Available online at www.sciencedirect.com

SCIENCE DIRECT®

International Journal of Solids and Structures 42 (2005) 1561–1576

INTERNATIONAL JOURNAL OF SOLIDS and STRUCTURES

www.elsevier.com/locate/ijsolstr

Strengthening fabric armour with silica colloidal suspensions

V.B.C. Tan *, T.E. Tay, W.K. Teo

Department of Mechanical Engineering, National University of Singapore, 9 Engineering Drive 1, 117576 Singapore

Received 20 March 2004; received in revised form 12 August 2004
Available online 27 October 2004

Abstract

This study investigates the ballistic performance of Twaron® CT615 plain-woven fabric impregnated with a silica colloidal water suspension (SWS) of different particle concentrations in water. The ballistic limits and specific ballistic energy of single, double, quadruple and six ply fabric systems impregnated with 0, 20, 40 and 50 wt% SWS particle concentration are compared to that of a neat untreated system. Results show that systems with 40 wt% SWS particle concentration yield the highest ballistic limit for single, double and quadruple ply systems, with the double ply system showing the greatest improvement. The ballistic limits of double ply systems with 40 wt% SWS particle concentration is 70% higher than the ballistic limit of neat double ply systems. The improvement in ballistic resistance is attributed to the increase in projectile-fabric friction and inter-yarn friction arising from the silica particle and silica clusters formed. The impact energy at the ballistic limit is normalized by the areal density of the multi-ply systems to give the specific ballistic energy. The double ply system with 40 wt% SWS particle concentration showed the greatest improvement with a 100% increase in the specific ballistic energy over neat double ply systems. However, the specific ballistic energy for quadruple and six ply systems with SWS is lower compared to the neat systems. High-speed photography showed that these systems experience more localized deformation on impact and this may limit the frictional effects. It is also shown that SWS impregnated double ply systems can be incorporated into six ply configurations to significantly improve overall ballistic performance.

Keywords: Fabric armor; Ballistic impact; Colloidal suspension; Shear thickening

* Corresponding author. Tel.: +65 6874 8088; fax: +65 6779 1459.
E-mail address: mpetanbc@nus.edu.sg (V.B.C. Tan).

0020-7683/$ - see front matter
doi:10.1016/j.ijsolstr.2004.08.013

1. Introduction

Fabric armour, such as Kevlar®, Twaron® and Spectra®, has been extensively used for flexible personnel ballistic protection due to its high strength, high tenacity and lightweight characteristics. The usual method to increase protection against more lethal ballistic threats is to add more layers of fabric or ceramic inserts at the expense of increased weight of the armour and reduced mobility of the user.

The effectiveness of fabric armour depends on several factors (Cunniff, 1992). The factors highlighted by Cheeseman and Bogetti (2003) are the material properties of the yarns; the fabric weave architecture; the projectile geometry; the interaction between individual fabric layers; far field boundary conditions; and the inter-yarn and fabric-projectile friction. Inter-yarn and fabric-projectile friction plays a significant role in the ballistic performance of the fabric and has been a subject of study of numerous researchers such as Briscoe and Motamedi (1990, 1992), Lavielle (1991) and Campos et al. (2003). Lee et al. (2001) reported that yarns within woven fabric armor are less likely to slip over one another and over the projectile when the inter-yarn and fabric-projectile friction are increased. Hence, the projectile is required to engage and break more yarns instead of simply pushing the yarns apart in order to perforate the fabric. This results in increased energy absorption. Briscoe and Motamedi also conducted ballistic tests on a satin weave of Kevlar® 29 and a "crow's foot" weave of Kevlar® 49 under three states of lubrication—"as received", Soxhlet extracted (scoured) and coated with a 5% solution of poly-dimethysiloxane (PDMS). The ballistic limit of the fabric was found to increase with decreasing levels of lubrication, leading them to conclude that modest changes to the inter-yarn friction could produce considerable changes in the ballistic performance of a fabric.

A previous study done by Lee et al. (2003) showed that the ballistic penetration resistance of Kevlar® fabric is enhanced by impregnating the fabric with a colloidal shear thickening fluid (STF), consisting of silica particles in ethylene glycol. Kevlar® targets of size 47.6×47.6 mm were impregnated with 2, 4 and 8 ml of STF per layer of fabric. Fragment Simulation Projectile (FPS) was fired at $\sim$244 m/s on targets placed against clay witnesses to measure the depth of penetration. They show that the energy absorption of four layers of Kevlar® is proportional to the amount of STF. In addition, four layers of Kevlar® impregnated with 8 ml of STF is found to have the same energy absorbed as 14 layers of un-impregnated layers. The performance enhancement provided by the STF was suspected to be the increased frictional interaction between the yarns.

A shear thickening fluid is a non-Newtonian fluid whose viscosity increases with increasing shear stress. Examples are concentrated particle colloidal suspensions such as photographic dies, paints, coatings and lubricants. When such fluid is subjected to a high-enough shear stress, it can lead to a rapid, sometimes discontinuous, increase in viscosity (Hoffman, 1997; Barnes, 1989). Brady and Bossis (1985) postulated colloidal clusters comprising compact groups of particles are formed in STF when shear forces drive particles nearly into contact. Short range lubrication forces between the clusters cause the increase in viscosity with increasing shear stress as the clusters become larger, making it more difficult for the clusters to slide past one another. Boersma et al. (1995) used Stokesian dynamics to analyze the response of suspensions and made similar conclusions. Maranzano and Wagner (2001) and Bender and Wagner (1996) predicted that the critical stress for the onset of shear thickening is scaled with particle size and volume fraction of the particles in the suspension. The energy dissipated by STF was determined by Lee and Wagner (2003) from Lissajous plots. The area enclosed by the stress-strain curve in the Lissajous plot indicates the amount of energy dissipated by the fluid.

