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RESEARCH ARTICLE

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Effect of elevated temperatures on wear and frictional performance of Pineapple Leaf Fiber-Reinforced natural rubber composites with the addition of multi-walled carbon nanotubes

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Abstract

Rubber composites are often used at high temperatures, particularly in practical applications, such as autoclave components, gaskets, and seals. This study investigated the effect of elevated temperatures on the friction and wear properties of pineapple leaf fiber (PALF)-reinforced natural rubber (NR) composites with the addition of multi-walled carbon nanotubes (MWCNTs). Commercial NR composites were prepared using a two-roll mill mixing method, followed by molding. The PALF and MWCNTs contents were fixed at 30 and 10 parts per hundred rubber (phr), respectively. The frictional force, coefficient of friction (COF), and specific wear rate (SWR) were studied in the temperature ranges from room temperature (RT) to 80°C under various applied loads (5, 10, and 15 N). A significant improvement in the wear properties of the composites was achieved with increasing temperature. The results showed that the inclusion of MWCNTs effectively enhanced the wear performance of the composites at elevated temperatures. Overall, this study provides valuable insights into the friction and wear characteristics of PALF-reinforced NR composites with the addition of MWCNTs, enhancing their end-use properties for high-temperature applications.

Highlights

- Improved wear and frictional properties of NR/30PALF composites with MWCNTs.
- MWCNTs enhance heat dissipation, reducing softening at elevated temperatures.
- Frictional force and COF decreased with increasing temperature and load.
- NR/30PALF/MWCNT composites showed smoother surfaces and lower wear rates.
- Thermal stability and wear resistance of the composites were enhanced.

KEYWORDS

elevated temperature, multi-walled carbon nanotubes (MWCNTs), natural rubber composites, pineapple leaf fibers (PALF), tribological properties

1 | INTRODUCTION

Elastomers are materials that exhibit both viscous and elastic properties under deformation. They exhibit a unique ability to return to their initial shape after being subjected to stress. They are relatively soft and deformable at ambient temperatures.[1] They greatly elongate and become flexible under stress due to their weak retained forces.[2–4] They are widely used in tribology because of their excellent compression, self-lubrication, and expansion resistance.[5] Rubber products, including gaskets, dampers, and autoclave components, are frequently used at high temperatures in practical applications.[6] Natural rubber (NR) is more affordable than synthetic rubbers and has a number of benefits, including superior elasticity, resistance to abrasion, and excellent dynamic mechanical properties. In research conducted by Alam et al., NR systems show more significant improvements compared to acrylonitrile-butadiene rubber-based composites, indicating a stronger chemical interaction between carbon nanotubes and NR chains, as demonstrated by thermogravimetric, x-ray diffraction, dynamic mechanical, and thermodynamic analyses.[7] However, synthetic rubbers are more thermally resistant than NR.[8,9] In addition, the unstable double bonds in NR are prone to degradation. Their tendency to deteriorate at high temperatures results in permanent changes in their mechanical, chemical, and physical properties, which limits their performance in applications.[10,11]

The performance of elastomers has come under increasing demand due to advancements in modern technology and harsh application conditions, such as high temperatures. Traditional materials such as carbon black (CB) are commonly used to improve the properties of elastomers, including tensile strength, hardness, and wear resistance. However, the manufacture and application of CB have the potential to cause significant environmental damage and are heavily reliant on petroleum resources. Additionally, its reinforcement in rubber composites requires a high content, typically ranging from 35 to 45 phr.[5,12] García et al.[13] concluded that the mechanical properties of rubber composites reinforced with the reinforcement of multi-walled carbon nanotubes (MWCNTs) at 10 phr were comparable to those of composites containing 40 phr of CB, where the concentration of CB was much greater than that of the MWCNTs. Additionally, MWCNTs possess superior properties which effectively enhance the performance of rubber composites. They are unidimensional with excellent aspect ratios and are composed of concentric graphene cylinders bound together by van der Waals forces.[14] MWCNTs exhibit a tensile strength of up to 200 GPa, which is approximately 100 times higher than that of steel. Their density is only one-sixth that of steel. Furthermore, MWCNTs have a Young's modulus of up to 1 TPa, which is equivalent to that of diamond and approximately five times greater than steel. Despite their high hardness, MWCNTs are flexible and capable of withstanding large amounts of stretching. The MWCNTs exhibit superior thermal and electrical conductivities, with potential values of up to 6000 W/mK and 10^6 S/cm, respectively.[12] Additionally, the mass production of MWCNTs is simpler and more affordable than that of single-walled carbon nanotubes. Therefore, MWCNTs have been investigated more frequently.[15]

