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Review Article

Wear performance and mechanical properties of MWCNT/HDPE nanocomposites for gearing applications

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ABSTRACT

MWCNT/HDPE nanocomposite spur gears prepared in concentrations of 0, 0.5, 1, 1.5, 2, and 2.5% by weight using centrifugal ball milling dispersion method followed by CNC milling. SEM examination revealed a sound dispersion of the MWCNT in the HDPE matrix until 2 wt.%. Nanocomposites exhibited higher decomposition temperature and thermal stability than neat HDPE. Yield strength increased linearly in nanocomposites up to 2 wt.%, and then it saturated. Nanofillers' addition steadily increased the young's modulus up to a weight fraction of 1.5 %, surging rapidly between 1.5 to 2 wt.%. In contrast, its rate of increase declined between 2 and 2.5 wt.%. The Taber abrasion test showed a reduction in wear loss of nanocomposites. The nanocomposites' toughness increased between 0 (neat HDPE) and 1.5 wt.% of MWCNT but declined at higher concentrations due to transition from ductile to brittle nature. At a torque of 5 N-m, the wear performance increased consistently with the increase in the concentration of nanofillers. At 10 N-m, 2.5 wt.% nanocomposite gears displayed a decline due to the increased brittleness. Satisfactory dispersion and developed interphase fervently contributed to the load transfer and mechanical properties. Nanofillers improved the wear resistance, hardness, and lowered plastic deformation. The gear damage mechanism changed from thermal bending to tooth cracking and deflection in the nanocomposite gears. The 2 wt.% MWCNT/HDPE nanocomposites emerged as potential gearing materials with enhanced hardness, tensile properties, uniform dispersion, thermal stability, wear performance, and reasonable toughness.

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Bahaa Mostafa Kamel a researcher at the Department of Mechanical Engineering, National Research Center, who is keen in carrying out research work and increasing his capabilities and skills as an engineer and Reliable scientist, who's trustworthy and meticulous Able to work on his own initiative or as a part of a team and can deal competently with administrative duties. I have finished my research work leading to the M.Sc. degree at the Faculty of Engineering, Cairo University. The subject of the thesis is 'modeling and simulation of tanks fabricated from composite materials'. I had my Ph.D. Degree from Cairo university faculty of engineering my Ph.D was in the field of enhanced lubricants by adding nanoparticles.Now my current work is related to improve the properties of metals, polymers and others by additives nanoparticles.

1. Introduction

Polymers and their composites are developed to replace metallic materials because of their lightweight, corrosion resistance, and economic fabrication. Several studies attempted to reinforce polymeric matrix with different size and orientations of inorganic and organic reinforcements [1,2]. Polymer-based nanocomposites dispersed with nano-sized fillers increasingly expanded as a thrilling new class of materials for their noticeable improved properties over neat polymers. The nanocomposites' significant characteristics depend mainly on nanofillers' dispersion in the matrix due to their affinity to agglomerate; therefore, uniformly distributed nanofiller/polymer composites pose the main challenge in research space.

Gear is a functional machine part generally used for transferring power and motion under various speeds and loads [3,4]. Major gearing components of office machines, food, and textile equipment employ polymers such as polycarbonates, nylon66, acetal, and nylon, owing to their low friction, less weight, noiseless engagement, and low cost. The gears' design made from the polymeric composites are expected to pursue Polypenco, British, and Engineering Science Data Unit (ESDU) standards [5,6]. Previous research used organic reinforcement as nanofillers and showed colossal enhancement in mechanical properties [7–9]. The strong adhesion with the polymer and the high ratio of area/volume of particles deliberated the power center and contributed to nanomaterials' superior property [10]. The presence of carbon nanotubes (CNT), graphene oxide (GO), NC (nitrogen-doped graphitic carbon) improved almost all mechanical properties of the polymer due to their excellent tensile strength, stiffness, electrical, and thermal properties [11–15]. In particular, the uniform dispersion of CNT resulted in noteworthy enhancements of the mechanical properties such as the tensile strength and young's modulus of the polymeric matrices [16,17]. The appropriate CNT properties attract researchers to explore their application in reinforcing the polymeric gears [18]. Singh et al. [19] investigated the thermal and wear behavior of high-density polythene (HDPE), polyoxymethylene (POM), and acrylonitrile butadiene styrene (ABS) for applications in making polymeric gears, employing injection molding process. ABS gears exhibited the closest agreement with the Mao model, succeeded by HDPE and POM. The failure studies at 900 rpm and 1.4 N-m torque revealed ABS gears failure ascribed to extravagant tooth wear, failure of HDPE gears ascribed to root cracking. The study recommended reinforcing the polymeric materials with a suitable reinforcement for gearing applications. Yousef et al. [11,20] developed a new CNT dispersion method using paraffin oil as a promoter material during the injection process to address the problems such as incomplete melting of pellets and the formation of blebs.

Furthermore, studies on CNT/acetal gears showed enhancement in the wear resistance due to CNT reinforcement. Afifi et al. [21] proposed a novel approach by using multilayer graphene nanoplatelets (MLNGPs) as a reinforcement in polyamide 6 (PA6) based spur gear. The results showed better wear and thermal behavior of spur gears. Sahu et al. [22] reported enhancement in the wear resistance of multidimensional carbon nanotubes MWCNT/HDPE nanocomposites. Most of the results said that the uniform distribution of MWCNT inside the polymeric matrix dramatically improves the mechanical and tribological characteristics [23–27].

Based on state-of-the-art, the present study's research design includes developing multiwalled carbon nanotubes (MWCNT)/HDPE nanocomposites in a nominal concentration of 0.5, 1, 1.5, 2, and 2.5% by weight. The study employs a ball milling dispersion method for effective and uniform distribution of MWCNT inside the HDPE matrix, followed by an injection molding process. The influence on tensile strength, elastic modulus, thermal stability, and wear characteristics was examined. Most of the published research reported the improvement in a few properties of the polymer nanocomposites. The present study includes developing MWCNT/HDPE nanocomposites in different concentrations and forming spur gears for actual performance evaluation of the nanocomposites. The scope of the study consists of a comprehensive assessment of the properties of MWCNT/HDPE nanocomposites. The research also includes microstructure characterization, thermal stability, hardness, tensile properties, weight loss in abrasion, impact strength, and wear performance of the nanocomposites in actual conditions on a gear test rig, and examination of the morphology of the damaged gears.

2. Experimental procedures

2.1. Materials

High-density polyethylene (HDPE) SHD7255LS-L was supplied in pellets from Braskem Netherlands BV suitable for the injection molding with good tenacity and impact properties combined with good stiffness. Table 1 gives the properties and grade of HDPE polymer, obtained from the supplier. The functionalized MWCNTs produced using chemical vapor deposition Technique (CVD) were supplied by Cheap-Tubes Inc., operated as nanofillers in the HDPE matrix. The non-functionalized CNTs are considered as a single graphite sheet with stacks of numerous single-walled carbon nanotubes, one

