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Improved Performance on Mechanical and Wear Properties of UHMWPE/GFs/Nanoclay Hybrid Composites

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Abstract

An effort has been made to improve the tensile strength, cyclic fatigue behavior, residual properties, and wear behavior of glass fiber (GF) reinforced ultra-high molecular weight polyethylene (UHMWPE) by adding various wt. % of Nano-clay (1%,3% and 5 wt.%). The composite formation and elements distribution was verified by Raman's study and SEM images. The improvements in tensile strength and tensile modulus were observed up to the addition of 3% of nano-clay reinforcement. The residual tensile strength and modulus were enhanced at various phases of fatigue cycles. Especially, UHMWPE/GF/3%Nano-clay specimens exhibit improvement in overall performance. The equivalent fatigue failure area is relatively decreased owing to Nano-clay reinforcement. Nano-clay in the composites assists in delaying failure due to delamination and suppresses subsequent failure by enhancing the fiber-matrix interfacial bond. The increasing wear resistance is achieved for an increasing wt. % of Nano-clay.

Keywords: *UHMWPE, Nanoclay, glass fibers, Mechanical properties, Wear behaviors*

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Introduction

Composites have characteristics that are not depicted by any of their components in isolation. The interface may be an abounding surface or zone where a discontinuity occurs, whether physical, mechanical, chemical, etc. An investigation of the mechanical properties of clay oxide was done and it was stated that it has interesting protective properties against corrosion. It was also found to enhance mechanical, thermal, and fire-resistance properties [1-3]. Some researchers also investigated the unique reinforcement properties of nanocomposites and defined them as a two-phase system [4, 5]. In an experiment conducted on the impact response of composite materials, it was concluded that woven composites were found to be superior to unidirectional composites in protection limit, in case of low-velocity impact [6].

Many studies are dedicated to refining the performance of the mechanical behaviors of hybrid composites reinforced with fiber and Nano-clay. Other than the mechanical behavior, the clay-epoxy reinforced hybrid composites show enhancements in many structures with less clay content. They exhibit improved thermal stability [7-9], condensed humidity, gas penetrability [10], and higher fire hindrance [9]. Nano-clay, in specific attributes to the valuable effects on cracking and strengthening fatigue of carbon fiber composite (CFRPs) [11]: e.g. enlarged mode 1 resistance to delamination [12], enhanced resistance on impact and tolerance [13], and improved strength on fracture impact [14]. Still, only limited studies have been carried out on the mechanical behavior of composites added with GFRP encompassing Nano-clay. As the persistence of our earlier studies with hybrid composites added by clay-GFRP reinforcements [15-17], this work precisely surveys the fatigue performance of GFRP composites affected by Nano-clay addition.

Ultra-high molecular weight polyethylene (UHMWPE) exhibits properties that could withstand severe operating conditions, unlike usual polymer modification. It was demonstrated that modifying UHMWPE via introducing ultrafine particles of inorganic clay materials promotes an increasing operational performance of ware made of UHMWPE [18]. Further, experimental investigation of the thermo-mechanical behavior of UHMWPE carbon-nanotubes composites under different cooling techniques showed its applicability in certain applications requiring distinct thermal properties [19]. It was also noted that UHMWPE possesses excellent strength, impact resistance, and abrasion resistance in a semi-crystalline form [20].

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An experimental investigation on the behaviors of wear and distribution of wear debris of UHMWPE against Si_3N_4 ball in bi-directional sliding was studied to evaluate its tribological properties [21]. Many researchers, concluded that numerous thermo-physical, mechanical behavior, and chemical-included cross-linked UHMWPE were determined by in-vitro tests, from which it was clear that cross-linking causes an increase in the wear resistance of polymer matrix composites [22, 23]. In a different approach, a study on friction lining of clutch using Finite Element Analysis under transient conditions by Ansys Software was conducted. The study was carried out using aluminum matrix composite, asbestos, etc. [24, 25]. The high-quality clutch plate was fabricated via the hand lay-up technique [26]. In another similar study using woven fabric composite, it was found their performance was better compared to convention metals used for lining in terms of heat resistance and wear [27]. The performance of friction material depends on (1) structural analysis, (2) stress, (3) deformation, and (4) strain of the friction materials [28]. Another similar study was carried out based on different dynamic conditions for improving the performance of clutch plates. The interface parameters such as contact pressure, speed, and temperature were taken into consideration. From the analysis, it was found that take-up judder played an important role in dynamics [29]. Further study on friction plates under dry and wet conditions revealed improved performance on the addition of carbon fiber in terms of increased wear friction characteristics [30]. A comparative study was conducted between copper-based and paper-based friction materials for the clutch. The specimens were tested for wear and coefficient of friction (COF). The result showed that the wear depth had liner proportionality with paper-based material and the wear varied greatly. Thus, enabling a choice of friction material based on applications [31, 32].