This study aims to ascertain the optimum silica particle concentration in water to attain the greatest improvement in the ballistic limits of single, double and quadruple ply of CT615 Twaron® fabric systems. The ballistic limits and specific ballistic energy of single, double and quadruple ply systems, impregnated with 0, 20, 40 and 50 wt% SWS particle concentrations in water are obtained from ballistic tests and compared to that of neat and untreated system.

2. Fabrication and testing of SWS treated specimens

2.1. Materials

The fabric used in the ballistic tests is Twaron® CT615. It is a plain-woven fabric comprising poly-(para-phenylene terephthalamide) (PPTA) yarns. The manufacturer's specifications for Twaron® CT615 are given in Table 1. Rectangular target specimens of dimensions 300(warp) × 120(weft) mm were prepared (Fig. 1). The two shorter edges were then wrapped round steel rods and clamped in a jig, leaving a target area of 125 (W) × 120 (H) mm as shown in Fig. 2.

The fluid used in this study is a silica-water suspension (SWS), i.e. it consists of silica colloids (Nissan Chemical MP1040) in water, as opposed to a suspension of silica colloids in ethylene glycol used by Lee and Wagner (2003). The silica particles have a nominal diameter of 100 nm. Water was chosen because it was observed to wet the Twaron® fabric spontaneously facilitating the impregnation process. The dry silica particles were weighed using a clinical weighing machine to determine the weight fraction of particles.

Table 1
Properties of Twaron® CT615

Linear density [$dtex_{nom}$] Warp & Weft	550 × 500
Weave type	Plain
Areal density	150 g/m^2
Thickness	0.25 mm
Breaking strength [N/5 cm] (warp/weft)	6.7/6.5

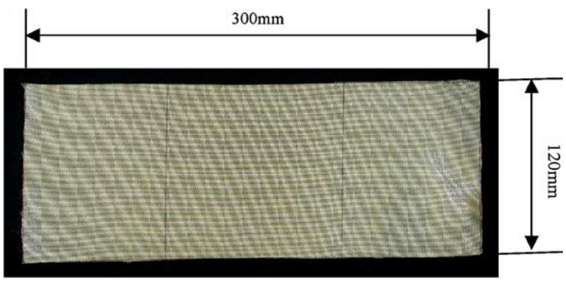

Fig. 1. Dimension of the target specimen.

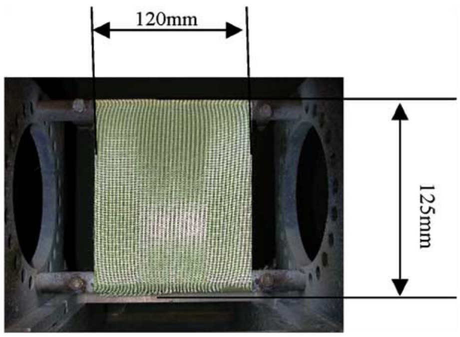

Fig. 2. Target specimen being clamped before impact tests.

Measured amounts of water were added to achieve the required particle concentrations of 0, 20, 40, 50 wt%. The suspension was then mixed using a magnetic stirrer for 3 h to ensure that the silica particles were well suspended within the water.

2.2. SWS impregnation of fabric targets

The impregnation of the target was done by soaking the fabric specimen with 4 ml of SWS of the required particle concentration for 20 min. For multiple ply systems, each ply was impregnated with 4 ml of SWS before being placed together. The areal densities of the impregnated fabric were determined by weighing the test specimens on a clinical weighing machine and dividing the mass by the area of the whole fabric target. The areal densities of different fabric ply system configurations are shown in Table 2.

Table 2
Areal density and ballistic limit of fabric armor systems tested

No. of ply(s)	Treatment/configuration	Areal density (g/m^2)	Ballistic limit (m/s)
Single	Neat	150	74
	0 wt% SWS	207	73
	20 wt% SWS	211	79
	40 wt% SWS	214	92
	50 wt% SWS	216	80
	20 wt% SWS (dried)	194	75
Double	Neat	300	135
	0 wt% SWS	412	122
	20 wt% SWS	420	177
	40 wt% SWS	430	223
	50 wt% SWS	434	168
	20 wt% SWS (dried)	390	152
Quadruple	Neat	600	273
	0 wt% SWS	832	242
	20 wt% SWS	840	302
	40 wt% SWS	856	307
	50 wt% SWS	864	285
Six	Neat	900	315
	40 wt% SWS	1284	306
	50 wt% SWS	–	295
	Four ply neat + space + two ply neat	900	302
	Four ply neat + 2-ply 40 wt% SWS	1032	349
	Four ply neat + space + two ply 40 wt%	1032	359

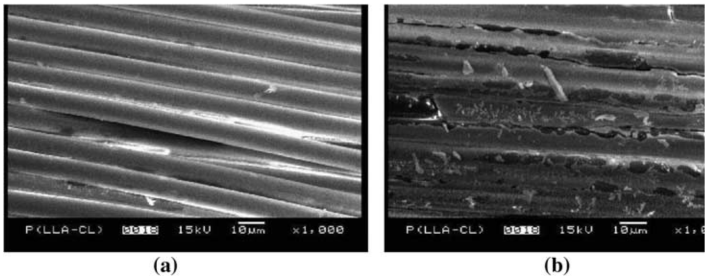

Fig. 3. SEM image (1000× magnification) of (a) neat, un-impregnated system and (b) system impregnated with 40 wt% SWS.

Fig. 3(a) shows the SEM image of a neat fabric target specimen at ×1000 magnification and Fig. 3(b) shows a fabric target specimen that is impregnated with 40 wt% SWS particle concentration. The water was removed prior to the SEM imaging by drying, leaving only the silica particles. SEM images were taken at several locations of the impregnated specimen to check that there was an even distribution of silica particles throughout the specimen. Fig. 3(b) shows that the impregnation process gives a good dispersion of the silica particles within the fibers of the yarn. However, very large clumps (∼1–10 μm) are found on the fibers, which could be due to the particles coalescing on the surface of the fibers when they are left to dry.

