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Study of the knife stab and puncture-resistant performance for shear thickening fluid enhanced fabric

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Abstract
This work developed a shear thickening fluid enhanced fabrics and the influence of the shear thickening fluid types on the knife stab and puncture resistance performance were investigated. The rheological properties of the shear thickening fluids were tunable by varying both the dispersing particles (silica, polymethylmethacrylate and polystyrene-ethylacrylate) and the mediums (ethylene glycol, polyethylene glycol 200 and polyethylene glycol 600). The mechanical properties of the shear thickening fluid reinforced fabrics were evaluated by the knife and spike drop tower testing, respectively. The hardness of the particles was the dominant factor for the knife stab resistance, while the inter-yarn friction played as the critical role for improving the puncture resistance. In comparison to neat fabric, the knife stab and puncture resistance of the shear thickening fluid-fabrics exhibited significant enhancement, which can be proven by the results of yarn pull-out testing and optical microscope images investigation. The enhancing effect was systematically discussed and the improving mechanism was analyzed. Because the influencing factors for the knife stab resistance and puncture resistance were different, the enhancing effect of the dispersing particles and the mediums for the shear thickening fluid-fabrics should be also different.

Keywords
Shear thickening fluid, Kevlar fabric, knife stab resistance, puncture resistance, liquid body armor

Introduction

Personal body armor mainly protects an individual from the damage caused by the weapons or projectiles. Traditional body armors are made of metal plates or ceramics, which are heavy, bulk and rigid, thus these armors are usually used for the protection of torso. Due to the limitation of the mobility and flexibility, they are difficult to be applied in protecting the hands, arms and legs. Therefore, considerable attention has been given to improve the flexibility and reduce the weight of the body armors.[1–3] In order to reduce the weight while maintaining the protection level, multiple layered light and flexible fabrics made from low density, high strength and high energy absorption fibers such as Kevlar®, Spectra®, Dyneema® and Twaron® have been widely introduced as base materials for soft body armor.[4–7] However, almost 20–50 layers fabric was required to satisfy the protection demands for typical ballistic threats. Clearly, this method reduced the comfort of the body armors which significantly limited their practical applications. There are two methods to lighten the body armors without compromising on performance: one is invent new materials which are made by lighter and stronger fibers; another is tailor the structure and composition of the present fabrics to get better performance.

Shear thickening fluid (STF) is a kind of particulate suspension whose rheological property takes place an

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abrupt change when encountering a strike. The apparent viscosity of STF changes so dramatically at a high-speed impact that it can transform from suspension to solid-like status. The viscosity comes back rapidly when the impact is removed, which indicates that the shear thickening effect is a reversible non-Newtonian behavior.[8–10] This transient thickening behavior is due to the formation of flow induced clusters (hydroclusters).[8,11–13] The rheological properties of these STFs have been carefully investigated under steady and dynamical measurements. Various theoretical and experimental methods have been developed to study their shear thickening effects.[14–18] Recently, it was found that the mechanical properties of the fabric materials could be highly improved by impregnating the STF into the neat fabrics. The U.S. Army Research Laboratory found that this technology can offer a new kind of body armor whose performance was equivalent or even better than the traditional soft body armor, while it decreased the thickness or stiffness of the fabrics. Therefore, the STF can be used to improve the body armor which not only makes the soldiers safer but also gives them more freedom of movement.[19]

The STF enhanced fabric have taken advantage of the shear thickening properties to improve the ballistic, stab and puncture protective properties.[20–23] Lee et al.[24] found that the ballistic resistance of Kevlar fabric could be enhanced after impregnating with STF, which was prepared by suspending the silica particles into ethylene glycol. Tan et al.[25] also reported an enhancement in ballistic resistance of Twaron fabric with a silica–water suspension-based STF. The improvement of the ballistic resistance was suspected to be attributed to the increased frictional interaction between the yarns.[26] To investigate the enhancing mechanism, Lee et al.[27] studied the effect of the silica particle size of STF on the ballistic performance of STF-Kevlar and STF-Heracron fabric under three different boundary conditions. Recently, the stab protection of the STF-based body armor has attracted increasing attention due to their practical applications. The stab threats can be divided into two categories, cut and puncture, which refer to the penetration by knives with sharp edges and by instruments with sharp tips (such as spikes), respectively. Decker et al.[28] and Mahfz et al.[29] investigated the stab resistance of STF-treated Kevlar and nylon fabric with different fabrication methods and found that the STF-treated fabric exhibited significant improvements over the neat fabrics. Kalman et al.[30] compared the penetration resistance of Kevlar fabric treated with silica, polymethylmethacrylate, and STF. Based on these researches, it was found that the enhancing stab resistance was relative to the increment of the inter-yarn friction and this was caused by the additives. The influence of the STF type on the property of the STF strengthened fabric was still a key research point to detail the enhancing knife stab resistance and puncture resistance. Since the damage modes of fabric under the knife and spike impactor are different, their enhancement mechanism needs to be analyzed respectively. The dispersing medium and the particle's type are important factors for the shear thickening effect.[14,31] The change of the STF-strengthened-fabrics' properties under different damage modes need to be claimed more clearly. Therefore, the relationship between the parameters of STF and the stab resistance mechanisms should be investigated under the knife and spike impactor. In order to get a better understanding of the stab resistance mechanisms, detailed experiments about the knife stab resistance and puncture resistance of STF enhanced fabric have pressing needs.

In this work, the influence of the STFs' components on the knife stab and puncture resistance performance of the STF enhanced fabric was studied. The intrinsic properties of the STFs were tunable by varying the dispersing particles from the spherical Silica (SiO_2), to polystyrene-ethylacrylate (PSt-EA) and polymethylmethacrylate (PMMA), and the dispersing medium from ethylene glycol (EG) to polyethylene glycol 200 (PEG200) and polyethylene glycol 600 (PEG600). The yarn pull-out,[32,33] drop tower test attached with knife and spike according to the National Institute of Justice (NIJ) standard for stab testing of protective armors (NIJ 0115.00, 2000) were conducted to evaluate their protection performance. The fabric failure modes under the knife and spike drop tower were analyzed and the mechanism for the enhancement effect on the knife stab and puncture resistance performance were carefully discussed.

Materials and methods

Preparation of STF

Rigid spherical SiO_2 particles were prepared through the catalyzing of tetraethyl orthosilicate by ammonia solution.[34] The soft spherical PMMA particles[35] and the PSt-EA spherical particles[36] with moderate hardness were both prepared in soap-free emulsion polymerization method. In this work, these particles with different hardness were suspended in EG to fabricate the STF, respectively. Besides EG, PEG200 and PEG600 with the molecule weight of 200 and 600 were also chosen as a dispersing medium to prepare the PSt-EA-based STFs. Each STF was placed in a ball mill grinding up to about 24 h. The STF samples were treated in vacuum for 2 h to exclude the bubbles prior to use.

Preparation of STF-fabric

The fabric used in the stab resistance tests was a type of plain-woven aramid high performance Kevlar fabric with an areal density of 200 g/cm^2. To fabricate the STF-fabric, the STF was firstly diluted in ethanol or water and then the suspension was mixed for 30 min in ultrasonic dispersion method to ensure the solution well-distributed. 10 cm × 10 cm layers Kevlar fabrics were cut and soaked in the solution individually for 10 min. After the impregnation, the fabric was dried at 70°C for 2 h in an oven to evaporate the ethanol or water from the sample. The weight of the fabric cloth was recorded before and after the impregnation. For different kinds of STFs, the particle volume addition of each fabric could be kept constant mostly by tailoring the dilution ratio of STF to ethanol or water. These STF-fabrics were arranged into multilayer targets and the detailed STF-fabric data are summarized in Table 1.

Methods

The neat and STF-impregnated fabrics were characterized by the scanning electron microscope (SEM) (JEOL, type: JSM-6700F). Rheological properties[37] were measured by using a rheometer (Anton Paar, Physica MCR301) with a cone plate of angle 2.007° and diameter 24.967 mm. The steady rheological testing, with the shear rate increasing from 1 s^{-1} to 250 s^{-1}, was employed to study the shear rate dependence of viscosity. All the experiments were conducted at the room temperature (25°C).

