Development of Stab Resistant Body Armor Using Silated SiO2 Nanoparticles Dispersed into Glutaraldehyde

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ABSTRACT

The development of flexible body armor has first been based on Shear Thickening Fluid (STF) which is a mixture of polyethylene glycol (PEG), water and silica at a specific weight ratio. The making process has been improved in incorporating through sonicating the silica particles to the mixture. Although the performances obtained were improved the stab resistance was not completely optimized to stop a penetration more than 45J/g/cm². The intention in this investigation was to study the actual components of the armor composite and to improve its stab performances. The outcome is a completely new approach regarding the fabrication route which differs from the previous STF making process. PEG has been removed and an extra component has been incorporated into the mixture. It is believed that this is the addition of this new chemical: Glutaraldehyde which provides the phenomenal stab performances.

Keywords: shear thickening fluid, glutaraldehyde, stab resistance

1 INTRODUCTION

The idea of making flexible body armor has been around for some time [2/3]. A crucial need has emerged from the battlefield to reduce the weight of the body armor in keeping its resistance. A lot of researches [2/3/11/12] have demonstrated the high potential of the STF regarding an impact but experiences conducted with glutaraldehyde has shown better results. This paper will then concentrate on the properties of the new Kevlar composite based on the addition of Glutaraldehyde.

Utilizing the different improvements that have been made for the STF making process, the new composite follows nearly the same fabrication route. It stays highly flexible and as presented in this paper the performances are extremely interesting.

2 EXPERIMENTATION

2.1 Materials and Synthesis

Previous fabrication procedure included 30nm size silica particles dispersed, by sonication, directly into a mixture of Ethanol, PEG and Silane at a ratio of 55:45 by weight of Silica to PEG. The new fabrication route differs from this making process by substituting Glutaraldehyde for PEG.

The Glutaraldehyde is incorporated according to the amount of silane agent present in the solution. Different types of silane can be used but the key component within the silane, which determines the amount of glutaraldehyde to introduce, is the amino-groups. The amino-groups are functional groups that contain a basic nitrogen atom. In our case, the silane possesses di-amino-groups and it is expected that the Glutaraldehyde creates "bridges" between the amino-groups.

Glutaraldehyde is not new; it is usually employed in medical and dental environment to disinfect equipments.
Also used in biochemistry applications [13] as a fixative, the glutaraldehyde kills cells by cross-linking their proteins. This cross-linker is an aldehyde such as formaldehyde a well known cross-linker and each of these cross-linkers induces subsequent covalent bonding. The covalent "bridge" created is stable mechanically and thermally making it hard to break.

Once the mixture is completed with all the different components, the solution is homogenized and mixed through sonic cavitation. After sonication for about three hours, the mixture was used to soak 12 layers of Kevlar fabric cut in dimensions of 12 in x 12 in. To impregnate the fabric, the layers were placed in a Ziploc along with the sonicated mixture. After a curing process of about 24h, the Kevlar composite is then dried out in a pre-heated furnace at 110°C for approximately thirty minutes. After each set of fabric is baked all the ethanol has evaporated. The 12 layers of Kevlar impregnated with the silated-silica-gluta mixture resulted in an areal density of 0.220g/cm². This fabrication procedure completely differs from the regular STF making process and mechanical tests show the performances of this new Kevlar composite.

2.2 Testing

Different sets of this Kevlar-composite have been fabricated using the above procedure, and using a drop tower constructed based on the Stab Resistance of Personal Body Armor, NIJ Standard-0115.0 (NIJ115) results from several experiments have been recorded. According to the NIJ115 standard a backing material, a nylon drop mass with a weight of about 2000 grams and a NIJ115 engineered spike were used to impact the target (fabric) at drop heights ranging from 0.05m to 1.0m. The velocities just prior to impact were recorded through a laser speed trap. Using the measured impact velocity, the total mass of the spike and drop mass; the actual impact energy was calculated. An interesting way to compare the different fabric is the depth of penetration recorded and measured by damaged witness papers placed underneath each layers of backing material. Doing this test gives excellent information to determine the stab resistance performances of each Kevlar composite.

