Modification of Ultrahigh Molecular Weight Polyethylene (UHMWPE) Ballistic Fibers for Enhanced Performance

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Abstract

The objective of this project was to modify UHMWPE fibers used in body armor to improve the fiber's ballistic performance. The developed nanocomposite material was composed of UHMWPE, Nylon-6 and reinforced with SWCNTs. The material was extruded by melt extrusion using paraffin oil as a solvent. The fiber was hot drawn, and strain hardened. The developed nanocomposite fiber shows an increase in normalizing velocity of 44-57% when compared to commercial fibers. The increase in normalizing velocity indicates that the material can better absorb the energy of a projectile and dissipate it faster. This means that body armor made with such fiber can offer the same level of protection while being lighter, with a lower aerial density.

Introduction

UHMWPE is the current state-of-the-art polymer precursor for ballistic fibers. UHMWPE fibers have highly extended chains providing high strength and modulus but low fracture strain. A hybridization approach with nylon 6 was undertaken to improve the ductility of UHMWPE. The reason for choosing nylon 6 is its high fracture strain, which is one order higher than that of UHMWPE fiber. To Increase the fracture strength and modulus, functionalized carbon nanotubes (CNT) were added to the hybrid mix and the composite was termed as Nano-Hybrid. The nanoparticle inclusion was used to share the tensile load along with UHMWPE and recover the strength and modulus lost due to hybridization. The use of CNTs functionalized with carboxylic acid (COOH) and octadecylamine (ODA), as shown in Figure 1, allows for better compatibility between the CNT and UHMWPE [1].

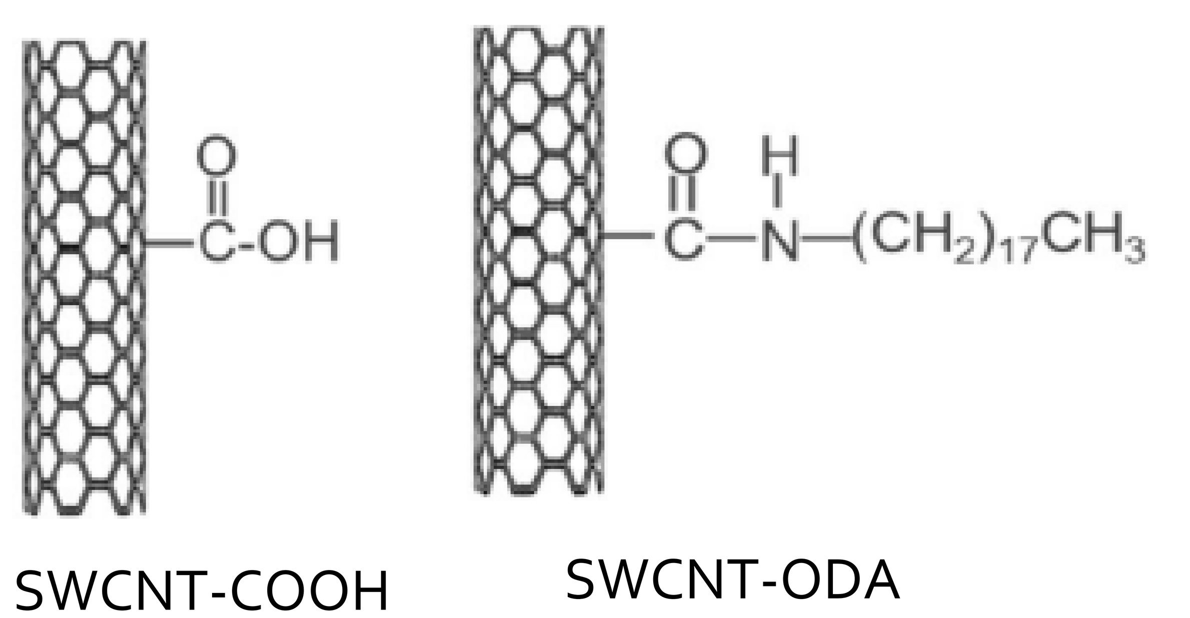

Figure 1 - Structure schemes of carboxylic acid and octadecylamine functionalization attached to CNT surface.

Fiber Synthesis

Nanotubes were first sonicated into a large volume of paraffin oil and then homogenized with UHMWPE and nylon 6. The ratio of UHMWPE to nylon 6 was 4:1 and the concentration of nanotubes was 2.0 wt%. The admixture was heated to form into a gel and then fed into an extruder (Figure 2a). The extruded filament was treated in a hexane bath (Figure 2b) and heat-stretched in a convection oven (Figure 2c) to remove paraffin oil and further align the polymer chains, respectively.