According to the NIJ standard 0115.00 (Stab Resistance of Personal Body Armor), the stab resistance tests were conducted on a drop tower. Two types of impactors mentioned in the NIJ standard 0115.00 as the 'engineered knife blade S1' and the 'engineered spike' were used. The stab resistance fabric targets were placed on the backing material as presented in Figure 1(a). The backing material consists of four layers of neoprene sponge, five layers of witness paper, a single layer of closed-cell polyethylene foam, and two layers of rubber. In the stab resistance testing, the knife or spike impactor was mounted to the drop mass, which was lifted to a fixed height and then dropped freely to impact the target. The impact energy loaded on the target varied with the height and weight of the drop mass. The depth of penetration increased when the number of penetrated witness papers increased. The number of penetrated witness papers was employed to indicate the stab resistance performance. The results indicated that if the same impact energy was applied, similar stab resistance performance was obtained. Therefore, in the following discussions, the impact energy was only varied by changing the drop height and the drop mass were fixed at 2.3 kg for knife and 2.2 kg for spike. For further investigation of the damage microcosmic mechanism, the fabric targets after drop tower were observed through the optical microscope and SEM. The images of SEM gave the morphology of a 2 cm × 2 cm piece from the second fabric layer.

In order to investigate the effect of the STF on the inter-yarn friction, a yarn pull-out test was conducted to obtain a relative measure of the friction between yarns in neat fabric and those treated with different kinds of the STFs. The electronic tensile machine was used to perform the yarn pull-out test. As shown in Figure 1(b), the top part of a single yarn at the center of the fabric specimen was clamped in the upper grip and the bottom part of the single yarn was cut. The bottom edge of the fabric specimen was clamped in the lower grip which was fixed, while the upper grip moved upward at a certain rate until the single yarn was pulled out completely. To remove the crimping effect, zero displacement was defined as the displacement when the pull-out force reached 0.1 N.

Table 1. Data of stab resistance test targets.

Addition component	Numbers of layers	Weight ratio to 20 layered neat fabrics	Average weight addition	Particle volume addition in solution	Medium volume addition in solution
None	20	100%	0	0	0
EG	20	101.6%	1.62%	0	3.61%
SiO_2-EG	20	107.2%	7.24%	5.84%	4.16%
	19	101.9%			
	15	80.4%			
	10	53.6%			
PMMA-EG	20	104.3%	4.33%	5.84%	3.62%
	19	99.1%			
	15	78.2%			
	10	52.2%			
PSt-EA-EG	20	104.0%	4.03%	5.83%	3.07%
	19	98.8%			
	15	78.0%			
	10	52.0%			
PSt-EA-PEG200	20	104.2%	4.18%	5.85%	3.35%
	19	99.0%			
	15	78.1%			
	10	52.1%			
PSt-EA-PEG600	20	104.3%	4.29%	5.85%	3.31%
	19	99.1%			
	15	78.2%			
	10	52.1%			

EG: ethylene glycol; PMMA: polymethylmethacrylate; PSt-EA: polystyrene-ethylacrylate; PEG: polyethylene glycol.

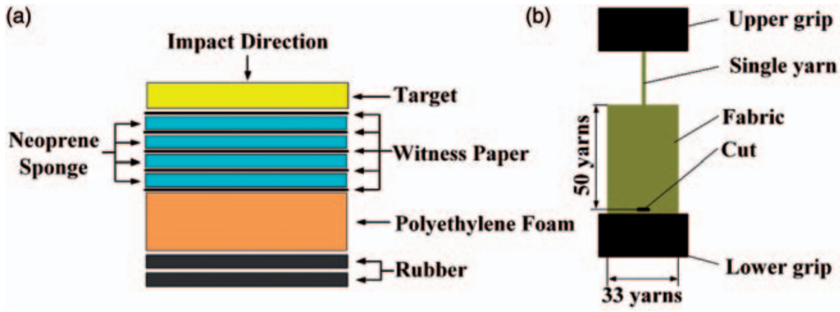

Figure 1. (a) Stab resistance testing fabrics and backing material; (b) schematic diagram for yarn pull-out test.

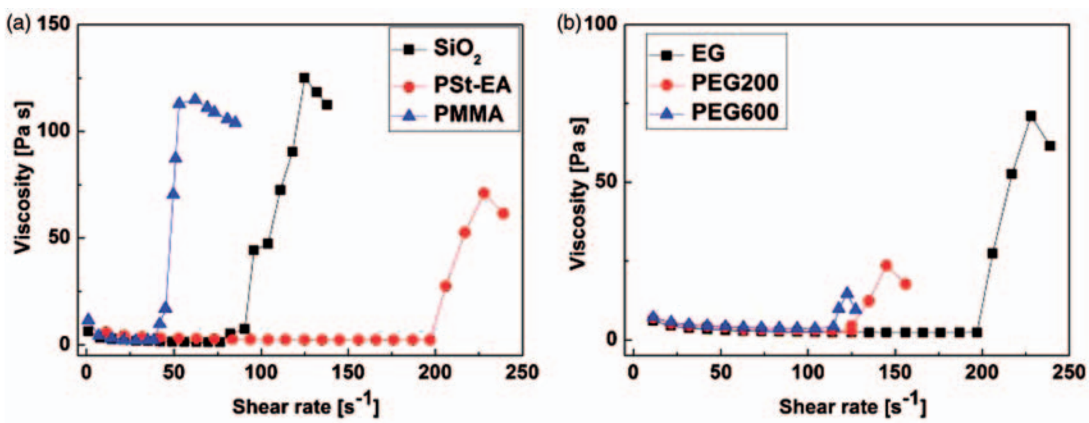

Figure 2. Rheological behavior of STF for steady shear flow: (a) EG solvent with different types of particles and (b) PSt-EA particles with different types of dispersing mediums.
STF: shear thickening fluid; EG: ethylene glycol; PSt-EA: polystyrene-ethylacrylate; PEG: polyethylene glycol; PMMA: polymethylmethacrylate.

The experiment data of the yarn pull-out force versus the loading displacement were recorded.

Results and discussion

Characterization of STF and the fabric

All these spherical SiO_2, PMMA and PSt-EA particles were uniform and the sizes were nominally 520 nm, 250 nm and 350 nm, respectively. By dispersing these monodispersed particles into different medium, different types of STFs have been prepared. The rheological test results of the STFs with various particles and dispersing medium are shown in Figure 2(a) and (b). All of them exhibited the shear thickening behavior and could be transformed from flowing liquids to solid-like materials by applying an external shear, which could be explained by the hydrocluster mechanism. It was found that the critical shear rates were tunable by varying the particle or dispersing medium. The shear thickening behaviors of these kinds of STFs used to fabricate the fabric were different. Therefore, it can be expected that the STF-fabric targets would exhibit different performances.

Here, all these STFs were impregnated into the fabric to improve the mechanical properties. Before the SEM observation, the EG was evaporated from the fabric due to the high vacuum and electron beam irradiation. Therefore, only the fabric and the particles were found in the SEM images. In comparison to the surface of neat Kevlar filament (Figure 3(a)), the STF-treated Kevlar filaments (Figure 3(b) to (d)) were rather rough. The filaments were attached with layers of particles within the yarn, indicating that the STF-Kevlar fabrics were surrounded by the STF effectively before the evaporation of the EG solvent. From the SEM images, it can be concluded that the impregnating process is workable and the STFs are well dispersed into each yarns of Kevlar fabric.

Fabric failure modes under the knife and spike impactors

To explore the fabric failure modes under the knife and spike impactors, the investigation of the morphologies

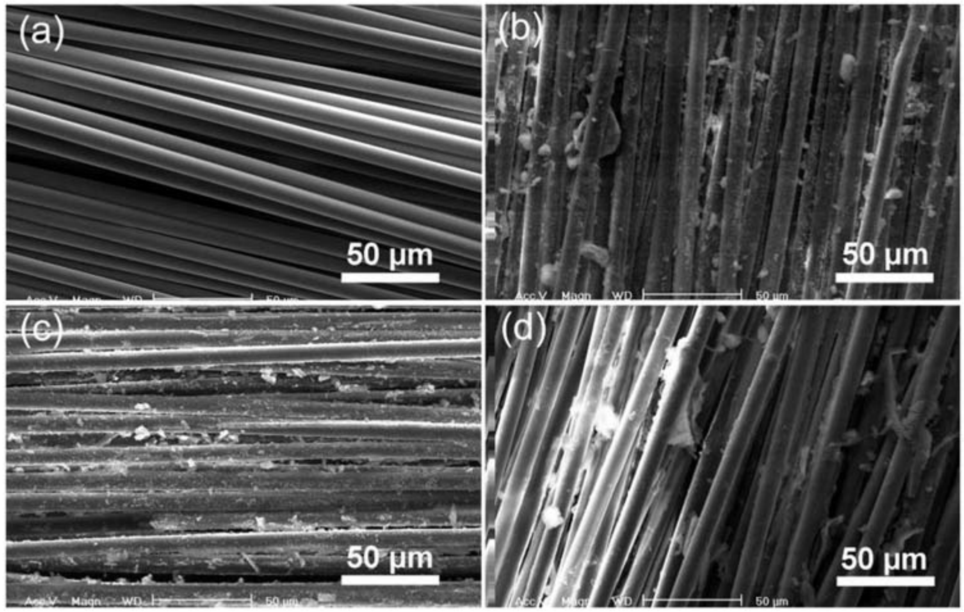

Figure 3. SEM micrographs of fabric: (a) neat Kevlar; (b) with SiO_2; (c) with PMMA; and (d) with PSt-EA.
SEM: scanning electron microscopy; PMMA: polymethylmethacrylate; PSt-EA: polystyrene-ethylacrylate.

