



Friction Modification Layer in Robotic Vehicle Wheel Lining Using Elastomer-Based Polymer Nanocomposites Reinforced with Carbon Nanostructures

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Abstract: The development of advanced materials for high-temperature and high-load applications has become increasingly critical in nuclear reactor inspection systems. Robotic vehicles operating inside reactor vessels require superior traction, thermal stability, and wear resistance under extreme environmental conditions. This study investigates the fabrication and characterization of elastomer-based polymer nanocomposites designed for enhancing frictional performance in robotic wheel linings. Fluorocarbon rubber (FKM) was selected as the base elastomer due to its excellent thermal and chemical resistance and was reinforced with Multiwalled Carbon Nanotubes (MWCNTs) and Nano Graphene Platelets (NGPs). The nanocomposites were fabricated using a two-roll mill blending process followed by compression molding and vulcanization. Characterization was conducted using X-ray Diffraction, Fourier Transform Infrared Spectroscopy, Scanning Electron Microscopy, and Energy Dispersive Spectroscopy. Tribological properties were evaluated using a pin-on-disc apparatus. The results demonstrate a significant enhancement in friction and wear resistance, with graphene-reinforced composites exhibiting superior performance. The study confirms that nanoparticle reinforcement is an effective approach for improving elastomer performance in extreme environments.

Index Terms - Fluorocarbon elastomer; Polymer nanocomposites; Carbon nanotubes; Graphene nanoplatelets; Tribological performance

I. INTRODUCTION

The increasing reliance on nuclear energy systems for sustainable power generation has significantly amplified the demand for advanced inspection and maintenance technologies capable of operating in hazardous environments. Reactor pressure vessels are critical components that must maintain structural integrity under extreme operating conditions, including high temperatures, radiation exposure, and mechanical stresses. The detection of defects such as microcracks, corrosion, and surface degradation is essential to ensure safe and reliable operation. However, direct human inspection is impractical due to the hazardous environment, necessitating the use of robotic systems for inspection and maintenance tasks [1,2].

Robotic vehicles designed for nuclear applications must exhibit high levels of mobility, stability, and reliability. Among the various components of these systems, the wheel lining material plays a crucial role in determining traction and maneuverability. Effective wheel lining materials must provide high friction, wear resistance, and thermal stability under demanding conditions. Conventional elastomeric materials often fail to meet these requirements, particularly under high load conditions where slippage can occur, leading to reduced operational efficiency [3,4].

Polymer nanocomposites have emerged as a promising solution for enhancing material performance. The incorporation of nanoscale fillers into polymer matrices enables significant improvements in mechanical, thermal, and tribological properties. Carbon-based nanomaterials such as Multiwalled Carbon Nanotubes and Nano Graphene Platelets are particularly attractive due to their exceptional mechanical strength, high aspect ratio, and excellent thermal conductivity [6–10].

The reinforcement of elastomeric materials has traditionally relied on fillers such as carbon black and silica. While these materials improve mechanical properties, their effectiveness is limited compared to nanoscale reinforcements. The introduction of nanotechnology has enabled the development of polymer nanocomposites with significantly enhanced properties. Nanofillers exhibit high surface area and strong interfacial interactions, which contribute to improved load transfer and mechanical performance [6,12].

Graphene nanoplatelets have demonstrated remarkable improvements in thermal conductivity, mechanical strength, and wear resistance due to their planar structure and large surface area. Similarly, carbon nanotubes provide excellent reinforcement due to their high tensile strength and ability to form network structures within the polymer matrix [8–10]. The dispersion of nanoparticles is a critical factor influencing composite performance. Poor dispersion leads to agglomeration, which reduces effectiveness. The use of surfactants and advanced mixing techniques has been shown to improve nanoparticle distribution [13]. Fluorocarbon elastomers are known for their excellent resistance to heat and chemicals, but their tribological properties require enhancement for high-load applications [11].

