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EXPERIMENTAL INVESTIGATION ON TRIBOLOGY AND MECHANICAL CHARACTERISTICS OF FUNCTIONALIZED GRAPHENE AND MWCNTs REINFORCED EPOXY HYBRID NANOCOMPOSITES

EKSPERIMENTALNA RAZISKAVA TRIBOLOŠKIH IN MEHANSKIH LASTNOSTI EPOKSIDNIH HIBRIDNIH NANOKOMPOZITOV, OJAČANIH S FUNKCIONALIZIRANIM GRAFENOM IN VEČSTENSKIMI OGLJIKOVIMI NANOCEVKAMI

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The development of epoxy-based hybrid nanocomposites reinforced with functionalized graphene and multi-walled carbon nanotubes (MWCNTs) has emerged as a promising strategy to enhance structural performance under combined mechanical and tribological characteristics. In this study, the tribological and mechanical characteristics of epoxy and its hybrid nanocomposites (EGpCn1–EGpCn5) was systematically evaluated under different loads, obtaining results that indicated a significant improvement in the wear resistance of the optimized formulations. Among all compositions, EGpCn3 demonstrated superior wear performance, exhibiting considerably lower material loss, smoother worn surfaces as well as evidence of nanofiller bridging and thin-film formation, which acted as protective layers against severe abrasive damage. Conversely, EGpCn5 revealed deep grooves, nanofiller bundles and pull-out regions, indicating poor dispersion and leading to accelerated wear degradation. Beyond tribological performance, the tensile properties of the hybrid nanocomposites also exhibited noteworthy enhancements, with EGpCn3 achieving the highest tensile strength of 69.12 MPa, corresponding to an almost 88 % increase over epoxy (36.71 MPa). This remarkable improvement can be attributed to strong interfacial adhesion, effective stress transfer and restricted crack propagation facilitated by the uniform graphene–MWCNT network. However, EGpCn5 again showed considerably lower tensile strength (27.12 MPa), where large voids, agglomeration and stepped fracture morphology confirmed the detrimental effect of poor nanofiller dispersion. Morphological examinations, using SEM, further demonstrated that the synergistic interaction of graphene and MWCNTs provided superior reinforcement by bridging microcracks, dissipating energy and enhancing load bearing capacity under both static and dynamic conditions.

Keywords: epoxy, graphene, MWCNTs, hybrid nanocomposites, wear, tensile strength

Razvoj polimernih hibridnih nanokompozitov na osnovi epoksi smole, ojačanih s funkcionaliziranim grafenom in več-stenskimi ogljikovimi nano-cevkami (MWCNT; angl.: multi-walled carbon nanotubes), se je izkazal kot obetavna strategija za izboljšanje strukturnih lastnosti materiala, ki je izpostavljen istočasno mehanskim in tribološkim obremenitvam. V tem članku avtorji predstavljajo študijo v kateri so sistematično ocenili tribološke in mehanske lastnosti epoksi smole in njenih hibridnih nanokompozitov (označenih z EGpCn1 do EGpCn5) z 1 do 5 mas. % funkcionaliziranih nano ploščic (FNP) pri različnih obremenitvah. Rezultati analiz so pokazali znatno izboljšanje odpornosti proti obrabi pri optimiziranih formulacijah. Med vsemi sestavami je EGpCn3 pokazal vrhunsko odpornost proti obrabi, saj je imel znatno manjšo izgubo materiala, bolj gladko obrabljene površine ter dokaze o premoščanju nanopolnil in nastanku tankih filmov, ki so delovali kot zaščitne plasti pred hudimi abrazivnimi poškodbami. Nasprotno pa je EGpCn5 imel po simulirani obrabi globoke utore, snope nanopolnil in območja izvlečenja vlaken. To kaže na slabo enakomernost porazdelitve ojačitvene faze, kar je vodilo do pospešene degradacije zaradi obrabe. Poleg triboloških lastnosti so se opazno izboljšale tudi natezne lastnosti hibridnih nanokompozitov, pri čemer je EGpCn3 imel najvišjo natezno trdnost 69,12 MPa. To je skoraj 88-odstotno povečanje v primerjavi z neojačano epoksi smolo (36,71 MPa). Izjemno izboljšanje so avtorji pripisali močni medfazni adheziji, učinkovitemu prenosu napetosti in omejenemu širjenju razpok, ki ga omogoča enakomerna mreža med grafenom in MWCNT. Kompozit EGpCn5 je imel precej nižjo natezno trdnost (27,12 MPa), ker so velike praznine, aglomeracija in stopničasta morfologija loma imele škodljiv učinek zaradi slabe disperzije (nenakomerne volumske porazdelitve) nanopolnila. Morfološke preiskave z uporabo vrstičnega elektronskega mikroskopa (SEM) so dodatno potrdile, da sinergistična interakcija grafena in MWCNT zagotavlja vrhunsko ojačitev s premoščanjem mikrorazpok, disipacijo energije in izboljšanje nosilnosti v pogojih statičnih in dinamičnih obremenitev.