of the fabric failure locations was necessary. The optical microscope and SEM images of neat fabric target after drop tower are shown in Figure 4. Clearly, the neat fabric targets showed significant puncture and cutting damage after the drop tower testing. From Figure 4(a), it is found that the filaments were separated within yarns and among yarns, and the fabric exhibited the 'windowing' effect. No significant filament fracture is observed according to Figure 4(c). However, there was a large extent of yarn cutting fracture in the target (Figure 4(b)), which indicated the cutting terribly breaks the fiber, and this result could be further demonstrated by Figure 4(d). As we know, the mobility of the filaments within yarns and among yarns is affected by the friction between yarns and within yarns. However, the fracture of the yarn is relative to its strength. Generally, the fabric failure includes the two above modes, while one case plays as the dominate role under a certain condition. Therefore, the fabric failure under the spike impactor is mainly attributable to the friction between the yarns and within yarns, and the one under the knife impactor is mainly attributable to the strength of the yarns.

Drop tower testing

The drop tower stab resistance performance of the neat Kevlar and different layers of STF (SiO_2-EG) – Kevlar targets against the knife impactor is shown in Figure 5(a). In this situation, the weight of the drop mass was fixed at 2.2 kg and the drop height varied from 5 cm to 60 cm. For the knife impactor, the penetration depth into backing material increased as the impact energy increased. When the number of layers of Kevlar fabric was the same, the STF-Kevlar target exhibited significant less penetration depth and better knife stab resistance in comparison to the neat Kevlar target. For the 20 layers-STF-Kevlar target, even no witness paper was penetrated in the testing situation. The penetration depth of the 19 layers-STF-Kevlar target was also significant less than the neat Kevlar target, while its weight ratio to 20 layers neat Kevlar target was 101.9% (Table 1). This means that when the weight of the targets is almost the same, the STF-Kevlar target exhibits better knife stab resistance than the neat Kevlar target. For the 15 layers STF-Kevlar target, whose weight ratio to 20 layers neat Kevlar target was 80.4% (Table 1), the penetration depth was slightly less than the neat Kevlar target. Obviously, the STF-Kevlar target was lighter and showed better performance than the neat Kevlar target. Meanwhile, for the 10 layers STF-Kevlar target, whose weight ratio to 20 layers neat Kevlar target was 53.6%, the knife stab resistance was approximate to the neat Kevlar target. As a result, the introduction of STF could not only lighten the weight but also strengthen the knife stab properties of the Kevlar target.

Figure 5(b) shows the drop tower puncture resistance performance of the neat Kevlar and different layers of STF (SiO_2-EG) – Kevlar targets against the spike impactor. The testing condition was similar to the knife impactor experiment. The drop height varied from 5 cm to 25 cm. With increasing of the impact

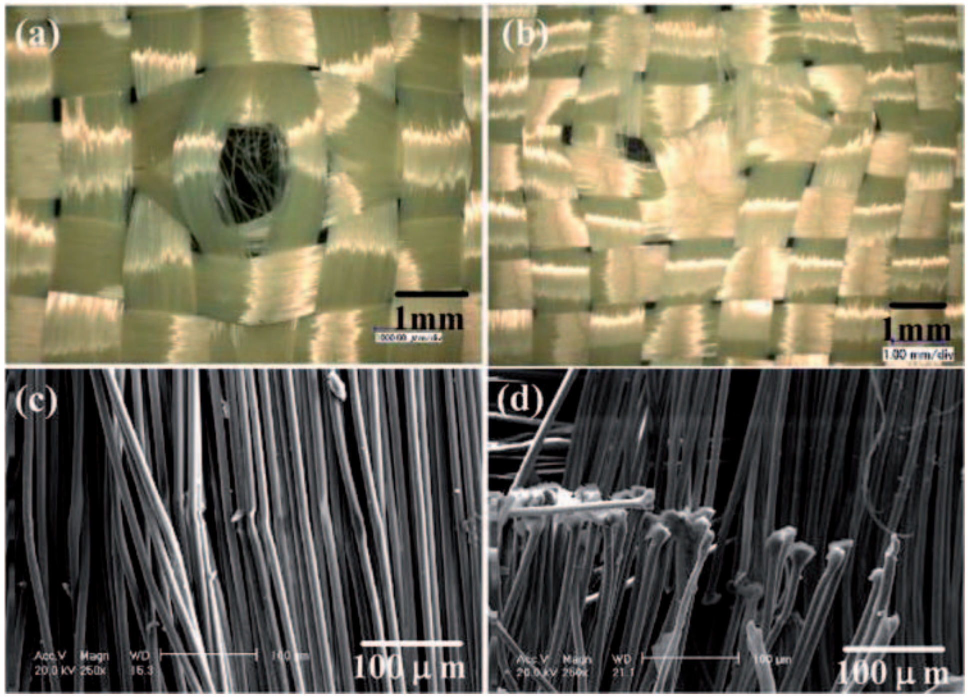

Figure 4. Back views of the target's last layer after drop tower through the optical microscope: (a) the spike impactor at $m = 2.2$ kg and $h = 25$ cm; (b) the knife impactor at $m = 2.3$ kg and $h = 50$ cm. SEM images of the second layer of the target after drop tower: (c) the spike impactor at $m = 2.2$ kg and $h = 25$ cm; (d) the knife impactor at $m = 2.3$ kg and $h = 50$ cm.

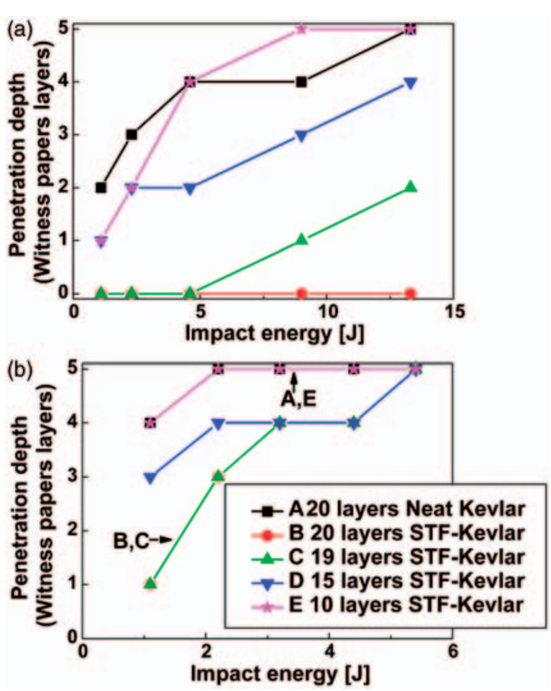

Figure 5. Drop tower results for neat Kevlar fabric and different layers of STF (SiO_2-EG) – Kevlar fabric against the impactor of the same weight: (a) knife; (b) spike.
STF: shear thickening fluid; EG: ethylene glycol.

energy, the depth of penetration into the backing material increased. For the 20 layers and 19 layers STF-Kevlar target, whose number of layers and weight were nearly the same as the 20 layers the neat Kevlar target, both exhibited significant less penetration depth and better puncture resistance in comparison to the neat Kevlar target. When the impact energy reached the value of 5.5 J, the targets all exhibited the maximum penetration depth of 5 layers of witness papers. Similar to the knife impactor, when the weight ratio of STF-Kevlar target to 20 layers neat Kevlar target was 80.4%, the target's penetration depth was slightly less than the neat Kevlar target. For the 10 layers STF-Kevlar target, whose weight ratio to 20 layers neat Kevlar target was 53.6%, the puncture resistance was the same as the neat Kevlar target. Therefore, the addition of STF could take into account both weight and protection level of the target.