From the literature studies, it was evident that many authors have explored the properties of UHMWPE in terms of thermal, mechanical, and optical points of view. It was found that only a few have explored the possibility of its applications and also none have explored the combination of UHMWPE with Nano-clay. In a system of clay-polymer, the clay Nano-particle leads to the interlayer spacing due to intercalation and breaking of the van der Waals forces due to exfoliation Clay crystals are used as a Nano-particle, it's referred to as intercalated clay, in this condition the chains of polymer are forming between the platelets of clay. If we use a single particle constituent of a clay unit, it is referred to as exfoliating, in this condition anisotropic dispersion of clay platelets was observed in the polymer [12, 13, 33]. Hence in this work, the development of a new friction lining clutch material using

UHMWPE with Nano-clay and glass fiber laminates material has been fabricated with the following objective: (i) To withstand high heat capacity during the engagement of the clutch, (ii) To increase the lifetime of friction lining material by reducing wear & tear properties, (iii) To decrease the coefficient of friction in the material, (iv) the power transmission from engine to drive shaft will be high, (v) To absorb the heavy shock load by having high impact strength, and (vi) It should not be affected by moisture, oil, and other environmental factors.

Materials and Methods

Materials Selection

Ultra-high molecular weight polyethylene (UHMWPE) was purchased from SAHNI Poly Chem India Limited, Ghaziabad, Uttar Pradesh, India. The average molecular weight of the polymer was ranging from $3.5X10^6$ and $7.5x10^6$ g/mole with a specific gravity of 0.925-0.945 and a density of 931 kg/m^3. The E-CR glass fiber was purchased from R.S. Enterprises, India. The binder Araldite HY951, hardener was also obtained from R.S. Enterprises, India. The modified MMT/nanoclay Cloisite 15A, with 1.25 meq /100g of cation exchange capacity (CEC) and 3.15 d- spacing (nm) was purchased from Southern Clay Products Inc. (TX, USA).

Fabrication Method

The composites are made of glass fiber and organoclay embedded with UHMWPE resin. Bisphenol was added with UHMWPE with the ratio of 1:3 and, phenylenediamine hardener was mixed with the ratio of 100: 14.5 by weight. Non-woven glass fabric weighing 2.60g / cc was used as the main component of the laminated compound [34]. Organoclay is dried at 75^{o}C for 8hrs in the oven before use. To reduce the viscosity of UHMWPE, the resin was heated in a glass pan to 75^{o}C. The content of organoclay varying in 0, 1, 3, and 5 wt% is mixed with resin-hardener [35]. The mixing is done at a speed of 3000 rpm cutting rate for 1 hour using an ultrasonicated fast shear mixer. After that, the variable color of the UHMWPE / clay mixture indicates the uniform dispersion of clays. The composite mixtures were removed from the vacuum oven, and then it was stirred to prevent the formation of blisters. Twelve squares of 30 cm of ply laminate are fixed by placing glass cloths in the order of packing [0/90] 3S on a molded metal plate [36]. To keep the fabrics in place, high care was given during laying hands. The molded laminates were coated with blood and peel plies

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inside the Teflon circular pool, treated at 80°C for 2 hours and 150°C for 8 hours, followed by back healing at 160°C for 2 hours in the machine [37]. Adding clay into UHMWPE certainly increases the resin viscosity, which may cause composite laminates to be larger than non-clay. To reduce viscosity and to eliminate stiffness variations, the resin temperature was raised to 75°C between all fabrication steps, including shear mixing, sonication, and gas venting, in addition to prior hand-laying after hardener was added with the hardened resin.

Measurements of Properties

The tensile strength and tensile modulus have been determined as per the ASTM D3039 standard using a UTM. A specimen of 230 mm in length 20 mm in width, and 2.5 mm thick was fitted at a crosshead speed of 2 mm/min. The strain was monitored using an extensometer (gauge length of 25 mm) attached to the specimen during loading. The cyclic fatigue (tension–tension) experiments were carried out as per the ASTM D3479 standard, using a UTM. All the experiments were conducted at the atmospheric conditions on a mode of load controlling, and with load amplitude of sine-wave category. The frequency level of 2 Hz was maintained for the fatigue test throughout the experiments to minimize the heat due to the adiabatic heating and in the specimen and both, the ends of specimens were taped for 40mm with glass fabrics to avoid failure during the experiments. The composite residual properties were determined with fatigue loading for different periods. The high load is maintained at 60% of the UTS of the composite specimens. The residual tensile strength and the residual modulus of the composite specimens were measured. The experimental procedure was repeated for all four specimens. The calculation of volume loss was achieved as per the ASTM G77-83.