Ključne besede: epoksi, grafen, večstenske ogljikove nanocevke, hibridni nanokompoziti, obraba, natezna trdnost

1 INTRODUCTION

Epoxy resins are widely employed in aerospace, automotive, and structural sectors due to their high strength-to-weight ratio, chemical resistance, and excellent adhesion to diverse substrates. However, epoxy is inherently brittle, with low fracture toughness and poor

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wear resistance, which restricts its performance in demanding environments.[1] To overcome these shortcomings, nanoscale reinforcements such as graphene and carbon nanotubes (CNTs) have been investigated extensively over the past two decades. Graphene, a two-dimensional monolayer of sp^2-hybridized carbon, exhibits extraordinary in-plane mechanical properties with a tensile strength of ≈130 GPa and a Young's modulus near 1 TPa, along with high surface area and thermal conductivity.[2] CNTs, on the other hand, provide a one-dimensional tubular geometry with aspect ratios often exceeding 1000, making them highly effective as load-bearing fillers that bridge microcracks and transfer stresses across the matrix.[3]

Early work demonstrated that epoxy reinforced with CNTs could achieve significant improvements in modulus and conductivity when dispersion and interfacial bonding were optimized.[4] Similarly, graphene nanoplatelets, when properly exfoliated and dispersed, impart high stiffness, strength, and barrier resistance even at low filler loadings.[5,6] The concept of combining graphene and CNTs into hybrid systems emerged as a route to exploit complementary geometries: graphene sheets act as crack stoppers and barrier layers, while CNTs connect and anchor these platelets, producing percolated networks for load transfer.[7] Hybridization studies revealed notable synergistic effects in epoxy, with simultaneous increases in tensile strength, fracture toughness, and tribological performance at low filler fractions.[8,9] For example, Rafiee et al. reported that graphene/CNT hybrids achieved superior modulus and strength at < 1 *w*/% loading, a performance not attainable with either filler alone. Such synergies have been attributed to optimized filler orientation, suppression of agglomeration, and the formation of continuous three-dimensional reinforcement networks.[10] Interfacial engineering remains central to realizing these benefits. Functionalization strategies, including acid oxidation, aminosilane grafting, and epoxide treatment, introduce polar or reactive groups that improve wettability, dispersion, and covalent bonding with epoxy.[11] Gojny et al. demonstrated that functionalized CNTs significantly enhanced both tensile and flexural properties by promoting stress transfer and reducing voids.[12] Similarly, functionalized graphene sheets resist restacking and integrate more effectively into the polymer network, allowing uniform stress distribution and delaying crack propagation.[13] Tribological behavior is another critical domain where hybrid nanofillers have shown promise.

Epoxy is highly susceptible to adhesive and abrasive wear, but the addition of carbon nanofillers reduces wear rate and stabilizes friction.[14] Graphene platelets form lamellar transfer films parallel to the sliding surface, reducing shear stresses, while CNTs disperse and fracture under load, filling surface grooves and mitigating ploughing damage. This combination leads to smoother worn surfaces and lower debris generation. Studies consistently confirm that functionalized hybrids outperform neat epoxy and single-filler systems, with wear rate reductions exceeding 40–60 % under dry sliding.[15] Solvent assisted mixing, probe sonication, and mechanical stirring are commonly used to disperse nanofillers, followed by vacuum degassing to eliminate voids. Controlled processing prevents CNT entanglement and graphene restacking, ensuring homogeneous microstructures. Excessive filler loading, however, increases viscosity and promotes agglomeration, leading to porosity and performance degradation. Hence, optimized low loadings of functionalized hybrids provide the best balance between strength and wear resistance. Despite significant progress, challenges remain in scaling hybrid nanocomposites for industrial applications. Issues include uniform filler dispersion at larger volumes, cost of high-purity nanofillers, and control over functionalization reproducibility.[16] The nanocomposite systems were fabricated by incorporating multi-walled carbon nanotubes (MWCNTs), graphene nanoplatelets (GNPs), and alumina (Al_2O_3) nanoparticles at a uniform loading of 0.2 *w*/% each. Their inclusion was intended to enhance functional performance by improving interfacial load transfer efficiency and tribological characteristics of the composite matrix.[17] Nevertheless, recent advances in processing and hybrid design are steadily bridging these gaps, making graphene–CNT reinforced epoxy nanocomposites a promising candidate for structural and tribological applications where simultaneous improvements in mechanical and wear properties are required.

