Development of Stab Resistant Body Armor Using Fumed SiO2 Nanoparticles Dispersed into Polyethylene Glycol (PEG) through Sonic Cavitation

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ABSTRACT

Traditionally, the development of shear thickening fluid (STF) begins with micron size silica suspended in water. This material is transformed into STF through centrifugation and exchange processes. In other approaches polyethylene glycol (PEG) is added in incremental quantity to the silica suspension and water is removed through evaporation, repeatedly, until the admixture reaches the desired ratio of silica to PEG by weight. STF developed in this manner is usually dissolved in ethanol and impregnated into Kevlar fabric and then dried to remove ethanol. The resulting composite is Kevlar impregnated with a mixture of PEG and silica. The intention, in this investigation, was to directly disperse nanometer size silica particles into a mixture of PEG and ethanol by ultra sonic cavitation. The approach bypasses the STF fabrication route but maintains the proper ratio of silica to PEG in the composite to provide desired stab resistance properties.

Keywords: shear thickening fluid, sonication, stab resistance

1 INTRODUCTION

The idea of making flexible body armor utilizing shear thickening fluid (STF) is not new. Researchers have studied STF/fabric composites for several years [1-4]. These studies report the ballistic performances of composite materials composed of Kevlar fabric impregnated with a colloidal shear thickening fluid (micron size silica particles dispersed in ethylene glycol). The impregnated Kevlar fabric yields a flexible, yet penetration resistant composite material. Ballistic penetration measurements have demonstrated a significant improvement due to the addition of shear thickening fluid to the fabric without any loss in material flexibility. Such enhancement in the performance has been attributed to the increase in the yarn pullout force upon transition of the STF to its rigid state during impact. Furthermore, STF impregnated Kevlar has vastly superior stab resistance in addition to flexible ballistic protection, which addresses a key failure mechanism of current Kevlar-based body armor. While these preliminary studies establishes clearly the viability of the STF/fabric composite as a future flexible body armor system, the entire scope of particle-polymer interaction along with the complexities associated with fabric impregnation must still be addressed before an optimal, lightweight STF/fabric system can be developed. A case in point is the use of nanometer sized particles in place of the current micron sized particles. Because of the gain in surface area with nanoparticles, it is believed that the surface energy available at the particle-polymer interface will be more, which should consequently develop improved bonding with the surrounding matrix and the fiber [5-7]. The benefits of nanoparticle infusion comes from the fact that the large amount of interphase zones in nanocomposites may serve as catalysts for prolific crack growth, creating a much greater amount of new surfaces [8-10]. The creation of new surfaces can serve as an efficient mechanism to dissipate kinetic energy in the event of an impact.

2 EXPERIMENTATION

2.1 Materials and Synthesis

Actual fabrication procedures include 7nm size silica particles dispersed, by sonication, directly into a mixture of PEG and ethanol at a ratio of 7.9:6.5:85.6 (SiO2:PEG:Ethanol) by weight. This ratio eventually resulted in a mixture of silica and PEG at 55:45 by weight after drying out ethanol. After sonication for about an hour, the mixture was used to soak 12 layers of Kevlar fabric cut in dimensions of 12 in x 15 in. To impregnate the fabric, the layers were placed in a Ziploc along with the sonicated mixture. After, approximately fifteen minutes, each individual fabric layer was laid flat in the furnace and baked at 75°C until they were dry, i.e. all the ethanol had evaporated. The 12 layers of Kevlar impregnated with the silica-PEG mixture resulted in an areal density of 0.495 psf. This fabrication procedure completely bypassed the heating and centrifugation of the mixture and the addition of ethanol prior to soaking.

2.2 Testing

Several Kevlar and Nylon composites were fabricated using the above procedures, and were tested using a newly developed drop tower. This drop tower was constructed based on the Stab Resistance of Personal Body Armor, NIJ Standard-0115.0 (NIJ115). In addition to the impregnated fabric, the drop tower tests included; NIJ115 backing material, nylon drop mass with a weight of 1790 grams with the NIJ115 engineered spike. The drop heights ranged from approximately 0.05 m to 1.0 m to produce theoretical impact energies from 1 J to 16 J with an increment of 1 J. The velocities just prior to impact were also 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. Along with the impact energy, the penetration depth is also a factor in classifying stab resistant body armor. The penetration depth was measured by damaged witness papers placed immediately underneath the fabric specimen and underneath consecutive sponge layers that compose the backing material. The impact energy along with the penetration depth is used to compare fabric composite performance.