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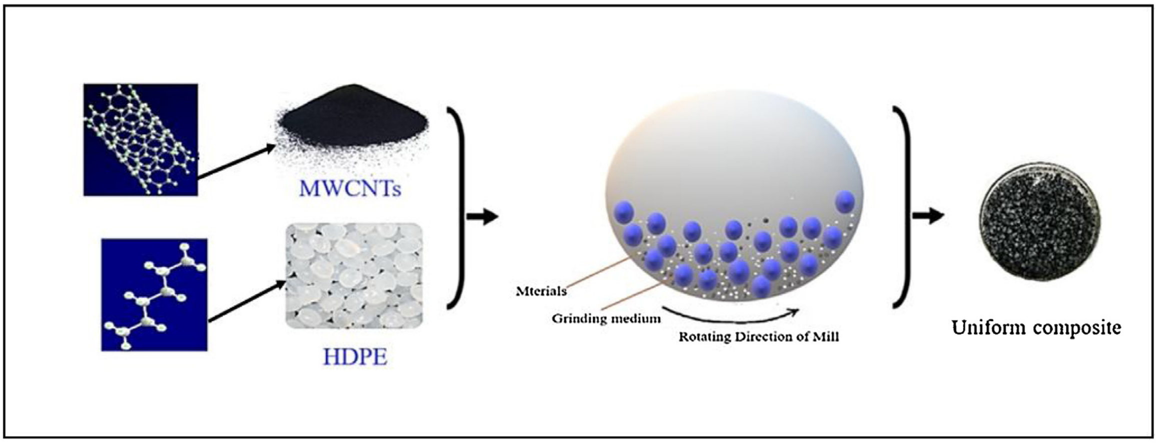

Fig. 1 – Schematic diagram of the powder preparation using ball milling.

Table 1 – The properties and grade of HDPE obtained from the supplier Braskem Netherlands BV.

Property	ASTM Methods	Units	Values
Yield Strength	D 638	MPa	26.7
Flexural modulus – 1% Secant	D 790	MPa	1270
Hardness (Shore D)	D 2240		63
Impact Strength (Izod)	D 256	J/m	45
Melt Flow Index Resistance to environmental stress cracking.	D 1693	g/10 minh/F50	30 < 5

in the other. Such CNTs exhibit inferior interfacial collaboration with the matrix, limiting their reinforcement potential.

Furthermore, the commercially available non-functionalized single-walled CNTs are in the form of entwined bundles of high aspect ratio and small diameters CNTs, making their uniform dispersion in the matrix difficult [28]. The functionalization of the CNTs may resolve such an issue by modifying their surface properties. The common functionalization includes covalent or chemical sidewall functionalization and non-covalent or physical functionalization.

2.2. *Polymer nanocomposite preparation*

HDPE pellets were dehydrated at 80 °C for 4 h before mixing to get rid of moisture picked up during transport and storage. Centrifugal ball mill (model S 100) having five ceramic balls of diameter 10 mm each, in a steel jar of capacity 50 cm^3, was used for MWCNT/HDPE powder preparation as shown in Fig. 1. The milling speed and time maintained at 600 rpm and 45 min, respectively, as recommended in previous studies to obtain a uniform distribution of MWCNT in the polymer matrix [29,30]. The water circulation through a jacket surrounding the jar dissipated heat generated during milling. Five compositions of MWCNTs/HDPE, namely, 0.5, 1, 1.5, 2, and 2.5 wt.%, were developed. Neat HDPE is referred to as 0 wt. % nanocomposite.

Neat HDPE and MWCNTs/HDPE granules were supplied through a hopper into a co-rotating intermeshing twin-screw extruder with mixing chamber temperature maintained $\sim$170 °C. A twin-screw extruder machine is much eminent than a single screw extruder (Brabender) for the following reasons. First, twin screw extruder has exceptional blending strength due to the intermeshing screws and the broad distinction of specialized screw designs that let the amplitude of mixing to precisely regulate leading to organize the degree of mixing. Second, the mixing capacity of single-screw extruders is minimal, having flow fetters to reinforce mixing through individual screw designs. Third, the twin-screw extruder is characterized by the flexibility to handle many operations in addition to its ability to handle multiple processes simultaneously, such as melting, mixing, cooking, venting, cooling, etc. But in the case of a single screw extruder, the throughput and screw speeds are contingent with restriction of screw designs. Fourth, twin-screw extruder can be used in mass production compared to the Bra bender. In contrast, the plasticizing ability of twin-screw extruder is faster and preferable. In a single screw extruder, the granular materials remain in the extruder for a more extended period, which leads to delay in the production time. Fifth, the operation is quite complex in a twin-screw extruder, which requires the highest efficiency control procedures than that of a single screw extruder, which is characterized by relatively simple operating procedures.

Controlling and optimizing Polymer nanocomposite's melt temperature inside the extruder is a stringent property to minimize the output resin degradation. Cylinder zone 1 is usually water-cooled with no obtainable heating; this ensures steady polymer flow, preventing early melting or polymer imputation to the feed hopper. Cylinder temperature in zone 2 (feed zone) was set at 170 °C. In this section, HDPE is compressed and preheated as it proceeds forward to zone 3. In zone 3 (transition zone), temperatures are elevated progressively to the desired melt temperature (maintained at 190 °C for HDPE as well as the nanocomposites). The polymer was totally melted in zone 4 (metering zone) at 204 °C, then transferred to the final zone (die zone). A temperature of 204 °C was found suitable for good flow in the die. The melt temperature was maintained constant during venting to preserve the volatility of gases being removed. The melted granules were pushed along the heater section by a screw thread having a provision for air escape to

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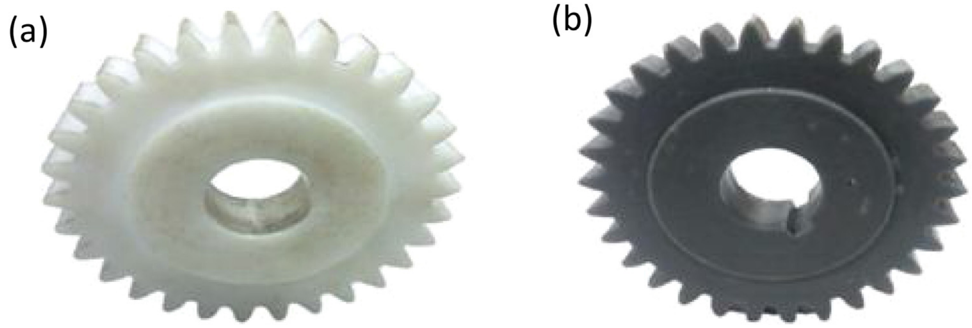

Fig. 2 – Spur gear (a) neat HDPE and (b) MWCNT/HDPE nanocomposite.

Table 2 – Specifications of the spur gear.

Parameter	Values
Pressure angle	20°
Teeth	30
Face-width	17 mm
Module	3
Center distance	91.5 mm

remove the air in the granules/chamber to preventing bubble formation [31].

High-density PE was molded in standard twin-screw injection molding equipment. Best results were obtained when HDPE was molded at temperatures ranging from 190 to 221 °C. Too high temperatures could cause problems with excessive flashing and burning and promoting shrink phenomena such as sink marks, warpage, shrinkage, and void formation. Therefore, the HDPE was melted at a temperature of 204 °C.

The proper injection pressure depends mainly on part size and configuration. The running pressure was maintained at 55 MPa and refilling pressure at 85 MPa. The 1st stage pressure should be high enough to fill ~99% of the die and avoid shrinkage, voids, sinks, and short shots. Too much pressure can cause parts to flash, burn, and stick in the mold or warp.

Both the injection pressure and temperature were optimized for HDPE for the ambient conditions in the laboratory (21−23 °C) in the pilot studies before preparing the nanocomposites. The same process configuration was fixed to produce neat HDPE.