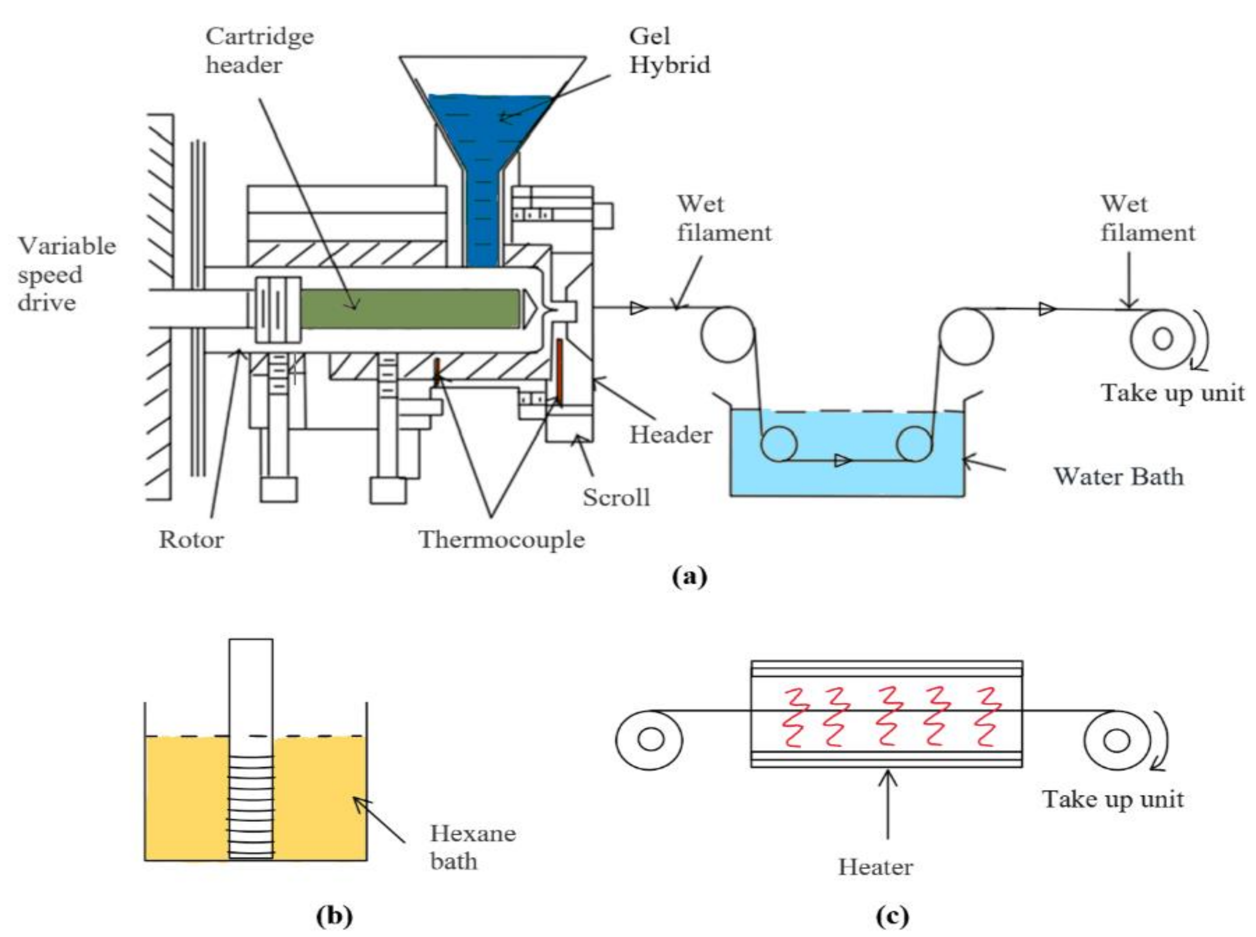

Figure 2 - Schematic view of melt extrusion using a Laboratory Mixing Extruder (LME).

Fiber Testing

Determining the mechanical properties such as modulus, strength, and fracture strain were necessary to calculate the normalizing velocity. Tensile tests were conducted at a quasi-static rate ($2.77 \times 10^{-3}\ s^{-1}$) Fiber was wound on PLA discs. The average diameter of nanotube-reinforced fiber varied from 45-50 µm. After strain hardening, the diameter was reduced to 35-40 µm range.