Yarn pull-out testing

The yarn slip in fabrics plays a key role in the mechanical properties of the fabric. The yarn pull-out from plain-woven fabrics could simulate the yarn slip. Yarn pull-out experiment is employed to investigate the friction among yarns and between the impactor and the yarns. In Figure 6, the yarn pull-out experiment consisted of two stages. During the first stage, the yarn changed from crimping to straight gradually from the top to the bottom due to the inter-yarn friction. The pull-out force rose rapidly until reaching a peak force. In the last stage, the yarn was pulled through the fabric and finally pulled out. The pull-out force decreased with increasing of the pull-out displacement. The force appeared to be oscillated, because the yarn moved up and down of the transverse yarns alternately due to the residual crimp. As soon as the yarn was pulled out completely, the pull-out force dropped to zero. This yarn pull-out results have the same two stages of the pull-out progress as discussed in Zhu's study.[38] For the neat fabric, the curves of pull-out force versus displacement at different pull-out speeds were similar (Figure 6(a)), which indicated that the pull-out force was almost independent on the pull-out speeds. In contrast, for the STF-fabric, the curves of pull-out force versus displacement were different, especially at the high pull-out speeds. In Figure 6(b), if the pull-out speed was relative low and varying from 5 mm/min to 100 mm/min, the force–displacement curves were almost kept stable. However, at the relative high pull-out speed, such as 200 mm/min and 400 mm/min, the pull-out force had a sudden increase compared with that at relative low pull-out speed. Therefore, the shear thickening of the additional STF could account for the increment of the pull-out force. According to Table 2, it was found that the pull-out peak force for the STF-fabric was always larger than that for the neat fabric no matter what the pull-out speed was. When the pull-out speed was low, the pull-out peak force for the STF-fabric increased by about 60% to 70% in comparison to the neat fabric. However, when the pull-out speed was relatively high, the shear thickening restricted the mobility of the yarns, which induced the increase of the inter-yarn friction force. As a result, the pull-out peak forces for the STF-fabric had a drastic increase by 156% and 194% in comparing to the neat fabric.

Effect of the particles' types on stab resistance

In general, the stab resistance can be divided into two categories: knife stab resistance and puncture resistance. In order to investigate the effect of the particle's types on the stab resistance performance, the targets with different kinds of STFs, which are listed in Table 1 and comprised different types of particles and the dispersing medium EG, were employed to compare the distinction of stab resistance performance through the drop tower testing. In Figure 7, for the 20 layers and 19 layers STF-fabric targets, regardless of the additional particles' type, the STF-fabric targets exhibited less penetration depth and better knife stab

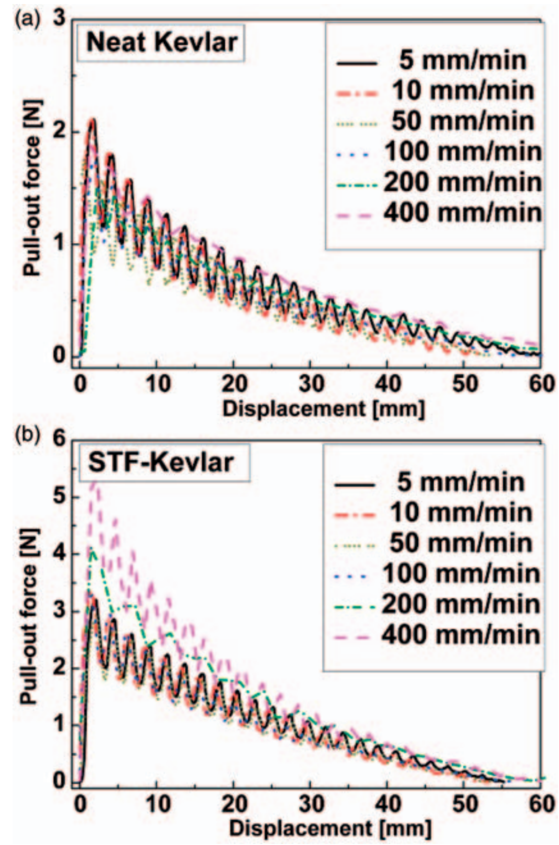

Figure 6. Pull-out load versus displacement curves for: (a) the neat Kevlar fabric and (b) STF (SiO_2-EG)-Kevlar fabric at different pull-out speeds.
STF: shear thickening fluid; EG: ethylene glycol.

Table 2. Comparison of the pull-out peak force for the neat fabric and the STF (SiO_2-EG)-fabric at different pull-out speed.

Pull-out speed (mm/min)	Pull-out peak force (N)		
	Neat fabric	STF-fabric	Increment (%)
5	2.0	3.2	60
10	2.1	3.5	67
50	1.8	2.9	61
100	1.8	3.1	72
200	1.6	4.1	156
400	1.8	5.3	194

STF: shear thickening fluid; EG: ethylene glycol.

resistance performance than the neat fabric target. For 15 layers fabrics, only the STF-fabric target with SiO_2 particles exhibited less penetration depth than the neat fabric target under all the impact energy in this work. The STF-fabric targets with PMMA and PSt-EA particles had the similar knife stab resistance performance to the neat fabric target. For 10 layers fabrics, the knife

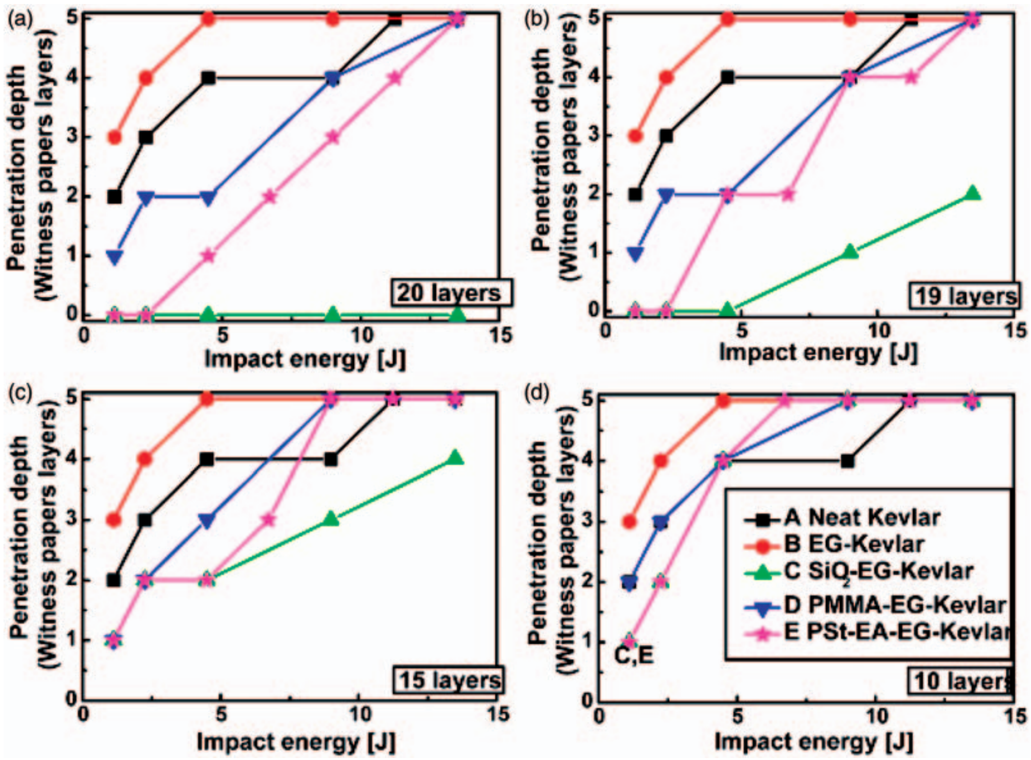

Figure 7. Drop tower results against the knife impactor for the neat fabric, EG-fabric and STF (with different types of particles)-fabric. The neat fabrics and EG-fabrics both have 20 layers. The STF-fabrics have (a) 20; (b) 19; (c) 15; and (d) 10 layers, respectively. STF: shear thickening fluid; EG: ethylene glycol; PMMA: polymethylmethacrylate; PSt-EA: polystyrene-ethylacrylate; PEG: polyethylene glycol.

stab resistance performance of the STF-fabric was similar to that of the neat fabric.

In general, the neat fabric target exhibits less penetration depth and better knife stab resistance performance than the EG-fabric target. The addition of EG lubricates the yarns in fabric, thus the inter-yarn friction decreases. The addition of STF induces the fabric target to have better knife stab resistance performance. For the STF-fabric targets, the target with SiO_2 particles exhibits the best knife stab resistance performance and the target with PMMA particles exhibits the worst knife stab resistance performance. According to the optical microscope results, the extent of damage is the least for the SiO_2-fabric and is the largest for the PMMA-fabric.