2.3. Ballistic impact tests

Target specimens were clamped along two opposing edges, as shown in Fig. 2 and were given a light pretension before impact tests. Fig. 4 shows the ballistic test setup. Ballistic tests were conducted using a smooth bore gas gun powered by high-pressure helium gas. Spherical projectiles of 12 mm diameter and 7 g mass were used. Laser-photodiode pairs, connected to a Cathode Ray Oscilloscope, were placed in front and behind the clamped fabric target to determine the impact and exit velocities of the projectiles.

Table 2 shows all the ballistic tests conducted. The tests can be grouped under three categories. The first set of ballistic tests is on single, double and quadruple ply systems that were impregnated with 0 (i.e. water only), 20, 40 and 50 wt% SWS particle concentration. These tests are aimed at determining the optimal combination of SWS particle concentration and number of fabric plies in multiple ply systems for ballistic resistance. The second set of ballistic tests was conducted on dry SWS impregnated single and double ply systems to evaluate the effects of the colloidal particle without water. A separate set of ballistic tests was also conducted on six ply fabric systems of various configurations to demonstrate how the performance of multiple ply systems can be enhanced by SWS. The six ply fabric configurations are shown in Fig. 5.

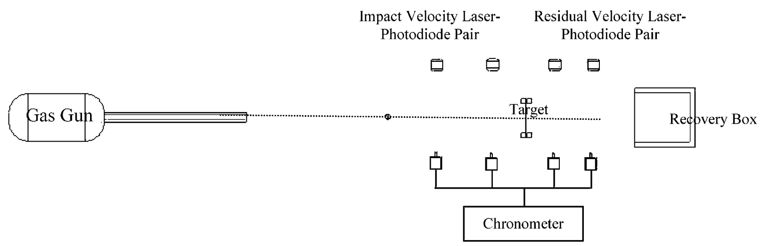

Fig. 4. Schematic diagram of experimental set-up.

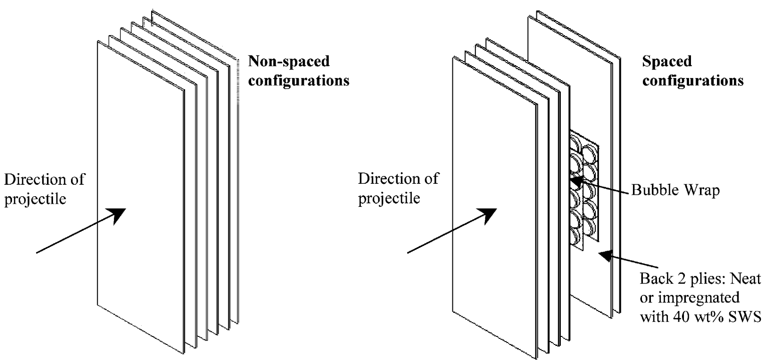

Fig. 5. Six ply fabric system configurations.

The ballistic limit and specific ballistic energy are used to evaluate the ballistic performance of the fabric systems. Ballistic limit is the velocity at which the projectile just penetrates the armor. To determine the ballistic limit of a system, impact tests were carried over a narrow range of impact velocities until the difference between the highest impact velocity that did not cause perforation and the lowest impact velocity that resulted in perforation was less than 5 m/s. The ballistic limit is taken as the average of the two velocities.

2.4. Yarn-pullout tests

The addition of SWS is not expected to change the material properties of the PPTA fibers. Instead its influence on the ballistic performance of the fabric armor system would be in the way inter-yarn slippage is affected. In order to investigate this effect, a quasi-static yarn-pullout test was conducted to obtain a rel-

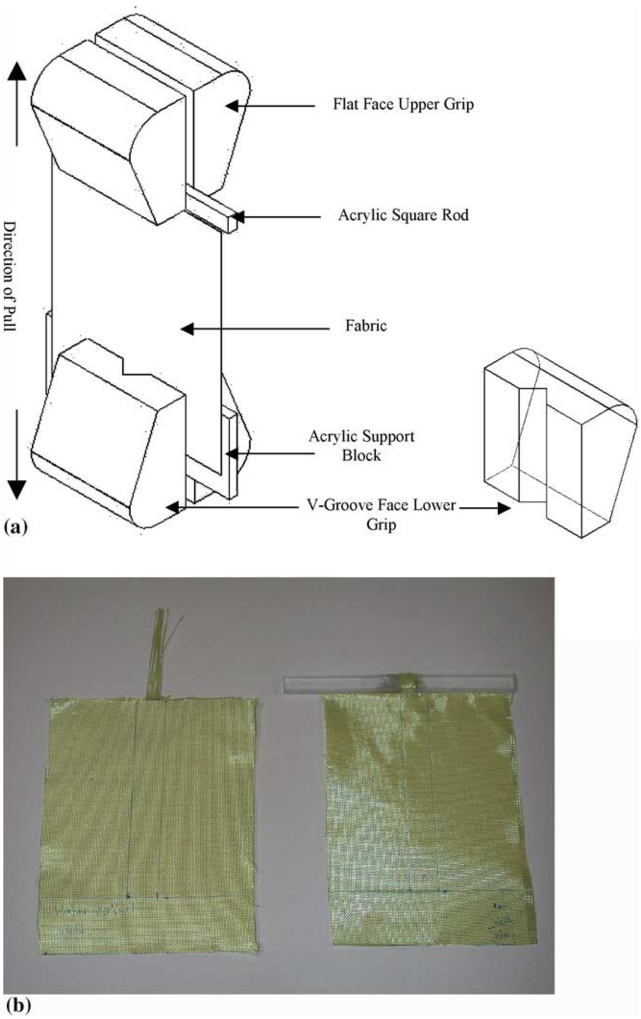

Fig. 6. Yarn-pullout test. (a) Experimental set-up. (b) Test specimen.