The use of natural fibers as reinforcements and alternatives to synthetic fibers has increased significantly. Compared with conventional synthetic fibers, lignocellulose fibers provide composites with a number of benefits, including biodegradability, renewability, low density, high stiffness, affordability, minimal health risks, and a high degree of processing flexibility.[16–19] Compared with other natural fibers available, pineapple leaf fibers (PALF) contain 81 wt.% of cellulose, which is considerably high. Cellulose is the primary ingredient that provides the fibers with strength, stiffness, and stability.[20,21] A significant proportion of the cellulose found in the PALF has the potential to create fibers that are both flexible and durable.[22,23] In this case study, MWCNTs and PALF were chosen as reinforcing fillers to create a hybrid reinforcement in NR composites.

The tensile properties and thermogravimetric analysis properties were investigated in the previous study. The results demonstrated that the inclusion of MWCNTs improved the thermal stability by decreasing the thermal degradation of the composites reinforced with 30 phr of PALF at high temperatures. In addition, the hybrid reinforcement of PALF and MWCNTs enhanced the tensile properties of NR composites at the low strain region.[23] However, this raises concern about the lifespan of the composites as temperature significantly affects the durability and characteristics of elastomers due to the inclusion of reinforcing fillers and the viscoelastic properties of the material.[24,25] Schallamach was among the earliest researchers to discover that the frictional force of rubber is dependent on both temperature and sliding velocity, rising slightly with increasing velocity and decreasing significantly with the addition of temperature.[26] This was mainly associated with the breakdown of crosslinks and partial disruption of the leading chains in the rubber matrix at higher temperatures.[27] As a result, elevated temperatures significantly affected the properties of the rubber composites.[28]

Most studies have focused on the impact of elevated temperatures on the mechanical properties, such as the tensile and fatigue properties of rubber composites.[6,24,29,30] However, few studies have examined the effect of elevated temperatures on the wear and friction properties of NR composites. Applications of NR composites that require stable and excellent wear resistance highlight the importance of understanding the impact of temperature on the friction and wear properties of NR composites. Despite the enhancement of the mechanical and physical properties, the hybrid reinforcement effect of PALF and MWCNTs on the wear and frictional properties of NR composites, particularly under elevated temperature conditions, remains underexplored. In this study, the influence of temperature has been evaluated by conducting sliding wear tests at elevated temperatures (room temperature (RT), 40, 60, and 80°C). This study aimed to elucidate the impact of hybrid reinforcement systems of PALF and MWCNTs on wear and frictional properties at elevated temperatures under varying applied loads (5, 10, and 15 N). Understanding the behavior of NR composites at high temperatures is crucial for applications requiring heat resistance and wear performance. This work aims to provide valuable insights into the potential of these hybrid reinforcements to improve wear resistance and maintain stable frictional performance under thermal stress. Engineers and industrial designers may find this knowledge helpful in choosing appropriate materials for their intended applications and increasing their life of service.

2 | MATERIALS AND METHODS

2.1 | Material preparation

Pineapple leaves were collected from a field in Changlun, Kedah, Malaysia. The scraping method was employed to extract PALF. After thoroughly cleaning the leaves, the waxy layer on the surface was scraped off using a dull tool. After extraction, the PALF was combined to remove foreign impurities. Subsequently, the fibers were dried for 48 h at RT to remove moisture. Following drying, the PALF was chopped into grains with an average size of 6 mm.

