Application of Shear Thickening Fluid (STF) to Modify UHMWPE for Improved Ballistic Protection in Soft Body Armors

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Soft body armors (SBA) are basically composite materials consisting of multiple layers of woven or unidirectional fabrics, such as Ultra-High Molecular Weight Polyethylene (UHMWPE), aramid, or carbon fibers. Overcoming the issues with hard body armors made of metal (steel plates) or ceramics, SBA gives the wearer a lot of flexibility for movement, especially around the neck and joints. These body armors operate to stop the bullet more efficiently by absorbing the kinetic energy stored in the bullet by deformation of the fabric laminate and rupture of fibers[1]. However, back face deformation is a serious problem for non-penetration injury to the wearer in the case of these fabrics due to lower interaction force among the fabrics[2]. Increasing the number of fabric layers can solve this issue, but this can increase the thickness of the composite significantly, restricting the bending ability. It can also become very bulky and heavy to restrict the agility of the wearer same as hard body armors.

Without compromising the flexibility and lightweight, a lot of options were explored recently to increase the ballistic performance by adding coating layers to the surface of the fabrics. The use of natural latex, graphite oxide, shape-memory alloys, and shear thickening fluid (STF) are widespread to improve the flexibility and energy-absorbing capability of the protective armor. Among these, STF is given much attention due to its higher thermal stability and non-toxicity[3].

Shear thickening fluids (STFs) are a new type of nanosuspension, which are formed by the dispersion of nanoparticles in the dispersant. These non-Newtonian fluids can be easily deformed under the application of a low shear force. However, these materials convert themselves into a hard solid-like materials at a high shear rate. The withstanding of the shear rate also depends on that particular material's properties. After removal of the shear force, they can transform back to their original liquid forms. At a high shear rate, STFs can absorb a significant amount of impact energy[4]. Mainly STF impregnation increases the friction between yarns which acts as a resisting force for pulling the yarns at the time of impact. Not only UHMWPE, but STF impregnation improved the ballistic protection for very commonly used aramid fibers (e.g. Kevlar) as well[5]. Now, the low density of UHMWPE along with its higher tensile strength in comparison to aramid fibers make them more desirable for the application.

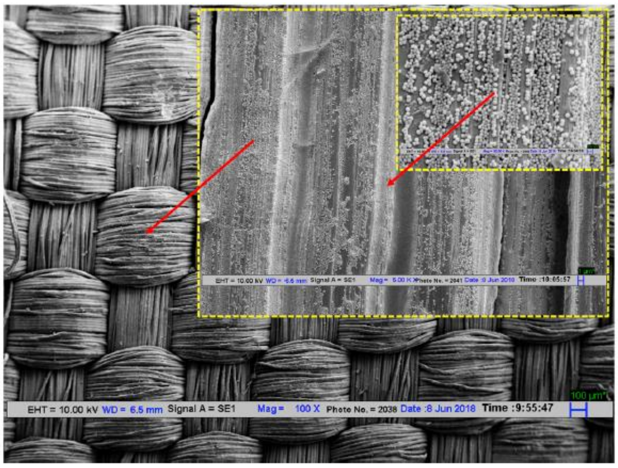

Fig 1. SEM images of UHMWPE fibers with silica Nanoparticles

Not only impregnation of STF play an important role in determining the ballistic performance, but also the design of the fabric is an important factor for its energy-dissipation mechanism during impact. It is reported that the ballistic performance of a single layer of unidirectional (UD) fabric was greater than that of 2D and 3D woven fabric[6]. In the UD fabrics, parallel fiber was laid in 0^0 and 90^0 orientations and held together using a compliant resin. The superiority of UD-UHMWPE fabric is due to the absence of the cross-over points or crimp which allows the reflective wave to get transmitted over large areas on impact.

Studies conducted by Mishra et al.[7] demonstrated the evaluation of the ballistic performance of neat and STF-treated UD-UHMWPE composites in the velocity range of 250-700 $m.s^{-1}$ at room temperature. A significant increase in the impact energy absorption in the STF-treated panels was observed in comparison to the neat ones at the same velocity. The performance to successfully resist a bullet penetration and prevent any non-penetration injury significantly increased with the number of layers (from 5 to 30 layers) without compromising a lot in weight due to better impact energy absorption and dissipation. The failure mechanism for the thinner panels (5 and 10 layers) was mainly localized damage and the layers were perforated through shear plugging at the impact region. With the increase in the panel thickness (20 and 30 layers), it was mostly tensile fracture of the high-tenacity fibers. While fiber stretching was observed on the back face of the STF-treated panel, fiber grouping/clustering was noticed in the neat panels. However, the STF-treated 30-layer panel was able to withstand the impact velocity of 509 ± 10 $m.s^{-1}$ without significant back face deformation. This improvement in ballistic efficiency is mainly attributed to the increased friction between the layers of the STF-treated UD-UHMWPE. Having minimal weight difference between neat and treated panels, STF impregnation improved the ballistic limit without affecting flexibility or adding more weight to the panel.