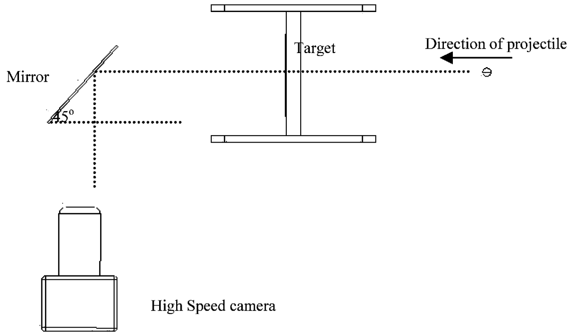

Fig. 7. Experimental layout for high-speed photography.

ative measure of the friction between yarns in neat Twaron® CT615 fabric specimens and those impregnated with 0, 20, 40, 50 wt% SWS particle concentration.

The test set-up is shown in Fig. 6. Ten yarns at the center of a fabric specimen were clamped in a flat-faced upper grip and the lower edge of the fabric specimen was clamped with a V-grooved lower grip. The groove in the lower grip allows yarns at the center of the fabric specimen to be pulled out when the grips are moved apart. The gauge length and the width of the test specimen were both 120 mm. The yarns were pulled at a feed-rate of 50 mm/min.

2.5. High-speed photography

High-speed photography was performed on a neat six ply fabric system and a six ply fabric system impregnated with 40 wt% SWS. The impact process was recorded at a frame rate of 30,000 frames per second (fps) with a resolution of 256×128 pixels per image. Fig. 7 shows the plan view of the layout of the camera and the ballistic test setup used to capture the rear view of the fabric target when impacted by the projectile.

3. Experimental results

3.1. Ballistic limits

The ballistic limits of the single, double and quadruple ply systems treated with SWS of various particle wt% are plotted in Fig. 8. The dotted horizontal lines indicate the ballistic limits of the neat single, double and quadruple ply systems. Fig. 8 shows that the ballistic limit of all three fabric ply systems increases with increasing SWS particle concentration from 0 wt% to about 40 wt%, after which, an increase in the concentration to 50 wt% results in a drop in the ballistic limit. Hence, although SWS enhances the energy absorbed by the fabric, there is an optimal SWS particle concentration of about 40 wt% SWS.

It is also noted that the double ply system displayed significantly greater improvement in ballistic limit compared to the single and quadruple ply systems and also the greatest drop in ballistic limit when the particle concentration is increased from 40 wt% to 50 wt%. The silica suspension affects the quadruple ply system to a lesser extent than the double ply system and the ballistic limit of the single ply system showed the least sensitivity to the suspension. This suggests that the silica suspension affects inter-ply interaction, therefore single ply systems are not as sensitive to the suspension whereas systems comprising more than four plies may be too stiff to experience relative ply sliding to benefit from the SWS. It should be noted while the ballistic limits of single ply systems are relatively less affected by the silica suspension, this does not

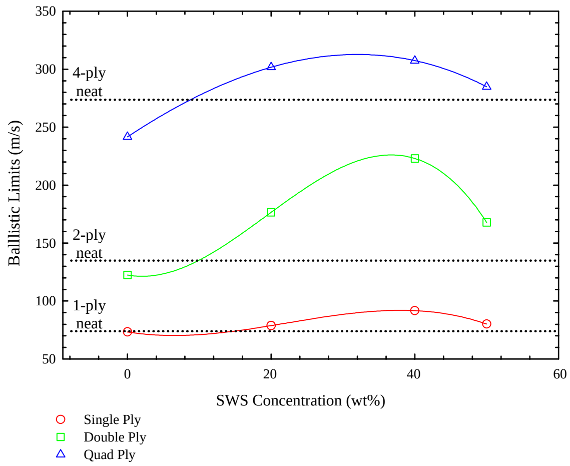

Fig. 8. Ballistic limits of single, double and quadruple ply systems under different treatments.

mean that single ply systems do not benefit at all from treatment with the silica suspension. In fact, neat single ply Twaron has a ballistic limit of 74 m/s while single ply fabric treated with 40 wt% silica suspension has a ballistic limit of 92 m/s.

3.2. Specific ballistic energy

The specific ballistic energy is the energy of the projectile at the ballistic limit divided by the areal density of the fabric system. This quantity gives the mass efficiency of the fabric system. Fig. 9 shows the variation of the specific ballistic energy. The double ply system impregnated with 40 wt% SWS has the greatest improvement with a specific ballistic energy of 0.414 J/g/m^2. This is nearly equal to the specific ballistic energy of a neat quadruple ply system of 0.435 J/g/m^2 as shown in Fig. 9. This means that an impregnated double ply system can effectively replace a neat quadruple ply system and yet provide better protection and more drapability in the armour. It is also observed that the specific ballistic energy of an impregnated quadruple ply system is lower than that of the neat system. Additional impact tests showed that the specific

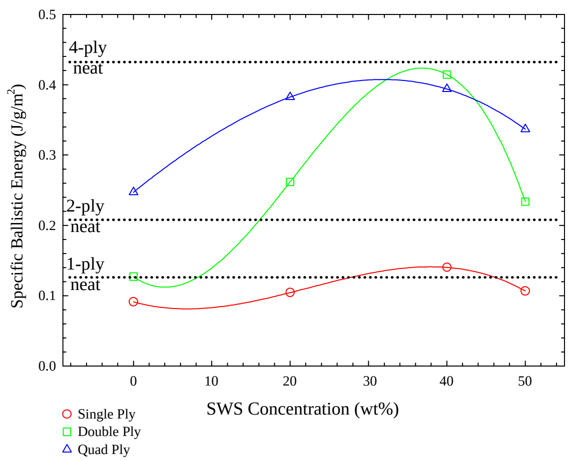

Fig. 9. Variation in the specific ballistic energy of single, double and quadruple ply system under different SWS particle concentrations.