Results and Discussion

Evaluation of GF and Nano-clay dispersion in of UHMWPE Matrix

The spectra of Raman's study of hybrid nanocomposite are shown in Figure 1. The spectra of UHMWPE/GF/Nano-clay were observed between 1000 and 2000 cm^{-1}. The characteristic peaks for UHMWPE/GF/3%Nanoclay, the equivalent to D and G bands, are at 1392 cm^{-1} and 1632 cm^{-1}. D band outlined the disordered structures, and the tangential stretching in constituents of the composite leads to the G band structure. The characteristic peaks of UHMWPE/GF/3%Nanoclay represent asymmetric and symmetric stretching modes

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of bonds in the reinforcements. Figure 1 shows the Raman Spectroscopy Evaluation of specimens, the G band in all the composites shows that the G band moved to the level of higher frequency. However, a higher shift in peaks of hybrid composites in the G band was observed for samples of 3% Nano-clays. The up-shift of the G band nearer to the maximum frequencies level can be attributed to the disentanglement of the fiber owing to the uniform dispersion as a consequence the polymer penetrated the GF bundles. The up-shift also characterizes high compressive stresses related to chains of polymer GFs representing the excellent transfer of load in the composites [37]. Distribution and bonding between polymer and GFs increased as nanofillers content increased. The morphology of the surfaces of the fabricated specimens was examined using SEM instruments without GF (Figure 2a) and with GF (Figure 2b).

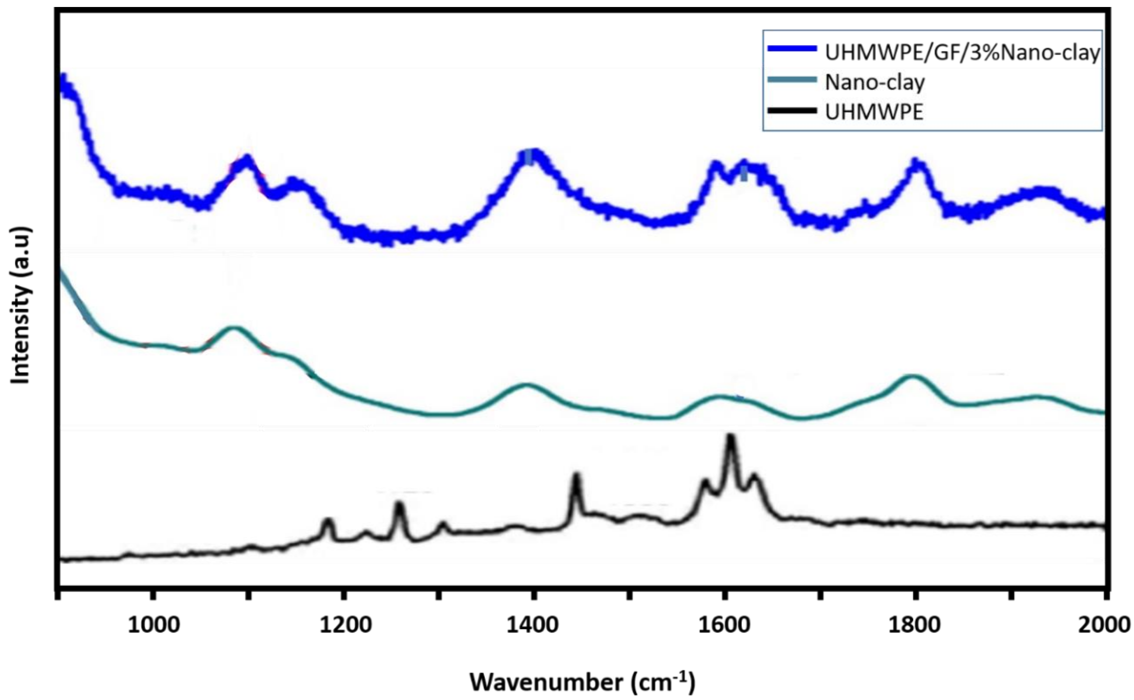

Figure 1. Raman Spectroscopy Evaluation of UHMWPE/GF/3% Nano-clay, Nano-clay and UHMWPE

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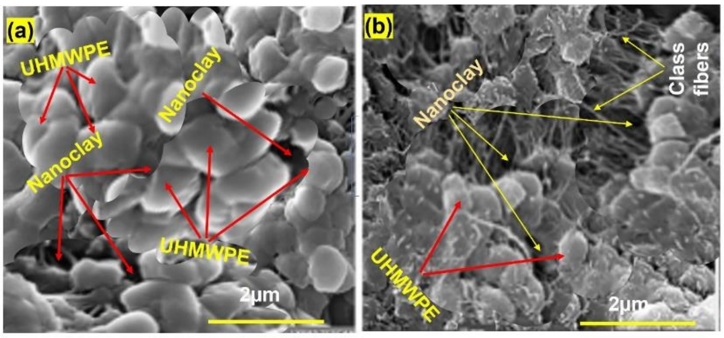

