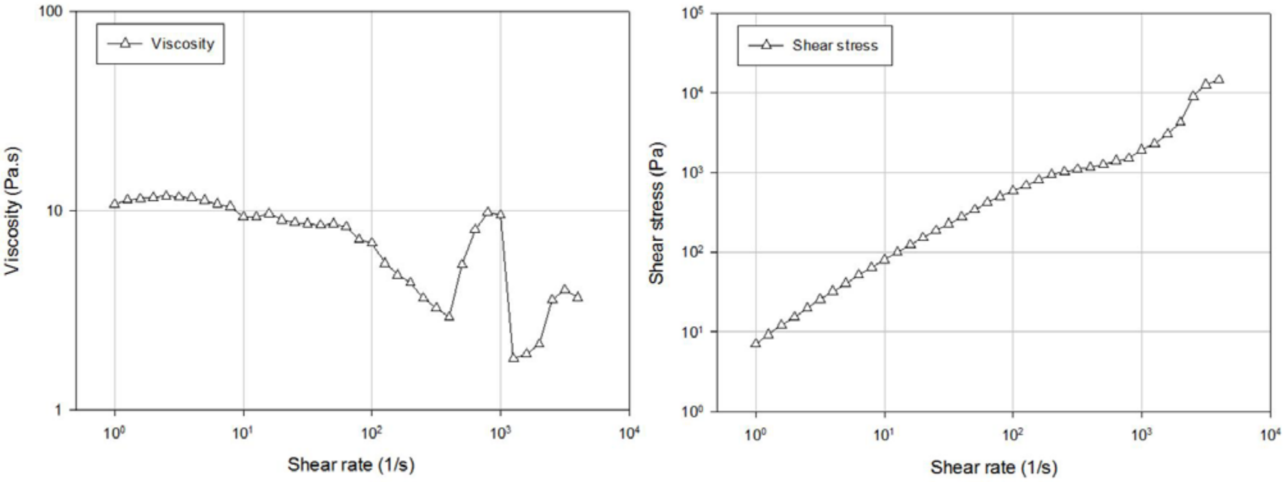

Figure 2 Rheological data of STF used in this study.

Picture frame test results Fig. 3 shows the typical results from the picture frame test. For comparison purpose, neat aramid fabrics were also tested and presented. Note that the shear strain rates were varied by controlling the puling speed of the crosshead. Shear stress and angle data were obtained at three shear rates (0.012, 0.213, and 0.970). Note that the stress was calculated using equation (1). Here, the length of the specimen was used because the fabric thickness was not clearly defined due to the discrete nature of the fabric [5]. Fig.3 shows that the shear rigidity of the fabrics increased as STF was coated. This is probably due to the impregnated silica particles, i.e., strong silica particles reinforced the fabric, in particular by increasing the frictional resistance. The nanoparticles impeded the tow shearing and fabric shear by increasing the friction between fibers.

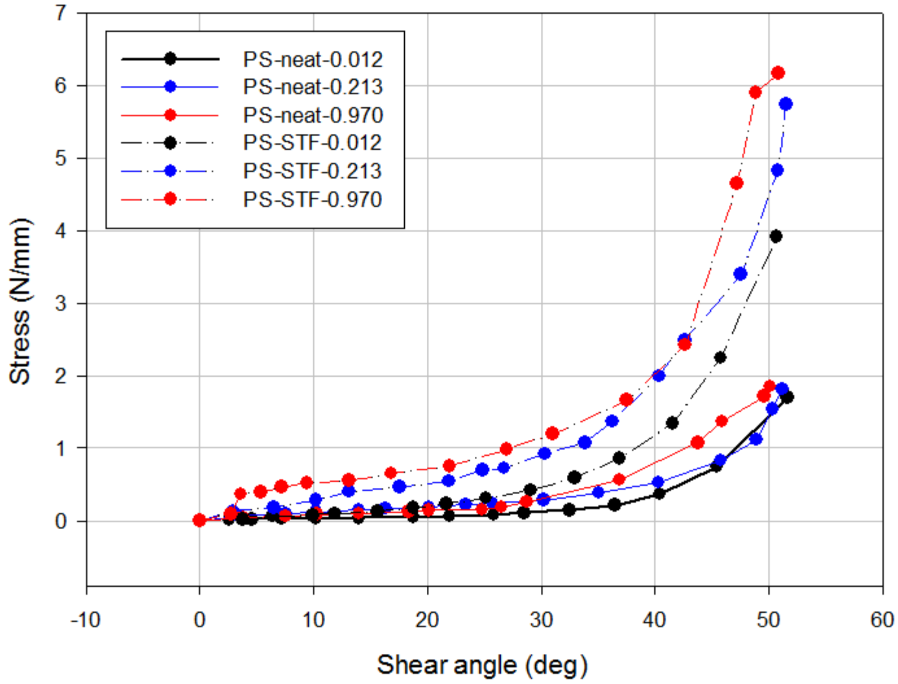

Figure 3 Shear stress and strain curves obtained from the picture frame test.

The rate effect of the fabrics can be observed in Fig.3. As the shear rate increased, the shear stress of the fabric increased, regardless of STF. The fabrics consisting of polyamide fibers (aramid) exhibited the rate effect due to the polymeric nature of the fibers and the frictional behavior over the crossover of warp and weft yarns in the woven fabrics. To evaluate the rate effect, some quantities were extracted from the stress and strain curve in Fig. 3. The shear strength (defined by the stress when fabric jammed) and stress at shear angle of 45° were obtained as listed in Table 1. The results show an apparent increase of the strength and stress at the characteristic shear rate, meaning that the material was toughened with increased shear rate. The rate effect of STF-treated fabric was larger than that of neat fabrics. Considering the increased shear stiffness at high shear rate and rheological properties of STF, it can be concluded that the shear thickening effect of STF-treated fabrics was revealed over the range of the shear strain rate taken in this study.

Table 1 Characteristic shear properties of neat and STF-treated fabrics.

	Neat fabric			STF treated fabric		
Specimen	Neat-0.012	Neat-0.213	Neat-0.970	STF-0.012	STF-0.213	STF-0.970
Strength [N/mm]	0.866 (0.725)	2.117 (0.263)	1.907 (0.110)	3.787 (0.424)	5.148 (0.410)	6.030 (0.374)
Stress at θ=45° [N/mm]	0.483 (0.227)	1.129 (0.339)	1.407 (0.248)	2.146 (0.373)	3.673 (0.591)	3.957 (0.334)

Summary

In this study, the shear properties of STF-treated aramid fabric was characterized using the picture frame test. The rate dependency of the shear stress was clearly observed in the STF-treated fabrics due to the STF. More systematic studies will be carried out to draw a concrete conclusion about this and will be presented at the Conference.

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