2 MATERIALS AND METHODS

2.1 Materials

The matrix system adopted in this investigation consisted of a commercial-grade epoxy resin, bisphenol-A diglycidyl ether (DGEBA), used as the base resin, and triethylenetetramine (TETA) employed as the curing agent. DGEBA is widely utilized for its strong adhesion to diverse substrates, chemical stability, and resistance to dimensional changes, with a viscosity in a range of 11,000–14,000 mPa·s at 25 °C and an epoxy equivalent weight (EEW) of 182–192 g/eq. The hardener, TETA, is a low-viscosity polyamine capable of initiating room-temperature curing and promoting a dense crosslinked network, thereby contributing to improved thermal and mechanical performance of the cured resin. To reinforce the matrix at the nanoscale, graphene nanoplatelets and multi-walled carbon nanotubes (MWCNTs) were incorporated, both sourced from BTCORP Generique Nano Pvt. Ltd., Bangalore, India. The use of these high-purity nanofillers, with consistent batch quality, ensured reliable performance during composite processing and characterization. The graphene used exhibits a typical thickness of ≈1–5 nm and lateral dimensions of up to several microns, with a surface area exceeding 300 m^2/g and an intrinsic thermal conductivity over 3000 W/m·K.

Graphene's sp^2-hybridized carbon lattice imparts exceptional stiffness (Young's modulus of ≈1 TPa) and strength (≈130 GPa). The MWCNTs used consist of concentric cylindrical layers of graphene, each with an outer diameter of 10–30 nm and a length of up to 10 µm, featuring aspect ratios greater than 1000. These nanotubes offer high tensile strength (up to 60 GPa), electrical conductivity (≈10^6 S/m), and thermal conductivity (> 3000 W/m·K), making them ideal for reinforcing the epoxy matrix in terms of both mechanical and tribological performance.

2.2 Functionalization of graphene

Functionalization of graphene is a critical step to improve its dispersion within polymer matrices and to enhance interfacial adhesion. In its pristine form, graphene tends to agglomerate due to strong π–π stacking and van der Waals interactions, which limit its effectiveness in composite systems. To address this, chemical functionalization – particularly through oxidative processes – is widely employed. The most common method involves the Hummers' or modified Hummers' method, where graphite is oxidized using a mixture of concentrated sulfuric acid, sodium nitrate, and potassium permanganate, resulting in the formation of graphene oxide (GO). The oxygen-containing functional groups such as hydroxyl (–OH), carboxyl (–COOH), and epoxy (–C–O–C) groups introduced on the graphene surface increase its hydrophilicity and compatibility with polar polymer matrices like epoxy. Covalent functionalization of graphene oxide (GO) can be achieved by reacting it with amine-terminated silanes, diamines, or other organo-functional agents. Such reactions graft active sites onto the GO surface, enabling the formation of strong chemical bonds with the polymer matrix during curing. These modifications not only improve nanofiller dispersion but also strengthen interfacial adhesion by promoting mechanical interlocking and enhancing load transfer between graphene sheets and the surrounding polymer. As a result, both the mechanical reliability and thermal stability of the composite are substantially improved.

2.3 Functionalization of multi-walled carbon nanotubes (MWCNTs)

Pristine multi-walled carbon nanotubes (MWCNTs) exhibit excellent intrinsic mechanical and electrical properties; however, their practical use is often restricted by low solubility, strong van der Waals interactions, and entanglement caused by their high aspect ratio and π-conjugated surfaces. To overcome these limitations and to promote better compatibility with polymer matrices, surface functionalization is frequently employed. A common approach involves acid oxidation, where nanotubes are treated with concentrated nitric and sulfuric acids under reflux conditions. This process introduces carboxyl (–COOH) and hydroxyl (–OH) groups on the CNT walls, improving wettability and dispersion while also providing active sites for subsequent chemical modification. Such functionalized MWCNTs (f-MWCNTs) can be coupled with agents like aminosilanes or epoxides, enabling covalent interactions with epoxy resins. Depending on the targeted matrix chemistry, additional strategies such as amidation or esterification may be applied to further tailor the surface properties. Non-covalent modification routes, including surfactant-assisted dispersion or π–π stacking with polymers, are also effective in enhancing compatibility while retaining the nanotubes' intrinsic conductivity and strength. Through these modifications, MWCNTs achieve more uniform dispersion within the host matrix, facilitate efficient stress transfer at the interface, and ultimately contribute to composites with improved mechanical strength, enhanced thermal stability, and better wear resistance.

