Defence Science Journal, Vol. 64, No. 3, May 2014, pp. 236-243, DOI : 10.14429/dsj.64.7322

Investigation on Impact Strength Properties of Kevlar Fabric using Different Shear Thickening Fluid Composition

R. Joselin* and W. Jacob Wilson

C.S.I. Institute of Technology, Thovalai-629 302, India,
**E-mail: joselinjerish@yahoo.co.in*

ABSTRACT

Great interest has aroused in developing high impact resistant fabrics based on the incorporation of a shear thickening fluid (STF) into high performance fabrics (Kevlar). This work developed a shear thickening fluid enhanced fabrics and the influence of the shear thickening fluid types against spike impact and the impact resistance performance were investigated. Silica nano-particle impregnated Kevlar fabrics exhibit significantly enhanced ballistic performance while retaining flexibility. It was found that fabrics impregnated with functionalized nanoparticles offer multiple resistance to the penetration of a sharp impactor. The improvement in protection is traced by the formation of siloxane bonds during functionalization. It exhibits significant improvement in shear stiffness and a slight increase in tensile stiffness. The impact strength properties of all samples were tested using impact testing and quasi-static testing apparatuses. Chemical compositions and microscopic structures were analyzed with Fourier transform infrared spectroscopy and scanning electron microscopy. The current study clearly displays a significant enhancement in penetration resistance of Kevlar fabric impregnated with different combination of STF's.

Keywords: Kevlar, impact resistance, scanning electron microscope, shear thickening fluid, silane coupling agent

1. INTRODUCTION

The primary objective of body armor research is to develop a low cost, lightweight, wearable garment system with improved impact resistance. Currently used body armors, particularly those for military use, are considered too heavy, limiting the agility and mobility of the wearer and eventually leading to increased casualties. Body armor standards require that an impactor should be stopped under impact, and the penetration depth into a backing material to the armor should not exceed 1.73 inches. If penetration depth exceeds this value, a wearer can acquire serious blunt trauma[1]. Therefore, the demand for substantial improvement in the performance-to-weight ratio of body armor as well as the performance-to-thickness ratio is very high. Conventional body armor materials, typically comprised of many layers of high performance Kevlar® fabric with optional ceramic tile inserts, are too bulky and stiffer for application in extremities protection[2].

Kevlar fibre is characterized by low density, high strength, and high energy absorption. Unfortunately, most ballistic fabrics produced using these high strength fibers provide little protection against spike threats and the resulting bulk and stiffness of the armor limits its comfort and flexibility. A material is needed which can offer the equivalent ballistic performance of existing body armor materials, but with significantly more compactness, low cost and flexibility. Shear thickening is a Non Newtonian flow behavior observed as an increase in viscosity with increasing shear rate or applied stress[3]. The phenomenon of shear thickening fluid is due to the suspension of highly concentrated oxide nano particles (silica) in solvent medium (polyethylene glycol). This shear thickening phenomenon can damage processing equipment and induce dramatic changes in suspension microstructure, such as particle aggregation, which results in poor fluid and coating qualities[4]. It has been demonstrated that reversible shear thickening in concentrated colloidal suspensions is due to the formation of jamming clusters bound together by hydrodynamic lubrication forces, often denoted by the term hydro clusters[5]. The performance enhancement provided by the STF may be due to an increase in the yarn pullout force upon transition of the STF to its rigid state. Shear thickening fluid based armor is not sufficient to protect the wearer against higher energy threats. Also the interface between STF and fibres can be significantly improved to achieve better adhesion[6]. Silane coupling agents are excellent surface modifiers that can enhance mechanical properties of STF by increasing inter particle friction[7]. Silanes are choice reagents in improving adhesion properties between fluids and fabrics, which will increase energy dissipation capabilities[8]. Shear thickening fluids composed of silica particles functionalized with silane coupling agents demonstrated better stab resistance during drop tower impact test and quasistatic tests. The objective of this study is to investigate the impact resistance properties of knitted Kevlar fabrics impregnated with different silane coupling agents that exhibit the shear thickening effect. At

Received 30 September 2013, revised 1 March 2014, online published 20 May 2014

low strain rates, associated with normal motion of the wearer, the fluid will offer little impediment to fabric flexure and deformation. However, at the high strain rates associated with a ballistic impact event, the fluid will thicken and enhance the ballistic protection of the fabric[9]. Tests are performed using spike impactor, based on the National Institute of Justice (NIJ) standard 0115.0, for stab protective armors. Additional results are included for quasi static stab loading of fabrics. The examination and analysis of distribution and interpretation of chemical bonding and structures of STF in fabrics is done using Scanning electron microscope (SEM) and Fourier transform infrared spectroscopy (FTIR). The performance of multilayer STF-Kevlar targets is compared to neat Kevlar target and Kevlar targets impregnated with only STF and of comparable areal density. Both quantitative depth-of-penetration data and qualitative descriptions of fabric damage are reported.

2. EXPERIMENTAL

2.1 Materials

2.1.1 *Shear Thickening Fluid*

The shear thickening fluid (STF) used in the targets is composed of silica particles (15 nm) suspended in polyethylene glycol 200 Mw (Sigma Aldrich) at a volume fraction approximately 52 per cent. This STF undergoes a shear thickening transition at a shear rate of 10^2 s^{-1}.