HDPE nanocomposite was injected into a die with a flange shape cavity with a thickness of 30 mm and a diameter of 150 mm. Due to shrinkage, the final specimen dimensions were maintained at ~144 mm diameter and ~29 mm thickness. Table 2 gives the specifications of the spur gear produced by computer numerical control (CNC) milling machine, and Fig. 2 shows the pictures of neat HDPE and MWCNT/HDPE nanocomposite gears, respectively.

2.3. Microstructure and thermal properties

Morphology and dispersion studies on the nanocomposite samples were carried out on ultra-high-resolution low vacuum SEM (FEI Nova NanoSEM, Weimar, Germany). The fractured specimen's surface morphology was examined to expose the role of MWCNTs' progression of fatigue damage mechanisms. Two different acceleration voltages, 2 kV and 20 kV employed while viewing the samples. The samples were attached to the sample holder with a conductive adhesive pad. Mapping function, line scan, and spot function trait were used.

Thermogravimetric analyses (TGA) of nanocomposite samples were carried out using simultaneous thermal analysis apparatus STD Q600. The analysis of carbon-based materials performed using a combined simultaneous measurement of mass change (TGA). Analysis of the nanocomposite samples was carried out under purged gas (N_2) flow horizontally through the furnace directly over the sample and reference crucibles over a temperature range of 22–700 °C at 10 °C /min.

2.4. Hardness, abrasion resistance and elastic properties

Rockwell hardness tester (Zwick/Roell device) was used to determine Rockwell's hardness. The results were reported with the M scale using a 6.35 mm indenting ball at a major load of 100 kg, according to ASTM D785. The mean of five readings was reported as hardness.

Dry tribological tests were carried out to estimate HDPE and MWCNTs/HDPE composites' preliminary wear behavior on a Taber abrasion tester Model 1700 (115/230 V; 60/50 Hz). The sample thickness was 6.35 mm. Two Taber abrasive wheels were brought in contact with the specimen surface at a contact load of 1000 g. The specimen turntable speed was maintained at 60 rpm. The weight loss technique determined the abrasion wear after 5000 cycles.

The tensile test was executed by a universal testing machine (TIRA test 28100) with a temperature chamber, as shown in Fig. 3. An automatic hollow die punch was used to cut the samples from the compression-molded sheets according to ASTM D638 type-I standard. To ensure the results' reliability, five specimens of each composition were tested under the same conditions, and the mean values and standard deviations were estimated, which did not yield remarkable differences.

The Charpy impact test is employed to determine the toughness of the material. A 2 mm V-notch with a 45° angle was made in the specimen of size 55 × 10 × 10 mm [32]. The pendulum weight of 2.036 kg and an arm's length of 39.48 cm struck on the opposite side of the notch [33]. The energy absorbed before fracture was recorded as the toughness.

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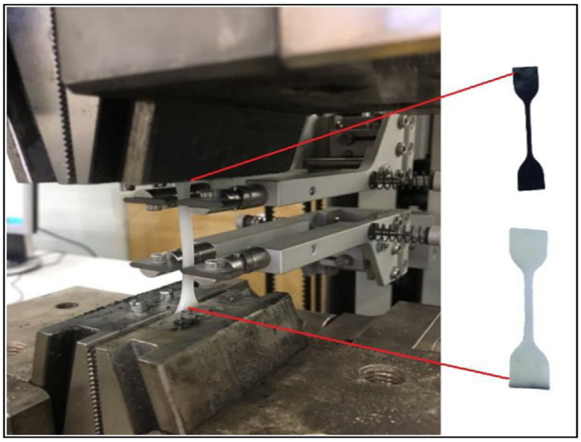

Fig. 3 – **Universal testing machine used to test tensile properties of HDPE and nanocomposites.**

2.5. *Gear wear*

A universal gear test rig was used to continuously measure gear surface wear under fixed load, speed, and the twisting moment [34]. The back-to-back theory was applied, which is widely used for testing wear in metallic gears [35]. Fig. 4 gives a schematic presentation of the universal gear test rig. A twisting moment of 5 and 10 N-m was applied on the gear pair by selecting speed and load combinations. The test rig included three units for different gear category tests (spur, worm, helical). The spur gear unit was used in this study. The test was conducted in the following array. (a) Assembly of the parts. (b) Running-in for 5 min without load. (c) Initial measurement of the mass of the specimen spur gears. (d) Adjustment of the spring and mass system to apply the load. (e) Final measurement of mass after running the test rig for the desired cycles. (f) Weight loss and cycle curves were schemed to exhibit wear versus cycles.

3. Results and discussions

3.1. *Morphological examination*

Conventional twin-screw extruder and hot pressing were employed to fabricate the MWCNT/HDPE samples after feeding the MWCNT/HDPE granules obtained by a ball milling machine. The fractured surfaces of the tensile specimen at different MWCNT concentrations were examined under a scanning electron microscope (SEM), the morphology of the different concentrations is shown for each compound. Fig. 5(a) exhibited a wide ratio of 2 wt.% MWCNT uniformly disseminated inside the HDPE matrix. Accordingly, the surface grew MWCNTs guarding the polymer against impending transverse cracks; that is lucrative to improve MWCNT/HDPE nanocomposites' overall properties. In Fig. 5(b), the red circles show HDPE with 1.5 wt.% MWCNT aggregates, ropes on surfaces, or ”tethersinside the HDPE matrix. Functionalized MWCNT bundles, ropes, and agglomerates after the fracture can be compared to Fig. 5(a). Fig. 5(c) shows vulnerable dispersion at 2.5 wt.% MWCNT congestion and aggregation, which may influence the impact strength and wear performance of HDPE 2.5 wt.% nanocomposites. The higher amount of MWCNT made by the selected dispersion method demonstrates a reverse impact. Idealistic dispersion demands excess time during different mixing. From Fig. 5(d), the softened debris is marked in 2.5 wt.% nanocomposite, which is not seen in 2 wt.% nanocomposite. As nanofillers' amount increased from 2 to 2.5 wt.%, due to the aggregation of nanofillers and their uneven dispersion, it led to the deterioration and softening of the nanocomposite. The nanocomposite at these locations yielded and soft debris consisting of the nanofillers aggregates and the detached HDPE chunks was observed. Inferred from the micrographs, transverse cracks proliferated perpendicular to all polymer directions, roving from one to another and eventually instituting a nearly flat fracture surface and the distribution of MWCNT well wetted by the polymer matrix. However, there are some regions with aggregates of the MWCNT, while some are devoid of it.

In the absence of proper chemical bonding amid the MWCNT and the HDPE matrix, Vander Waals nexus is the only mode responsible for molecular unity within the nanocomposite matrix. Therefore, the mechanical properties of nanocomposites can significantly improve [36]. Functionalized MWCNTs are covalently bonded to obtain polymer nanocomposites. Fig. 6 shows three-dimensional representation of functionalized MWCNT inside HDPE. It was observed in Fig. 6 (1) that carboxylic acid (COOH)-MWCNT has dominated all over the matrix. In contrast, polymer molecules have saturated with the carbon nanotubes and stimulate them to form bonds among themselves and with the polymer molecules. Fig. 6 (2)–(4) demonstrated the efficient distribution of MWCNT. The distribution is relatively uniform in Fig. 6 (4),