Fluorocarbon elastomers are widely used in high-temperature applications due to their excellent resistance to heat and chemical degradation. However, their frictional performance can be further improved through nanoparticle reinforcement. This study aims to develop FKM-based nanocomposites reinforced with carbon nanostructures and evaluate their suitability for robotic wheel lining applications.

II. MATERIALS AND METHODS

The present investigation employed a carefully designed experimental methodology to develop elastomer-based nanocomposites with enhanced tribological performance suitable for robotic wheel lining applications. Fluorocarbon rubber (FKM) was selected as the base matrix material due to its well-established resistance to high temperatures, aggressive chemical environments, and oxidative degradation. The molecular structure of FKM, characterized by strong carbon–fluorine bonds, provides excellent thermal stability and makes it an ideal candidate for extreme operating conditions typically encountered in nuclear reactor inspection systems [11].

The reinforcing nanofillers used in this study included Multiwalled Carbon Nanotubes (MWCNTs) and Nano Graphene Platelets (NGPs). MWCNTs were selected due to their high tensile strength, cylindrical morphology, and ability to form interconnected reinforcing networks within polymer matrices. Their high aspect ratio facilitates efficient stress transfer across the matrix, thereby improving mechanical and tribological performance. Nano Graphene Platelets were chosen for their two-dimensional planar structure, exceptionally high surface area, and superior interfacial interaction potential, which enable improved load distribution and enhanced barrier properties. These nanomaterials have been widely reported to significantly enhance the performance of elastomeric systems [8–10].

Table 1: Chemical Compositions

Materials and Ingredients for compounding	Compounding ingredient function	Composition (gm)
Elastomer (FKM)	Primary material- Raw composite rubber material	50
Filler (MWCNT)	Used as reinforcing agent to enhance the property of composite material	3
Dispersing agent (SDS)	Used to uniformly disperse the reinforcing material in the composite material	2
Vulcanizing Agent (DiCumyl Peroxide)	Used to achieve final product	2

To ensure effective dispersion of nanoparticles within the elastomer matrix, sodium dodecyl sulfate (SDS) was employed as a dispersing agent. SDS acts by reducing surface tension and minimizing van der Waals attraction forces between nanoparticles, thereby preventing agglomeration and promoting homogeneous distribution throughout the matrix. In addition, vulcanization agents, including dicumyl peroxide were used to initiate cross-linking reactions, while magnesium oxide and calcium carbonate served as activators and stabilizers during the curing process [5,13].



Figure 2. Addition of Ingredients into ingredients at the rubber mix mills



Figure 3. Collection of bottom of the roller

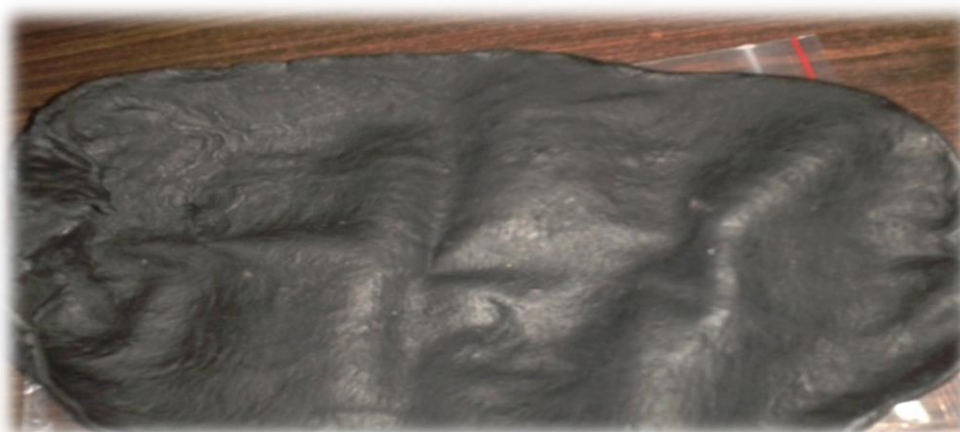


Figure 4. Blended sheet of nanocomposite material with Multiwalled Carbon Nanotube