2.1.2 *Kevlar Fabric*

The Kevlar fabric used in all targets was rib type knitted aramid (polyparaphenylene terephthalamide), 24 yarns per inch, and high performance fabric with areal density of 130 g/m^2. The Kevlar layers were cut to 15 cm x 18 cm and stacked in four layers and a stitch was provided to hold it together.

2.1.3 *Silane Coupling Agents*

To improve the penetration resistance of the target fabric, silica particles were functionalized with a silane coupling agent. Silane coupling agent is used to form a durable bonds between inorganic and organic materials such as silica particles and polyethylene glycol. The silane coupling agents used in this work are Methyl trimethoxy silane (MTMS) and Vinyl triethoxy silane (VTES) purchased from Sigma Aldrich. Methyl trimethoxy silane (MTMS) has a density of 0.995 g/cm^3 and molecular weight of 136.22 g/mol. Vinyl triethoxy silane (VTES) has a density of 0.885 g/cm^3 and molecular weight of 190.31 g/mol. The inorganic compatibility comes from the alkoxy group attached in the silicon atom in silane molecular structure. The bond is hydrolytically unstable and in presence of moisture hydrolyses to an intermediate Si-OH bond. It condenses with the surface bound OH groups on the inorganic surface to form stable bonds.

2.2 Target Preparation

Target 1 is taken as the neat Kevlar fabric in four layers, cut in the dimensions of 15cm x 18 cm without impregnating with any STF. Actual fabrication procedures include the mixing of silica particles, polyethylene glycol and ethanol in a ratio of 7.9:6.5:85.6 by weight. This ratio eventually results in a mixture of silica and polyethylene glycol at 55:45 by weight after drying out ethanol. The addition of ethanol aids in the dispersion and breakup the silica agglomerations and to aid the infusion of STF mixture into the Kevlar fabric. After an hour of continuous stirring, the mixture was used to soak 4 layers of Kevlar fabric cut in dimensions of 15 cm x 18 cm. To impregnate the fabric, the layers were stitched together and placed in sealed plastic bag along with the STF mixture. After fifteen minutes, it is placed inside an oven and baked at 70°C until it was dry, i.e. all the ethanol had evaporated. The four layers of Kevlar impregnated with the STF mixture resulted in an areal density of approximately 0.120 g/cm^2. Thus target 2 is prepared. Functionalization of silica particles is done to prepare target 3 and 4. The modification of silica particles with the use of silane is followed according to manufacturer's procedures and early studies. First the MTMS is added to 95 per cent of ethanol and 5 per cent water to yield 2 per cent final concentration of silane. Then it is mixed with silica particle and stirred continuously for 3 h at room temperature. Then it is allowed to dry to get modified silica particles. This functionalized silica particle is mixed with polyethylene glycol and ethanol and allowed to impregnate with four layers of Kevlar fabric, dried in oven to obtain target 3. Target 4 is obtained by mixing VTES with ethanol and water and stirred continuously at 60 °C for 2 h. Then the functionalized silica obtained after drying is mixed with polyethylene glycol and ethanol as above procedure for 3 h and allowed to impregnate with four layers of Kevlar fabric. Then it is allowed to dry in oven and the target 4 is obtained. The total weight of target, amount of STF added and its areal density were calculated and shown in Table 1. These STF impregnated targets were sealed in polyethylene film pouch.

Table. 1 Description of prepared targets

Target	Description	Total weight (g)	Weight of STF added (g)	Areal density (g/cm^2)
1	4 layers of neat Kevlar fabric only	32.50	0	0.120
2	4 layers of Kevlar fabric impregnated with STF	80.17	47.67	0.296
3	4 layers of Kevlar fabric with functionalized STF (STF + MTMS)	86.36	53.86	0.316
4	4 layers of Kevlar fabric with functionalized STF (STF + VTES)	95.68	63.18	0.354

2.3 Impact Tests

The impact tests performed are based on the NIJ Standard 0115.0 for stab resistance body armor. The NIJ-specified impactor used is the spike. The spike is rigidly mounted to the crosshead hammer using a tool fixture arrangement in a charpy impact tester. The prepared targets are placed on a multi layer foam backing shown in Fig.1 as specified by the NIJ standard 0115.0. This backing consists of four layers of 5.8 mm thick neoprene sponge, followed by one layer of

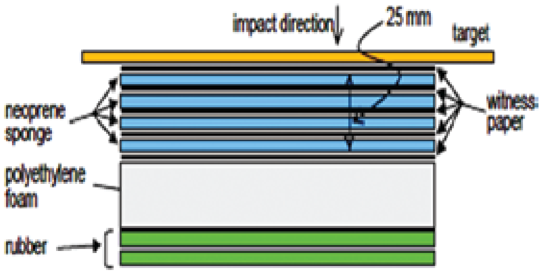

Figure 1. Multilayer foam backing construction.

31 mm thick polyethylene foam, backed by two 6.4 mm thick layers of rubber. Synthetic polymer based polyart witness papers were placed between the target and foam backing and behind each layer of neoprene sponge[10]. To perform an impact test, the spike impactor is mounted to the crosshead hammer of specific mass. The hammer is dropped from a fixed heights to impact the targets in two energy levels namely, 24 J and 36 J. The depth of penetration of into the targets is quantified in terms of the number of witness paper layers penetrated by the impactor[11-15]. Two sets of experiments were performed for each target. For the first set, the hammer with mass 3.567 kg is dropped from a fixed height of 0.714 m, so that impact energy of 24 J is obtained. For the second set of experiments, the drop height is fixed at 1m, so that impact energy of 36 J is obtained. Tests were performed on all targets and same targets were used for all tests, with each impact point spaced at least 6mm from the target edge and from the previous impact locations. The targets were held firmly using a metal frame in place and strapped along with the backing material using nylon strap. The sharpness of the impactor was monitored between tests, so it did not vary systematically during experiments.