Strain hardening was done by cyclic loading the fiber past its yield point. At each cycle, the load is incrementally increased. This process promotes large-scale orientation of chain molecules and lamellar crystals. Due to repeated loading and unloading, molecular segments in the polymer tend to come closer to the nanotubes.

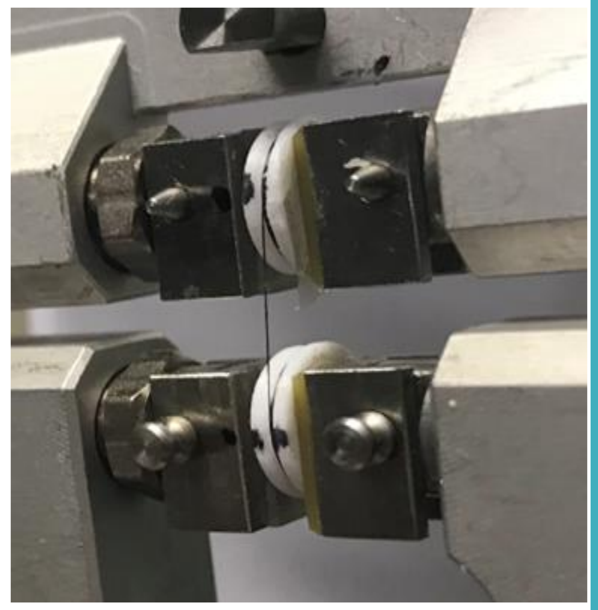

Figure 3 – Fiber being tensile tested with PMMA clamps and PLA discs.

Results

The normalizing velocity is a quality index that is expressed as the product of fiber's toughness and tensile wave speed divided by its density [2, 3] as shown below:

$$\sqrt[3]{\Omega} = \left(\frac{\sigma_{y\,max} \varepsilon_{y\,max}}{2\rho_y} \sqrt{\frac{E_y}{\rho_y}} \right)^{1/3}$$

where, $\sigma_{y\,max}$, $\varepsilon_{y\,max}$, ρ_y and E_y are fracture strength, fracture strain, density, and modulus of the fiber, respectively. Subscript "y" refers to yarn. It is clear from equation (1) that any increase in $\sigma_{y\,max}$ and $\varepsilon_{y\,max}$ will enhance the energy absorption, and an increase in modulus E_y will improve the tensile wave speed. The combined effect will therefore be an increase in normalizing velocity.

A summary of the tensile test data before and after strain hardening is listed below, in Table 1.

Table 1 - Tensile test results before and after strain hardening

Fiber Type	Young's Modulus [GPa]	Ultimate Strength [GPa]	Fracture Strain [mm/mm]	Normalizing Velocity [m/s]
Neat UHMWPE	2.16 / 3.76	0.40 / 0.48	0.94 / 0.58	668/ 792
UHMWPE-Nylon	0.62	0.24	2.8	558
Nano-Hybrid (SWCNT)	10.2 / 6.59	0.88 / 0.91	0.10 / 0.50	637 /812
Nano-Hybrid (SWCNT-COOH)	2.44 / 6.45	1.0 / 2.3	0.49 / 0.59	741 / 1243
Nano-Hybrid (SWCNT-ODA)	5.60 / 13.0	0.94 / 2.8	0.52 / 0.47	870/ 1274

** Values are shown as and Before / After Strain Hardening*

The results in Table 1, further reveal that modulus and strength increased significantly due to nanotube reinforcement and strain hardening. Although fracture strain decreased, it remained high enough resulting in a larger normalizing velocity, as shown in Figure 4.