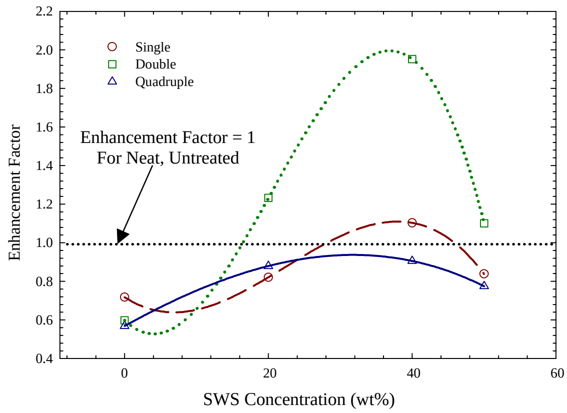

Fig. 10. Enhancement factor of impregnated single, double and quadruple ply system compared to the neat, un-impregnated system.

ballistic energy of a six ply system impregnated with 40 and 50 wt% is lower than the neat six ply system as indicated in Table 2. This shows that the ballistic performance is not mass efficient if four or more plies of impregnated fabric are used.

The energy absorbed by four plies of STF treated woven Kevlar fabrics was also studied by Lee et al. (2003). They showed that a four ply treated system can absorb the same impact energy as 14 plies of neat Kevlar fabric. However, the tests were performed on different fabric of different make (Kelvar KM-2, Style 706 from Hexcel Aramid) and size and with fragment simulating projectiles instead of spherical projectiles.

3.3. SWS enhancement factor

The SWS enhancement factor is proposed to provide a better measure of the improvement in the ballistic performance of the impregnated system over the neat system. It is the ratio of the specific ballistic energy of the impregnated system to that of the respective neat system, i.e.

$$\text{Enhancement factor} = \frac{\text{Specific ballistic energy of impregnated system}}{\text{Specific ballistic energy of neat system}} \tag{1}$$

Fig. 10 shows the enhancement factors for fabric systems of different number of plies with various SWS particle concentrations. By definition, a neat system would have an enhancement factor of one. The enhancement factor shows that the highest percentage improvements in the specific ballistic energy are 8.3% for single ply system and 90.4% for double ply system at 40 wt% SWS. However, the specific ballistic energy of the quadruple ply system decreases by at least 11.4% with SWS impregnation.

3.4. Effects of water and silica particles

Except for the neat specimens, almost all the tests were performed on specimens immediately after they were removed from the SWS, i.e. the specimens were moist during the impact tests. Two sets of tests were performed on SWS treated specimens after they have been left to dry. These tests involved single and double ply specimens soaked in SWS with 20 wt% of particles. The specimens were left to dry before they were subjected to impact tests. Tests were also conducted on moist specimens soaked in water without any silica colloids. The results of these tests are shown in Fig. 11. For single ply systems, the dried SWS treated specimens and the specimens soaked in water showed similar ballistic limits to that of the neat fabric. These ballistic limits are slightly lower than that of the moist single ply fabric treated with 20 wt% SWS. For

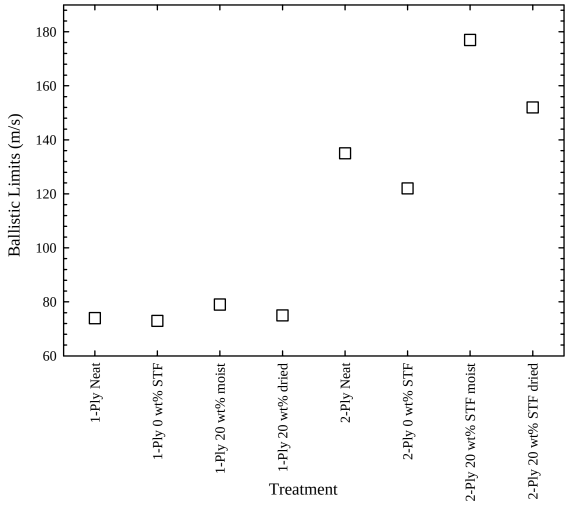

Fig. 11. Ballistic limits of single and double ply systems under different treatments.

the double ply systems, the fabric system soaked in water recorded ballistic limits 10% lower than the neat double ply system whereas the dried specimens showed a 12.6% increase in the ballistic limit. However, this is still much less than the 31% increase in ballistic limit for the moist specimen treated with 20 wt% SWS. These observations show that the improvement in the ballistic resistance of the fabric systems is not due to the water or the silica colloids acting alone but working together as constituents of a colloidal suspension. In fact, it is observed from Figs. 8 and 9 that the ballistic limits and specific ballistic energy of systems soaked in water is lower than the neat system regardless of the number of plies of fabric. Similar observations were also reported by Egres et al. (2003).

3.5. Impacts above ballistic limit

Ballistic tests were conducted for two double ply systems—neat and impregnated with 40 wt% SWS—for velocities ranging from 80 to 550 m/s. From Fig. 12, it is shown that the double ply system impregnated with 40 wt% SWS has significantly higher energy absorption over the neat system for a velocity range between 160 and 320 m/s. The energy absorbed by the fabric is taken to be the loss in kinetic energy of the projectile after it perforates the fabric systems. At impact velocity of 170 m/s, the energy absorbed by the system with SWS is about twice that of the neat double ply system. However, when the impact velocity is increased to 360 m/s, the percentage increase in energy absorbed is reduced to 20%. Hence, improvement in ballistic resistance due to the impregnation of SWS is highest close to the ballistic limit and decreases at higher impact velocity.