The impact test procedure used in this study differs from the NIJ study in two ways. First, the NIJ standard uses two-mass, damped impactor. This damping is more closely to the realistic impact dynamics than our rigidly-mounted impactor[16]. So our energy values cannot be directly compared to NIJ-based energy values. Secondly, NIJ standard measures the penetration depth based on measuring the final location of the spike in the backing material. This approach is very inaccurate, time consuming[17]. Our witness paper approach is objective, rapid and simple to implement.

2.4 Quasistatic Impact Test

To complement the impact test, quasistatic impact tests were also performed. The spike impactor was mounted to the upper grip of a universal testing machine with the target placed below the impactor and on top of the same multi-layered backing as used in the previous impact tests. The spike impactor was then pushed into the target at a rate of 5mm/s to a total depth of 30 mm. Load versus displacement data was recorded.

3. RESULTS AND DISCUSSION

3.1 Impact Test Results

The impact test results for a series of targets composed of 4 layers of Kevlar fabric and impregnated with different STF composition (see Table 1) are shown in Fig. 2 and summarized in Table 2. The impactor should be stopped in all targets. Fig. shows the penetration depth for these targets and with the targets 3 and 4 impregnated with functionalized STF showing significantly less penetration depth than the targets without impregnating functionalized STF. The clay witness penetration profiles also show a marked difference in shape, as deep penetration profiles in non-functionalized STF targets, while blunt and shallow penetration profiles in targets impregnated with functionalized STF. These results clearly shows that, even though the non functionalized STF impregnated target does show improvement relative to the neat Kevlar, the functionalized STF impregnated targets shows significant improvement in impact resistance. The unimpregnated and non functionalized targets show that the Kevlar yarns that were directly impacted by the impactor pullout significantly from the weave, producing the well-documented cross pattern in the fabric. Note that the Kevlar layers exhibit little actual fibre breakage, although some fibre stretching near the impact point may have occurred.

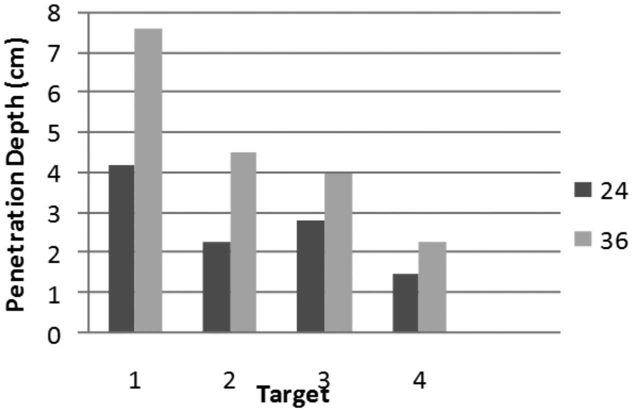

Figure 2. **Effect of STF fictionalisation on impact performance of STF-Kevlar targets.**

Table 2. **Impact performance of targets for impact energy 24 J and 36 J**

Target	Description	Penetration depth for 24 J (mm)	Penetration depth for 36 J (mm)
1	4 layers of neat Kevlar fabric only	42	76
2	4 layers of Kevlar fabric impregnated with STF	23	45
3	4 layers of Kevlar fabric with functionalised STF (STF + MTMS)	28	40
4	4 layers of Kevlar fabric with functionalised STF (STF + VTES)	15	23

3.2 Quasistatic Impact Test Results

Quasistatic tests performed with spike impactor were able to penetrate the targets materials and showed similar qualitative deformation behaviour during loading. Backing layer penetration was also similar; penetrating 3 witness layers for functionalized STF targets and 4witness layers for STF-Kevlar targets and 5 witness layers for unimpregnated Kevlar targets. This difference can be explained by comparing the load-displacement curves for these targets.

The functionalized STF-Kevlar targets experience significantly higher loads to peak displacement than the other targets (340 N, 420 N *vs* 262 N, 315 N respectively) as shown in Table 3. This difference indicates that the functionalized STF-Kevlar targets are more efficiently loading the spike and resisting the penetration. The neat Kevlar fabric target becomes penetrated at a small displacement and load and thereafter provides little resistance to further penetration. While the functionalized STF-Kevlar targets shows little damage or penetration in fibre when comparing with others.

The difference in load-displacement curves for the targets under quasistatic test on velocity of penetration of 5mm/s is shown in Fig. 3. It demonstrates that the final load for the functionalized STF-Kevlar targets is dramatically higher than that of impregnated and non functionalized STF targets (492N *vs* 260N respectively).