Figure 5. Blended sheet of nanocomposite material with Nano Graphene Platelets

The fabrication of nanocomposites was carried out using a laboratory-scale two-roll open mill, which is a conventional and effective technique for elastomer processing. Initially, the FKM was subjected to mastication on the mill under controlled temperature conditions to reduce viscosity and improve processability. Mastication plays a crucial role in enhancing the plasticity of the elastomer, allowing for better incorporation of fillers and additives. Following this step, the nanofillers were gradually introduced into the softened elastomer matrix in small increments to ensure uniform dispersion. The addition process was carefully controlled to avoid sudden loading, which could lead to nanoparticle agglomeration.

The mixing process involved repeated cutting, folding, and shearing of the material to facilitate homogeneous distribution of nanofillers and additives. The presence of SDS during mixing significantly improved the dispersion quality, resulting in a uniform distribution of nanoparticles within the matrix. Once the mixing process was completed, the compounded material was sheeted into uniform thickness and allowed to rest to relieve internal stresses and stabilize the structure prior to vulcanization.

Vulcanization was performed using a compression molding technique at a temperature of 120°C under controlled pressure conditions. The curing time was maintained between 15 and 20 minutes to ensure adequate cross-linking of polymer chains. This process resulted in the formation of a three-dimensional network structure within the elastomer, enhancing its mechanical strength, elasticity, and resistance to deformation. After curing, the samples were removed from the mold and allowed to condition at room temperature for a period of 24 hours to achieve structural stabilization.

Two distinct sets of nanocomposite samples were prepared, one reinforced with MWCNTs and the other with NGPs, each at a controlled filler concentration to enable comparative analysis. Care was taken to maintain consistent processing conditions across all samples to ensure reproducibility and reliability of results.

The characterization of the fabricated nanocomposites was carried out using a combination of advanced analytical techniques. X-ray Diffraction (XRD) analysis was performed to investigate the structural characteristics and phase composition of the materials, providing insights into crystallinity and nanoparticle dispersion. Fourier Transform Infrared Spectroscopy (FTIR) was used to analyze chemical bonding and identify functional group interactions between the polymer matrix and nanofillers. Scanning Electron Microscopy (SEM) was employed to examine surface morphology and dispersion quality at the microstructural level, while Energy Dispersive Spectroscopy (EDS) provided elemental composition and distribution analysis.

Tribological performance was evaluated using a pin-on-disc apparatus under controlled experimental conditions. The tests were conducted at specified loads and sliding velocities to simulate real operating conditions. The coefficient of friction was calculated based on the ratio of frictional force to normal load, while wear behavior was assessed by measuring material loss after testing. These measurements provided quantitative data on the frictional and wear performance of the nanocomposites, enabling a comprehensive evaluation of their suitability for high-load applications [14].

III. RESULTS AND DISCUSSION

The structural, chemical, and tribological properties of the developed fluorocarbon elastomer nanocomposites were systematically analyzed to understand the influence of carbon-based nanofillers on material performance.