The distinction of the knife stab resistance performance for the STF-fabric targets with different types of particles must be responded for the fabric damage mechanism. The fabric damage under the knife drop tower was primarily due to the cutting fracture of yarns. Therefore, the difference of the particles hardness leaded to the distinction of the knife stab resistance performance. The SEM images of the fabric target after knife drop tower (Figure 8) indicated that the addition of STF with different types of particles typically strengthened the yarns in fabric. In Figure 8(a), the filament ends for the neat fabric were flattening and clean. However, the filament ends for the STF-fabric were contrastively larger and not neat (Figure 8(b) to (d)). Particularly, in Figure 8(b) the filament ends for the STF-fabric were divided into thin filaments by the action of the knife blade and the hard SiO_2 particles and the thin filaments kink with each other. This kinking enhanced the knife stab resistance performance. For the STF-fabric with PSt-EA particles, only a small amount of kinking of the thin filaments was observed, because the hardness of PSt-EA particle was smaller than SiO_2 particle. The hardness of the PMMA particle was the smallest, thus little kinking of the thin filaments could be found. Besides the kinking of the thin filaments, the action area by knife blade was larger for the STF-fabric than that for the neat fabric. During the knife stab testing, the knife firstly pushed the yarns until the yarns were cut. Because the inter-yarn friction force for the STF-fabric was larger than the neat fabric, the mobility of the yarns strengthened by the STF was smaller, which further lead to the better knife stab resistance. In conclusion, the knife stab resistance performance for the neat fabric target is the worst in all the targets. For the STF-fabric targets, the hard SiO_2 particles target exhibits the best knife stab resistance performance, and the soft PMMA particles

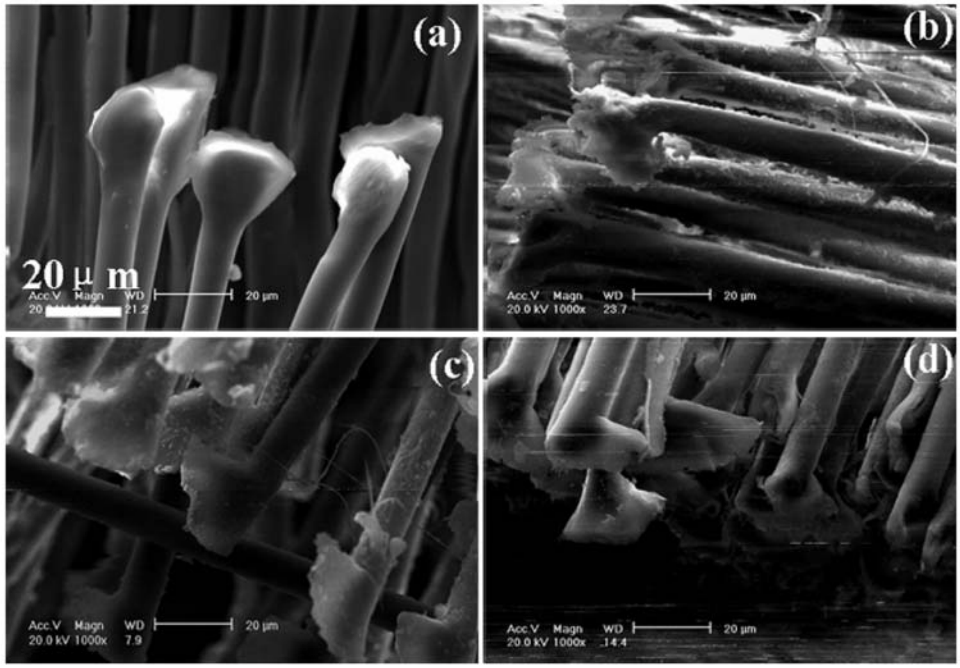

Figure 8. SEM images of the fabric target after knife drop tower ($h = 50$ cm): (a) neat Kevlar; (b) SiO_2-EG-Kevlar; (c) PMMA-EG-Kevlar; (d) PSt-EA-EG-Kevlar.
SEM: scanning electron microscopy; EG: ethylene glycol; PMMA: polymethylmethacrylate; PSt-EA: polystyrene-ethylacrylate.

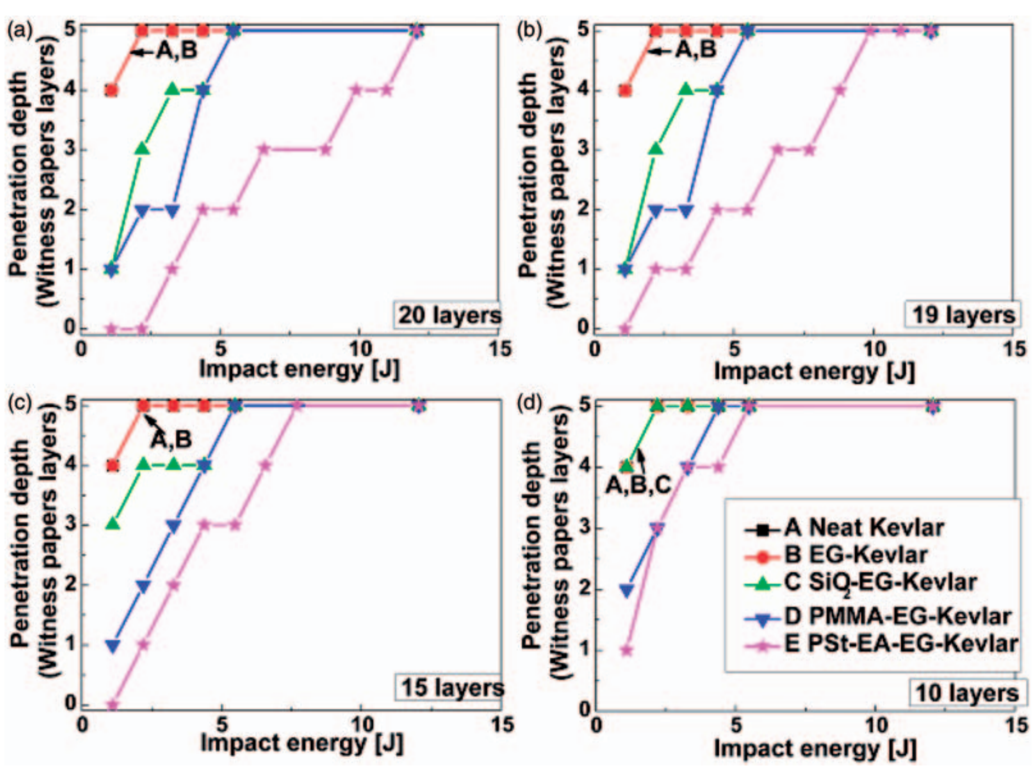

Figure 9. Drop tower results against the spike impactor for the neat fabric, EG-fabric and STF (with different types of particles)-fabric. The neat fabrics and EG-fabrics both have 20 layers. The STF-fabrics have (a) 20; (b) 19; (c) 15; and (d) 10 layers, respectively.
STF: shear thickening fluid; EG: ethylene glycol; PMMA: polymethylmethacrylate; PSt-EA: polystyrene-ethylacrylate.