Table 3. Quasistatic impact performance of targets for velocity at penetration 5 mm/s

Target	Description	Load (N)
1	4 layers of neat Kevlar fabric only	262.17
2	4 layers of Kevlar fabric impregnated with STF	314.46
3	4 layers of Kevlar fabric with functionalized STF (STF + MTMS)	339.56
4	4 layers of Kevlar fabric with functionalized STF (STF + VTES)	419.47

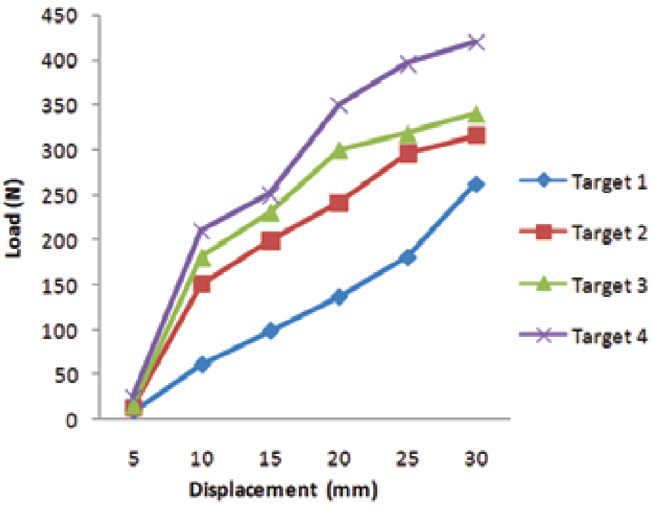

Figure 3. Load vs. Displacement during Quasistatic testing.

3.3 Fourier Transform Infra Red Analysis

It is observed, in Figs. 4, 5, and 6 that the modified silica nanoparticles absorb more energy than the silica particles without silane. The largest peak wave number 1090 cm^{-1}, represents the siloxane bond (Si-O-Si) which naturally occurs in silica. The infrared (IR) absorption of the siloxane bond increased from approximately 0.2 to over 1.0 with the addition of silane for modification of the silica nano particles, indicating an increase in the number of chemical bonding.

The peak is sharper signifying a stronger siloxane bond. Figure 6. shows an increase in area under the curve

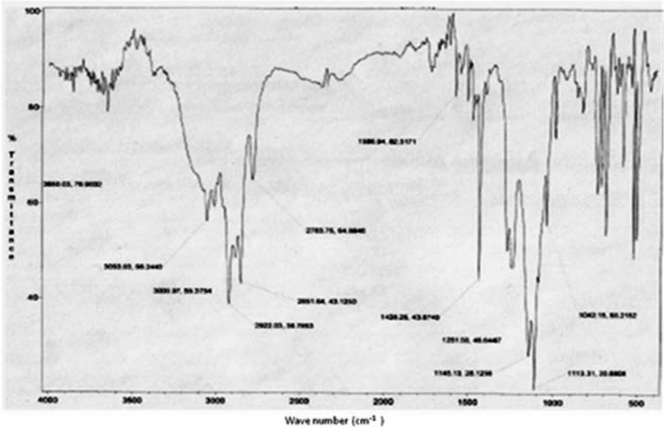

Figure 4. FTIR result of unmodified STF.

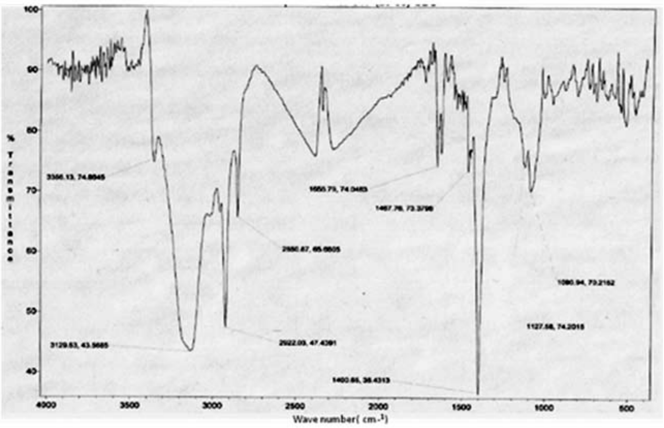

Figure 5. FTIR result of modified STF with MTMS.

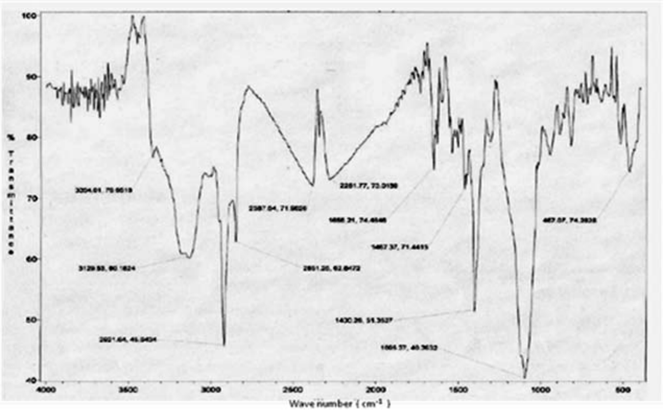

Figure 6. FTIR result of modified STF with VTES.

suggests an increase in concentration of Si-O-Si bonds due to functionalization. At approximately 1250 cm^{-1}, there is another spike that has increased due to the modification of silica particles. This enhanced peak indicates formation of a new carbon-hydrogen (C-H) single bond because of surface modification of silica particles. The presence of other high frequency bonds, such as methyl (CH_3) group and the methylene (CH_2) group arising from the silane linker is apparent at approximately 2920 cm^{-1} (please see Table. 4).