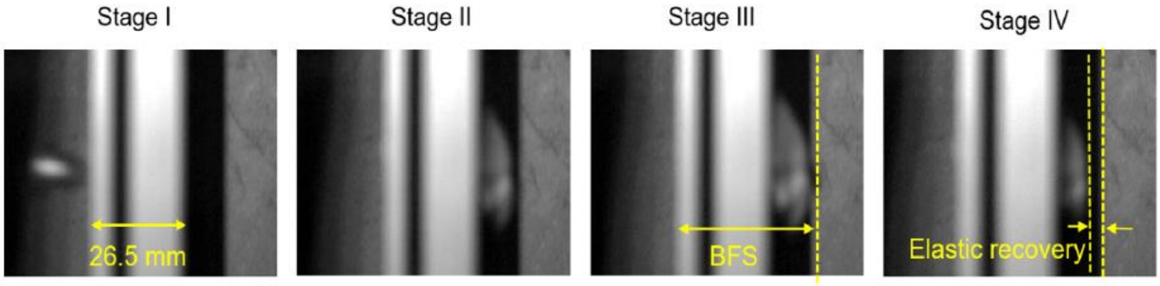

Fig 2. High-speed images of the bullet impact effect on the UHMWPE

Apart from the conventional STF fluids with nanoparticle suspension, a lot of attention has been focused on other alternatives as STF materials for surface treatment of UHMWPE. Double-network hydrogels consisting of a highly cross-linked brittle network and a loosely cross-linked ductile network demonstrate superior toughness and energy dissipation properties. In this class of STF, the key point is the construction of multiscale structures as sacrificial bonds, where the bicontinuous hydrogel (BH) is comprised of an interpenetrating polymer-hard phase and polymer-soft phase with tunable hydrogen bonding interaction between the polymer chains. Qiu et al.[9] used this strategy to combine double-network hydrogels with rigid yet flexible fibers (UHMWPE) to create a composite BH-UPF$_n$, where the rigid fibers increase the specific strength, while the tough hydrogel matrix dissipates energy.

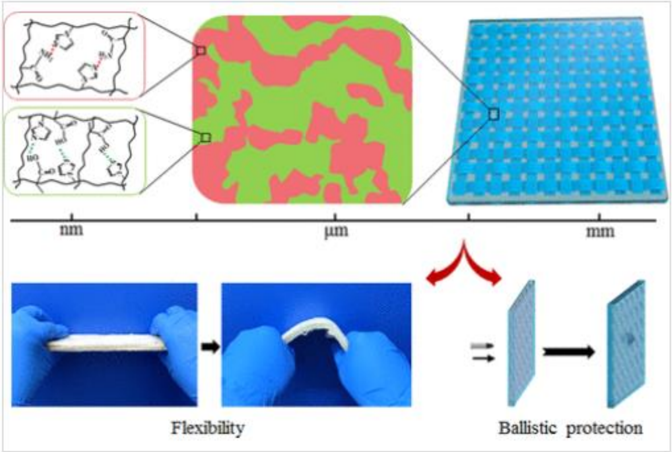

Fig 3. Multiscale structure of the BH-UPF$_n$ composite and its flexibility

The hydrogels were synthesized by free radical polymerization of Methacrylic acid (MAAc), acrylamide (AAm), 1-vinylimidazole (VI), with the desired properties achieved with the molecular unit $M_{12}V_1A_6$ copolymer hydrogel. The strong hydrogen bonding interaction between MAAc-VI forms the hard phase, while the weaker hydrogen bonding between AAm-VI forms the soft phase with interpenetrating layers. During the impact, the polymer hard phase and polymer soft phase deformed equally, but the polymer hard phase sustained more stress due to the high stiffness and ruptured first by breaking the hydrogen bond aggregates, transferring the stress to the polymer soft phase that dispersed the stress to a large area. The composite showed excellent tearing resistance due to the increased friction between the fibers and the BH matrix and the rupture of the multiscale structure. BH-UPF$_{15}$ composite was able to stop a flying bullet at a speed of 300 m.s^{-1}, while it completely penetrated the UPF$_{15}$ matrix. Although UPF$_{30}$ stopped the same bullet, it showed a large back face deformation of 1.03 cm, while it was only 0.32 cm for the BH-UPF$_{15}$ composite.

In the last part, it's important to understand the interplay between STF impregnation and fabric structure in terms of different sett and areal densities. Aurora et al.[8] demonstrated that fabrics woven with coarser 1350 denier yarns with STF treatment improved the impact resistance and yarn-pull-out force as well as withstanding the impact force for a longer duration. For firm structures woven from 400 denier yarns with higher sett (ends per inch × picks per inch or EPI×PPI), STF treatment deteriorates the impact resistance due to stress concentration, although the lower sett value (low EPI×PPI) showed improved performance. When the fabric is very firm with high values of EPI×PPI, the inability of the yarns to slide past each other due to high friction prohibits the generation of shear required for hydro-clustering of impregnated silica particles, such that no shear thickening occurs. Hence, rather than reinforcing the fabric structure to facilitate enhanced impact energy absorption, STF treatment degrades the performance of fabric structures having the requisite level of inter-yarn friction in their neat form due to stress concentration. This finding established the fact that inter-yarn friction due to STF incorporation cannot be considered as the whole factor for improved ballistic performance without considering the fabric structure.

In summary, the incorporation of STF with proper fabric structure significantly improved the ballistic performance of UHMWPE fabrics by engaging more fibers and preventing their relative sliding during impact. Due to their non-Newtonian nature, STF materials greatly absorbed the impact energy and weakened the impact force on the back side of the armor, significantly decreasing the bulge deformation. All these factors along with the high flexibility and lightweight nature of the composite make STF-incorporated UD-UHMWPE fabric one of the best candidates to make soft body armors for military personnel.

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