3.6. Six ply fabric systems

Although double ply systems showed the greatest benefit from SWS impregnation, practical applications of fabric armor usually require more than two plies of fabric. Additional ballistic impact tests were done on several six ply fabric configurations with the aim of exploiting the high-energy absorption capability of the impregnated double ply system.

The descriptions of the various six ply systems are given in Table 2 and Fig. 5. Fig. 13 shows the ballistic limits of the various six ply systems. The ballistic limit of the neat six ply system is used as a reference. It can

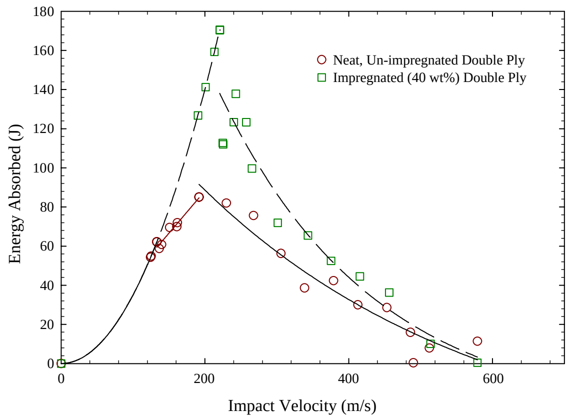

Fig. 12. Fabric energy absorption for double ply systems (neat and impregnated with 40 wt% SWS).

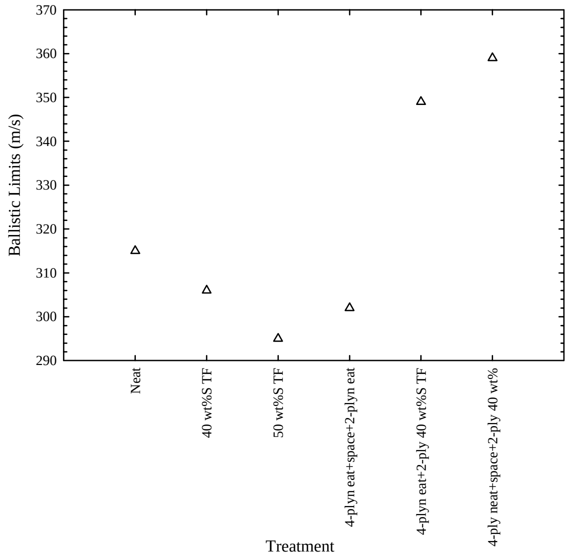

Fig. 13. Ballistic limits of six ply systems with different treatments.

be seen that six ply systems treated with SWS of 40 and 50 wt% particle displayed slightly lower ballistic limit than the neat system. This is consistent with the results of ballistic tests on quadruple ply systems which showed that the ballistic limit decreases when particle concentration of the SWS increases above 40 wt% and that the effect of SWS diminishes with more plies of fabric.

In order to exploit the big improvement in the ballistic resistance of SWS treated double ply systems, only the back two plies of fabric were treated with 40 wt% SWS. The impregnated double ply system is placed at the rear because it has improved energy absorption only in the velocity range of 160–320 m/s as shown in Fig. 13, meaning that it most effective when the projectile energy is reduced towards the end phase of the perforation process. The ballistic limits were obtained for six ply configurations with the two treated plies in contact with the front four neat plies and with the two treated plies separated from the front four ply by an air-gap i.e. with a layer of bubble wrap in between. Both configurations showed higher ballistic limits than the neat system—11% increase for the non-spaced system and 14% increase for the spaced system.

3.7. Effects of friction

The quasi-static load required to pull out the yarns in the yarn pullout tests is shown in Fig. 14. The peak of each curve represents the pullout load when pulled yarns started sliding over orthogonal yarns (i.e. inter-yarn frictional force). It is observed that the highest peak pullout load of 650N is recorded for specimens impregnated with 40 wt% SWS. This load is 150N greater than that for a neat specimen. It can also be seen that increasing the SWS particle concentration to 50 wt% did not increase the inter-yarn friction further. The inter-yarn frictional force for the specimen impregnated with 0 wt% SWS (i.e. soaked in water without silica colloids) is lower than the neat specimen indicating that water reduces inter-yarn friction. This makes it easier for the yarns of the fabric to slide past one another and be pushed apart by the projectile. Hence, the projectile is able to perforate the fabric with fewer broken yarns. Egres et al. (2003) also reported the addition of colloidal STF to woven fabrics increases yarn pullout force.

Frictional effects, such as inter-yarn friction and projectile-fabric friction, play a significant role in enhancing the energy dissipation of the SWS-fabric composite (Briscoe and Motamedi, 1992; Lavielle, 1991; Campos et al., 2003). The ballistic limits of all three fabric ply systems are increased by increasing the particle concentration of the SWS up to the optimum particle concentration of about 40 wt%. The increase in the peak pullout loads with an increase in SWS particle concentration as seen from the yarn pullout tests suggests that inter-yarn friction plays an important role in the energy dissipation by the fabric. The increase in the inter-yarn friction is also evident from the post-perforation analysis of the fabric specimens. Fig. 15 shows yarns close to the impact point which were pulled out of the fabric during projectile perforation. The extent of the yarn pullout is less when the fabric was impregnated with 40 wt% SWS, compared to the neat fabric. Furthermore, lengths of pulled out yarns are greater when the fabric is impregnated with 0 wt% SWS (i.e. water only) as shown in Fig. 15(b) compared to the neat fabric shown in Fig. 15(a). This is further evidence that the absence of silica particles and the presence of water reduce inter-yarn friction, making it easier for yarns to be pulled towards the impact point.