Figure 2. The SEM images of Composite specimens (a) without GFs and (b) with GFs

Static and Cyclic Tensile Properties

Figure 3 reviews the tensile strength and tensile modulus of UHMWPE/GF/x% Nano-clay hybrid composites comprising various % of Nano-clay (x=1, 3 & 5 wt. %). The tensile strength and tensile modulus were increased with an increasing percentage of Nano-clay content up to 3%, The improved tensile value was obtained due to the enhanced bonding at the reinforcements-matrix interface. The durable interfacial adhesion between the reinforcements and the matrix materials was vital for strong reinforcement. The increased surface area and the formation of the oxygen functional groups on the surface of the reinforcement leads to the enhanced bonding strength to either the nano-clay and/or GPs in the matrix., whereas with an increasing percentage of Nano-clay from 3% to 5% content, the strength tends to be reduced comparatively at a high clay content (5%) due to the agglomeration of Nano-clay.

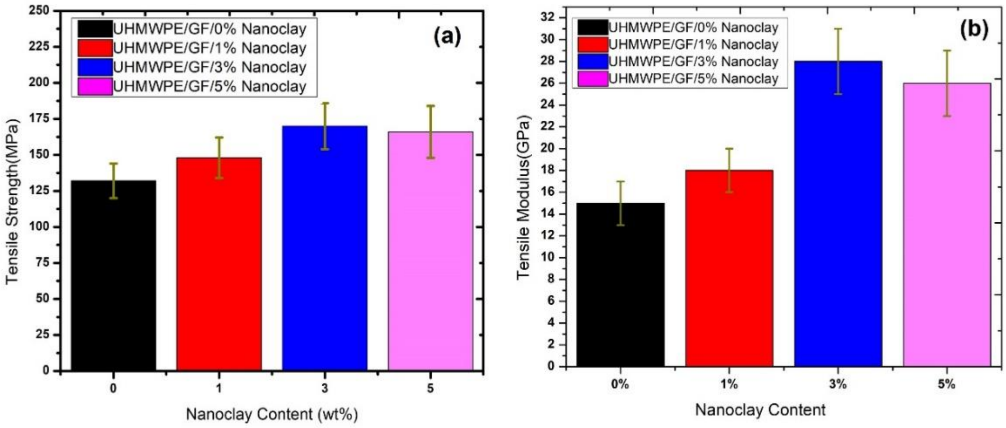

Figure 3. (a) Tensile strength (b) Tensile modulus of UHMWPE/GF/Nano-clay hybrid composites

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Figure 4 exhibits the residual tensile strength and residual tensile modulus of UHMWPE/GF/Nano-clay hybrid composites determined after a given number of cycles. The residual properties composites revealed a steady decline with an increase in the number of fatigue cycles with minor variations between the specimens. The reinforced composites exhibit a developed residual throughout the life of the whole fatigue period

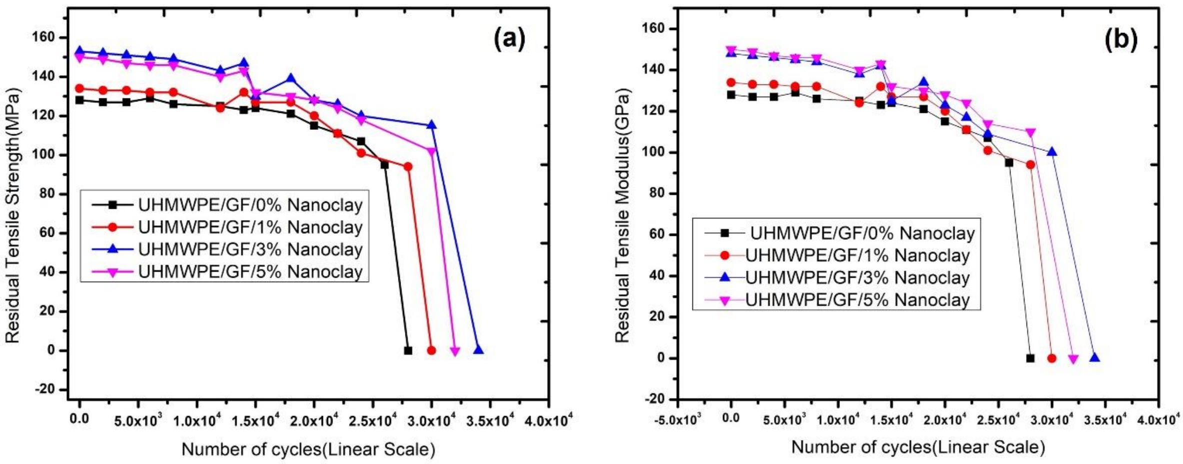

Figure 4. (a) Residual tensile strength and (b) Residual tensile modulus of UHMWPE/GF/Nano-clay hybrid composites.