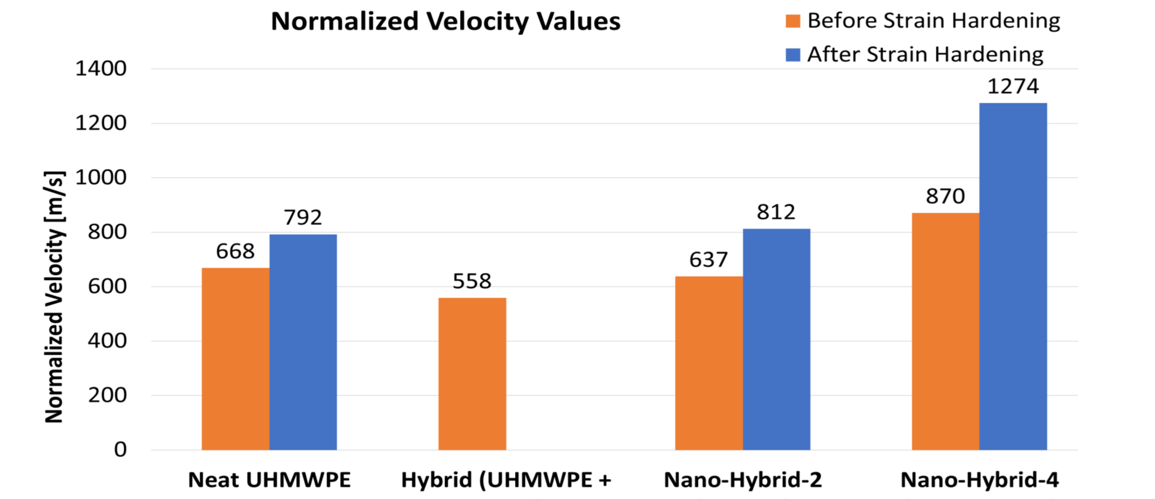

Figure 4 – Comparison of normalized velocities for different fiber types.

Figure 5 show the microscopic features of the fiber. nylon forms into microspheres (droplets) while the UHMWPE form into long chains aligned with the fiber axis. Then CNTs are dispersed throughout the fiber, mostly aligned with the fiber axis.

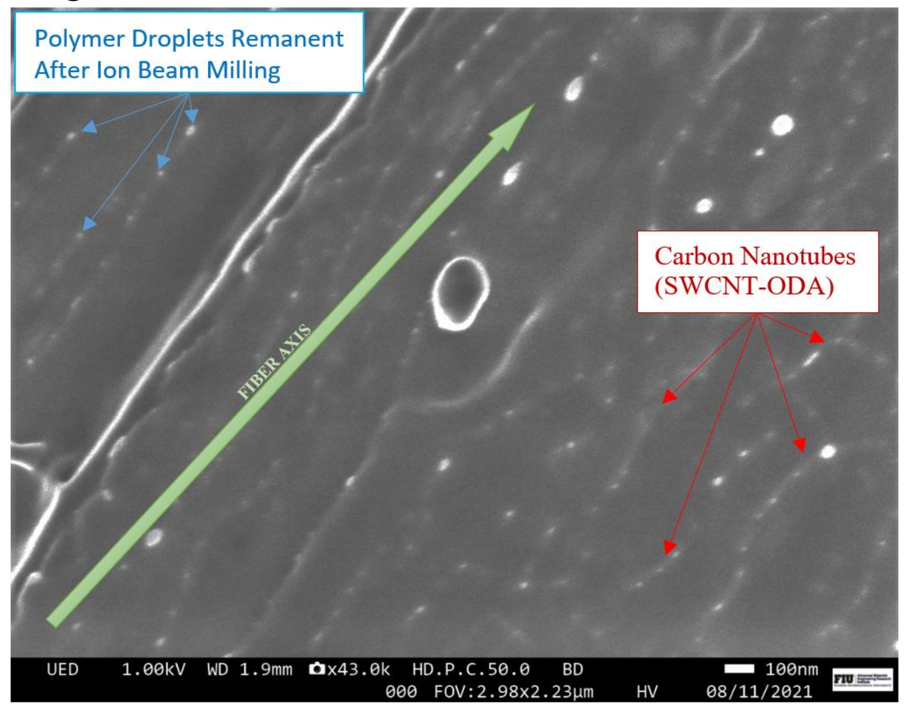

Figure 5 – Scanning electron microscope picture of Nano-Hybrid (SWCNT-ODA) fiber.

Conclusion

- The use of functionalized SWCNTs improved the compatibility with the polymer matrix as shown by the improved mechanical properties.
- The Normalizing velocity of neat UHMWPE fiber increased from 668 to 870 m/s due to hybridization and nanotube (SWCNT-ODA) reinforcement indicating a 30% improvement.
- After strain hardening, normalizing velocity increased to 1274 m/s demonstrating a phenomenal enhancement of 91%.
- When compared to Dyneema SK-75 and Spectra 2000, the SWCNT-ODA reinforced fiber displayed a normalizing velocity 44% and 57% higher, respectively.

Acknowledgements

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References

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