Table 4. Experimental FTIR assessment for STF materials (cm^{-1})

Chemical compound	Group	Wave numbers (cm^{-1})		
		Target 2	Target 3	Target 4
PEG	OH Stretch	-	-	-
	CH_2 aliphatic	2922	2922	2921
	C-O-C ether	1113	1092	1095
Silica	C-O-C ether	1113	1090	1095
	Si- CH_2	1400	-	-
	Si-O-Si Siloxane	1042	1092	1095
MTMS	CH_2-CH_3 aliphatic	-	2922	-
	Si- CH_2	-	-	-
	Si-O-CH_3	-	-	-
	Si-O-CH_3	-	1090	-
VTES	CH_2 aliphatic	-	-	2920
	C-H	-	-	1250
	Si-O-CH_3	-	-	1092
	Si-O-Si siloxane	-	-	1092

3.4 Micro Structural Analysis

The improved performance of the Kevlar composite is attributed to the infusion of the silica and polyethylene glycol mixture to coat the fabric[18-20]. The distribution of such coating mixture over the fabric as well as the surface area of the tows can be seen by viewing it at a microscopic level. In addition to the distribution of the mixture infusion, it is important to see the agglomerations that are expected to occur with dispersing silica nanoparticles in the PEG and ethanol. Although the clusters will occur during increase in shear rate, the objective is to still maintain a size in the nano meter range. The microstructure and agglomeration within the targets were analysed using scanning electron microscope (SEM)[21,22].

3.4.1 Unmodified STF- Kevlar Microstructure

A thin coating of silica-PEG mixture formed over the surface of the Kevlar fabric is shown in Fig. 7. This coating is present at the top and bottom of the fabric covering the entire area of the laminate. This coating offers the first line of resistance during the spike penetration. The coating consists of agglomerated silica particles embedded in the body of the matrix as seen in Fig. 8. Because of the high concentration of silica particles, they could not be dispersed fully within the matrix[23].

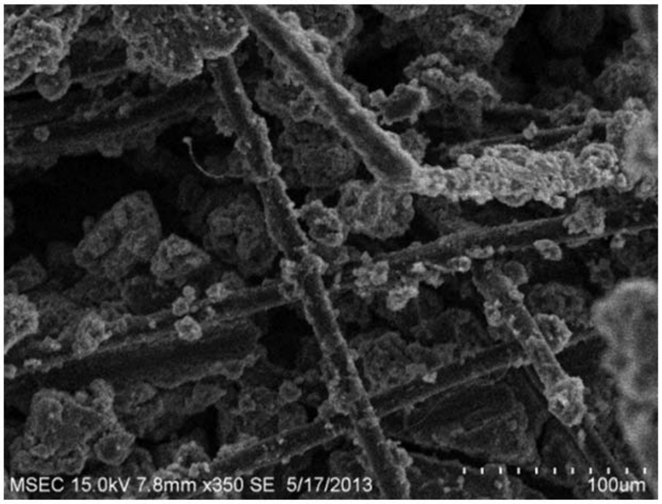

Figure 7. A thin coating of STF mixture on the surface of the Kevlar fabric.

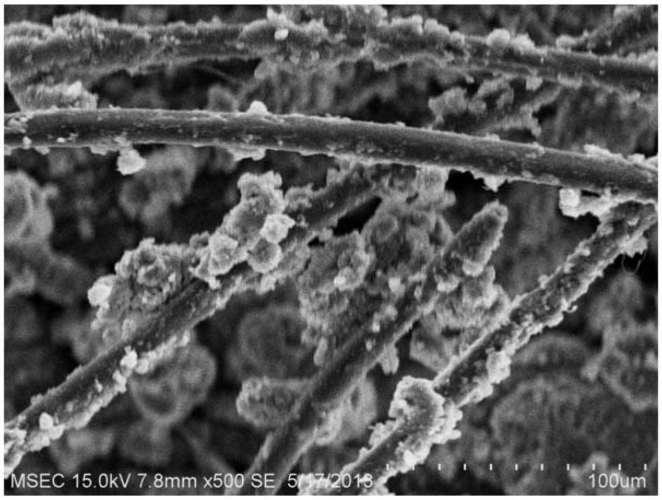

Figure 8. Agglomerated unmodified silica particles and PEG mixture

Nevertheless, the agglomerated particles are still in nanometer range. A large number of such tows are shown in Fig. 9. Here a large number of agglomerated particles are adhered to the fibre tows especially in region where they are bonded with the neighbouring tows. The presence of the particles at this inter-tows area offers resistance when the spike penetrates through this region. It is observed that the mixture of unmodified STF-PEG incorporates multiple phases of resistance on to the Kevlar fabric[24].

3.4.2 Functionalized STF- Kevlar Microstructure

Figure 10 shows agglomerated silica particles in the coating over the Kevlar fabric. The modified silica particles mixed with the PEG result in agglomerations ranging from approximately 6 to 15 micrometers. Figure 11 demonstrates significant improvement corresponding to the adhesion of STF to the fabric layers. There is still consistent coating on the surface of the tows and between adjacent tows.