Fatigue Damage Index

Figure 5 illustrates the damage index (D), graphed between the fatigue cycles and different clay contents (x=0, 1, 3, and 5%). It was observed that at the initial stage (0– 10 k cycles) of fatigue the hybrid composites revealed higher failure than the composites without clay (x = 0%). The fatigue damage index D varies between 0 and 1, and a low value (D = 0.01 to 0.07) means a little reduction in the modulus owing to fatigue. Hence, D is a macroscopical measure of damage due to fatigue owing to the factors of composites cracks, the interface failures between reinforcements and matrix are considered by a macroscopic for the modulus reduction [38]. Later the early damage period, the composite continued a moderately lengthier steady period with fewer indices of damage for the remaining period of fatigue life. The failure in the neat composite (x = 0%) occurs earlier than in the hybrid composites (x = 1, 3 and 5%). The increasing clay content and the increasing fatigue life, except for 5 wt% Nano-clay added hybrid composites due to the possibility of agglomeration of clay particles. The commencement of cracks was happening from the agglomerated region of particles and leads to poor fatigue strength. The early stage is the crack formation stage. The inter-molecular de-bonding has occurred during the initial stage of fatigue attack and leads to the cracks in nanoscale size and it takes a reasonably long time to propagate the damage in the hybrid composites. The other notable strengthening and crack arrest mechanisms presented by Nano-clay lead to fracture toughness. [39, 40]. Due to the heterogeneous nature of the interfacial region, its morphology, mechanics, and chemistry were stimulating the constraining effect of the surrounding reinforcements.

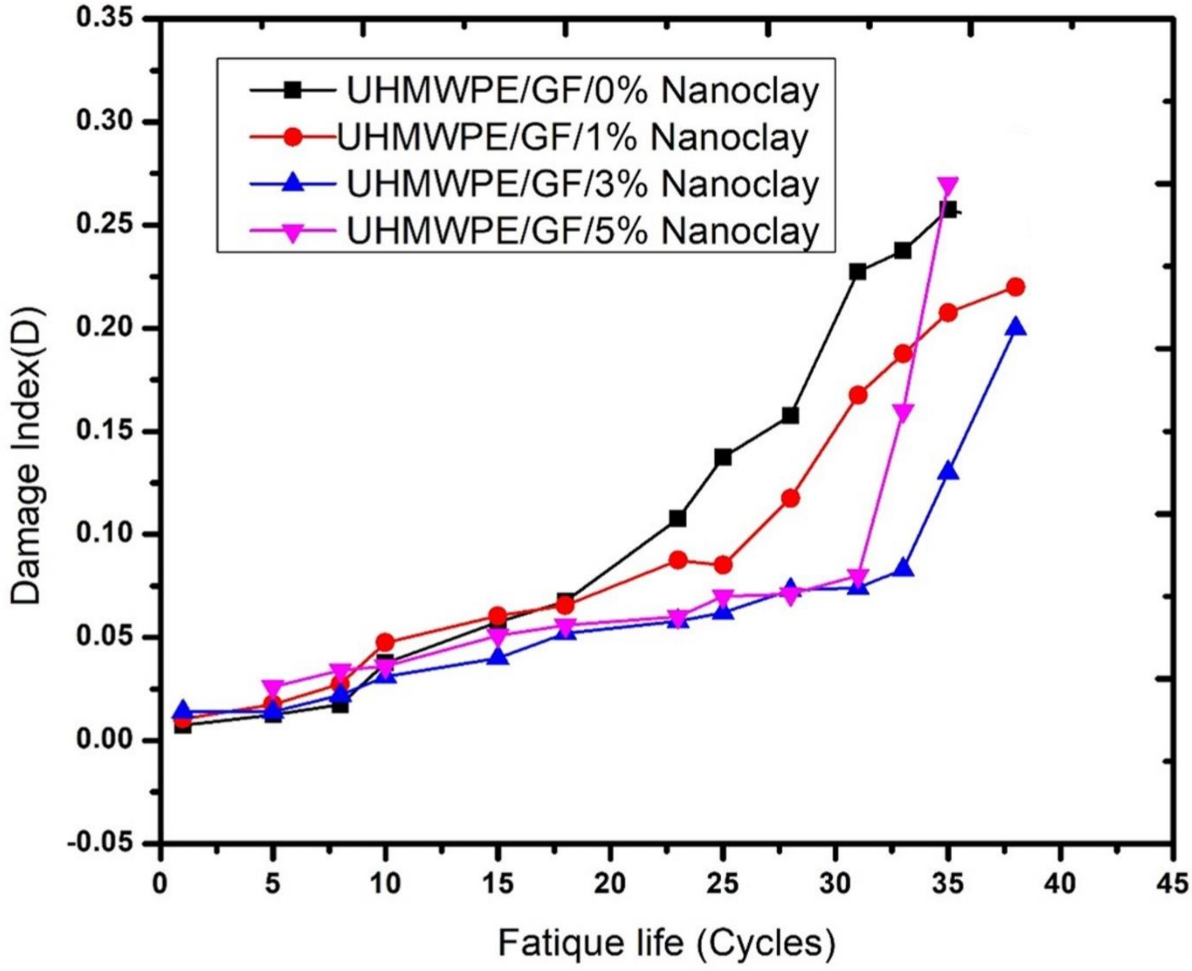

Figure 5. Damage index, D, plotted a function of fatigue cycles for hybrid composites containing different clay contents