2.4 Hybrid nanocomposite sample preparation

Hybrid nanocomposite specimens were prepared through a systematic and controlled methodology to achieve uniform nanofiller dispersion, defect-free curing, and optimal performance in wear resistance, tensile strength, and microhardness, in accordance with ASTM testing standards. Functionalized graphene nanoplatelets (FGP) and functionalized multi-walled carbon nanotubes (FMWCNTs) were incorporated into a bisphenol-A diglycidyl ether (DGEBA) epoxy matrix, with triethylenetetramine (TETA) as the curing agent. Initially, separate aqueous dispersions of FGP and FMWCNTs were prepared to promote complete de-agglomeration and uniform distribution. These dispersions were subjected to probe-type ultrasonication at 20 kHz and 750 W for 30 min, while maintaining the bath temperature below 30 °C using an external cooling system to prevent thermal degradation. The functionalized nanofillers were then introduced into the epoxy resin following a two-stage sequential mixing approach, wherein graphene was first incorporated into the epoxy followed by MWCNTs, resulting in enhanced homogeneity and superior interfacial bonding compared to direct hybrid dispersion. The resin–filler mixture was mechanically stirred at 500 min^{-1} for 10 min and subsequently vacuum degassed to eliminate entrapped air bubbles, thereby minimizing void formation during curing. The bubble-free mixture was then cast into clean acrylic molds of standard test dimensions. Curing was performed at ambient temperature for 24 h, followed by post-curing in a hot-air oven at 60 °C for 2 h to ensure complete cross-linking. Based on the varying weight percentages of FGP (0.1–0.5 *w*/%) and a constant 0.3 *w*/% of FMWCNTs, the prepared specimens were designated as Epoxy, EGpCn1, EGpCn2, EGpCn3, EGpCn4, and EGpCn5, as presented in **Table 1**. For each formulation, five replicate samples were fabricated to enhance statistical reliability and reproducibility of the results. Prior to testing, all cured specimens were surface-polished with 800- and

1200-grit emery papers to remove surface irregularities and ensure precise dimensional conformity.

2.5 Dry sliding wear test

The dry sliding wear performance of the epoxy-based hybrid nanocomposites reinforced with functionalized graphene nanoplatelets (FGPs) and multi-walled carbon nanotubes (FMWCNTs) was assessed using a pin-on-disc tribometer (DUCOM TR20, Bangalore, India) in compliance with ASTM G99. Tests were carried out under ambient laboratory conditions without lubrication to represent realistic contact wear. Cylindrical specimens with dimensions including a length of 30 mm and a diameter of 10 mm were prepared for evaluation. Each sample was mounted against a rotating EN31 hardened steel counterface with a 25-mm wear track, ensuring a uniform and stable contact surface. Prior to every test, the steel disc was carefully cleaned with acetone to eliminate traces of oil, debris, or contaminants, while the specimen faces were polished with 800-grit emery paper to achieve a smooth, flat contact zone. This preparation minimized variations in contact pressure during sliding and ensured reliable reproducibility of wear measurements. The disc speed was maintained at 200 min^{-1}, under normal loads of (20, 40 and 60) N to examine the effect of loading on wear resistance. Each test run lasted 30 min under constant load and speed conditions. For every test configuration, five replicate specimens were evaluated, and the average values were used in the final analysis to ensure statistical reliability. The specimen mass was recorded before and after testing using a high-precision digital balance with an accuracy of 0.1 mg, and the wear rate was calculated as mass loss per unit sliding distance. The test setup was integrated with a data acquisition system to record frictional force, wear depth, and temperature rise in real time, ensuring accurate and reproducible results. Based on the composition, the tested samples were categorized as pure epoxy (Epoxy) and hybrid nanocomposites containing 0.1–0.5 *w*/% FGP with a constant 0.3 *w*/% FMWCNTs, labeled as EGpCn1, EGpCn2, EGpCn3, EGpCn4, and EGpCn5. This wear evaluation provided clear insights into the influence of nanofiller content and applied load on the tribological performance of the hybrid nanocomposites, highlighting the role of synergistic graphene–MWCNT reinforcement in reducing material loss under sliding contact.

Table 1: Epoxy with various weight fractions of functionalized grapheme & MWCNTs and the labels

Matrix	Nanofiller weight fraction in %		Label
	FGP	FMWCNTs	
Epoxy	0	0	Epoxy
	0.1	0.3	EG_pC_n1
	0.2	0.3	EG_pC_n2
	0.3	0.3	EG_pC_n3
	0.4	0.3	EG_pC_n4
	0.5	0.3	EG_pC_n5