This adhesion to the tows is credited to the silane coupling agent that was used to modify the silica particles and as a result, this adhesion feature visible even after a fibre has been

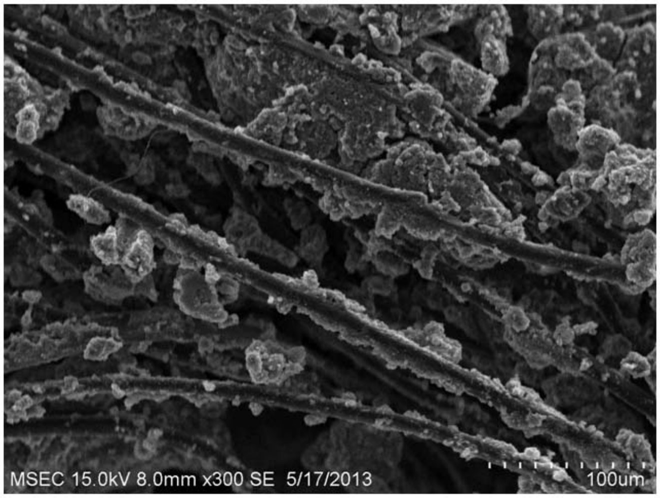

Figure 9. The silica-PEG mixture adhering to the surface of the Kevlar tows

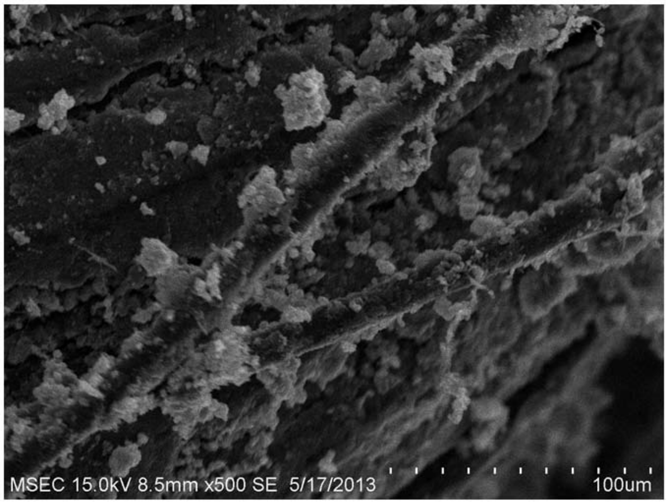

Figure 10. Agglomeration of the silica and PEG mixture on the Kevlar fibre with a size range of approximately 6µm to 15µm.

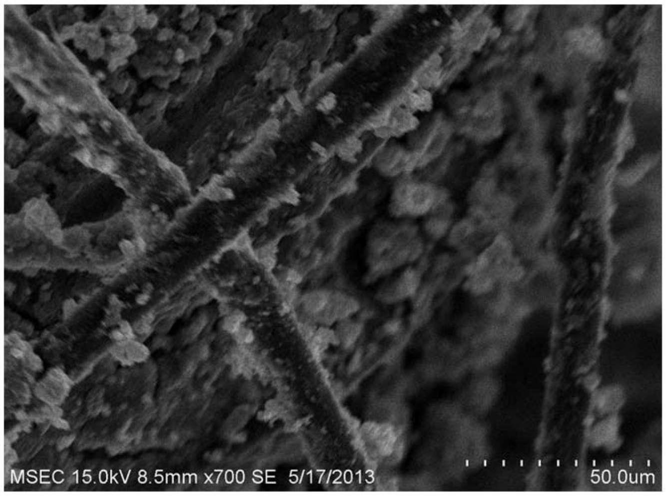

Figure 11. Functionalized silica particle adhesion to the tows of the Kevlar fabric.

impacted from spike during the test[25-27]. It is projected that, the loss of impact resistance at higher impact energy in target 3 was due to the larger agglomerations, where size of majority of particles was beyond the nanoscale range in the mixture that coat the Kevlar fabric, seen in Fig.12. This reduces the surface energy, in turn reducing particle inter affinity with the PEG but improves adhesion with the fabric. The silated silica-PEG mixture with VTES covered the entire Kevlar fibre as seen in Fig. 13, and the concentration of silica between the fibres and dispersed over the regions of fibres away from interstitial spaces.

Comparing to the previous three fabric composites, this appears to be the best coating of the fibres, which enhances the multiple phases to enable for impact resistance.

During the impact test, there is less time to deform due to sudden impact. The results of Table 2 clearly demonstrate that under our test conditions, impregnating neat Kevlar fabric with functionalized STF enhances the impact strength properties of the fabric. More precisely, the addition of modified STF to

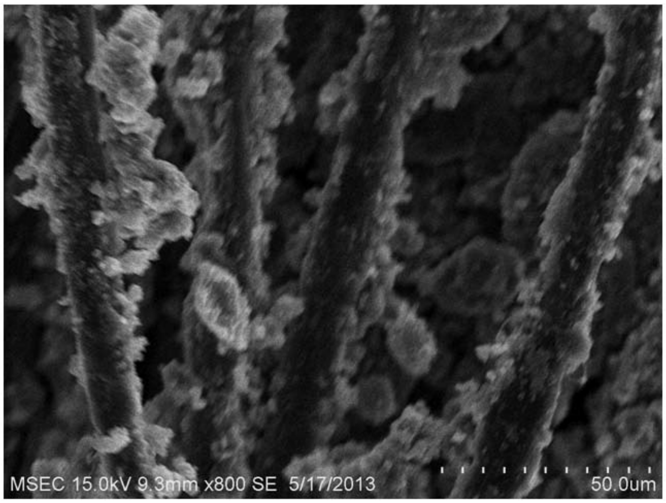

Figure 12. A close-up of the particle adhesion retained on the fractured fibre, which reveals particle agglomerates under a micron.