Fatigue Damage Growth Analysis

From the Figure 6. it is observed that both materials revealed uniform damage dispersals over the entire gauge length up to failure developed in the future. It is perceived that the hybrid composites exhibit comparatively better damage resistance than the composites without nano-clay (x=0%). The initial stage of fatigue loading at below 10 k cycles. The clay-added GFRP hybrid composites continued more stable up to 30k cycles before final damage than the composites without clay(x=0), confirming significantly developed damage-resistance features. From the result, the fatigue failure in the laminated hybrid composites was brought into the two stages of failure. The initiation and steady growth of damage in stage-I and the rapid damage growth to failure in stage II. It shows that the UHMWPE/GF/Nanoclay composites had a lengthier period in Stage I than the composites without nanoclay (i.e., approximately 0–30 k cycles).

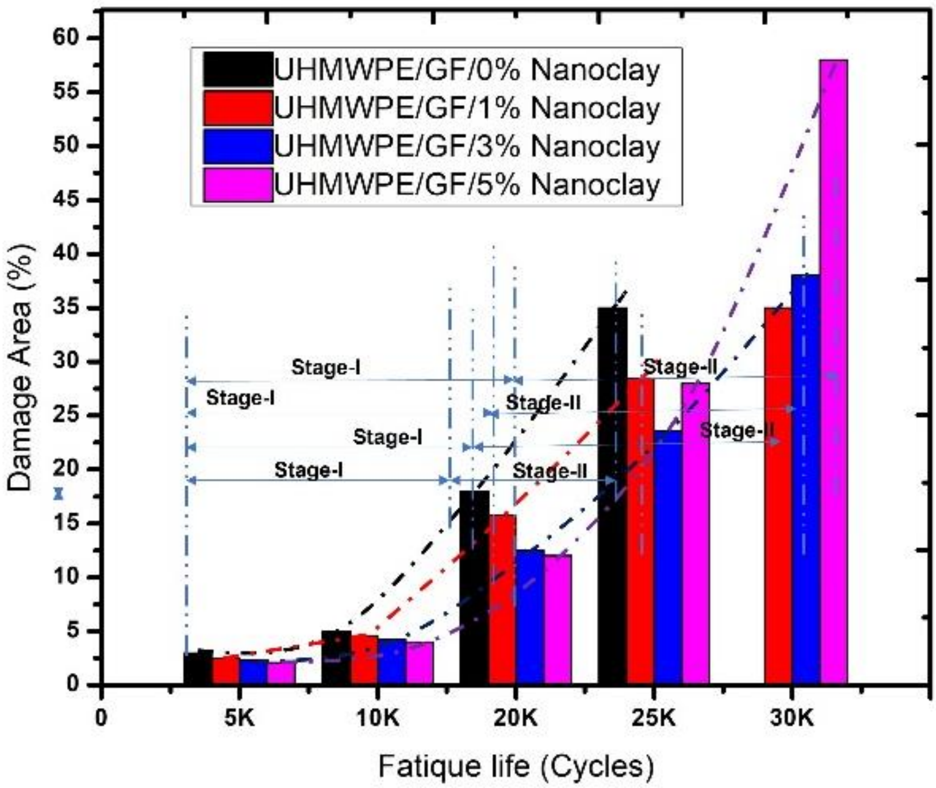

Figure 6. Damaged area divided by total gauge area plotted as a function of fatigue life

Wear Rate of UHMWPE/GF/Nano-clay Composites

The width of the wear track employed at the contact surface of the hybrid composite was utilized to estimate the parameters of wear using a universal measuring microscope. The width of the wear track and wear rate of synthesized hybrid composites at varying sliding speeds (0.25, 0.5, and 1m/s) and applied loads are tabulated in Table 1. The synthesized hybrid composites' wear rate significantly increased for all the hybrid composites. It is observed that the rate of wear of the nanocomposite increases with an increase in normal

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load. The wear resistance of composites decreases with an increase in the percentage of Nano-clay [41, 42]. It can be seen that the percentage of Nano-clay increased from 3 to 5 wt% leading to a considerable reduction in the specific wear rate. The order of wear resistance of hybrid composites was in the order of 5 > 3 > 1 > 0% by weight of Nano-clay. Also, it reveals that the 5 wt.% of Nano-clay filled composite exhibits the high wear resistance for all loads. The transfer film formation on the contact surfaces prevents particle fragmentation of the hybrid composites [43, 44].

