The Mechanical Properties of UHMWPE Fiber-Knitted Composites

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ABSTRACT

UHMWPE fiber weft-knitted fabric was modified using a VARTM liquid oxidation molding process. The matrix was epoxy resin. The layer was prepared with vertical symmetry by knitting composite layers 10 and 16 with the unmodified and modified plain weft-knitted fabric of the composite using the two-layer blessing method. Three-point unconstrained bearings were used to conduct tensile and bending tests, and tensile stress-strain curves were obtained using Origin software. Finally, the modification results were observed using a TM3030 scanning electric microscope (SEM). The SEM results reveal longitudinal notches on the treated fiber surface, which improved the interface adhesion to the resin. However, the single yarn strength was reduced by approximately one fifth. After the modification, the knitted fabric's maximum tensile strength increased by 37.7%, and the maximum tensile strength increased by 46.35 percent. The maximum bending force increased by 37.3-53%, and the maximum bending load increased by 53.3-62 percent.

Keywords: UHMWPE weft-knitted composite; modification; tensile property; bending resistance

INTRODUCTION

At the beginning of 1980s, Holland DSM successfully developed a high-performance organic fiber, referred to as UHMWPE, using ultra-drawing technology and gel spinning. UHMWPE fiber has a high strength and a high modulus, and UHMWPE fibers are smooth and chemically inert. Furthermore, they have strong acid and alkali corrosion resistance, light resistance, and resistance to heat aging. Their density is approximately 0.97 g/cm^3. UHMWPE fiber-reinforced composites are indispensable in industry today. In recent years, many scholars have studied modified UHMWPE fiber, but there no results or conclusions are available in terms of the tensile and bending properties of modified UHMWPE fiber composites.

Niloofar Bahramiana [1] aimed to evaluate the effect of corona and silane fiber surface treatment on the mechanical properties of the UHMWPE FRCs. The results showed a change in the surface mechanical properties and chemistry of the corona-treated UHMWPE fibers. The fibers that were exposed to a corona for 5 s showed greater surface nanohardness. In the FRCs, the specimens reinforced with 5 s corona-treated silanized fibers showed greater mechanical properties (flexural modulus, flexural strength, and fracture toughness). Yanhua Xu [2] processed basalt fiber into yarns having different fineness and knitted woven and composite fabrics and created multi-layered biaxial weft-knitted fabrics. The basalt fiber and the ethylene composite material were then combined using the VARTM process, and the authors tested the bending properties in different directions and compared the relationship between the characteristic curve and the yarn strength. Simona Matei [3] used four types of resins (namely, T 19-38 /500, T 19-38 /700, L 50-54, and A 19-00) and two types of reinforcing materials: Kevlar pulp and glass fibers. From the composites prepared in the injection phase (a homogeneous mixture of matrix and fibers), standard samples were created to analyze the mechanical properties by pressing the composites into a metallic mold and analyzing the actual physical (density and component proportions) and mechanical (specific resistance, elastic modulus, and elongation) properties. Ruipei Li [4] used a potassium chromium solution of UHMWPE fibers that were surface modified and prepared using UHMWPE fiber/EP composites; the purpose was to enhance the bending bonding strength between the UHMWPE fiber and the epoxy resin (EP) matrix. The results revealed clearly detectable traces on the UHMWPE fibers caused by the liquid phase oxidation of the surface, and the surface roughness was increased significantly. The crystallinity increased 11.3%, and relative to the contact angle of the ethylene glycol, the contact angle decreased by 14.12 degrees. Kondo [5] applied electron beam irradiation graft polymerization (EB) to UHMWPE. The maximum grafting rate was 23.6%, and the SBR compound grafted fiber maximum grafting rate increased with the fiber's initial modulus and the linear strength. The initial modulus increased approximately five fold when the fiber content was 10%. Lin, S.P. [6] used surface modification methods for plasma surface treatment and used chemical treatment methods on the fiber surface, which was observed using electron energy spectrum and scanning electron microscopy (SEM). These authors drew the following conclusions: two types of fiber surface modifications using UHMWPE fiber and epoxy resin matrix composites exhibited improved bending adhesion and slightly improved tensile strength after formation. However, a significant decrease in the elongation relative to a non-processed UHMWPE fiber composite was observed form the enhanced stress/strain measurements and the SEM micrographs. The resin matrix was found to improve the tensile strength significantly. Enomoto, Ichiro [7] improved the dyeing properties of UHMWPE through surface treatment using radiation grafting polymerization and selected methyl methacrylate (MMA), acrylic acid (AA) and styrene (st) as monomers. Connecting the functional relations between the branch rate and irradiation time resulted in the following conclusion: the dyeing concentration increases as the grafting yield increases, and the ST is a successful cationic dye. Hossein Rahmani [8] discussed the reinforcing mechanism of amine functionalization on carbon fibers (CFs) and illustrated the differences between aliphatic and aromatic compounds. The structural and surface characteristics of the functionalized CFs were investigated using X-ray photoelectron spectroscopy (XPS), Fourier transform infrared spectroscopy (FT-IR), and SEM. The following conclusions were drawn: SEM micrographs confirmed the improvement of interface adhesion between the modified CFs and the epoxy matrix. Finally, PAB was found to be a promising candidate to functionalize CF to improve the bending properties of the CF/epoxy composites.