Table 1 lists the properties of raw materials and rubber additives used in this study. Rubber additives act as curing agents in rubber systems to activate vulcanization. Zinc oxide (ZnO) and stearic acid were employed as activators for the sulfur vulcanization system, and N-cyclohexyl-2-benzothiazole sulfonamide (CBS) was used as an accelerator for the sulfur curing agent.[31]

2.2 | Preparation of natural rubber composites

A two-roll mill was employed to create NR compounds reinforced with PALF and MWCNTs following the formulation and mixing schedule described in Table 2. In the previous study, the impact of PALF loadings on the wear properties of NR composites was investigated. The findings suggested that the composite reinforced with 30 phr of PALF with the inclusion of MWCNTs exhibited better wear performance.[32] Thus, the PALF content is fixed at 30 phr in this case study. As shown in Table 2, each component was successively introduced into the internal mixer and blended for an allotted amount of time. However, this variation may influence the homogeneity of the ingredients in the NR compounds. The NR compounds were vulcanized using a hydraulic compression molding press machine (SCM-150, Santec Exim, India) at 150°C under a clamping pressure of 10 t according to the corresponding optimum cure time.

TABLE 1 Raw materials and rubber additives properties.

Materials	Properties	Source
NR	Grade SMR CV 60	GMR Trading Sdn. Bhd.
ZnO	Activator	A. R. Alatan Sains Sdn. Bhd.
Stearic acid	Activator	A. R. Alatan Sains Sdn. Bhd.
Sulfur	Vulcanising agent	A. R. Alatan Sains Sdn. Bhd.
N-cyclohexyl-2-benzothiazole sulfonamide (CBS)	Accelerator	Sou Bond Sdn. Bhd.
MWCNTs	Black powder, 99.9% pure	BT Corp Generic Nano Private Ltd

TABLE 2 Formulations and mixing sequence for natural rubber compounds.

Ingredients	Quantity (phr)	Mixing sequence (min)
NR	100	10
PALF	30	3
MWCNTs	0, 10	4
ZnO	5	2
Stearic acid	2	2
Sulfur	4	2
N-cyclohexyl-2-benzothiazole sulfonamide (CBS)	1	2

2.3 | Characterization

A pin-on-disc tribometer (K93500; Koehler, USA) was used to evaluate the wear and friction properties of the composites. Under loaded conditions, the specimen was placed in contact with a rotating steel disc. The tribometer operates on a rotating mechanism that provides controlled and repeatable testing conditions. Specimens 16 mm in diameter and 10 mm in thickness were prepared. The initial weight of each specimen was recorded. The counterface discs were cleaned with acetone and dried to remove debris and contaminants before testing. The test disc was composed of hardened ground steel (EN31) with a hardness of 60 HRC. The tests were performed under three normal loads of 5, 10, and 15 N. Each test was conducted for 360 s. The sliding speed was maintained at 40 revolutions per minute (rpm), and the total sliding distance covered during each test was 60 m.

A hole was drilled in the specimen holder, and a temperature sensor was inserted into the drilled hole to detect the temperature changes in the specimens. After the specimen was mounted onto the pin holder, the temperature sensor was securely positioned in the drilled hole to detect the temperature changes accurately during the test. Subsequently, the heating system was activated, and the specimen was heated to the testing temperatures (40, 60, and 80°C) while monitoring the temperature displayed directly from the instrument. The specimens were maintained at a stable temperature prior to the sliding wear tests. The pin-on-disc contact configuration is shown in Figure 1.

Following the sliding wear test, a high-precision analytical balance (Ningbo Yinzhou Qun'an Experimental Instrument Co., Ltd., JAB 2204 N) was used to record the weight loss of specimens. The instrument presented the coefficient of friction (COF) and tangential friction forces directly. The weight loss was recorded to calculate the specific wear rate (SWR) using the following equation:

$$\text{Specific wear rate (SWR)} = \frac{\Delta m}{\rho_r L F_n}, \quad (1)$$

where Δm is the mass loss during the test (g), ρ_r is the density of the NR composite (g/mm^3), L is the sliding distance (m), and F_n is the normal load (N).