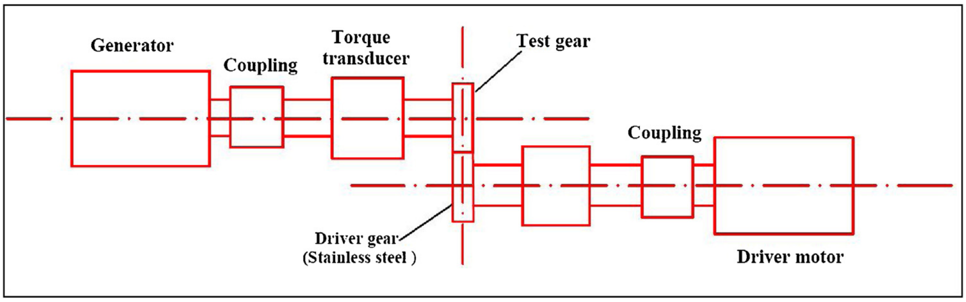

Fig. 4 – **A schematic universal gear test rig.**

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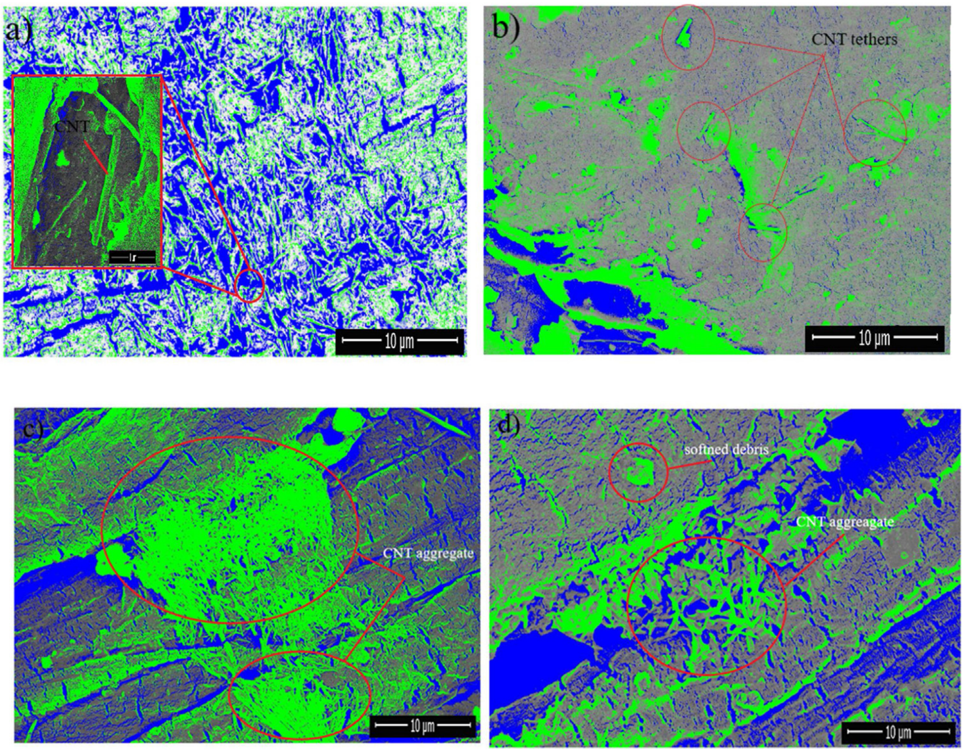

Fig. 5 – SEM micrographs of the fracture surfaces of MWCNT/HDPE nanocomposites (a) 2 wt.%, (b) 1.5 wt.%, and (c, d) 2.5 wt.% MWCNT encasement aggregates inside the polymer.

containing 2 wt.% MWCNT but segregation may be observed in Fig. 4 (5) having 2.5 wt.% MWCNT. The effect of concentration and distribution of MWCNT in the nanocomposites is expected to impact the properties. Its impact on the mechanical, thermal, and wear properties shall be discussed in the subsequent sections. This is contingent since only Van der Waals forces exist amid the innumerable concentric MWCNT tubes and the polymer. In contrast, the outer tube is bonded covalently to the matrix. The type of MWCNT, treatment techniques, and similarity between MWCNT and steward polymer obsessively improve matrix property [37].

3.2. *Thermal stability*

Crystallization and melting properties of neat HDPE and MWCNT/HDPE nanocomposites are of considerable interest to the researchers because crystal structures and crystallinity of polymers play a significant role in determining the mechanical properties. Fig. 7 (a) gives the TGA thermograms of neat HDPE and MWCNT/HDPE nanocomposites. The decomposition temperature of neat HDPE is lower than the composition of HDPE/MWCNT, demonstrating enhancement of nanocomposites' thermal stability ascribed to the addition of MWNTs. By increasing the amount of MWNTs, the residual weight of MWCNT/HDPE nanocomposites increased steadily. The decomposition of the neat HDPE and the MWCNT/HDPE nanocomposites started at around 400 °C and continued up to nearly 500 °C. The weight loss of neat HDPE at 782 °C is about 85%.

In contrast, in MWCNT/HDPE nanocomposites, the weight loss is between 52–60%. Hence the retention of 25%–33% is achieved, indicating improved thermal stability and resistance to thermal degradation in the nanocomposites. The temperature at which degradation started in the materials is plotted against the composition in Fig. 7 (b). One may observe that the decomposition was initiated in neat HDPE at around 310 °C while in 2.5 wt. % MWCNT/HDPE nanocomposites, it began at around 370 °C (an increment of about 19%). Hence, it is conclusively evident that the addition of MWCNTs to HDPE has significantly improved the thermal stability.

3.3. *Tensile and impact test results*

The continuity of force transfer between the boundary of nanofillers and the polymer matrix can be measured by tensile strength and young's modulus [21]. Fig. 8(a) shows the effect of MWCNT concentration on the yield strength.. The yield strength increased almost linearly as the nanofillers are introduced in HDPE up to a concentration of 2 wt.%, confirming that the nanofillers enhance the tensile properties of polymers [4]. Due to the uniform dispersion of the MWCNT in the HDPE matrix, the yield strength improvement of about 12% is recorded at MWCNT concentration of 2 wt.% compared with neat HDPE, even though this is a small amount. There is a minor saturation in the rate of increase of yield strength between the MWCNT concentrations of 2 and 2.5 wt. % ascribed to the aggregation of the MWCNT, as observed in