In summary, UHMWPE fibers have been modified using a potassium chromium solution, and a number of studies have been conducted to study the mechanical properties of the UHMWPE and the composites [9-20]. However, no systematic testing of the tensile and bending properties has been performed because it is not convenient for certain modified UHMWPE fibers and products. Therefore, woven weft-knitted fabrics using UHMWPE fibers, the oxidation treatment of fabrics, and composites prepared using the VARTM process were investigated in the current study, and the effect of oxidation processing of the knitted fabric on the tensile strength and bending performance of the composite for products is reported.

EXPERIMENTAL

Materials and Instruments

The raw materials consisted of the UHMWPE fiber with properties shown in *Table I*. The manufacturing equipment was hand driven flat knitting.

TABLE I. Performance parameters of the UHMWPE fiber.

Fineness (D)	Fracture tension (N)	Elongation (%)	Fracture strength (N/tex)	Proportion (%)
100	35	2.42	345.2	82

The treatment was chemical reagent chromium oxidation. The experimental instruments and the reagents were as follows: a balance, beaker, boiling water bath, glass rod, safety gloves, potassium chromium, distilled water, and concentrated sulfuric acid. The ratio of the modified liquid water: potassium chromium: concentrated sulfuric acid was 12:7:150. The processing temperature was 80°C, and the reaction time was 3 minutes.

Experimental Process

Change in Strength Before and After Modification

The test instrument was an INSTRON tensile tester. The method was the same as the experimental methods used in the study of carbon fiber monofilament tensile strength testing. The samples consisted of the following: UHMWPE fiber, yarn, and modified yarn. Results reported are the average values from the testing of 5 samples. *Table II* indicates that the fiber strength was enhanced 37.1% after twisting; however, the yarn strength decreased by 18.7%.

TABLE II. Yarn strength test results.

Yarn	Maximum Load/N
Bouquet of fiber	35
Yarn	48
Modified yarn	39

Fiber Surface Morphology Before and After Modification

The surface morphology of the UHMWPE fiber was studied using a TM3030 SEM. As shown in *Figure 1* and *Figure 2,* the surface of the original UHMWPE fiber was smooth. However, after modification, the surface of the fibers became rough as a result of corrosion. There was an increase in the surface roughness and contact area with the resin, which increased the bond between the yarn and the resin because the surface of the UHMWPE fiber contained many small horizontally aligned cracks. The vertical direction also featured deep grooves and a symmetrical distribution, and the crack depth was up to 1 to 2 microns, which is sufficient to allow chemical molecules to enter and contact the material, accelerating oxidation and promoting corrosion. However, the fiber surface exhibited prominent candle-like carved structures and longitudinal surface cracks, and the fiber was damaged by an increase in the processing time and processing temperature; thus, it is important to control the experimental time and temperature. From a micro-scale perspective, the fiber surface contact angle decreased, and the surface contained oxygen-rich polar groups, such as light base fiber, that increased after processing. The surface polarity difference improved the fiber non-crystalline surface area. It contained candle-like structures, the number of folded chain crystals decreased, and amylose crystallization increased. The fiber crystallinity increased after chromium treatment. Increased chromium acid treatment liquid with a strong oxidizing agent generally results in physical and chemical changes. The fiber surface can produce a light, Ke base and carboxyl or other polar groups that can improve the bonding strength between the fiber and resin. The physical performance was characterized by the dissolution of the non-crystalline fiber surface part not only on the surface of the longitudinal crack but also in a longer gap due to etching in the lateral direction, as shown in *Figure 4.*

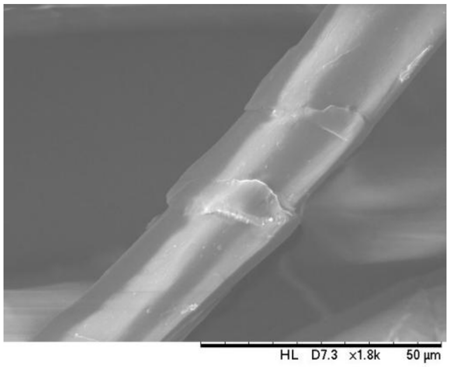

FIGURE 1. UHMWPE fiber.