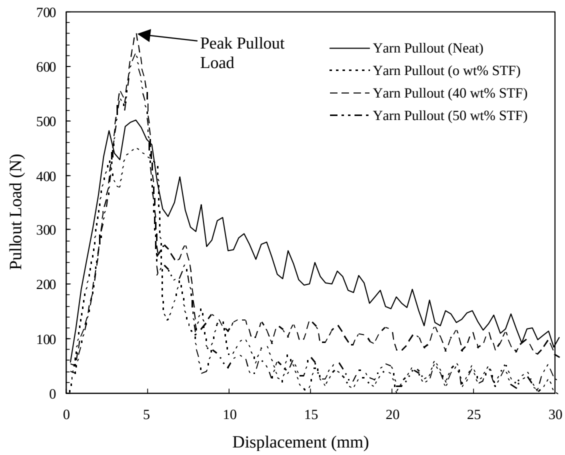

Fig. 14. Variation of yarn pullout load with pullout displacement.

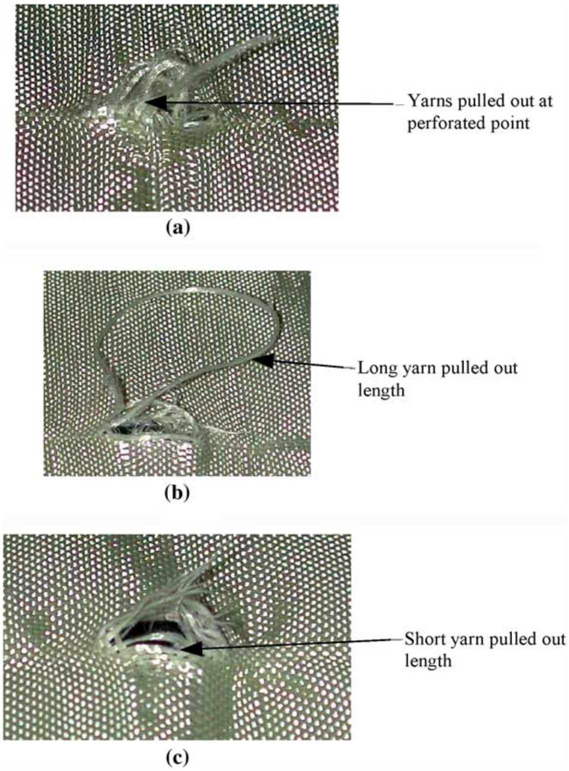

Fig. 15. Back view of perforated target specimen near its respective ballistic limits. (a) Neat fabric, (b) fabric soaked in water and (c) fabric impregnated with 40 wt% particle SWS.

The effects of shear thickening could have enhanced the ballistic performance of the fabric because the inter-yarn friction is increased. At a high-enough shear stress, such as in a ballistic impact, the SWS may undergo shear thickening where clusters of particles are formed. These clusters of particles are bigger and irregularly shaped and thus may have contributed to the increase in the inter-yarn friction. It is difficult to ascertain the magnitude of energy dissipation by shear thickening during the ballistic impact process. However, rheology tests on STF using the rheometer have been carried out to yield Lissajous plots that show the amount viscous energy dissipation by the fluid, giving an appreciation of the role of shear thickening (Lee and Wagner, 2003).

Projectile-fabric friction also contributes to the enhanced performance. Tan et al. (2003) referred fibrillation to the splitting of a fiber along its length. It is a consequence of an abrasion action of the projectile pressing against and sliding across the fabric. It is reported to be more prominent at low velocities near the ballistic limit of the system. Fig. 16 shows that the impregnated specimen has its fibers fibrillated, indicating that there may be significant frictional forces between the projectile and fabric during the ballistic impact, giving rise to frictional energy dissipation.

3.8. Fabric deformation at perforation

The improvement in ballistic performance of impregnated ply systems is achieved at the expense of increased weight. Although the ballistic limit of the impregnated quadruple ply system is higher as compared to the neat quadruple ply system, the specific ballistic energy is lower than the neat fabric system. For the

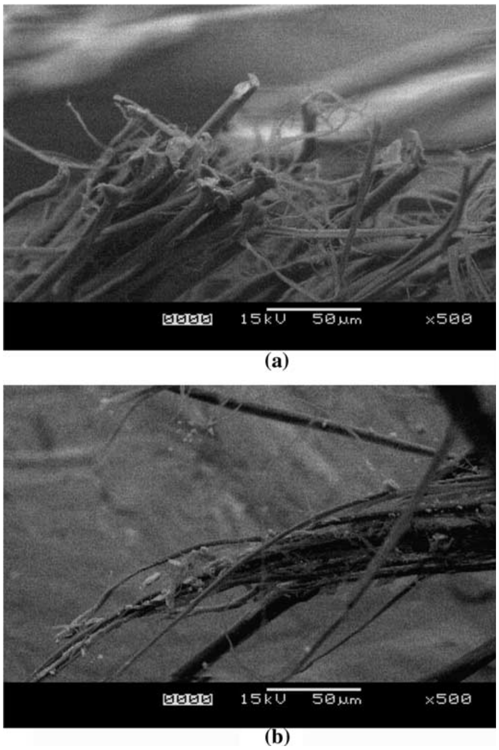

Fig. 16. SEM images at 500× magnification. (a) Fibers from a neat, untreated specimen impacted at 80 m/s and (b) fibrillated fibers from a specimen impregnated with 40 wt% SWS particle concentration and impacted at 95 m/s.

six ply systems impregnated with 40 and 50 wt% SWS, both the ballistic limits and specific ballistic energy are lower than that of a neat six ply system. Such thick fabric systems are much stiffer than the single and double ply systems. The frictional effects due to relative yarn motion are less pronounced for these already stiff systems than for double ply systems. Fig. 17(a) and (b) show the rear views of a neat six ply system and a six ply system impregnated with 40 wt% SWS at the onset of projectile perforation at 360 m/s. Only the top half of the fabric target was captured to obtain a higher magnification. The bottom half of the fabric is assumed to be symmetrical to the top. Fig. 17(a) shows the deformation of the neat six ply systems. Treating the specimens with SWS makes the deformation more localized as shown in Fig. 17(b), i.e. the amount of fabric deformed for the neat target is larger than that of the impregnated target, indicating that less fabric is used for the target impregnated with 40 wt% SWS to absorb the impact energy of the projectile. Hence,

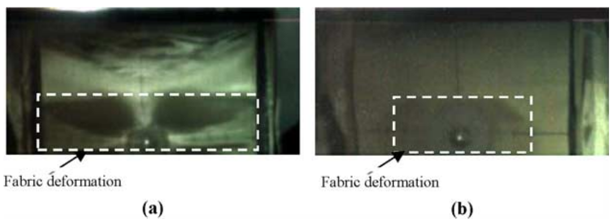

Fig. 17. High-speed photography of six ply system with projectile velocity of 360 m/s and frame rate of 30,000 fps. (a) Neat fabric and (b) fabric impregnated with 40 wt% SWS.