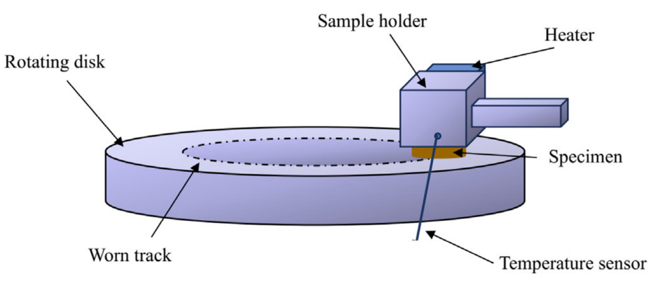

FIGURE 1 Instrumentation representation of sliding wear test.

3 | RESULTS AND DISCUSSION

3.1 | Wear properties

The evolution of frictional force during the sliding of the specimens under different applied loads at elevated temperatures is illustrated in Figures 2–4A,B to further compare the wear and frictional properties of the NR composites with different compositions.

Due to their unique surface chemistry and low elastic moduli, elastomers exhibit complex wear and friction properties.[33] All composites exhibited a rapid increase in the frictional force during the first stage, followed by a steady decline and stable values at all temperatures. At the initial stage, the deformation of the specimen due to rubbing between the contacting surfaces contributed to the elevation of the frictional force. Consequently, material deformation results in the generation of a transfer film between the contacting surfaces. The transfer film acts as a lubricating layer between the contacting surfaces, leading to reduced frictional resistance, followed by a gradual decrease in the frictional force. The generation of the transfer film smoothed the remaining debris between the contacting surfaces, resulting in a stable frictional force.[34,35]

The frictional force evolutions at elevated temperatures under varying applied loads of NR/30PALF composite are presented in Figures 2A–4A. The frictional force showed a decreasing trend with increasing temperature up to 80°C. At higher temperatures, the softening of the rubber matrix reduced the hardness of the specimens. This modified the lubricating conditions occurring at the sliding interface, reducing the frictional force at the same applied load.[33,36] Additionally, it was observed that an increase in the frictional force was associated with the addition in the applied load. As the specimens were subjected to greater deformability at higher loads, this was attributed to the larger frictional force.[37] The results indicated that the applied loads and frictional forces were proportional.

Figures 2B–4B illustrate the frictional force evolution at elevated temperatures under varying loads of the NR/30PALF/MWCNT composites. In comparison, it is observed that the frictional force values from 40 to 80°C decreased relative to those at RT due to the softening effect of the specimens at higher temperatures.[33] This reduced the overall stiffness and hardness of the composite, as the deformation of the material was greater under the load. Additionally, the frictional force tended to be closer for NR/30PALF/MWCNT composites, along with the increment of temperature from 40 to 80°C at all applied loads. This indicated that the frictional behavior of the composite was consistent even at high temperatures. Because MWCNTs have high thermal