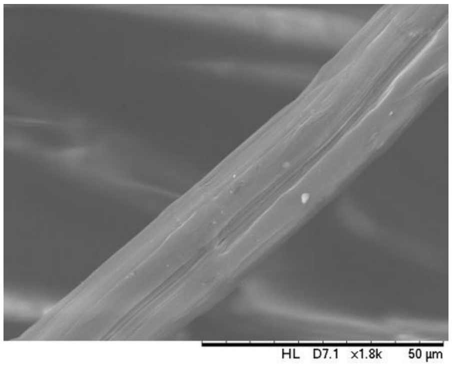

FIGURE 2. Modified UHMWPE fiber.

Tensile Test and Bending Test

The tensile tests were in agreement with the fiber-reinforced plastic test methods used to determine the properties of general and fiber-reinforced plastics. The experimental instrument was an INSTRON tensile tester. The test was performed with reference to glass fiber-reinforced fibers, and the plastic bending performance test method was GB1448-83. The experimental method was a three-point bending test without the support constraint. The instrument used was an INSTRON [21-24].

RESULTS AND DISCUSSION

Tensile Test Results and Discussion

Table III shows the results of the tensile test. The conclusions were as follows: the tensile loading and tensile strength was increased for the weft plain-knitted fabric composite material after modification. The $[P]_{10}$ maximum tensile load was increased by 37.65%, the $[P]_{10}$ maximum tensile strength increased by 37.7%, the $[P]_{16}$ maximum tensile load increased by 46.37%, and the $[P]_{16}$ maximum tensile strength increased by 46.35 percent.

TABLE III. Test parameter results.

Sample	Maximum tensile load/N	Tensile strength/MPa
$[P]_{10}$	3,362.24	44.83
Modified $[P]_{10}$	4,628.29	61.71
$[P]_{16}$	4,729.60	37.84
Modified $[P]_{16}$	6,922.81	55.38

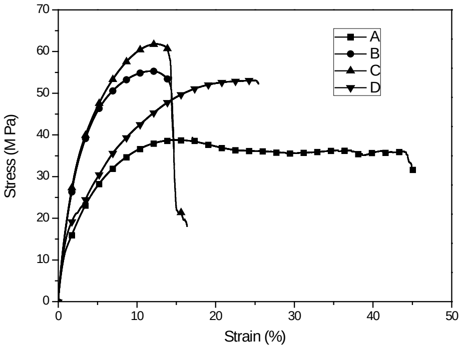

FIGURE 3. Tensile stress-strain curve of the modified and unmodified fiber ($[P]_{10}$ of the 10th floor layer).

The results were superior when the yarn was modified with the adhesive resin. The tensile properties of the composite modified composite board after the rapid decrease are shown in *Figure 3B*, and *Figure 3C* shows the composite board after modification. *Figure 3A* and *Figure 3D* refer to the unmodified material. *Figure 3A* and *Figure3B* correspond to $[P]_{16}$, and C and D correspond to $[P]_{10}$. As the tension increased, the crystallinity of the UHMWPE fiber increased, and the grain size decreased significantly during the stretching process. The whole stage can be divided into three sub-stages: the fast growth stage, the progressive stage and failure stage; the energy absorption capacity of composite materials mainly depends on the bonding between the fibers and resin. Partial detachment occurred between the fiber and the resin, resulting in a layered composite plate. The main stress area featured prominent deformation and discoloration. With increasing tensile strength, the long period of the fiber and the orientation degree of the crystal region increased gradually. The tensile strength also increased gradually. As a result, the yarn and the composite plate both failed. However, the change in the yarn was relatively flat, indicating that the adhesiveness of the yarns and resin was not satisfactory, resulting in the yarn with the resin slipping and a decline in the strength utilization. The specific fracture cracks are shown in *Figure 4*. The corrosion by the potassium chromium causes the fiber surface to appear to have a different degree of cracks in the transverse and longitudinal directions, and a relative displacement exists between the fiber and fiber in the stretching process due to the friction between the cracks, which tends to hinder the displacement between the fiber and thus improve the maximum tensile load and tensile strength. Conversely, the chemical reaction caused by the potassium chromium at the fiber surface produces a light Ke base, and the carboxyl and other polar groups improve the bond strength between the fiber and the resin, which also hinders the stretching process. A matrix of tiny cracks appeared during the tensile test and was sufficient to support the substrate and the fabric together in the tensile test, as shown in *Figure 5*.