3 RESULTS AND DISCUSSION

3.1 Stab Test

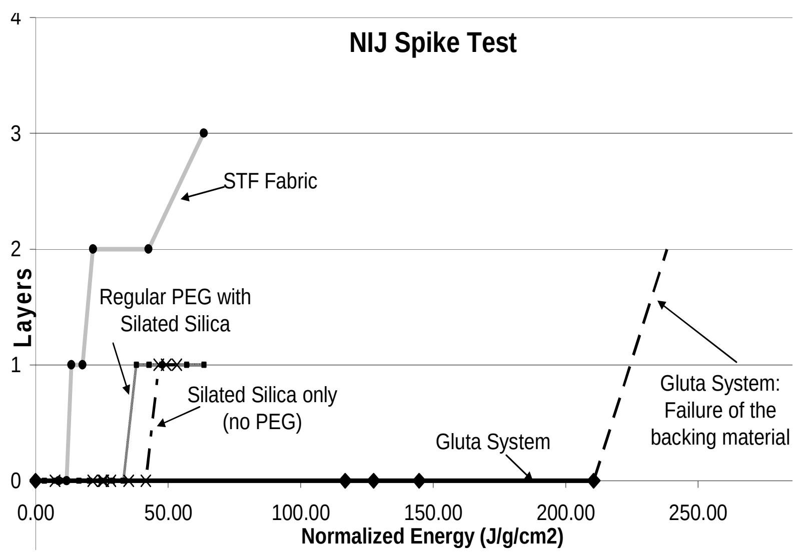

Figure 1: *Results for different Kevlar composite normalized with aerial density after spike impacts*

The impact energies were normalized by dividing them by the areal density of the respective fabric composite and plotted against the penetration depth. The results, shown in Figure 1, are significant. Indeed the gluta-system clearly shows high improvements compare to the STF fabric that has been already improved by removing the PEG. The '0-level penetration' increases by 4.5 times the No PEG and by 10 times than that of STF system.

An important point has to be made regarding the gluta-system result. Indeed the fabric showed so good resistance to the impact that at a certain energy level the failure is not occurring from the fabric but from the backing material. At high energies the Kevlar composite is not penetrated but is pushed through the backing material by the spike. To a certain extent the fabric is going to be penetrated. The penetration is however very small and no bigger than a dot which is another crucial difference with the previous composites fabricated.

The gluta-system is consequently a major improvement in the researches leading to the manufacture of a flexible body armor. The increase of the stab resistance to about 4.5 times more than the Silated-Silica without PEG can only be explained by the addition of Glutaraldehyde into the solution.

3.2 Microstructure

In an attempt to explain the improvements in the stab resistance of the Gluta-System-Kevlar composites over the different Kevlar composites, SEM and FTIR studies have been performed. A thin coating of Silated-Silica with Glutaraldehyde formed over the surface of the Kevlar fabric is shown in Figure 2. This coating is encompassing every single yarn of the fabric. Previous studies have shown that this coating offers the resistance during the spike penetration. The coating is consisted of agglomerated silica particles embedded in the body of the matrix as seen in Figure. 3.

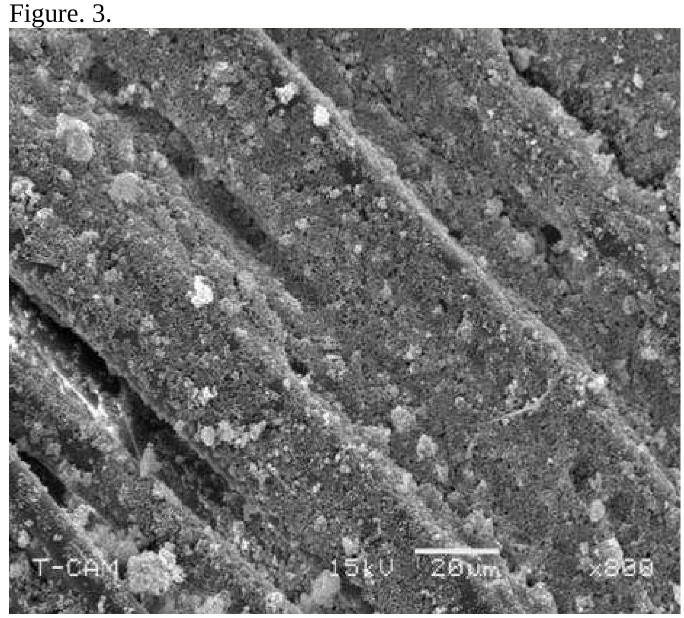

Figure 2: *A thin coating of the Silated silica particles with glutaraldehyde on the surface of the Kevlar fabric*