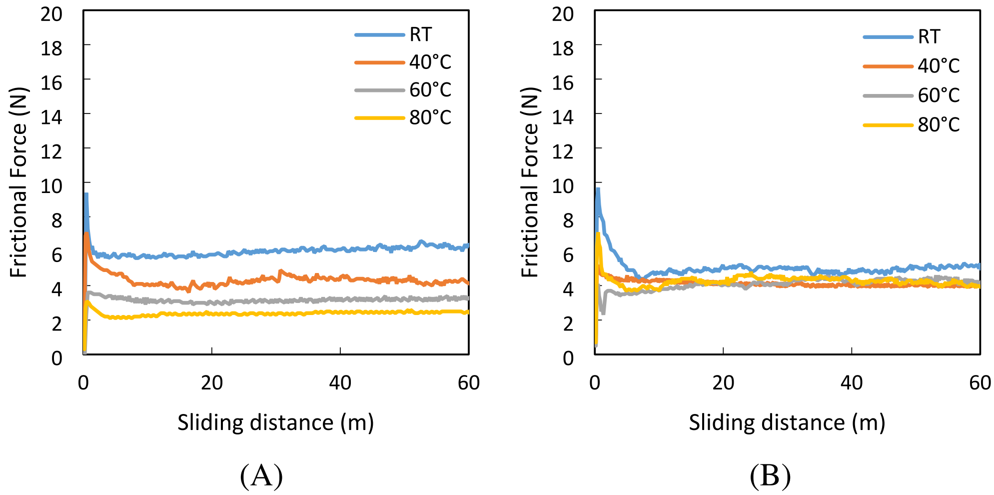

FIGURE 2 Frictional force versus sliding distance of (A) NR/30PALF and (B) NR/30PALF/MWCNT under an applied load of 5 N at elevated temperatures.

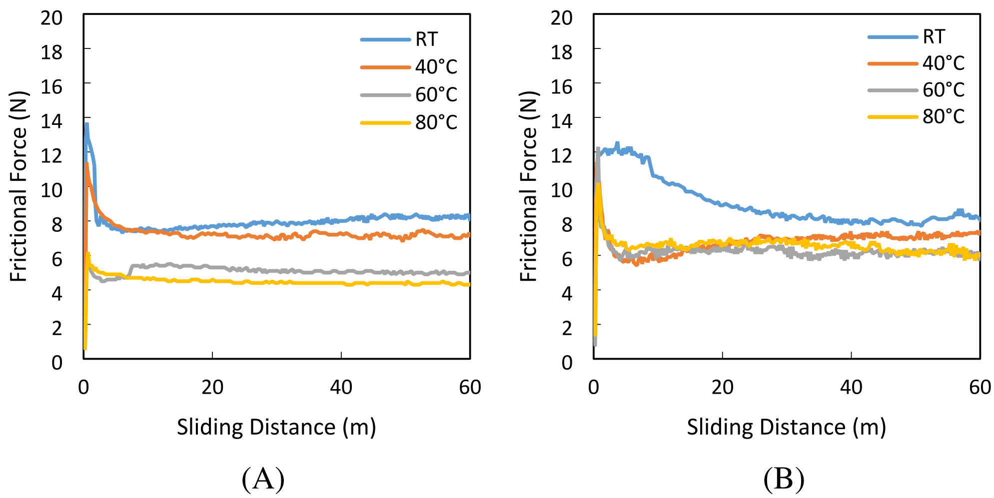

FIGURE 3 Frictional force versus sliding distance of (A) NR/30PALF and (B) NR/30PALF/MWCNT under an applied load of 10 N at elevated temperatures.