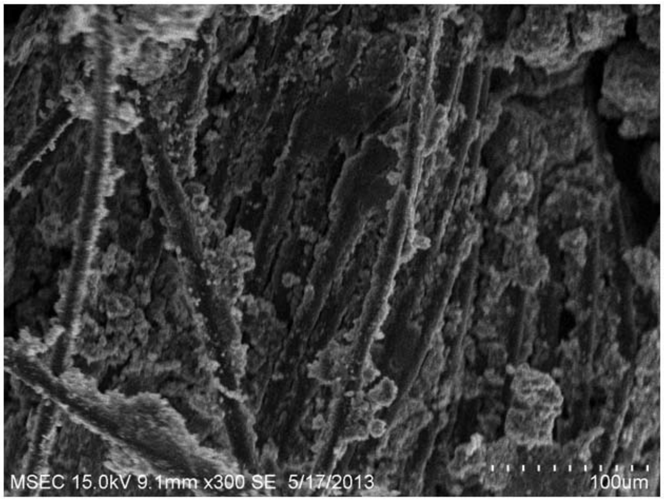

Figure 13. Adhesion of the functionalized silica and PEG coating over the Kevlar tows and between adjacent tows.

the fabric increases the amount of impacting energy that is absorbed by the target. These results suggest that the modified STF constraints the Kevlar yarns as they are pulled through the fabric. The increase in energy dissipation in the impregnated target could be due in part to an increase in force required to pull out each yarn from the fabric, so that less total pull out is required to absorb the impacting energy. In the case of quasistatic testing, the force is applied over a period of time. During this time, the backing material absorbs the energy and in turn deforms. The total depth of penetration, which includes the thickness of the composite (3 mm), the single layer witness paper (0.178 mm) and the spike protruding past the witness layer by 0.50 mm. The other 55.32 mm (of the 60 mm) was the deformation of the backing material. Also looking at Fig. 3 there is no major peaks drop offs to designate a sudden penetration, which indicates that the spike under quasistatic loading is slowly and continuously penetrating the composite while deforming the backing material. A technique has been established to functionalize nanoscale silica particles and utilize them in the fabrication of the flexible fabric composite. Impact resistance of the composite with functionalized silica particles exceeds any of the present systems. The functionalized system does not allow any penetration up to 6 J - 8 J and only one layer penetration throughout the loading range up to 12 J - 15 J. SEM and FTIR studies have shown that the key to the enhancement in impact resistance may be due to the nano scale dimension of the particle in the system and increase in bonding strength between silica and PEG due to functionalization. Although the prediction of maximum depth of penetration is not accurate when comparing with early studies, it can capture the trend of the experimental values.

4. CONCLUSIONS

It has been demonstrated that flexible fabric composite can be developed by dispersing nanoscale silica particles into a mixture of PEG and ethanol and substituting the STF fabrication route to functionalization. It was also shown that the performance of the newly developed nanoparticle based composites is superior to that of the conventional STF- based composites. Comparisons with fabrics impregnated with non-functionalized STF shows that the shear thickening effect is critical to achieving enhanced performance. Also, when compared with neat Kevlar fabrics and unmodified Kevlar fabrics, the functionalized STF based Kevlar fabrics provides more protection, yet it is much thinner and more flexible. The performance enhancement provided by the STF may be due to an increase in the yarn pull out force upon transition of the STF to its rigid state.

ACKNOWLEDGEMENTS

I would like to thank, Dr I. Siva, Centre of Composite Materials, Kalasalingam University, Krishnankovil, Virudhunager District and Dr N. Selvakumar, Department of Mechanical Engineering, Mepco Schlenk Engineering College, Sivakasi, for their valuable suggestions and the facilities provided for these experiments. I am also grateful to Mr. Pandi and Mr Ganesh, for their experimental assistance for impact testing, FTIR and SEM analysis.