3 RESULTS AND DISCUSSION

3.1 Stab Test

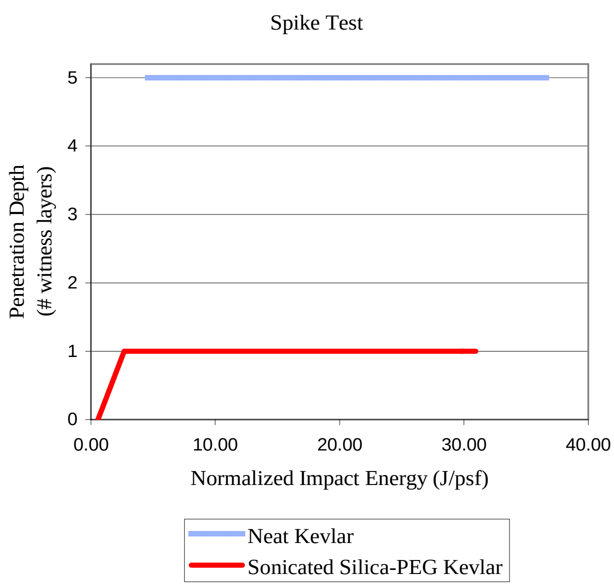

Figure 1: Results for Neat Kevlar compared to sonicated Silica-PEG impregnated/Kevlar composite normalized with areal density after spike impacts

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 show that although the STF fabrication route was bypassed, the sonicated mixture of nanophased silica particles and PEG can attribute remarkable stab resistance properties to neat Kevlar fabric as shown in Fig. 1. The depth of penetration for the sonicated Silica-PEG impregnated Kevlar composite is four times less than that of the neat Kevlar.

3.2 Microstructure

In an attempt to explain the improvements in the stab resistance of the Silica-PEG-Kevlar composites over the neat Kevlar, extensive SEM studies have been performed. A thin coating of silica-PEG mixture formed over the surface of the Kevlar fabric is shown in Fig. 2. This coating is present both at the top and bottom of the fabric encompassing the entire area of the laminate. We believe this coating offers the first line of resistance during the spike penetration. The coating is consisted of agglomerated silica particles embedded in the body of the matrix as seen in Fig. 3.

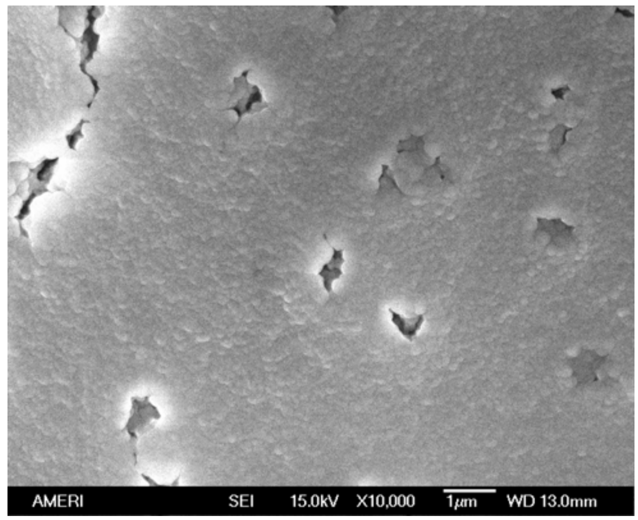

Figure 2: A thin coating of the silica-PEG mixture on the surface of the Kevlar fabric