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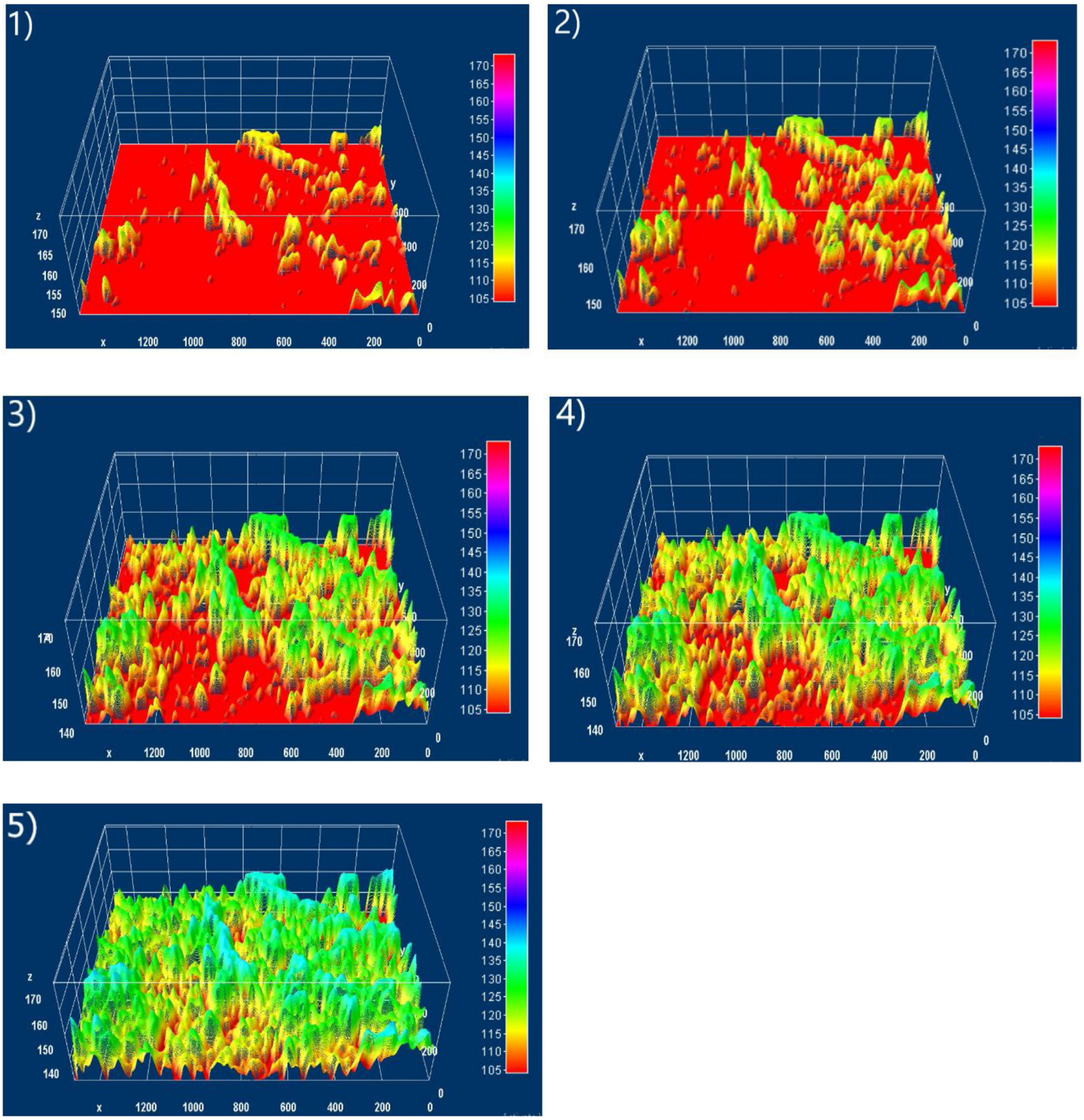

Fig. 6 – Three-dimensional representations of COOH-MWCNT inside HDPE at different concentrations. (1) 0.5 wt. % (2) 1.0 wt.% (3) 1.5 wt.% (4) 2.0 wt.% and, (5) 2.5 wt.%.

the SEM micrographs in Fig. 5(c). Fig. 8(b) presents young's modulus of neat HDPE and MWCNT/HDPE nanocomposites at different concentrations. The addition of nanofillers steadily increased young's modulus up to a weight fraction of 1.5%. The improvement from neat HDPE to 2.5 wt.% nanocomposites is 6%, 15%, 24%, 49%, 59% respectively. The young's modulus increases rapidly between 1.5 to 2 wt.% ascribed to the uniform dispersion of MWCNT in the matrix. Its rate of increase declines between 2 to 2.5 wt.% due to the aggregation of the MWCNT, which limited the benefit of nanofillers. The augmentation in all compositions compared to neat HDPE indicates enhanced stiffness and the tensile properties. Several published studies reported a ductile transition to more brittle behavior due to the increase in MWCNTs content [38,39]. Lastly, the incorporation of MWCNTs has a positive effect on the tensile properties of HDPE.

A typical tensile stress-strain plot of neat HDPE and MWCNT/HDPE nanocomposites is given in Fig. 9. Zero wt.% curve represents neat HDPE. As the amount of MWCNT increases, the ultimate tensile strength is increased, in congruity with young's modulus and yield strength, presented in Fig. 8. The neat HDPE replicates a characteristic thermoplastic material. It is noteworthy that as the nanofillers are introduced, both, the strength and ductility are enhanced; however, there is no marked improvement in the strength between 2.0 wt.% and 2.5 wt.% nanocomposites due to the aggregation of nanofillers. But one may observe a plastic deformation between 2.0 wt.% and 2.5 wt.% MWCNT as the inappropriate bonding with the matrix and weaker intermolecular interaction of the polyethylene chains [40] dominates. Even though the strain is higher at the point of fracture in 2.5 wt.%

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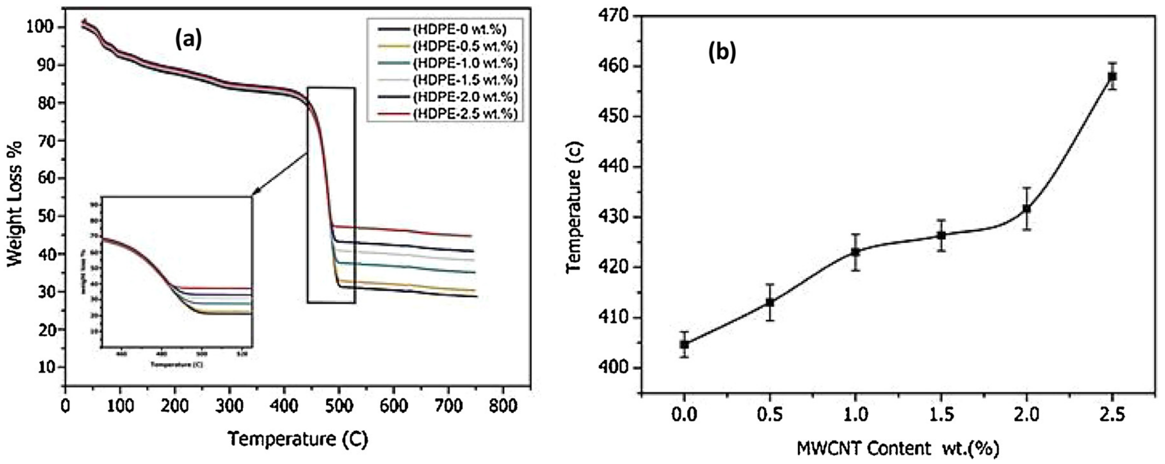

Fig. 7 – HDPE and MWCNT/HDPE nanocomposites in different compositions; (a) TGA curves, (b) Decomposition temperature.

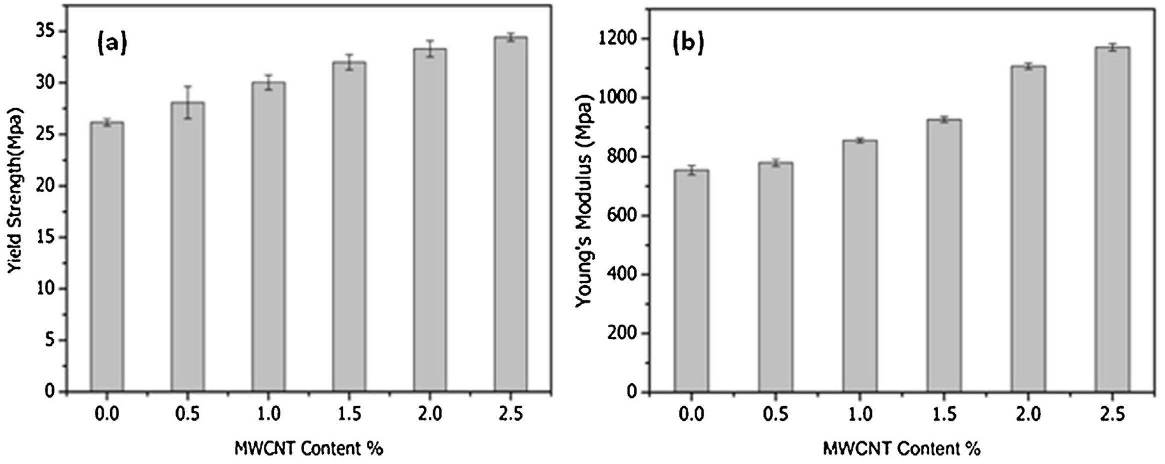

Fig. 8 – Elastic properties of neat HDPE and MWCNT/HDPE nanocomposites in different compositions; (a) Yield strength. (b) Young's modulus.