Table 1: Synthesized hybrid composites at varying sliding speeds

v/m/s	Load in N	UHMWPE/GF with 0% Nano-clay		UHMWPE/GF with 1% Nano-clay		UHMWPE/GF with 3% Nano-clay		UHMWPE/GF with 5% Nano-clay	
		WTW	SWR	WTW	SWR	WTW	SWR	WTW	SWR
0.25	10	3.10	1.98	3.38	1.77	3.58	1.68	3.67	1.37
	20	3.93	2.68	3.98	2.59	3.99	2.48	2.10	2.27
	30	3.97	3.39	4.19	2.98	4.38	2.84	4.47	2.73
0.5	10	3.69	1.98	3.97	1.58	3.99	1.49	4.01	1.36
	20	4.28	2.91	4.71	2.74	4.78	2.59	4.88	2.36
	30	4.63	3.82	4.98	2.98	4.99	2.67	5.03	2.46
1	10	3.99	1.99	3.99	1.98	5.17	1.92	5.26	1.73
	20	4.81	2.98	4.98	2.82	5.38	2.69	5.47	2.53
	30	4.92	3.97	5.18	2.98	5.84	2.80	5.93	2.56

WTW – Wear Track Width in mm

SWR – Specific Wear Rate in (g/N^{-m}) $X10^{-7}$

Coefficient of friction of UHMWPE/GF/Nano-clay Composites

Figure 7 shows the graph of the Coefficient of friction (COF) for the applied load of 10N, 20N, and 30N for various percentages of Nano-clay filled UHMWPE/GF/x% Nano-clay (x = 1, 3, and 5%) composites at a sliding distance of 1000 m. Due to the variations in the contact area and the polymer shear strength, the coefficient of friction (COF) reaches steady-state (24). Owing to the addition of Nano-clay in the hybrid composites, it exhibits a significant reduction in the COF as the clay content increases. The COF increase as the load increases (from 10N to 30N) for the sliding distance of 1000m for all nanocomposites. The All-hybrid composite reveals a comparable trend. Due to the cooling of the polymer, during

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cooling in the mold, the formation of hard skin over the surface. The area of contact and the transfer film formation influence the COF. The composites UHMWPE/GF/5%Nanoclay reveal lower COF, which lies between 0.23–0.25 for the load of 10N to 30N. The uniform dispersion of the Nano-clay on the surface of the composites and the transfer film formation act as an agent of self-lubrication. The result shows that the COF depends on the load and % of reinforcements. The attribution of this kind of behavior is owing to the strengthening mechanism due to the interfacial reaction between the matrix and reinforcements and the high specific surface area of the Nano-clay [45, 46].