2.6 Tensile test

The tensile properties of the fabricated epoxy-based hybrid nanocomposites reinforced with functionalized graphene nanoplatelets (FGP) and functionalized multi-walled carbon nanotubes (FMWCNTs) were evaluated using an Instron universal testing machine (Instron 3369) in accordance with ASTM D638 standards. The specimens were precisely machined into a dog-bone geometry with a gauge length of 25 mm and an overall length of 63.5 mm to ensure consistent and reliable stress–strain measurements. All samples were visually inspected for surface defects and conditioned at ambient laboratory temperature to minimize the influence of residual stresses or moisture absorption. Testing was performed under controlled environmental conditions at a constant crosshead speed of 5 mm/min. The specimen ends were firmly secured in self-aligning grips to prevent slippage or misalignment during loading. Real-time data acquisition enabled precise recording of load and displacement values, from which the ultimate tensile strength, Young's modulus, and elongation at break were determined. For statistical reliability, five replicate specimens were tested for each composition, including pure epoxy (Epoxy) and hybrid formulations containing 0.1–0.5 *w*/% FGP with a constant 0.3 *w*/% FMWCNTs, designated as EGpCn1, EGpCn2, EGpCn3, EGpCn4, and EGpCn5. Upon completion of testing, fractured specimens were retained for morphological examination using scanning electron microscopy (SEM) to analyze filler dispersion, interfacial bonding, and failure mechanisms. This tensile testing approach provided a comprehensive evaluation of the reinforcing efficiency of graphene–MWCNT hybrid nanofillers in enhancing the mechanical performance of the epoxy matrix.

3 RESULT AND DISCUSSION

3.1 Dry sliding wear characteristics

The specific wear rate of the epoxy matrix and the fabricated hybrid nanocomposites reinforced with functionalized graphene nanoplatelets (FGP) and functionalized multi-walled carbon nanotubes (FMWCNTs) was systematically evaluated under applied loads of (20, 40 and 60) N across sliding distances of 157–942 m. The results revealed significant improvement in wear resistance for all hybrid formulations compared to epoxy, with the degree of enhancement being strongly dependent on the filler composition and applied load as shown in Figure 1a–c. Noteworthy, the EGpCn3 formulation exhibited superior wear resistance under all loading conditions, achieving enhancements of approximately 88.49 % (20 N), 83.82 % (40 N), and 76.54 % (60 N) at the highest sliding distance compared to epoxy. This remarkable performance can be attributed to the optimized synergy between graphene and MWCNTs, which facilitates the formation of a robust load-bearing and lubricating network within the epoxy matrix. Fur-

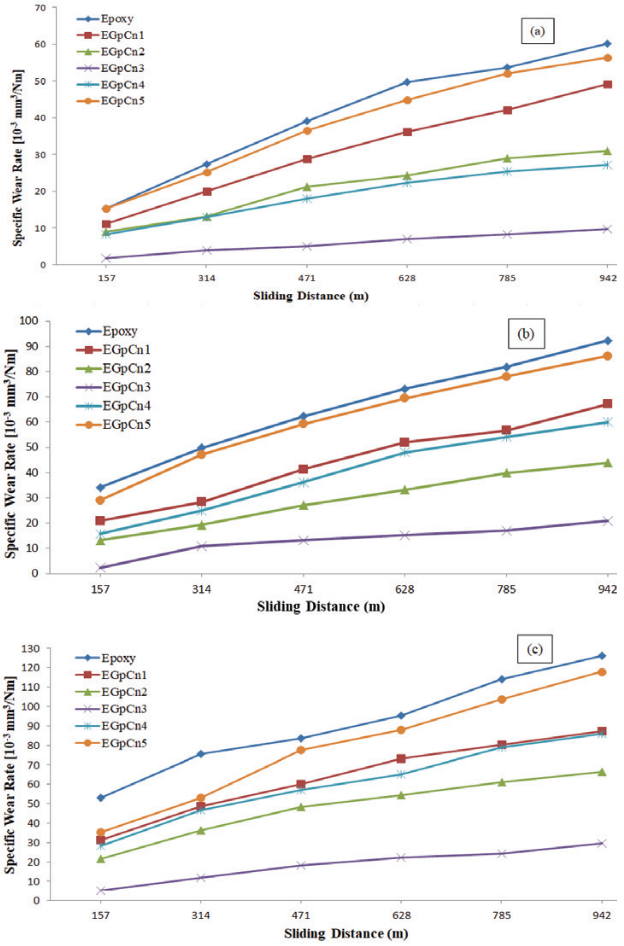

Figure 1: a) specific wear rates of epoxy and hybrid nanocomposites at the load of 20 N, b) 40 N, c) 60 N

thermore, during sliding, graphene nanoplatelets tend to align parallel to the wear track, forming a protective tribofilm that substantially reduces direct asperity contact. Simultaneously, MWCNTs undergo dispersion and partial fracture, filling micro-voids and bridging surface cracks, thus considerably lowering the probability of crack propagation and material removal. However, EGpCn1 and EGpCn2, while showing considerable improvement over epoxy, displayed a gradual reduction in the wear rate that did not reach the level of EGpCn3. This can be linked to their relatively lower filler content, which may not sustain a continuous protective film throughout prolonged sliding. Nevertheless, these compositions still achieved wear resistance improvements in a range of 27–50 %, indicating the inherent benefits of hybrid nanofiller reinforcement even at modest loadings. In contrast, EGpCn4 and EGpCn5 initially demonstrated better wear resistance than epoxy but showed increasing wear rates at longer sliding distances. EGpCn5, in particular, approached epoxy-like wear behavior under extended operation.