Table 3 – Mechanical properties of different compositions of MWCNT/HDPE nanocomposites.

Composition	Rockwell hardness	Taber abrasion weight loss (mg)	Impact strength (KJ/m^2)
Neat HDPE	43.3 ± 0.5	63.324 ± 0.4	17.86 ± 0.9
MWCNTs/HDPE Nanocomposites			
0.5 wt.%	61.8 ± 0.5	60.554 ± 0.5	25.28 ± 0.8
1.0 wt.%	63.43 ± 1.1	59.818 ± 0.4	27.5 ± 1
1.5 wt.%	62.13 ± 0.9	57.578 ± 0.3	30.9 ± 0.7
2 wt.%	65.22 ± 0.8	54.69 ± 0.5	22.4 ± 1
2.5 wt.%	68.08 ± 0.9	52.562 ± 0.4	13.68 ± 1.1

nanocomposites, it would be erroneous to interpret this behavior as improved ductility.

3.4. *Hardness, abrasion rate, and toughness results*

Table 3 gives the experimental results of the hardness, Taber abrasion test, and impact strength of neat HDPE and MWCNTs/HDPE nanocomposites. Increasing the percentage of MWCNTs leads to improved hardness, giving the peak value at a concentration of 2.5 wt.% MWCNTs, where the enhancement is up to 57%. This behavior may be attributed to the strengthening effect of MWCNTs [21,41,42]. The previous studies also reported an increase in the micro-hardness of HDPE based nanocomposites [43–45]. The Taber abrasion test of neat HDPE and its nanocomposites with different concentrations of MWCNTs shows that the wear loss of MWCNTS/HDPE reduced substantially with the increase of the concentration of MWCNTs. This reduction in weight loss is synchronous with the enhancement of hardness.

Furthermore, on increasing the percentage of MWCNTs, the impact strength increased up to 1.5 wt.% MWCNT and then reduced at the concentrations of 2.0 wt.% and 2.5 wt.%. The impact strength of the polymers lacks in general. Once the nanofillers were added to HDPE, it lead to an increase in mechanical and wear properties, including the impact strength. But the further addition of MWCNTs (beyond 1.5 wt.%) leads to an increase in brittleness with hardness and compromising the toughness. The transition from ductile behavior to brittle on increasing nanofillers' concentration

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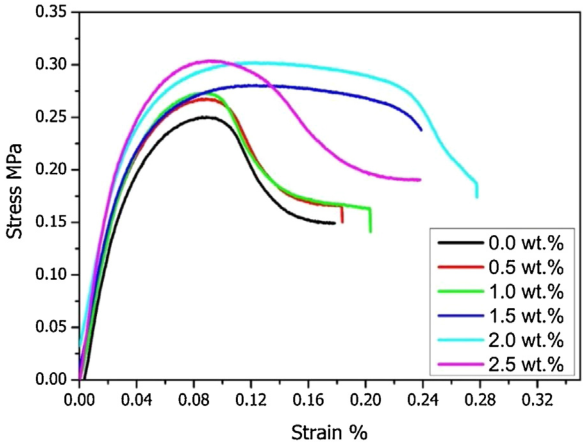

Fig. 9 – Stress-strain curve of HDPE with different concentration of MWCNTs.

was reported earlier [38,39]. Due to similar reasons, the decline in impact strength was observed. Inadequate adhesion of the nanofillers at higher concentrations (Fig. 6 (5)) may further complement the reduction of toughness. Tensile strength and toughness increased after the addition of amine functionalized MWCNTs and got wholly dispersed in the polymer matrix compared to pristine HDPE.

3.5. *Actual wear performance of HDPE and HDPE/MWCNT nanocomposite spur gears*

Wear of gears can be classified into different types such as crack, debris formation, weight loss, and tooth thickness reduction. In polymeric nanocomposites, the wear debris is formed by releasing MWCNT aggregates combined with the unbounded or loosely bonded HDPE chunks [46]. Weight loss is the most characteristic suitable test for polymer gears if the material doesn't have a high alliance for water [47]. HDPE considered as the least water-absorbing polymer with 0.01 % weight absorption compared with POM (0.5%) and PA6 (1.9%) respectively [20,21]. Fig. 10 (a) and (b) show the weight loss of test gears made from different material compositions (neat HDPE, 0.5, 1.0, 1.5, 2.0., and 2.5 wt.% MWCNT/HDPE nanocomposites) tested under applied torques of 5 and 10 N-m respectively. The weight loss was reduced in nanocomposites compared with neat HDPE. At a torque of 5 N-m, the wear performance increased consistently with the increase in the nanofillers. 2.5 wt.% MWCNT/HDPE spur gear displayed catchy wear performance, and the weight loss decreased up to 85% compared to neat HDPE. However, at a higher torque of 10 N-m, the weight loss decreased consistently up to 1.5 wt.% in MWCNT, but the 2.0 wt.% MWCNT outperformed 2.5 wt.% nanocomposite. At higher torque (10 N-m), in 2 wt.% nanocomposite, the weight loss decreased up to 69% compared to the neat HDPE spur gear. This illustrates the modulation of 2 wt.% MWCNT augmented the surface's resistance against the adhesive wear, which rendered the surface smoother than neat HDPE. The wear was higher in 2.5 wt.% nanocomposite by 24% compared to 2 wt.% nanocomposite due to the increased brittleness and reduced toughness of the material. Furthermore, polymer's load-bearing capacity may minify because of thermal mellowing, compromising the wear resistance. The wear rate was predominantly linear, and signatures of wear evident on the gears' teeth. The presence of MWCNT nanofillers played a pivotal role in containing the wear loss and imparted resistance against plastic deformation. MWCNTs acted as a booster, and the nanocomposite spur gears exhibited superior performance compared to neat HDPE, attributed to their uniform distribution in the polymer matrix.