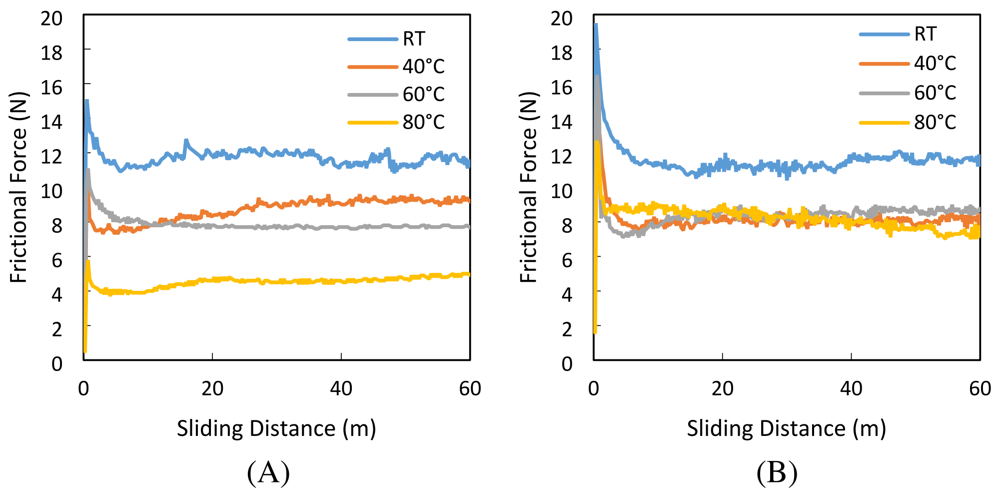

FIGURE 4 Frictional force versus sliding distance of (A) NR/30PALF and (B) NR/30PALF/MWCNT under an applied load of 15 N at elevated temperatures.

conductivity, they enhance heat dissipation and thus decrease heat build-up at higher temperatures.[38,39] This finding is in accordance with the thermogravimetric analysis properties from the previous study, where the presence of MWCNTs enhanced the thermal stability of the composites. This was associated with the acceleration of the rate of heat transfer owing to the high specific areas of MWCNTs.[23] This demonstrates that the inclusion of MWCNTs in the composite improves heat resistance at higher temperatures, which can effectively enhance wear resistance and service life.

In summary, the results show that temperature and applied load have a significant impact on the wear and frictional behavior of the NR composite. These findings suggest that the inclusion of MWCNTs prevented localized overheating, improved heat dissipation, and enhanced the resistivity of the material to wear and deformation at higher temperatures, leading to more uniform frictional forces across different elevated temperatures. The comparisons between NR/30PALF and NR/30PALF/MWCNT composites highlight the role of MWCNTs in enhancing wear resistance and stabilizing frictional behavior at elevated temperatures.

The variation in the applied load on the COF of the PALF-reinforced NR composites with the inclusion of MWCNTs at elevated temperatures is shown in Figure 5A,B.

It is widely known that the *COF* is generally less than 1 for most materials. In contrast to rigid materials, rubber comes in contact with other surfaces and can yield COF values ranging from 1 to 2. When the value of the COF is above 1, more force is required to slide an object along the surface than the normal force of the surface acting on the object.[40] This is attributed to a relatively large adhesion friction.[41]

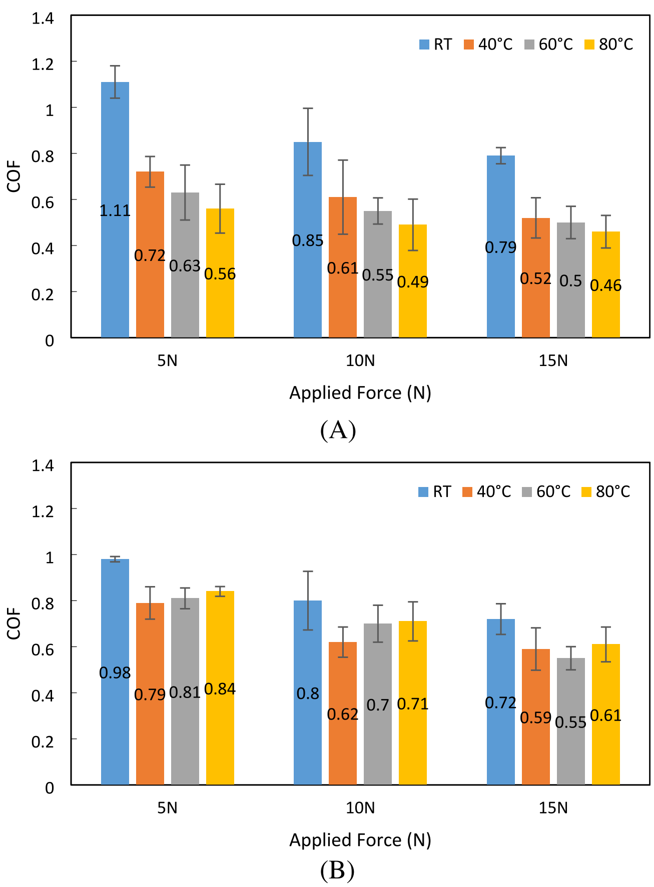

FIGURE 5 COF of (A) NR/30PALF and (B) NR/30PALF/MWCNT at elevated temperatures under varying applied loads.