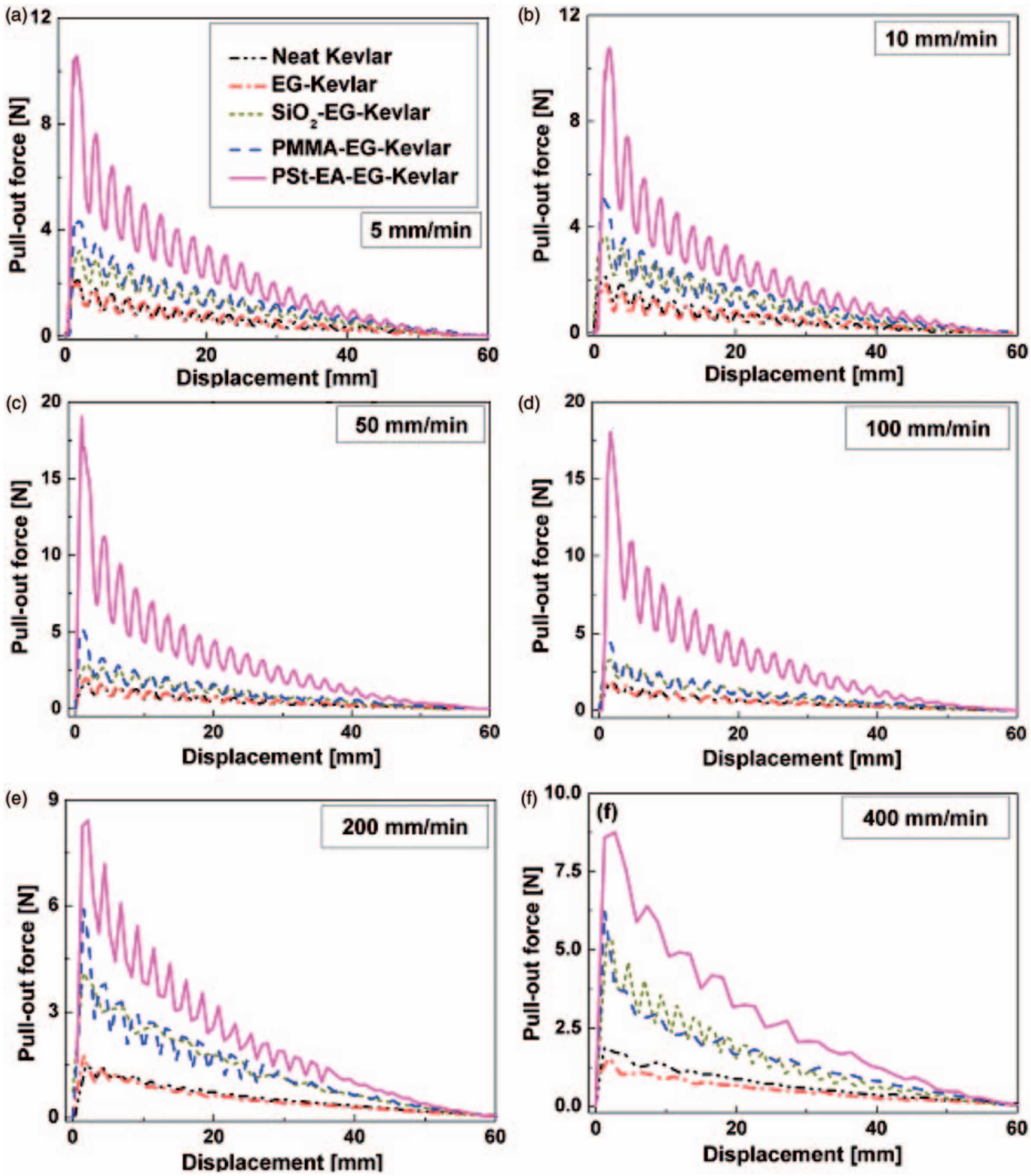

Figure 10. Yarn pull-out results for the neat fabric, EG-fabric and STF (with different types of particles)-fabric at different pull-out speeds: (a) 5 mm/min; (b) 10 mm/min; (c) 50 mm/min; (d) 100 mm/min; (e) 200 mm/min; (f) 400 mm/min.
STF: shear thickening fluid; EG: ethylene glycol; PMMA: polymethylmethacrylate; PSt-EA: polystyrene-ethylacrylate.

target has the worst knife stab resistance performance. The results show that the interaction of the particles and the filaments is important for the knife stab resistance of the fabrics. Harder particles tend to result in a greater strengthening in intension of the filaments than softer particles.[30]

Figure 9 shows the drop tower results against the spike impactor for the neat fabric, EG-fabric and STF (with different types of particles)-fabric. For 20 layers, 19 layers and 15 layers STF-fabric targets, regardless of the additional particles' type, the STF-fabric targets exhibited less penetration depth and better puncture resistance performance in comparison to the neat fabric target. For 10 layers STF fabric, the target with PMMA particles and PSt-EA particles exhibited better puncture resistance performance, and

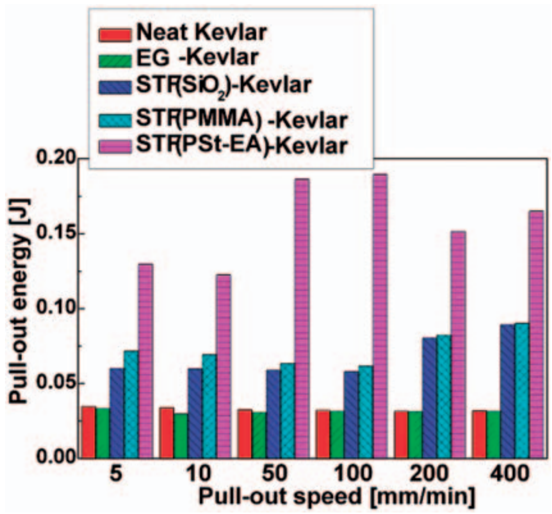

Figure 11. Comparison of the pull-out energy for the neat fabric, EG-fabric and STF (with different types of particles)-fabric at different pull-out speeds.
STF: shear thickening fluid; EG: ethylene glycol; PMMA: polymethylmethacrylate; PSt-EA: polystyrene-ethylacrylate.

the target with SiO_2 particle exhibited similar puncture resistance performance as compared with the neat fabric target. The puncture resistance performance for the neat fabric target was similar with the EG-fabric target. In general, the fabric targets by adding the STF behave better puncture resistance performance than the neat fabric target. Among these STF-fabric targets, the target with SiO_2 particles exhibited the worst puncture resistance performance and the target with PSt-EA particles exhibited the best puncture resistance performance. There was less obvious puncture damage in the STF-fabric targets. For the STF-fabric targets, no significant yarn fracture was observed.

The fabric damage under spike drop tower was primarily due to the parting of the filaments within yarns and between yarns, and the puncture of spike tip through the fabric. The distinction of the puncture resistance performance for the STF-fabric targets with different types of particles could be interpreted by the fabric damage mechanism. This distinction was responded for the difference of inter-yarn friction for the STF-fabric with different types of particles. The inter-yarn friction could be measured by the yarn pull-out testing. In Figure 10, during all the pull-out speeds, the yarn pull-out forces for the STF-fabric with different types of particles were larger than that for the neat fabric. This could explain that why the STF-fabric targets had better puncture resistance performance than the neat fabric target. The yarn pull-out force for the EG-fabric was slightly smaller than that for the neat fabric, but the distinction was so small that the puncture resistance performance for EG-fabric seemed to be similar to the neat fabric. For the STF-fabrics, the pull-out force for the PMMA-fabric was slightly larger than that for the SiO_2-fabric, and the pull-out force for the PSt-EA-fabric was the largest. The trend of the pull-out force for different fabrics was in accordance to the trend of the puncture resistance performance for different fabric targets. The pull-out energy was defined as the area under the pull-out force curve and represented the total energy required during yarn pull-out. The histogram of pull-out energy versus pull-out speed is plotted in Figure 11 by integrating the curve of the pull-out force versus the displacement shown in Figure 10. Figure 11 summarizes the comparison of the pull-out energy for the neat fabric, EG-fabric and STF-fabric with different types of particles. It was clear that the pull-out energy for the PSt-EA-fabric was the largest, and the one for the PMMA-fabric was slightly larger than that for the SiO_2-fabric. Taking the 10 mm/min pull out speed as an example, the pull-out energy of the PSt-EA-fabric was calculated to be 0.12 J, which was about 4 times larger than the neat fabric (0.03 J). For the SiO_2-fabric and PMMA-fabric, the values were 0.6 and 0.7 J respectively, which indicated that the strengthen effect of the PSt-EA-based STF was higher than the other two STFs. The larger the pull-out energy is, the larger the energy consumption during the friction action among the yarns is. Correspondingly, with increasing of the pull-out energy, the puncture resistance performance increased. Based on the above analysis, it is found that the pull-out testing agrees well with the spike drop tower testing.

Effect of the dispersing medium' types on stab resistance

The neat fabric target and the STF-fabric targets with different kinds of dispersing medium were also employed to compare the distinction of knife stab and puncture resistance performance through the drop tower testing, in order to investigate the effect of the dispersing medium's types on the knife stab and puncture resistance performance. It could be found from Figure 12 that the fabric target with EG had the least penetration depth, while the fabric target with PEG600 had the most penetration depth under both the knife and spike drop tower testing. This phenomenon also can be demonstrated in the optical microscope images for the targets under the knife and spike drop tower (Figure 13).