REFERENCES

1. Lee, Y.S.; Wetzel, E.D. & Wagner N.J. The ballistic impact characteristics of Kevlar® woven fabrics impregnated with a colloidal shear thickening fluid. *J. Mater. Sci.,* 2003, **38**(13), 2825-2833.
2. Lee, Y.S.; Wetzel, E.D.; Egres Jr., R.G. & Wagner, N.J. Advanced body armor utilizing shear thickening fluids. Proceedings of the 23rd army science conference, 2002.
3. Rangari, V.K.; Hassan, T.A.; Mahfuz, H. & Jeelani, S. Synthesis of shear thickening fluid using snochemical method. NSTI-Nanotech 2006, **2**, pp.637-640.
4. Lee Y.S. & Wagner N.J. Dynamic properties of shear thickening colloidal suspensions. *Rheology Acta*, 2003, **42**(3), 199 -208.
5. Wetzel, E.D.; Lee, Y.S.; Egres, R.G.; Kirkwood, K.M.; Kirkwood, J.E. & Wagner N.J. *In* the Proceedings of Numiform, 2004.
6. Erges Jr., R.G.; Decker, M.J.; Halbach, C.J.; Lee, Y.S.; Kirkwood, J.E.; Kirkwood, K.M.; Wetzel, E.D. & Wagner N.J. Stab resistance of shear thickening fluid STF-Kevlar composites for body armor applications. *In* the Proceedings of the 24th army science conference Orlando, Florida, November 29- December 2, 2004.
7. Clements, F.E. & Mahfuz H. Enhancing the stab resistance of flexible body armor using functionalized SiO_2 nanoparticles. *In* the Proceedings of 16th international conference on composite materials, 2007.
8. Gelest, Gelest silane coupling agents: connecting across boundries, Gelest, Inc., 2006.
9. Mahfuz, H. Functionalized nanoparticles and their influence on the properties of nanocomposites. Presented at the annual review meeting for ONR, Washington, D.C., 2006.
10. National institute of justice. Stab resistance of personal body armor NIJ standard-0115.0, 2010. Internet: www.ncjrs.gov/pdffiles1/nij/183652.pdf.
11. Hassan, T.A.; Rangari, V.K. & Jeelani, S. Sonochemical synthesis and rheological properties of shear thickening silica dispersions. Ultrasonics Sonochemistry, 2010, **17**, pp.947-952.
12. Szczepanski, J.M. Modification and integration of shear thickening fluids into high performance fabrics. Paper 761, 2011. MS Thesis.
13. Daoshun Xue, Hu, Hong. Mechanical properties of biaxial weft-knitted flax composites. *Materials Design*, 2013, **46**, 264-269.
14. Xinglong, Gong; Yulei, Xu; Wei, Zhu; Shouhu, Xuan; Jiang, Weifeng & Jiang, Wanquan. Study of the knife stab and puncture-resistant performance for shear thickening fluid enhanced fabric. *J. Composite Mater.*, 2013, 1-17.
15. Jiang, WQ; Sun, YQ & Xu, YL. et al. Shear-thickening behavior of polymethylmethacrylate particles suspensions in glycerine-water mixtures. *Rheol Acta*, 2010, **49**(11–12), 157–1163.
16. Zhu, D.; Soranakom, C. & Mobasher, B. Experimental study and modeling of single yarn pull-out behavior of Kevlar 49 fabric. *Composite Part A: Appl. Sci. Manuf.*, 2011, **42**(7), 868–879.

17. Brown, E., Forman, N.A. & Orellana, C.S. Generality of shear thickening in dense suspensions. *Nature Mater.*, 2010, **9**(3), 220–224.
18. Xu, YL; Gong, XL & Peng, C. Shear thickening fluids based on additives with different concentrations and molecular chain lengths. *Chin. J. Chem. Phys.*, 2010, **23**(3), 342–346.
19. Perillo, G.; Vedivik, N.P. & Echtermeyer, A.T. Damage development in stitch bonded GFRP composite plates under low velocity impact: Experimental and numerical results. *J. Composite Mater.*, 2014. doi:10.1177/0021998314521474.
20. Pushparaj, Maria Antoine & Fathima, Zeenath. Composite integrated material of Al layers with Kevlar material and the specification test result. *Chem. Mater. Res.*, 2012, **2**(2), pp.
21. Ding, Jie; Tracey, Phillip; Li, Weihua; Peng, Gangrou; Whitten, Philip G. & Wallace, Gordon G. Review on Shear Thickening Fluids and Applications, 2013
22. Robert, J. Rabb & Eric, P. Fahrentholdy. Simulation of large fragment impacts on neat and STF Kevlar fabric barriers. *In* the 52nd AIAA Structural Dynamics and Materials Conference., 2011.
23. Mauricio, Lastres. Modeling and optimization of coatings on multilayered ballistic fabric shielding. University of California,2013, pp.25-30. MS Thesis.
24. Lee, B.W. & Kim, C.G. Computational analysis of shear thickening fluid impregnated fabrics subjected to ballistic impacts. *Advanced Comp. Mat.*, 2012, **21**(2), 177-192.
25. Mamivand, M. & Liaghat, G.H. A model for ballistic impact on multi-layer fabric targets. *Int. J. Impact Eng.*, 2010, **37**, 806-812.
26. Ahmad, M.R.; Hassim, N.; Ahmad, W.Y.W.; Samsuri A. & Yahya, M.H.M. Utilizing natural rubber latex in improving ballistic impact performance of unidirectional fabric systems. *In* the IEEE Symposium on Business, Engineering and Industrial Applications. 2012, pp.458-461.
27. Bakar, N.A.; Salleh, J.; Ahmad, M.R.; Ahmad, N.A. & Suhaimi, S.A. Puncture resistance of nanofilled coated high strength woven fabric. *In* the IEEE Symposium on Business, Engineering and Industrial Applications. 2012, pp.477-480.

CONTRIBUTORS

Mr R. Joselin Completed UG in JMIT, Chitradurga in the mechanical Engineering discipline and completed PG in the discipline of computer aided design in Sathyabama institute of science and Technology, Chennai. Now working as a Professor in Mechanical Engineering department, C.S.I. Institute of Technology, Thovalai for the past 16 years also did research in the field of Acoustic Emission at Jawaharlal Nehru Technological University, Hyderabad. Having more than 14 National/International journal publications and 25 conference papers. Now working in the area of composite pressure vessels, power cables and NDT. Research contact with VSSC/ISRO, HAL etc.

Mr W. Jacob Wilson, completed UG and PG in C.S.I. Institute of Technology, Thovalai in the Mechanical Engineering discipline and now working as a Assistant Professor in Mechanical Engineering department, VEL Tech, Chennai for the past one year