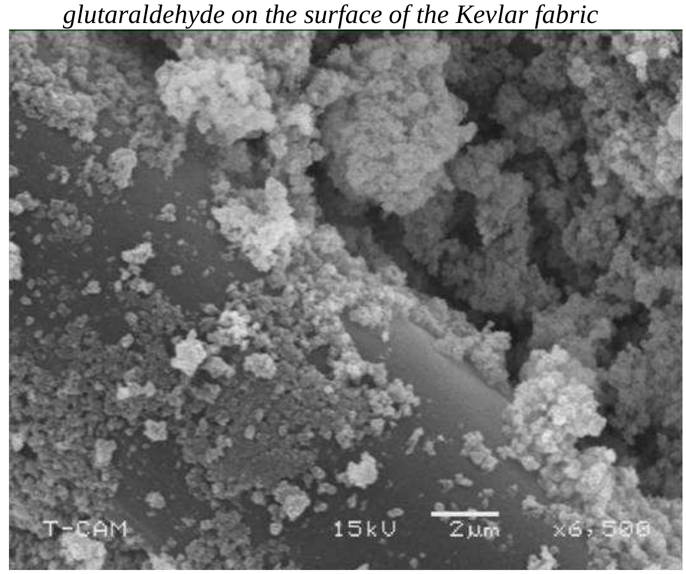

Figure 3: *Agglomerated Silated SiO_2 particles and Glutaraldehyde mixture*

The mechanism of this particular resistance property to the spike penetration can be explained by the analysis of the operation mode of the glutaraldehyde. Indeed extensive researches have been conducted in the bio-chemistry field regarding the fixative property of the chemical. Usually used to fix cells for electron microscopy, the glutaraldehyde attacks cells by crosslinking their proteins. It specifically works as an amine-reactive homobifunctional crosslinker. Our interest in this chemical stays in its property to create strong covalent bonds that "bridges" one silated-silica particles to another. This specific reaction is made possible by using monomeric glutaraldehyde which polymerizes by aldol condensation reaction. This reaction usually occurs at alkaline pH values.

In a simple way the aldol condensation is a basic organic reaction in which an enolate ion reacts with a carbonyl compound to form strong covalent bonds between two carbons. This reaction requires an alcoholic environment. In our case the aldehyde group of glutaraldehyde is linking with the silated silica by creating bonds with amino-groups as well as other glutaraldehyde groups as shown on Figure.4. As a result it creates a network between the different compounds present in the solution.

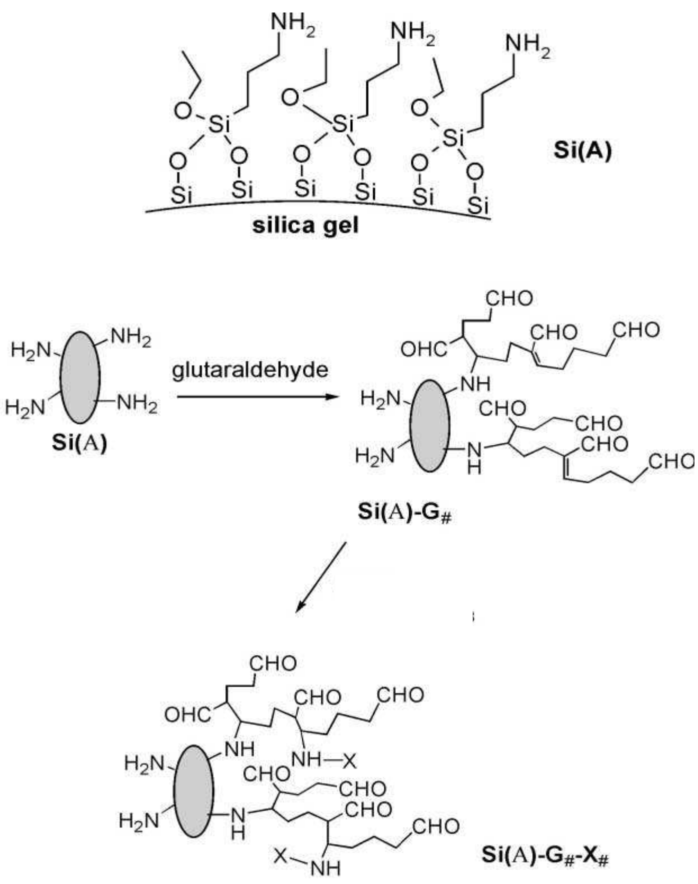

Figure:4. *Glutaraldehyde cross-linking reaction*

To further understand exactly the microstructure of the Glutaraldehyde Kevlar Composite FTIR (Fourrier Transform InfraRed spectroscopy) has been performed on the glutaraldehyde system as well as on the silated silica particles. The FTIR approach reveals the type of bonds and their frequencies within the solution by measuring the absorption or the transmission of infrared waves. In our case the spectrum is recorded with the transmission against the wave number. Four sets have been tested such as three different Gluta-system based in different ratio and the silated silica. Results shown in the Figure 5, demonstrate that the gluta-system performs better than the silated silica with 30 nm particles. The chemical bond revealed by the analysis is the siloxane (Si-O-Si) bond at around 1100 cm^{-1}. The peak of the gluta1 is a relative improvement compared to the silated silica particles. The peak observed and the area covered by the gluta1 curve shows quantitatively that the addition of glutaraldehyde has increased the concentration of Si-O-Si bond strength and number.