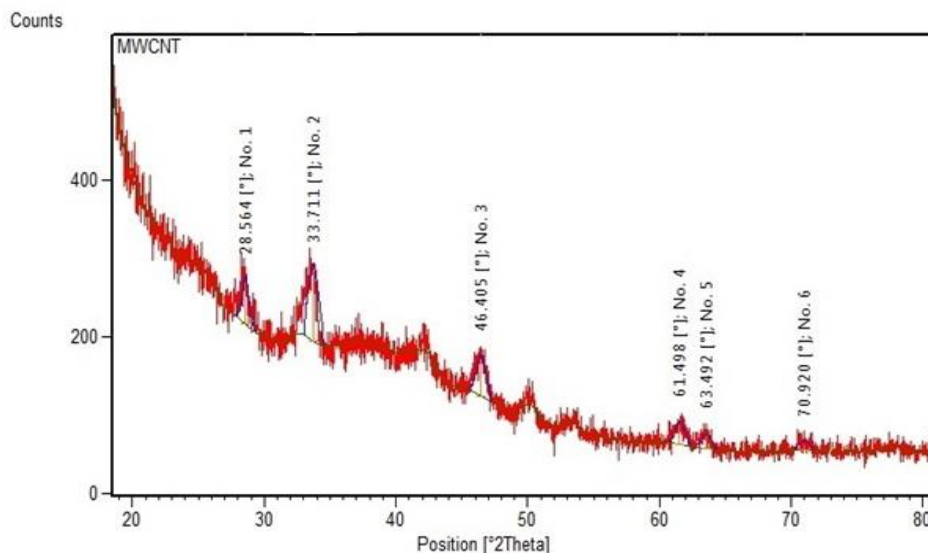


Figure 6. XRD analysis of the prepared sample

The results obtained from X-ray Diffraction analysis reveal that the pure fluorocarbon elastomer exhibits a predominantly amorphous structure, characterized by a broad halo in the diffraction pattern. This behavior is typical of elastomeric materials, where polymer chains are arranged in a disordered manner. Upon the incorporation of Multiwalled Carbon Nanotubes, distinct diffraction peaks corresponding to graphitic structures emerge, confirming the successful integration of nanotubes into the polymer matrix. In contrast, the Nano Graphene Platelet reinforced composite exhibits broadened peaks and reduced crystallinity, indicating uniform dispersion and strong interfacial interaction between graphene sheets and the polymer matrix. Such behavior has been associated with improved mechanical and tribological properties in graphene-based composites [8–10].

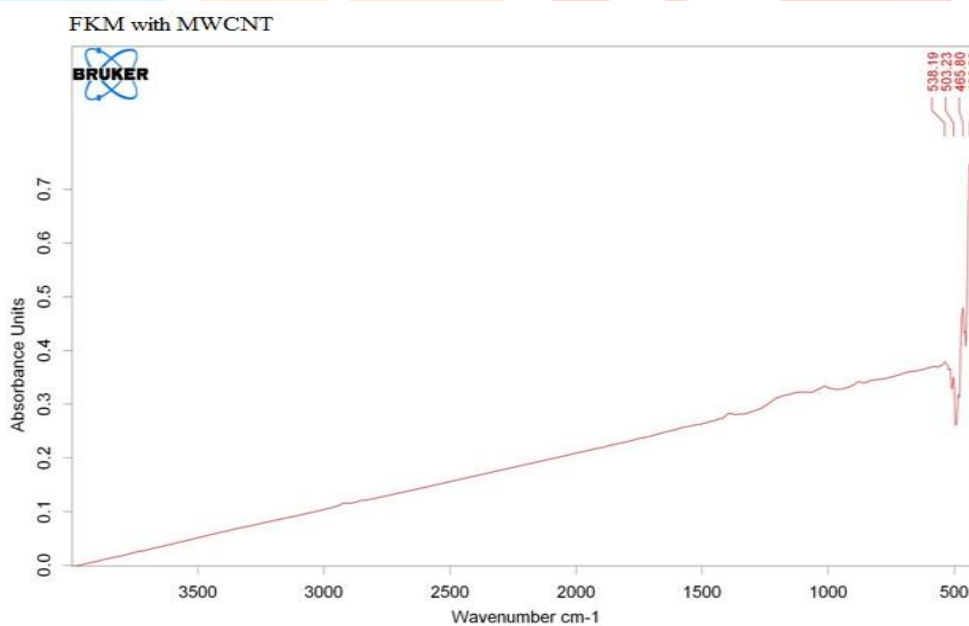


Figure 7. FTIR analysis of the prepared sample

Fourier Transform Infrared Spectroscopy analysis provides further insight into the chemical interactions within the composites. The spectrum of pure fluorocarbon elastomer shows characteristic peaks corresponding to carbon–fluorine bonds and polymer backbone vibrations. After the addition of nanofillers, noticeable changes in peak intensity and position are observed, indicating strong interactions between the polymer matrix and the nanofillers. These interactions restrict polymer chain mobility and enhance structural stability. Similar observations have been reported in previous studies on nanocomposite materials, where strong interfacial bonding contributes to improved mechanical performance [6,8].