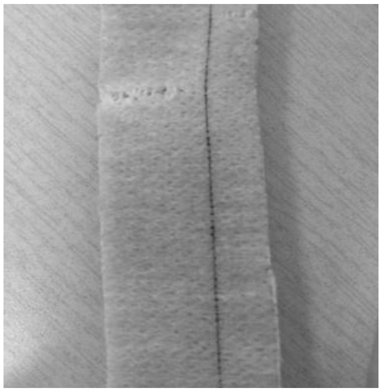

FIGURE 4. Fracture form of the composite plate.

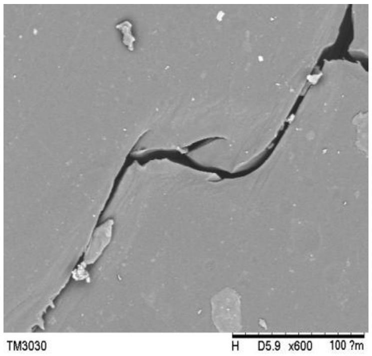

FIGURE 5. Substrate stretch and microscopic damage.

Table IV shows the results of the bending test. The weft plain-knitted fabric composite knitted fabric can be observed after modification. As the composite bending force and the bending stress were increased, the $[P]_{10}$ maximum bending force increased by 37.3%, the $[P]_{10}$ maximum bending load increased by 62%, the $[P]_{16}$ maximum bending force increased by 53%, and the $[P]_{16}$ maximum bending load increased by 53.3 percent.

TABLE IV. Bending test results.

Sample	Maximum bending force/N	Maximum bending stress/MPa
$[P]_{10}$	64.63	36.42
Modified $[P]_{10}$	88.76	59.17
$[P]_{16}$	209.39	50.25
Modified $[P]_{16}$	321	77.03

The data were obtained by testing after calculation, and the analysis of the composite bending stress-strain curve was then conducted using Origin software.

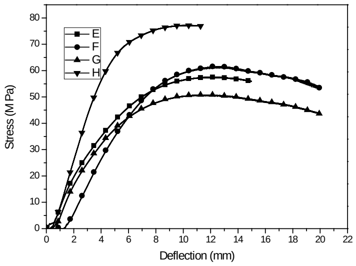

FIGURE 6. Stress-strain curve of the modified and unmodified composite bending.

The stress and strain relationship of the sample initially increased linearly. The vertical test pressure head moved downward and the specimen did not move in the horizontal direction, as shown in *Figure 6F* and *H*, which show the composite board after modification; *Figure 6E* and *G* refer to the unmodified material. *Figure 10E* and *F* correspond to [P]10, and *Figure 6G* and *H* correspond to [P]16.The whole stage can be divided into three sub-stages: initial stage, the progressive stage and failure stage; the energy absorption capacity of composite materials mainly depends on compression angle and the load displacement process .It is primarily the resin that was subject to the bending load at this stage, and the resin behaved satisfactorily and did not undergo fracture. It is generally hypothesized that bending damage primarily initiates in the resin matrix. That is, the materials exhibit satisfactory toughness and bending strength, similar to high-strength polyethylene. The second part refers to the curved part of the specimen that achieves the maximum bending stress. This region reflects the maximum bending stress of the different composites. This finding shows that the modified yarn composite's bending capacity improved significantly. The bending capacity of the complete composite decreased after the destruction of the resin. The sample in compression underwent permanent deformation that occurred in the head position, but tearing failure or delamination did not appear due to the damage to the composite's bending capacity. Therefore, the bending failure was caused by the resin, which was destroyed in the sample, as shown in *Figure 7*. The modification of the maximum bending force was greater than without modification because the fiber surface active groups, such as the hydroxyl groups, caused bonding between the fiber and resin. The fiber and resin were not easily separated when the bending force increased to the maximum, as shown by the microscopic analysis. The oxidation by the potassium chromium acid causes the fiber surface to crack, and there are different degrees of etching that produce different degrees of concave and convex surfaces. These cracks in the longitudinal and transverse direction will overlap between the fibers, and when the fiber is subject to the bending force, frictional resistance arises. This improves the maximum bending force, as shown in the macroscopic analysis. The matrix appears to have undergone no breakage in the process of bending, as shown in *Figure 7*; however, the substrate surface contains tiny cracks, as shown in *Figure 8*. This result shows that the matrix is subject to bending force, resulting in deformation due to the substrate extrusion force, as shown in *Figure 9*. This behavior suggests the matrix is in the process of undergoing the full bending force. Cracks arise for two reasons. One is mechanical crushing. The second is that the bending extrusion effect causes the tiny cracks on the surface of resin matrix intermediate points to expand and contract on both ends of the specimen gradually, resulting in resin and fiber debonding with the increase of bending load.