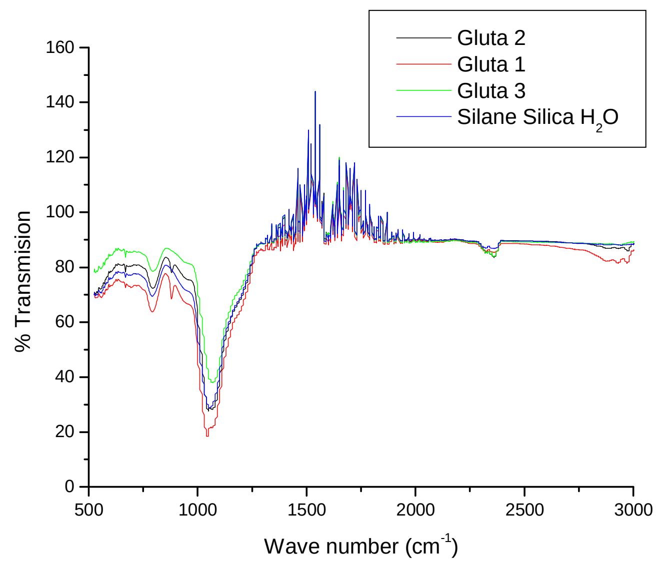

Figure: 5 *FTIR spectrum of different gluta-systems and silated- SiO_2*

4 SUMMARY

Although this new Kevlar composite stands apart from the usual STF fabrication route the stab resistant performance of the Gluta-system-Kevlar composite shows a remarkable increase compared to the previous Kevlar composite fabricated. Origins of these improvements are believed to be, for one, by the replacement of the PEG to Silane and Glutaraldehyde, and secondly, the size advantage of employing nanometer size particles which increases the number of links between the different components. The addition of glutaraldehyde as a linker between the silated silica particles is consequently believed to be the key component in increasing the stab resistance property.

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REFERENCES

1. Y.S. Lee and N. J. Wagner, *Rheol. Acta* **42** (2003) 199.
2. Y.S, Lee, E.D. Wetzel and N.J. Wagner, *Journal of Materials Science* **38** (2003) 2825-2833.
3. E. D. Wetzel, Y. S. Lee, R. G. Egres, K. M. Kirkwood, J. E. Kirkwood, and N. J. Wagner, *Proceedings of NUMIFORM*, 2004.
4. Egres, R. G., Lee, Y. S., Kirkwood, J. E., Kirkwood, K. M., Wetzel, E. D. and Wagner, N. J. *Proceedings of the 14th International Conference on Composite Materials*, July 2003.
5. Nathaniel C., Mahfuz, H., Rangari, V., Ashfaq, A. and Jeelani, S., "Fabrication and Mechanical Characterization of Carbon/Epoxy Nanocomposites," Composite Structures, 67 (2005) 115-124.
6. Mahfuz, H., Adnan, A., Rangari, V.K., Hasan, M.M., Jeelani, S., Wright, W.J. and DeTeresa, S.J., "Enhancement of Strength and Stiffness of Nylon 6 Filaments through Carbon Nanotubes Reinforcements," *Applied Physics Letters*, 88, 1 (2006).
7. Rodgers, R., Mahfuz, H., Rangari, V., Chisholm, N., and Jeelani, S., "Infusion of Nanoparticle into SC-15 Epoxy; an Investigation of Thermal and Mechanical Response," *Macromolecular Materials & Engineering*, 2005, 290, 423-429.
8. R. Birringer and H. Gleiter, in "Encyclopedia of materials science and engineering", R. W. Cahn, (Ed.), Pergamon Press, 1988, Suppl. Vol. 1, p. 339.
9. H. Gleiter, "Nanocrystalline Materials," in Progress in Materials Sci., 33 (1989) 223-315.
10. R. Dagani, "Nanostructural materials promise to advance range of technologies," Chem. Eng. & News, (Nov. 1992) 18-24.
11. H. Mahfuz, F. Clements and J. Stewart "Development of Stab Resistant Body Armor Using Fumed SiO2 Nanoparticles Dispersed into Polyethylene Glycol (PEG) through Sonic Cavitation" in NSTI 2006 paper 1143.
12. Hassan Mahfuz, Floria E. Clements "Enhancing the Stab Resistance of Flexible Body Armor using Functionalized SIO_2 Nanoparticles" in ICCM-16-2007
13. Hyunsook Kim,a Myoung-soon Kim,a Hyesun Paik,a Yeon-Sook Chung,a In Seok Hong and Junghun Suha,"Effective Artificial Proteases Synthesized by Covering Silica Gel with Aldehyde and Various Other Organic Groups" in Bioorganic & Medicinal Chemistry Letters 12 (2002) 3247–3250