This trend is likely due to filler agglomeration and non-homogeneous dispersion at higher graphene contents, resulting in localized stress concentrations and premature filler pull-out. The presence of such agglomerates disrupts interfacial bonding, and beyond a certain sliding distance, portions of the worn surface lose their protective layer, leading to accelerated material removal. The experimental investigation confirm that hybrid nanofillers deliver considerably lower wear rates when optimally dispersed, with EGpCn3 exemplifying the most superior performance due to balanced filler loading and excellent interfacial bonding. This combination effectively controls wear mechanisms through tribofilm formation, microcrack bridging, and load-sharing at the nanoscale, which are key attributes that make hybrid graphene–MWCNT systems highly promising for advanced tribological applications.

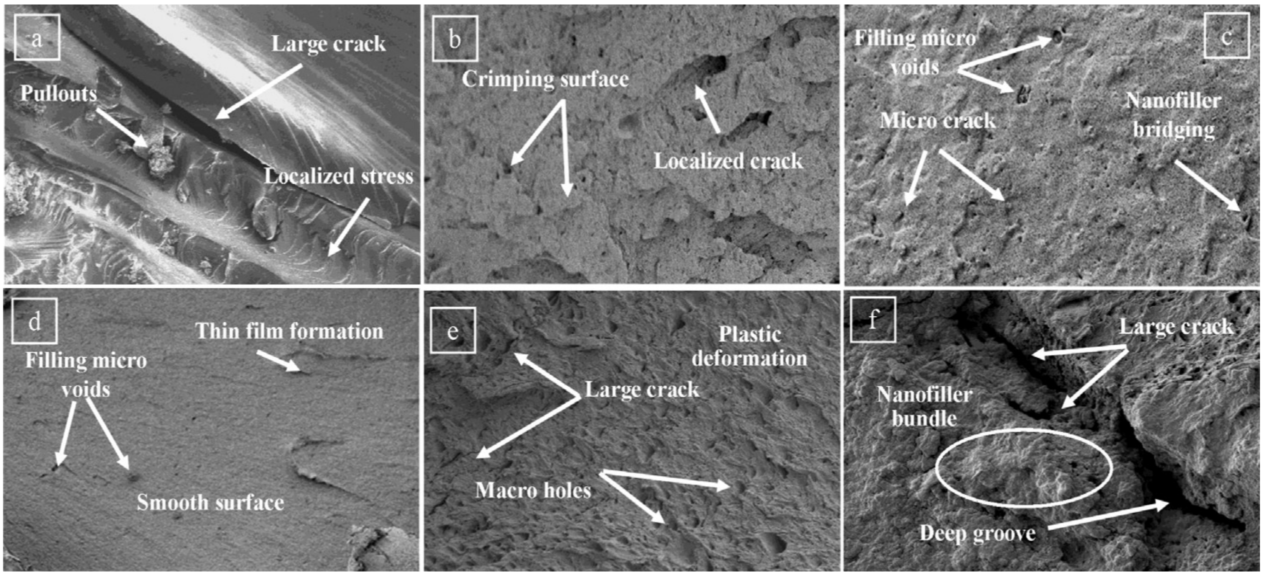

Figure 2: (a–f) Worn surface morphology analysis of pure epoxy and its hybrid nanocomposites at the sliding load of 60 N

3.2 Worn surface morphology analysis

SEM micrographs of the worn surfaces at 60 N provide a detailed insight into the wear mechanisms governing the epoxy matrix and its hybrid nanocomposites. In the pure epoxy (**Figure 2a**), the surface is dominated by large cracks, localized stress regions, and evident pull-outs, indicating severe brittle fracture and poor load-bearing capacity under high stress. Such a morphology reflects the inability of epoxy to resist crack propagation once initiated, leading to catastrophic material removal.

In contrast, EGpCn1 (**Figure 2b**) exhibits a crimping surface with localized cracks, suggesting that the inclusion of nanofillers redistributed the stresses more effectively than epoxy, though localized failures remain visible. EGpCn2 (**Figure 2c**) presents a noteworthy improvement where microcracks and voids are considerably filled, and nanofiller bridging is evident; this bridging effect of graphene sheets and MWCNTs restricts crack opening and delays propagation, thereby enhancing the wear resistance. Furthermore, EGpCn3 (**Figure 2d**) demonstrates superior wear morphology with a thin-film formation and a comparatively smoother surface, indicating significant improvement in the load transfer and self-lubricating behavior of graphene. The micro-void filling and uniform distribution of nanofillers created a barrier against crack growth, explaining the considerably lower wear rate observed experimentally. However, EGpCn4 (**Figure 2e**) reveals macro holes, plastic deformation, and large cracks, suggesting partial agglomeration and non-uniform dispersion of nanofillers; although some reinforcement effect is present, it is less effective compared to EGpCn3. Beyond this, EGpCn5 (**Figure 2f**) shows large cracks, deep grooves, and the presence of nanofiller bundles, highlighting poor interfacial bonding due to filler agglomeration. Such clustering promotes stress concentration zones and accelerates material removal, making its performance nearly equivalent to epoxy at extended sliding distances.