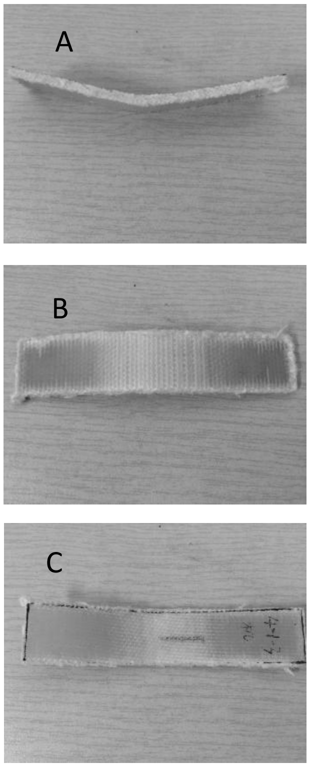

FIGURE 8 . Bending failure diagram (a) profile, (b) upper surface, and (c) lower surface.

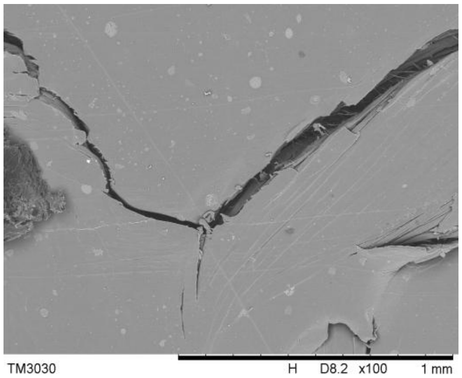

FIGURE 8. Microscopic damage caused by substrate bending.

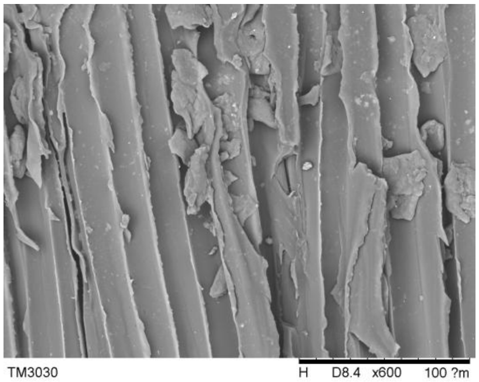

FIGURE 9. Lower surface of the micro-scale damage.

CONCLUSION

Based on the results presented, the following conclusions are possible:

(1) The yarn cross section decreased due to the corrosive effects of the potassium chromium, and the unit area of the fiber increased due to the pulling force when the fabric was stretched, which caused a decrease in the strength of the yarn by 18.7% after modification.

(2) The tensile load and tensile strength were increased in the weft plain-knitted fabric composites after modification. The reason for this increase was the resin and the fiber. The fiber-to-fiber contact, which arose from potassium chromium etching of the fiber surface, improved the bonding performance, the tensile strength and the bending properties of the UHMWPE fiber. The tests showed the following: the maximum tensile strength increased by 37.7%, the maximum tensile strength increased by 46.35%, the maximum bending strength increased by

approximately 45%, and the maximum bending load increased by approximately 60%.

(3) In general, the 16-layer knitted fabric showed a larger increase in mechanical properties relative to the 10-layer fabric.

(4) The tensile and bending of UHMWPE fiber-knitted fabric can be divided into three stages: the fast growth stage, the progressive stage and failure stage. The longest is the rapid growth stage.

FUNDING

Supported by the National Natural Science Foundation of China (51403154; 11602168).

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