The effect of the dispersing medium on the puncture resistance performance of the fabric target is more obvious than that on the knife stab resistance

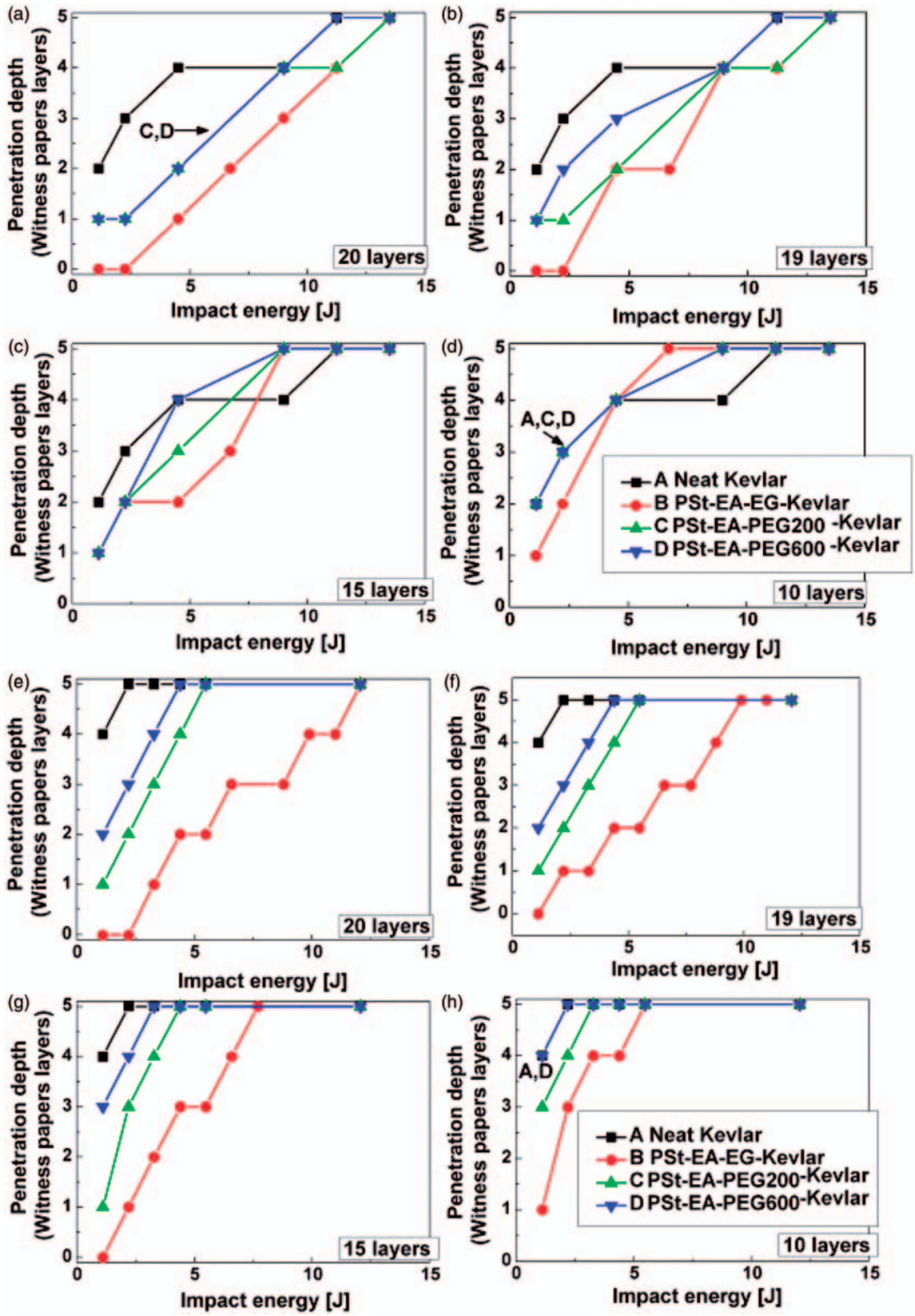

Figure 12. Drop tower results for the neat fabric and STF (with different types of dispersing medium)-fabric: (a)–(d) knife, (e)–(h) spike. The neat fabric has 20 layers. The STF-fabrics have (a) (e) 20, (b) (f) 19, (c) (g) 15 and (d) (h) 10 layers, respectively.
STF: shear thickening fluid; EG: ethylene glycol; PEG: polyethylene glycol; PSt-EA: polystyrene-ethylacrylate.

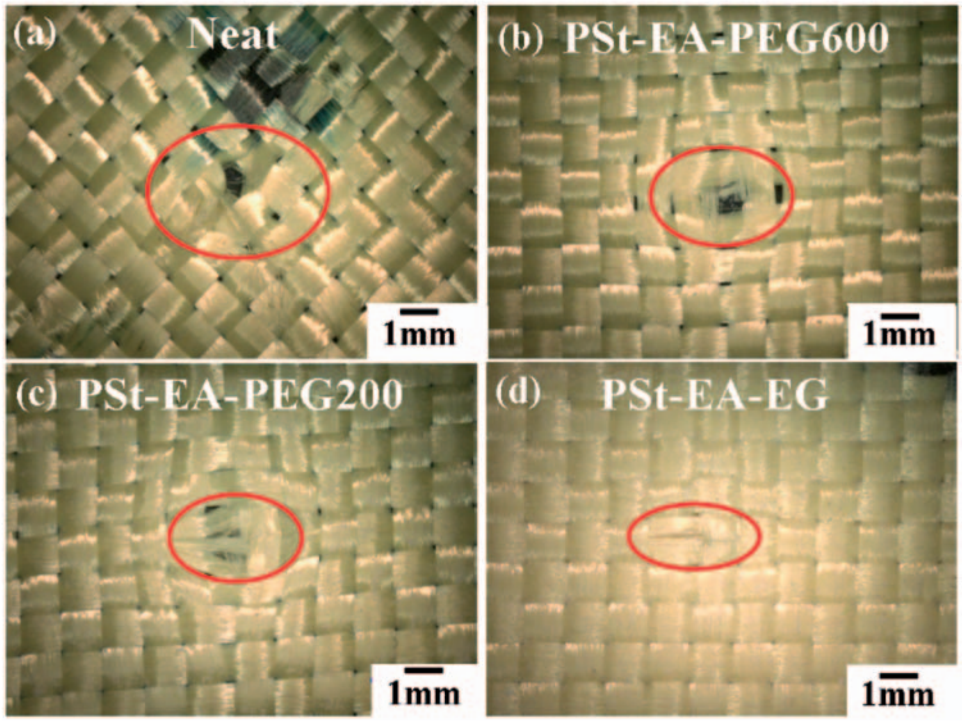

Figure 13. Optical microscope images of the fabric target after knife drop tower ($h = 5$ cm) for the neat fabric and STF (with different types of dispersing medium)-fabric.
STF: shear thickening fluid; PSt-EA: polystyrene-ethylacrylate; PEG: polyethylene glycol; EG: ethylene glycol.

performance. From the above analysis, it is found that there are two major factors affecting the stab resistance performance. One factor is the hardness of the particles, while the other factor is the inter-yarn friction. Because the fabric damage under the knife drop tower is mainly caused by the cutting of the yarns in fabric, the distinction of the knife stab resistance performance for the fabric target is due to the distinction of the hardness of the particles. This reason is under domination, because the effect of the inter-yarn friction on the knife stab resistance performance is relatively small. In contrast, the fabric damage under the spike drop tower is mainly caused by the parting within the yarns and among the yarns, and then the spike tip could puncture through the fabric. In this case, the distinction of the puncture resistance performance is primarily due to the difference of the inter-yarn friction.

The effect of the dispersing medium on the inter-yarn friction is demonstrated in Figure 14, which showed the yarn pull-out results for the neat fabric and the STF-fabric with different dispersing medium at different pull-out speeds. The pull-out force for the fabric with EG was the largest, and the one for the fabric with PEG200 was slightly larger than that with PEG600. By integrating the curve of the pull-out force versus the displacement (Figure 14), the histogram of pull-out energy versus pull-out speed is plotted in Figure 15, which showed the comparison of the pull-out energy for the neat fabric and STF-fabric with different types of dispersing medium at different pull-out speeds. Similarly, the pull-out energy for the fabric with EG was the largest, and the pull-out energy for the fabric with PEG200 was slightly larger than that for the fabric with PEG600. When the speed was kept at 100 mm/min, the pull-out energy for the fabric with EG was 0.19 J, which was about 5 times larger than the PEG200 based STF and PEG600 based STF. With increasing of the pull-out energy, the energy consumption during the friction action among the yarns and the puncture resistance performance increased correspondingly. If the particle was kept the same, the inter-yarn friction forces for the fabric with different dispersing medium were different. It has been discussed above that the dispersing medium highly affected the shear thickening rheological behavior (Figure 2), therefore, the mechanical properties of the STF-fabric changed correspondingly by varying the dispersing medium. The mobility of yarns in fabric, which was restricted by the inter-yarn friction, played an important role in the fabric failure of the 'windowing' effect.[26] Finally, the influence of the fabric with different dispersing medium on the inter-yarn friction was according to that on the knife stab and puncture resistance performance.