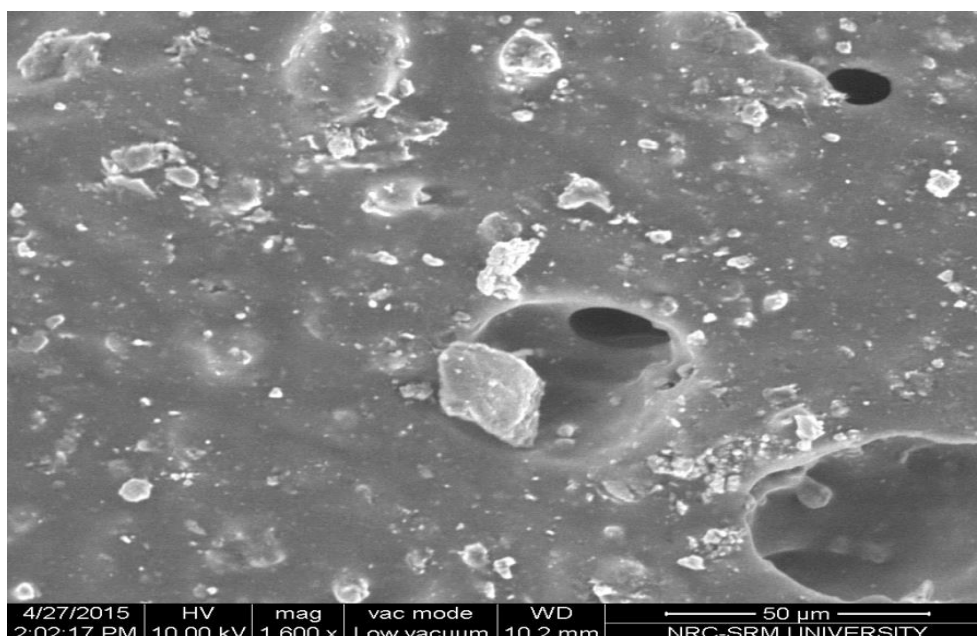


Figure 8. SEM analysis of the prepared sample

Scanning Electron Microscopy analysis reveals significant differences in surface morphology between pure elastomer and reinforced composites. The pure elastomer exhibits a smooth and homogeneous surface, whereas the nanotube-reinforced composite displays a network-like structure formed by interconnected nanotubes. This network enhances load transfer and improves mechanical strength, although some agglomeration is observed. In contrast, the graphene-reinforced composite exhibits a uniform layered structure with well-dispersed platelets. The planar geometry of graphene allows for better interaction with the polymer matrix, resulting in improved stress distribution and enhanced surface properties. The effectiveness of nanoparticle dispersion is attributed to the use of dispersing agents and controlled mixing conditions [13].