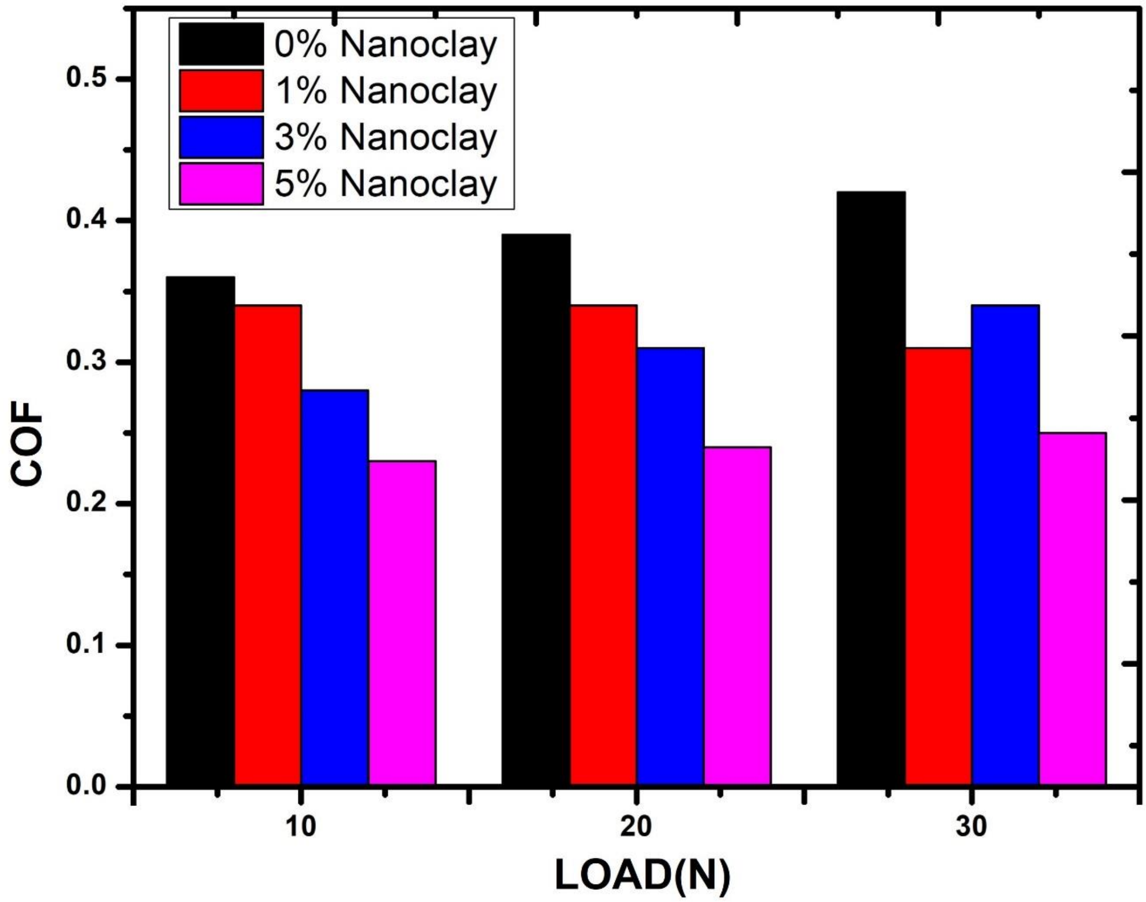

Figure 7. Coefficient of Friction of UHMWPE/GF/X% Nano-clay (X=1%, 3% and 5%)

Worn-out Surface Morphology

SEM images of worn-out surfaces of 1, 3 and 5 wt% nanoclay reinforced composites are shown in Figure 8(a–c), respectively. When the glass fibers are in contact with nanoclay and the UHMWPE matrix, they offer higher abrasion wear resistance. The images of UHMWPE/GF/1%Nanoclay composite showed a greater number of fractured fibers than

UHMWPE/GF/5%Nanoclay composite. It was observed that the fibers are fractured and fiber pull-out was noticed in the low wt% nanoclay reinforced composites. The SEM images of higher wt% nanoclay show that there is no either fiber pull-out or matrix pull-out. It shows that there is admired interaction between the reinforcements and matrix materials.

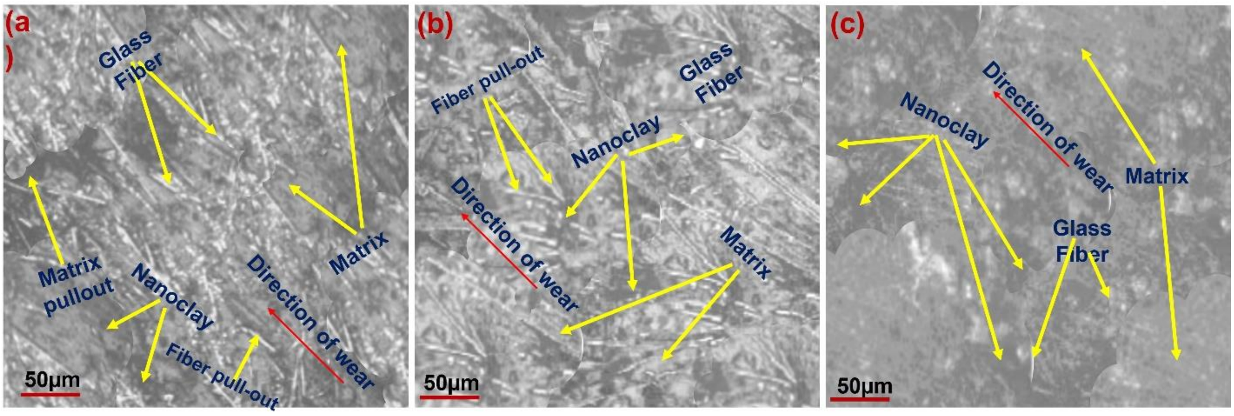

Figure 8. SEM images of fractured surface of (a) UHMWPE/GF/1%Nanoclay (b) UHMWPE/GF/3%Nanoclay (c) UHMWPE/GF/5%Nanoclay

Conclusion

An investigation has been made on tensile strength, cyclic fatigue behavior, residual properties, and wear behavior of UHMWPE/GF/x% Nano-clay (x=1%, 3%, and 5%) composites. The static, residual tensile strength, and static, residual modulus of UHMWPE/GF/Nano-clay composites were significantly improved by the addition of Nano-clay. The presence of Nano-clay in the polymer matrix increased the tensile strength and tensile modulus than the 0%Nanoclay composite. The fatigue life was comparatively increased with the addition of Nano-clay to the GFRP composite and the high performance was achieved. The addition of Nano-clay suppressed the damage growth due to fatigue loading of GFRP composites in terms of damage area over the whole fatigue life except the very early stage of loading. The fractured surface SEM images show that the stronger bonding between the Nano clay and matrix materials prevents the pull-out of materials and offers higher resistance to material wear.

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No conflict of interest.

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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