3.6. *Gear damage morphology*

The SEM micrographs of 2 wt.% MWCNT/HDPE nanocomposite gear teeth after wear tests are illustrated in Fig. 11(a) and (b) outlining the SEM image of the gear tooth surface after exposure to 5 N-m. MWCNT specified along with wear marks of width around 84–126 nm. The SEM images indicate the uniform distribution of MWCNT inside HDPE. Elevated sliding friction amid the contacting surfaces resulted in increased heat accumulation, leading to the plastic flow at the tooth apex. The MWCNTs block the propagation of a crack in the transverse track on the surface of the polymer. The improved

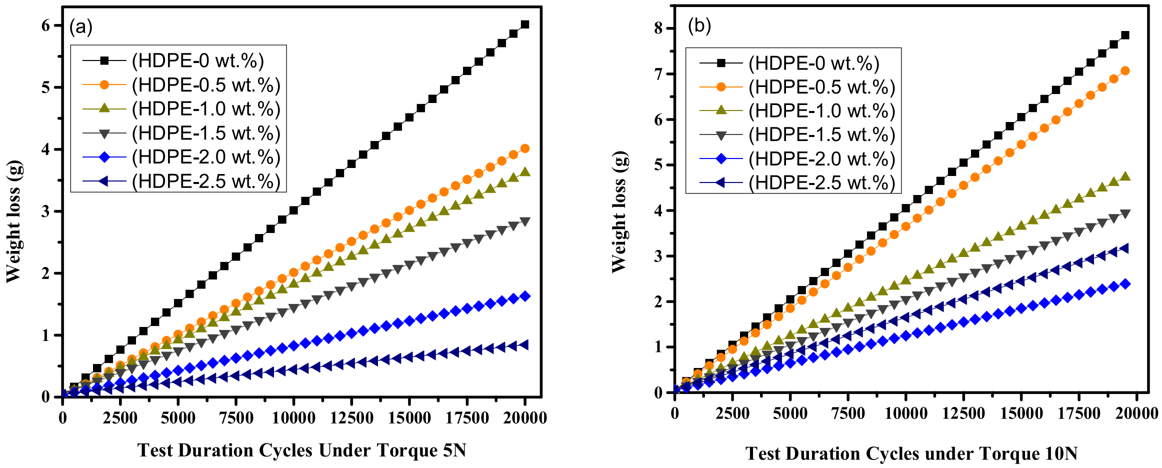

Fig. 10 – Wear performance of spur gears made from neat HDPE and MWCNT/HDPE nanocomposites in different concentrations. (a) Weight loss @ torque of 5 N-m. (b) Weight loss @ torque of 10 N-m.

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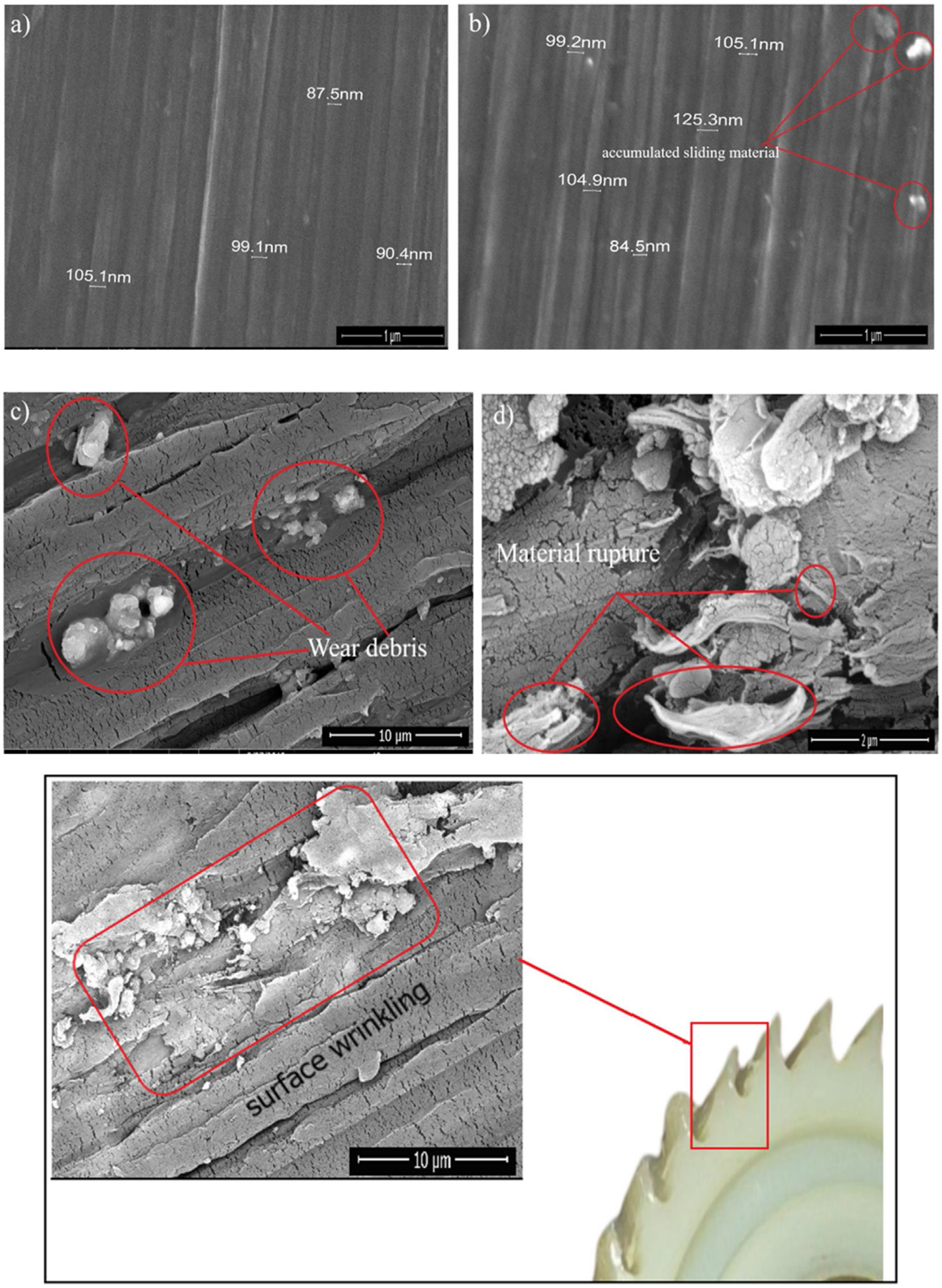

Fig. 11 – SEM of 2 wt% MWCNT/HDPE spur gear surface: (a, b) @5N-m. (c, d) @10N-m, and (e) Pure HDPE spur gear.

mechanical properties, stable thermal behavior, and high hardness increased MWCNT/HDPE gears' performance consequential in ominously better gear fatigue life due to the crack repelling abilities of MWCNTs that prolongs the absolute fracture of the nanocomposite gear. The neat HDPE gears showed squeaky wear, whereas MWCNT refrained the tooth wear reduction [48,49]. The progress of HDPE's thermal stability after adding MWCNT, discussed in Section 3.2 is the main reason to reduce the friction and exhibit high wear performance of HDPE/MWCNT gears. The reason seemingly from the alteration in the MWCNT progression topology in the interlaminar regions, their interaction with the interlaminar matrix cracks, and induced interconnectedness between the polymer grains inside the matrix. Fig.11(c) and (d) show wear marks of 2 wt.% MWCNT at 10 N-m, which conceptualizes that the increase of MWCNT cannot form a guarantor bond to reduce the wear hence resulting in gear weight loss. This asserts the association between thermal effects and failure and that the presence of MWCNT does not suppress the adhesive friction-induced on a rough surface. A rupture crack was detected at the tooth tip in Fig. 11(d), persuaded by the cyclic interaction fatigue during gears testing. At high loads and due to the vulnerable distribution of MWCNT, nanoparticle agglomeration renders fragile features. The thermal-softening during higher torque (10 N-m) at failure, dominated the effect of 2 wt.% MWCNT presence and induced debris buildup at