Based on the above discussion, it is found that the fabric failure modes for the knife impactor and the

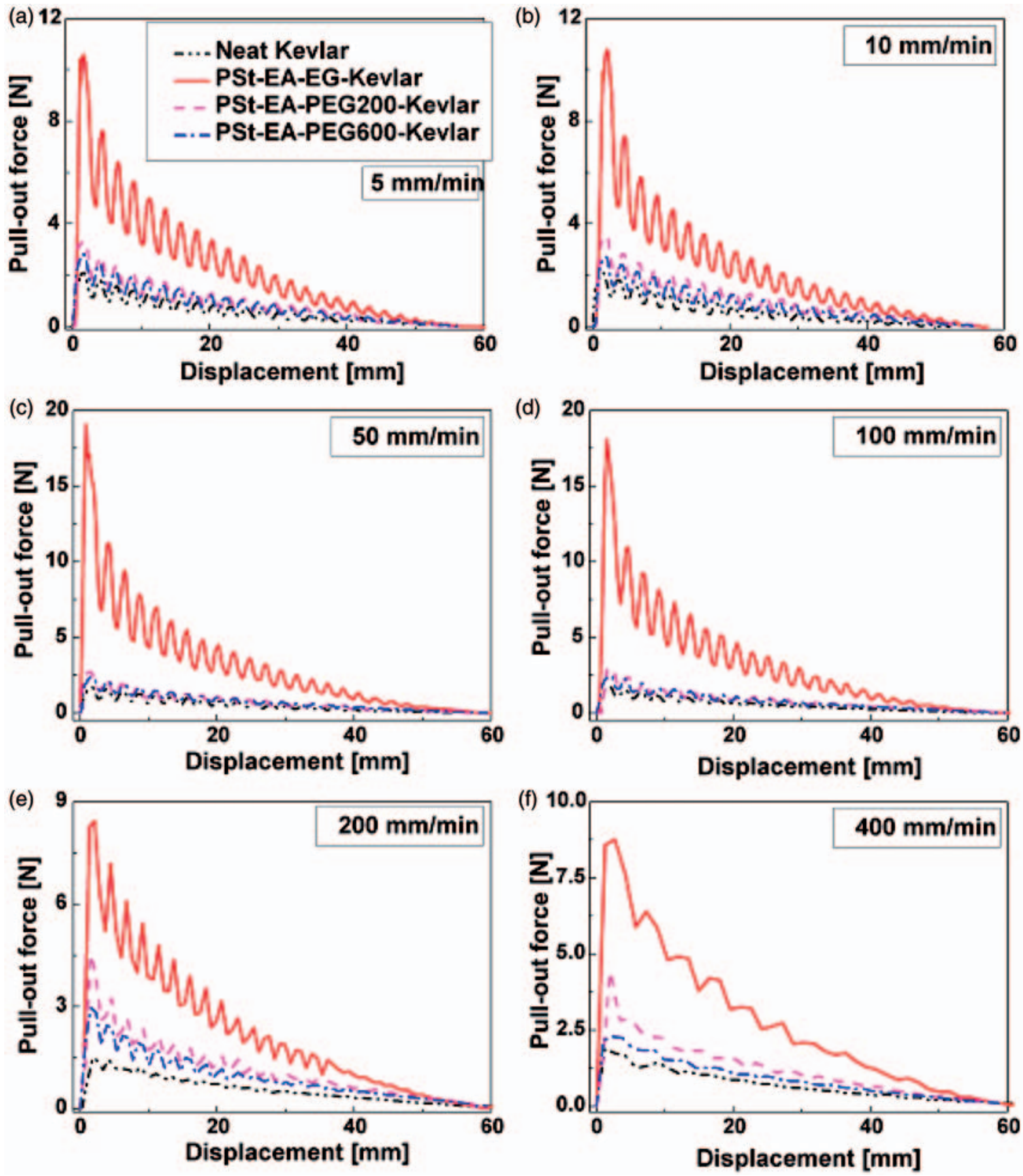

Figure 14. Yarn pull-out results for the neat fabric and STF (with different types of dispersing medium)-fabric at different pull-out speeds: (a) 5 mm/min; (b) 10 mm/min; (c) 50 mm/min; (d) 100 mm/min; (e) 200 mm/min; (f) 400 mm/min.
STF: shear thickening fluid; PSt-EA: polystyrene-ethylacrylate; PEG: polyethylene glycol; EG: ethylene glycol.

spike impactor are different. The stab resistance includes the knife stab resistance and the puncture resistance. For the fabric failure under the knife drop tower, the cutting of the yarns in fabric is dominant, while the parting within the yarns and among the yarns is dominant for the fabric failure under the spike drop tower. Therefore, the dominant influencing factors for the cutting and puncture resistance performance of the fabric targets are different.

The yarns' strength is critical to enhance the knife stab resistance performance of the fabric target. After the addition of STF, the yarns' equivalent strength in fabric significantly improved. With increasing of the particle's hardness, the yarns' equivalent strength in fabric increases (SiO_2 > PSt-EA > PMMA > neat). The target with hard SiO_2 particles exhibits the best knife stab resistance performance and the target with soft PMMA particles exhibits the worst knife stab resistance performance. Meanwhile, the parting within the yarns and among the yarns is related to the yarns' mobility. The mobility of yarns in fabric is determined by the inter-yarn friction,

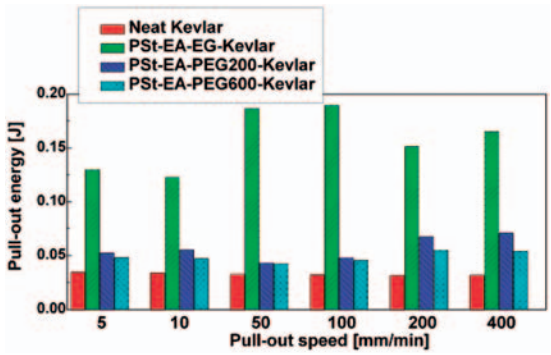

Figure 15. Comparison of the pull-out energy for the neat fabric and STF-fabric with different types of dispersing medium at different pull-out speeds.
STF: shear thickening fluid; PSt-EA: polystyrene-ethylacrylate; PEG: polyethylene glycol; EG: ethylene glycol.

which is the dominant factor for the puncture resistance performance of the STF-fabric target. The inter-yarn friction is judged by the pull-out force. For the fabric with PMMA particles the pull-out force is slightly larger than that for the fabric with SiO_2 particles, and the pull-out force for the fabric with PSt-EA particles is the largest (PSt-EA > PMMA > SiO_2 > neat). The pull-out energy is also improved by the impregnation of STF. For the fabric with PSt-EA particles, the improvement is the highest up to 494% in comparison to the neat fabric. Even for the fabric with SiO_2 particles, the improvement is still 74%. As a result, the target with SiO_2 particles exhibits the worst puncture resistance performance and the target with PSt-EA particles exhibits the best puncture resistance performance.

Besides the enhancement effect of STF's particles, the dispersing medium is also an important factor for the cutting and puncture resistance performance. For the fabric failure under the knife drop tower, the filaments within yarns or between yarns also have a small relative displacement. In comparison to the equivalent yarns' strength, the inter-yarn friction is a secondary factor for the knife stab resistance. The penetration layers by varying the inter-yarn friction could only change 1 or 2 layers. In contrast, by varying the equivalent yarns' strength, the penetration layers could reach 5 layers, which is the largest in this testing range. For the fabric targets with the same particles, the enhancement factor becomes the inter-yarn friction for both the knife stab resistance and the puncture resistance. Because of shear thickening of STF, the filaments within yarns and between yarns could be restricted and the mobility is reduced, which induces the increment of inter-yarn friction. The trend for the different fabric targets under the knife drop tower is similar to the trend for the different fabric targets under the spike drop tower. For the fabric with PEG600, the improvement of the pull-out energy is 30% in comparison to the neat fabric, while the EG-fabric exhibits the largest pull-out force (494%). The fabric target with EG exhibits the best knife stab and puncture resistance performance and the fabric target with PEG600 exhibits the worst knife stab and puncture resistance performance.

Conclusions

In this work, a series of the STF strengthened fabric were prepared by directly impregnating the STF into the Kevlar fabric. The knife stab and puncture resistance performance of the STF-fabric targets were systematically analyzed by using the knife and spike drop tower testing. The knife stab resistance performance of the STF strengthened fabric was dominated by hardness of the STF particles and the fabric strengthened by the SiO_2 based STF exhibited the highest knife stab resistance, while the puncture resistance performance was dependent on the inter-yarn friction and the target with PSt-EA particles exhibited the best puncture resistance performance. Finally, the influence of the dispersing medium also affected the knife stab and puncture resistance performance and it was found that the low molecular weight solvent led to the better mechanical property which may be due to the increment of inter-yarn friction. Although it was estimated that the knife stab and puncture resistance performance was highly influenced by the interactions between the STF particles and the yarns, the detailed mechanism was still unclear and this will be conducted in our future work.

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Conflict of interest

None declared.

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