SWS treatment of already stiff fabric systems does not lead to improvement in the ballistic resistance because the fabric deformation is very localized. Instead, SWS treatment could lead to a reduction in the energy absorbed by the target.

4. Conclusion

The ballistic limits of fabric armor systems can be improved by impregnating the fabric with SWS. It was found that the ballistic limits of single, double and quadruple ply fabric systems increase with the concentration of silica particles in the SWS up to an optimum of 40 wt%. Beyond 40 wt% concentration, the ballistic limit starts to decrease. The effectiveness of the SWS is also dependent on the number of fabric plies in the armor system. For systems with four or more plies, the effect of SWS is less pronounced. In fact, for six ply systems, SWS could lead to degradation in ballistic resistance. For quadruple ply systems, the absolute ballistic limit is increased with SWS treatment but the specific ballistic limit is reduced. High-speed photography on six ply systems (neat and impregnated with 40 wt%) has shown that the impact damage of the impregnated system is more localized because the SWS reduces transverse deformation thus decreasing the amount of energy dissipated by the fabric.

The largest improvement in ballistic limit is for a double ply system impregnated with 40 wt% SWS. The ballistic limit improved by 65% while the specific ballistic energy increased by almost 100% as compared to the neat double ply system. The specific ballistic energy of the double ply system with 40 wt% SWS is even higher than that of the neat quadruple ply system.

Although six ply fabric systems impregnated with 40 and 50 wt% SWS were found to have lower ballistic limits than neat six ply systems, it was found that if only the last two plies of the six ply system are impregnated with 40 wt% SWS, the ballistic limit of the hybrid six ply system is improved by 14%.

A strong correlation is noted for the quasi-static yarn pullout load and ballistic specific ballistic energy. Both yarn pullout tests and ballistic tests on SWS treated specimens showed that the pullout load and specific ballistic energy increases with particle concentration of the SWS up to 40 wt%, above which there is no further increase in pullout load and ballistic limit.

References

Barnes, H.A., 1989. Shear thickening ("dilatancy") in suspensions of non-aggregating solid particles dispersed in Newtonian liquids. Journal of Rheology 33, 329–366.

Bender, J., Wagner, N.J., 1996. Reversible shear thickening in monodisperse and bidisperse colloidal dispersions. Journal of Rheology 40, 899–916.

Boersma, W.H., Laven, J., Stein, H.N., 1995. Computer simulation of shear thickening of concentrated dispersions. Journal of Rheology 39, 841–860.

Brady, J.F., Bossis, G., 1985. The rheology of concentrated suspensions of spheres in simple shear flow by numerical simulation. Journal of Fluid Mechanics 155, 105–129.

Briscoe, B.J., Motamedi, F., 1990. Role of interfacial friction and lubrication in yarn and fabric mechanics. Textile Research Journal 60 (12), 697–708.

Briscoe, B.J., Motamedi, F., 1992. The ballistic impact characteristics of aramid fabrics: the influence of interface friction. Wear 158 (1–2), 229–247.

Campos, R., Bechtold, T., Rohrer, C., 2003. Fiber friction in yarn—a fundamental property of fibers. Textile Research Journal 73, 721–726.

Cheeseman, B.A., Bogetti, T.A., 2003. Ballistic impact into fabric and compliant laminates. Composite Structures 61, 161–173.

Cunniff, P.M., 1992. An analysis of the systems effects of woven fabrics under ballistic impact. Textile Research Journal 62 (9), 495–509.

Egres, R.G., Lee, Y.S., Kirkwood, J.E., Kirkwood, K.M., Wetzel, E.D., Wagner, N.J., 2003. Novel flexible body armor utilizing shear thickening fluid (STF) composites. SME International Conference on Composite Materials, ICCM-14. San Diego, CA.

Hoffman, R.L., 1997. Explanations for the cause of shear thickening in concentrated colloidal dispersions. Journal of Rheology 42, 111–123.

Lavielle, L., 1991. Polymer–polymer friction—relation to adhesion. Wear 151, 63–75.

Lee, Y.S., Wagner, N.J., 2003. Dynamics properties of shear thickening colloidal suspensions. Rheologica Acta 42 (3), 199–208.

Lee, B.L., Walsh, T.F., Won, S.T., Patt, H.M., Song, J.W., Mayer, A.H., 2001. Penetration failure mechanisms of armour-grade fiber composites under impact. Journal of Composite Materials 35 (18), 1605–1633.

Lee, Y.S., Wetzel, E.D., Wagner, N.J., 2003. The ballistic impact performance of Kevlar woven fabric impregnated with a colloidal shear thickening fluid. Journal of Materials Science 38 (13), 2825–2833.

Maranzano, B.J., Wagner N.J, 2001. The effects of inter-particle interactions and particle size on reversible shear thickening: hard sphere colloidal dispersions. Journal of Rheology 45, 1205–1222.

Tan, V.B.C, Lim, C.T., Cheong, C.H., 2003. Perforation of high-strength fabric by projectiles of different geometry. International Journal of Impact Engineering 28, 207–222.