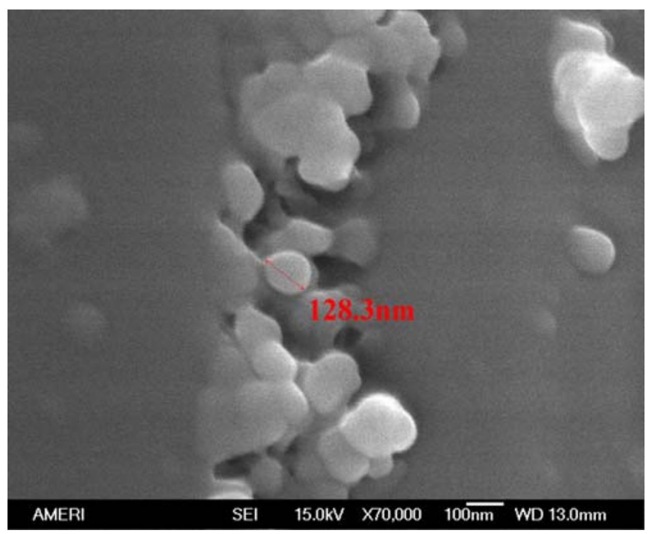

Figure 3: Agglomerated SiO_2 particles and PEG mixture

The diameter of the agglomerated particles is around 100-150 nm as shown in Fig. 3. These relatively large size particles have been formed due to the agglomeration of ~7nm silica particles in presence of PEG. Because of the high concentration (55%) of the silica particles, they could not be dispersed fully within the matrix. Nevertheless, the agglomerated particles are still in the nanometer range and should introduce desirable impact resistance feature into the matrix. Once this thin layer is penetrated, the subsequent resistances are offered by the fiber tows impregnated with the particles and the PEG. A number of such tows are shown in Fig. 4. It is seen in Fig. 4 that a large number of agglomerated particles are adhering to the fiber tows especially in the region where they are bonded with the neighboring tows. We believe the presence of the particles at this inter-tows area also offer a substantial resistance should the spike penetrate through this region. A more magnified view of the interface between a fiber-tow and the surrounding matrix is shown in Fig. 5.

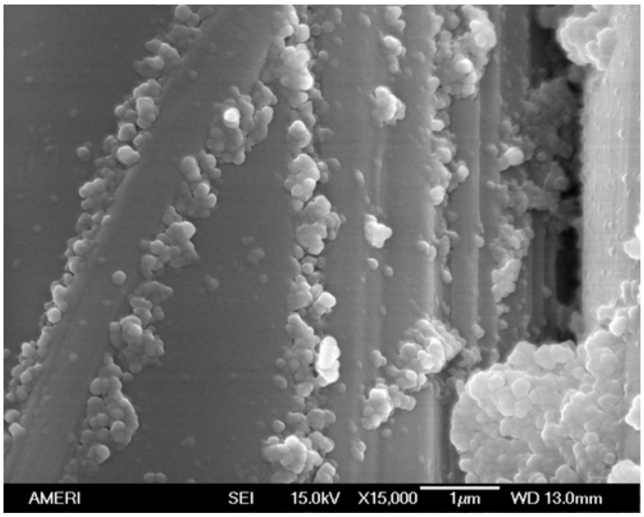

Figure 4: The silica-PEG mixture adhering to the surface of the Kevlar tows

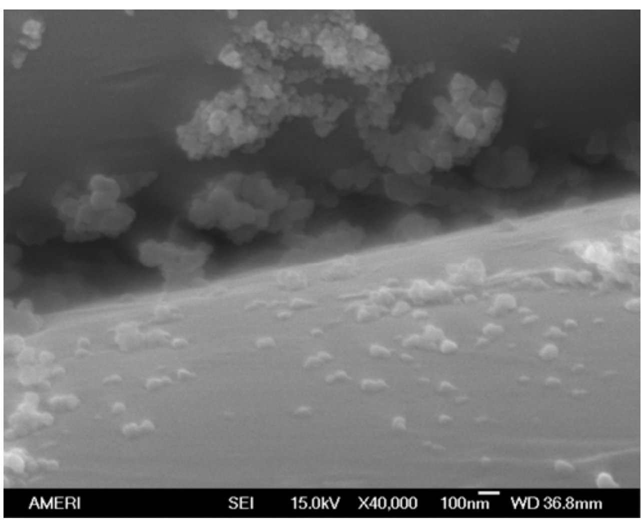

Figure 5: The silica-PEG mixture is not only on the individual tows, but in between adjacent tows

This figure clearly demonstrates a good bonding of silica particles to the Kevlar fiber, as well as to the PEG containing these particles. In addition to the development of such interfaces, the surface of the fiber-tow away from the interface zone is also seen impregnated with coated silica particles (Fig. 5). These particles which are mainly spread over the filaments would surely offer resistance if the spike penetrates through the tow itself rather than between the tows. We therefore, observe that the mixture of silica-PEG incorporate multiple phases of resistances on to the Kevlar fabric.

4 SUMMARY

Although the STF fabrication route is bypassed, the stab resistant performance of the Silica-PEG-Kevlar composite shows a tremendous increase compared to neat Kevlar. These improvements are believed to be, for one, by the preferred ultra sonic cavitation route over mechanical mixing and secondly, the size advantage of employing nanometer size particles over microns. Ultra sonic cavitation has accelerated and intensified properties for diffusion, dissolution, dispersion and emulsification [5]. These characteristics enforce modifications of the particle surface to enhance the interaction between the particle (SiO_2) and the polymer (PEG). The decrease in particle size allows for more surface area to give rise to a large interface enhancing the interaction described above. The SEM scans provide substantial evidence that the coated particles are dispersed over the Kevlar fabric, as well as, the individual tows and crevices between adjacent tows. These bonds between particle-to-particle and particle-to-fabric are what are believed to have given such improvement in stab resistant characteristics to Kevlar fabric.

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