As shown in Figure 5, the COF gradually decreased as the applied load increased. At a low load (5 N), the interfacial bonding between the NR specimens and the counterpart surface remained largely intact. As a result, the friction between the contacting surfaces increased.[34] The COF of the composites was considerably high at lower loads because of the strong interfacial adhesion, and the bonding could not be broken successfully. This enhanced friction between the specimen and the counterpart surface, which led to a higher COF at a low load.[35] At 15 N, the frictional heat accumulates, followed by the softening of the rubber matrix. This phenomenon reduced the frictional resistance of the specimens during sliding. Consequently, higher applied loads lowered the frictional resistance on the surfaces of the specimens and further decreased their COF.[42,43]

At all applied loads, the COF values of the NR/30PALF/MWCNT specimens at high temperatures were more consistent because the variability of the COF was lower than that of the NR/30PALF specimens. The inclusion of MWCNTs prevented local heat build-up in the specimens, which weakened the rubber matrix and provided multiple pathways for heat diffusion during the sliding process. Due to the outstanding thermal conductivity of the MWCNTs, the degree of softening of the rubber matrix was reduced at higher temperatures.[43] This indicates that MWCNTs significantly affect the COF of the NR composites at elevated temperatures by playing a crucial role as a high-temperature-resistance additive.[42,44] This was attributed to the enhanced wear resistance of the composites, even at high temperatures.

In comparison, the effect of elevated temperature was more evident for the NR/30PALF composite. Under the same applied load, the COF steadily decreased as the temperature increased. The heat accumulated in the specimens could not be quickly dissipated because of the poor thermal conductivity of the rubber matrix. This resulted in the softening of the rubber matrix. Continual sliding further increased the heat generation, which caused the softening of the rubber matrix to a higher degree.[42,45] Additionally, the adhesion between the contacting surfaces was reduced, which improved the lubrication effect. This contributed to the generation of a continuous transfer film during sliding. Consequently, this phenomenon reduces the wear resistance, and the COF value is lower than that of the NR/30PALF/MWCNT composite.

In summary, the findings show that the temperature and applied load have a significant impact on COF behavior. The drop in the COF values of the NR/30PALF composites at higher temperatures was primarily due to the thermal softening of the NR matrix. This contributes to a lower resistance to sliding, resulting in a drop in the COF as the temperature increased. The inclusion of the MWCNTs enhanced the thermal conductivity of the composites, contributing to their superior heat dissipation as the temperature increased. The stable COF values along with the increment of temperature suggested that the MWCNTs were effective in maintaining the wear and frictional properties of the composite across a range of temperatures. These results demonstrate the synergistic effect of PALF and MWCNTs, particularly in maintaining wear performance at elevated temperatures, which is essential for high-performance and environmentally sustainable NR composites. This greatly enhanced the wear and frictional properties of the NR composites.

The SWR of the NR composites prepared in 30 phr of PALF with the inclusion of MWCNTs at elevated temperatures is illustrated in Figure 6.

The SWR of the composite raised exponentially with an increase in applied load. During the sliding test, the asperities on the surfaces of the specimens were rubbed. Shearing stress caused molecular chain breakage, increasing mass loss. The softening effect on the specimen surface at high loads was responsible for increased mass loss when the load surpassed 5 N.[46] Previous study showed that the inclusion of MWCNTs enhanced the hardness of NR composites.[23] Owing to the reinforcing effect of MWCNTs, it was possible to build a structure inside the matrix to support the composite and strengthen its bonding strength and hardness.[43] Thus, the SWR of the NR/30PALF/MWCNT composites is lower than that of the NR/30PALF composite under all conditions.