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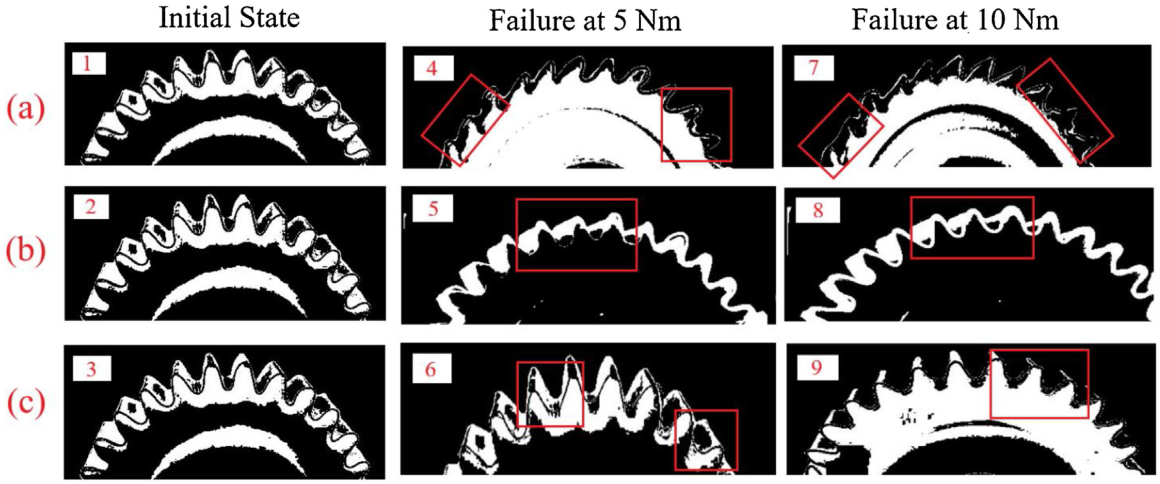

Fig. 12 – Wear characteristics of HDPE nanocomposite spur gears at 5 and 10 N-m torque. (a) Neat HDPE. (b) 2 wt.% MWCNT/HDPE. (c) 2.5 wt.% MWCNT/HDPE.

the tooth surface may lead to plastic deformation. The abrasive wear tracks showed little debris formation in Fig. 11(c). They were united with MWCNT particles as a white spot, which can often be considered as gaps inside the gears due to shortcomings or defects during the manufacturing process. Fig. 11(e) showed the gear teeths' total deterioration while reaching 20×10^3 cycles than MWCNT/HDPE gear. For pure HDPE surface, wrinkling marks appeared due to local plastic flows beside the slide's direction are explicit in the plain area of the HDPE tooth. Furthermore, linear wear has occurred employing fractures after going through running in and linear wear period.

3.7. *Gear damage mechanism*

Fig. 12(a) highlights the failure mechanisms for HDPE nanocomposite spur gears at different torque. Neat HDPE has not endured the exorbitant thermal damage caused by the surface temperature elevation of HDPE gear tooth at failure at a temperature below glass transition (T_g) temperature. Simultaneously, HDPE's physical properties changed in attitude analogous to glassy or crystal state and had exemplified as rubber material [50]. As a result of the elevated torque and heat gathered at the surface, the thermal conductivity decreased. Therefore, the gear damaged because of the thermal bending phenomenon resulting in total tooth deterioration accrued on the root and tip area. The high temperature caused by the applied torque led to teeth deviation and teeth reduction in pitch grooves' proximity. Fig. 12(b) shows 2 wt.% MWCNT/ HDPE gear tooth wear at 5 and 10 N-m, respectively. The significance of COOH-MWCNT bonding curbed the thermal bending, improved thermal stability, and minimized wear. The pivotal role of MWCNT is demonstrated by decreased tooth wear and improving durability. The tooth cracking was not eventuated, and stress concentration regions (grooves) resisted to collapse at high loads and temperature, but a slight erosion of the teeth appeared.

Hence, the damage mechanism of gears changed from thermal bending (in neat HDPE) to slight tooth wear for 2 wt. % MWCNT/HDPE gears. Further addition of MWCNT in 2.5 wt.% MWCNT/HDPE, at a torque of 10 N-m, partial thermal softening signs occurred followed by teeth abrading along face width. Therefore, a crack fracture initiation sign appeared at the dedendum line, as showed in Fig. 12(c). Eventually, because of the thermal effects of applied torque, thermal bending accelerated at the tooth's flank and profile links. Accordingly, the inclusion of MWCNT slightly changed the damage mechanism comparing to neat HDPE. Tooth cracking, tooth deflection, and partial tooth bending were observed. But in 2, 2.5 wt.% MWCNT gears, minor symbols of tooth deflection, and no flagrant thermal tooth bending was observed due to afflicted thermal and dimensional stability. Therefore, the gear effectiveness of HDPE nanocomposites greatly influenced by the weight and dispersion of MWCNT content.

4. Conclusions

The present study explored the potential application of MWCNT/HDPE nanocomposites in gearing applications. MWCNT/HDPE nanocomposites prepared in concentrations of 0.5, 1, 1.5, 2, and 2.5% by weight using the centrifugal ball milling dispersion method to obtain nanocomposite granules.

The nanocomposites' surface characterization using SEM revealed sound dispersion of the MWCNT in the HDPE matrix until 2 wt%, also detecting the presence of some regions devoid of MWCNT and some with aggregates at higher concentration (2.5 wt.%). MWCNT/HDPE nanocomposites exhibited higher decomposition temperature and thermal stability than neat HDPE. The thermal degradation temperature increased by 19%, and the retention of weight increased by 33% in the 2.5 wt.% nanocomposites compared with the neat HDPE. The yield strength and tensile strength increased almost linearly as the MWCNT were introduced in neat HPPE up to a concentration of 2 wt.%. There was a minor saturation in the increase of yield strength between the concentrations of 2 and 2.5 wt.% ascribed to the aggregation of the MWCNT. The addition of nanofillers steadily increased the young's modulus up to a weight fraction of 1.5 %, which increased rapidly between 1.5 to 2 wt.% ascribed to the uniform dispersion of MWCNT in the matrix till this composition. In comparison, the rate of increase of tensile properties declined between 2 to 2.5 wt.% due to the aggregation of the MWCNT, which limited the benefit of nanofillers. Increasing the percentage of MWCNTs lead to the improvement in hardness, maximum hardness exhibited at 2.5 wt.%, where the enhancement was up to 57%, attributed to the strengthening effect of the MWCNTs. The Taber abrasion test shows that the wear loss of nanocomposites reduced substantially with the increase of the concentration of MWCNTs and synchronous with the enhancement of hardness. The toughness of the nanocomposites increased from 0 (neat HDPE) to 1.5 wt.%. It declined after that due to the transition from ductile to brittle nature at higher concentrations of MWCNT and inadequate adhesion of MWCNT with the matrix. At a torque of 5 N-m, the wear performance increased consistently with the increase in the nanofillers. 2.5 wt.% MWCNT/HDPE spur gear displayed best wear performance, and the weight loss decreased approximately by 85% compared to neat HDPE. But, at a higher torque of 10 N-m, the weight loss consistently reduced up to 1.5 wt.% of MWCNT. After that, 2.0 wt.% MWCNT outperformed 2.5 wt.% nanocomposite due to the material's increased brittleness at higher concentrations. MWCNTs acted as a booster, and the nanocomposite spur gears exhibited superior wear performance. SEM results revealed that nanoparticles' presence improved the wear performance with lower plastic deformation in the nanocomposite gears. The nanocomposite gears failed at a higher torque. The gear damage mechanism changed from thermal bending to tooth cracking and deflection in nanocomposite gears.

The composition of 2 wt.% MWCNT/HDPE nanocomposites emerged as a potential gearing material with enhanced hardness, tensile properties, uniform dispersion, thermal stability, wear performance, and reasonable toughness. The exploration of a higher concentration of MWCNT and other nanofillers may require changes in the processing and provide an opportunity for future investigations.

Declarations of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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