3.3 Tensile characteristics

The tensile characteristics of the epoxy and hybrid nanocomposites reveal a distinct trend governed by the interplay between dispersion, interfacial adhesion, and structural reinforcement mechanisms of the graphene MWCNT network as shown in **Figure 3**. The epoxy exhibited a baseline tensile strength of 36.71 MPa, while the incorporation of nanofillers led to a significant improvement in load-bearing capacity. EGpCn1 and EGpCn2 demonstrated gradual enhancement, with strengths of 47.12 MPa and 53.89 MPa, corresponding to 28 % and 47 % improvements, respectively, attributable to better stress transfer through functionalized graphene platelets and CNT bridging. The most noteworthy performance was achieved in EGpCn3, which reached 69.12 MPa (an 88 % improvement over epoxy) reflecting the formation of a superior synergistic network. At this optimum composition, graphene provided crack deflection and high in-plane stiffness, while CNTs dispersed, bridged microcracks, and redistributed localized stresses, thereby delaying catastrophic crack propagation. Furthermore, the functional groups on nanofillers facilitated strong chemical bonding with the epoxy matrix, ensuring efficient load transfer. However, EGpCn4 showed a decline to 45.33 MPa, as partial agglomeration and resin starvation introduced stress concentrators, diminishing the reinforcement effect. Beyond this, EGpCn5 dropped to 27.12 MPa, considerably lower than epoxy, due to extensive agglomeration, voids, and heterogeneous dispersion that promoted premature debonding and brittle failure.

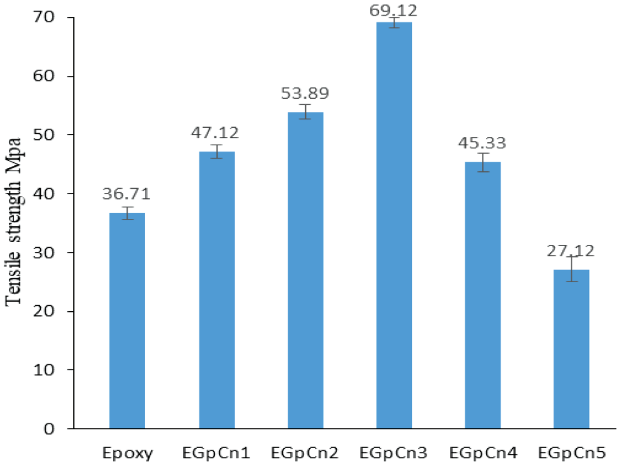

Figure 3: Tensile strength of epoxy and its hybrid nanocomposites

Thus, while moderate incorporation of graphene and CNTs considerably improved tensile resistance, excessive loading beyond the optimal level undermined homogeneity and structural integrity, highlighting the critical role of nanofiller dispersion and interfacial compatibility in achieving superior mechanical performance. The hybrid composites demonstrate noteworthy improvement in tensile strength up to an optimal nanofiller concentration, beyond which the benefits diminish due to agglomeration and heterogeneity. The results reaffirm that the balance between filler dispersion and interfacial bonding is crucial for achieving superior mechanical properties, with EGpCn3 emerging as the most effective formulation.

3.4 Tensile fracture surface morphology analysis

The tensile fracture surface morphology (**Figure 4a–c**) provides a clear distinction between the behavior of epoxy and the hybrid nanocomposites, particularly EGpCn3 and EGpCn5. The fractured surface of pure epoxy (**Figure 4a**) reveals a brittle and stepped fracture pattern, indicative of its inherently low toughness and inability to undergo significant plastic deformation before failure. The absence of energy-dissipating