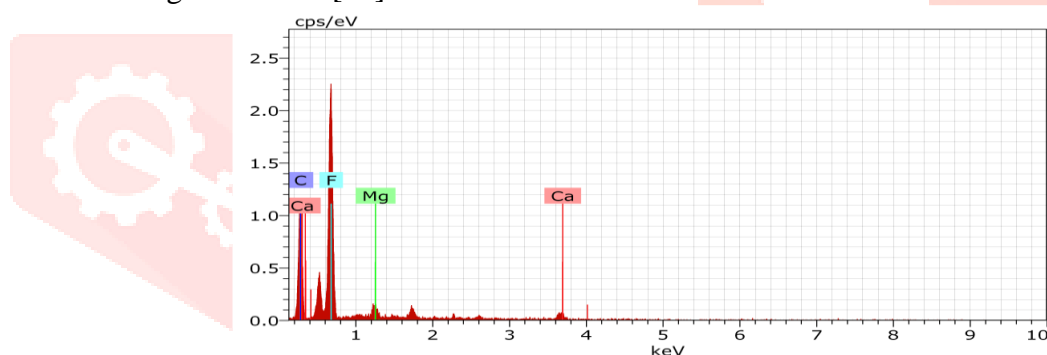


Figure 9: EDS analysis of the prepared sample

Energy Dispersive Spectroscopy confirms the presence of key elements such as carbon, fluorine, magnesium, and calcium in the composites. The increased carbon content in reinforced samples verifies the successful incorporation of nanofillers. The uniform distribution of elements indicates effective mixing and homogeneity of the composites.

Table: 2. Tabulation for Coefficient of Friction and Wear Rate

S.No.	Sample	Load (Kg)	Speed (rpm)	Normal Force, FN (N)	Friction Force, FF (N)	Coefficient of Friction, μ (no unit)	Wear Rate (mg/rev)
1.	FKM	2	150	0.6	0.174	0.29	0.22
2.	Sample 1 (with MWCNT)	2	150	0.6	0.228	0.38	0.194
3.	Sample 2 (with NGP)	2	150	0.6	0.246	0.41	0.176

Tribological testing demonstrates a significant improvement in frictional performance. The coefficient of friction increases with the addition of nanofillers, with graphene-reinforced composites exhibiting the highest values. This improvement is attributed to increased surface roughness, enhanced contact area, and strong interfacial bonding, which resist sliding motion. The results are consistent with previous studies that highlight the role of nanofillers in improving frictional properties [3,4].

Wear analysis shows that reinforced composites exhibit lower material loss compared to pure elastomer. Graphene platelets act as barriers to crack propagation and reduce wear debris formation, resulting in improved durability. Carbon nanotubes also enhance wear resistance, although to a lesser extent. The combination of high friction and low wear indicates that the developed nanocomposites are well-suited for high-load applications. Overall, the results demonstrate that carbon-based nanofillers significantly enhance the structural, chemical, and tribological properties of fluorocarbon elastomers. Graphene-reinforced composites exhibit superior performance due to their morphology and interfacial characteristics, making them suitable for robotic wheel lining applications.

IV. CONCLUSIONS

This study presents the successful development of fluorocarbon elastomer-based nanocomposites reinforced with Multiwalled Carbon Nanotubes and Nano Graphene Platelets for friction enhancement in robotic wheel lining applications. The incorporation of carbon-based nanofillers significantly improves the structural, chemical, and tribological performance of the base elastomer, demonstrating their effectiveness in high-load and high-temperature environments.

The experimental results confirm that nanoparticle reinforcement enhances interfacial interactions within the polymer matrix, leading to improved load transfer and mechanical stability. Structural and morphological analyses indicate that uniform dispersion of nanofillers plays a crucial role in achieving optimal performance. The presence of well-distributed nanoparticles contributes to improved stress distribution and reduces the likelihood of localized failure.

Tribological evaluation reveals a noticeable increase in the coefficient of friction and a reduction in wear rate for reinforced composites compared to unfilled fluorocarbon rubber. Among the investigated fillers, Nano Graphene Platelets exhibit superior performance due to their planar structure and higher surface area, which promote stronger interfacial bonding and better load distribution. Multiwalled Carbon Nanotubes also contribute to performance enhancement, although their effectiveness is influenced by dispersion quality.

Overall, the developed nanocomposites demonstrate a favorable combination of high friction, improved wear resistance, and thermal stability, making them suitable for demanding applications such as robotic inspection systems in nuclear reactor environments. The findings of this study provide valuable insights into the design of advanced elastomeric materials and highlight the potential of carbon nanostructures in enhancing tribological performance.

V. COMPETING INTERESTS

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

VI. ACKNOWLEDGMENT

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