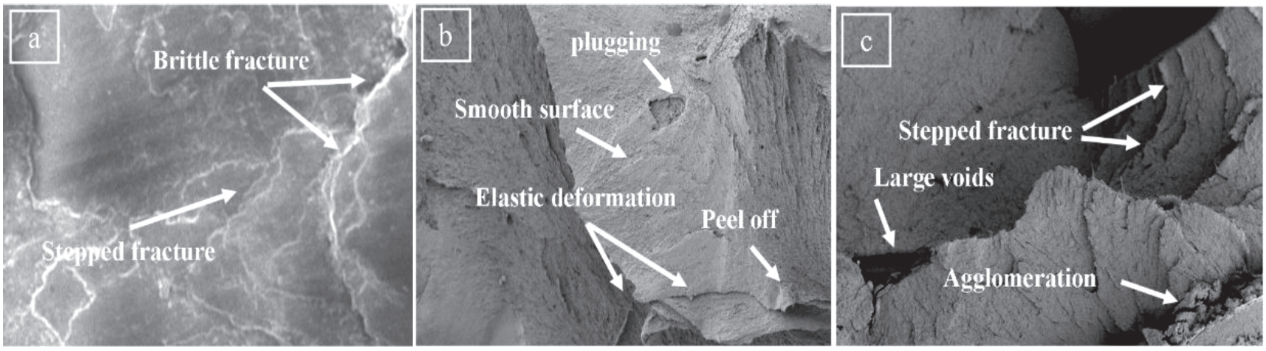

Figure 4: Tensile fracture surface morphology analysis of a) epoxy; b) EGpCn3; c) EGpCn5

mechanisms results in rapid crack propagation, leaving behind sharp fracture planes characteristic of brittle polymers. In contrast, EGpCn3 (**Figure 4b**) exhibits superior fracture resistance, as evidenced by the presence of smooth surfaces, localized plugging, elastic deformation zones, and peel-off regions. These features signify effective load transfer from the matrix to the well-dispersed graphene and MWCNTs, which bridge microcracks and restrict their propagation. The fillers act as stress-transfer reinforcements and also deflect cracks, thereby improving toughness and delaying catastrophic failure. This morphology highlights the noteworthy role of hybrid nanofillers in imparting ductile fracture characteristics to the otherwise brittle epoxy matrix. However, the fracture surface of EGpCn5 (**Figure 4c**) displays stepped fractures, large voids, and noticeable agglomeration of nanofillers. Such non-uniform dispersion and filler clustering create localized stress concentrations, which initiate premature crack growth and reduce effective reinforcement. Although the presence of fillers should ideally enhance crack resistance, the inferior dispersion quality in EGpCn5 negates these advantages, leading to compromised mechanical properties compared to EGpCn3. Thus, the comparative analysis demonstrates that while epoxy fails in a brittle manner, EGpCn3 achieves significant improvement in fracture toughness due to homogeneous nanofiller dispersion and crack-bridging mechanisms, whereas EGpCn5 suffers from filler agglomeration and void formation, resulting in reduced performance despite the presence of nanofillers.

The tensile fracture surface analysis clearly correlates with the tensile strength results. Epoxy (36.71 MPa) shows a brittle and stepped fracture with limited energy absorption, confirming its inherently brittle nature. In contrast, EGpCn3 (69.12 MPa) exhibits smooth surfaces, elastic deformation, and peel-off regions, which reflect effective stress transfer and crack-bridging by well-dispersed graphene and MWCNTs, leading to superior toughness and noteworthy strength improvement. However, EGpCn5 (27.12 MPa) reveals stepped fractures, voids, and agglomeration, indicating poor dispersion and localized stress concentrations, which considerably lower its tensile strength despite the presence of nanofillers. Thus, while epoxy remains brittle, EGpCn3 demonstrates significant improvement in fracture resistance, whereas EGpCn5 highlights the detrimental effect of filler agglomeration.

4 CONCLUSIONS

The dry sliding wear analysis revealed a significant improvement in the wear resistance for all hybrid nanocomposites compared to epoxy, with EGpCn3 consistently demonstrating the superior performance under (20, 40 and 60) N loads. This enhancement was attributed to the synergistic effect of well-dispersed graphene and MWCNTs, which acted as lubricating layers and microcrack arrestors.

EGpCn1 and EGpCn2 showed a gradual improvement in wear resistance with increasing graphene content, whereas EGpCn4 and EGpCn5 exhibited a decline at higher filler concentrations, with EGpCn5 showing values nearly comparable to epoxy due to filler agglomeration and non-uniform dispersion.

Wear morphology confirmed that graphene nanoplatelets formed a protective tribolayer while MWCNTs dispersed and fractured to fill surface voids and restrict crack propagation, thereby delaying material removal. Conversely, poor dispersion in EGpCn5 led to localized material detachment under high loads.

Tensile strength results highlighted a considerable improvement, with EGpCn3 achieving a nearly 88 % higher strength than epoxy, validating the efficiency of the optimal hybrid ratio. This superior performance is attributed to the effective load transfer between the matrix and nanofillers.

In contrast, EGpCn5 exhibited considerably lower tensile strength than epoxy, indicating that excess nanofiller caused agglomeration, stress concentration sites, and poor interfacial bonding, ultimately weakening the matrix.

This investigation establishes that the optimized formulation (EGpCn3) not only offers noteworthy wear resistance but also superior tensile properties, demonstrating the potential of graphene–MWCNT hybrid reinforcement to outperform conventional epoxy in demanding structural and tribological applications.

The demonstrated performance improvements at relatively low nanofiller loadings indicate favorable prospects for scalability as excessive filler usage and processing complexity are avoided.

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