The SWR increased gradually for both the NR/30PALF and NR/30PALF/MWCNT composites as the temperature increased at all applied loads. This is due to the softening of the NR matrix at higher temperatures. The increased frictional heating between the contacting surfaces reduced the viscoelastic contribution during sliding.[47] This reduced the hardness, making the specimens more vulnerable to wear under sliding conditions. Therefore, it is more difficult for the specimens to resist wear deformation at higher temperatures, leading to an increased SWR.

In comparison, the inclusion of MWCNTs effectively reduces the SWR of the composites. Based on the previous study, the NR/30PALF/MWCNT showed a significant improvement in hardness where it exhibited 62.8 Shore A.[23] The high hardness of the NR/30PALF/MWCNT contributed to its greater resistivity against the applied stress, which decreased the real contact area and delayed the frictional force. Additionally, the self-lubricating capability of the MWCNTs reduced wear deformation.[43] Because MWCNTs have high thermal conductivity, heat is dissipated more effectively during sliding, and the thermal degradation of the NR matrix is reduced.[38,39]

In contrast, the NR/30PALF/MWCNT composites exhibited a lower SWR than the NR/30PALF composites due to the reinforcing effects of the MWCNTs, such as high thermal conductivity and high hardness. These characteristics contribute to the enhanced heat dissipation and reduced thermal degradation of the NR matrix during sliding at elevated temperatures. This indicates the effectiveness of MWCNTs as a hybrid reinforcement material in enhancing the tribological performance of NR composites, making them more suitable for high-temperature and high-load applications. The NR/30PALF/MWCNT composite demonstrated better resistance to the wear mechanism, indicating its suitability for applications involving higher loads and elevated temperatures.

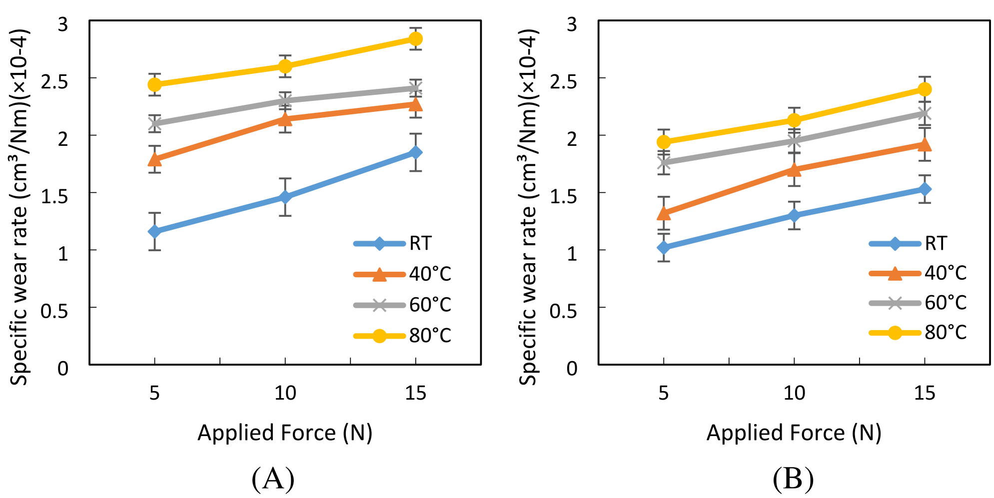

FIGURE 6 Specific wear rate of (A) NR/30PALF and (B) NR/30PALF/MWCNT at elevated temperatures under varying applied loads.

3.2 | Microscopic analysis

The worn surface morphologies of the NR composites reinforced with 30 phr PALF with the inclusion of MWCNTs under 15 N at elevated temperatures are illustrated in Figures 7 and 8A–D. Worn surface morphologies are used to analyze the wear and grooves generated during the sliding process and provide insight into the wear and friction behaviors of materials during wear deformation.[33]

Under a high load (15 N), frictional heat generated by contact compression and shearing stresses between the contacting surfaces softened the NR matrix to a certain extent. This is attributed to increased friction heat and delayed friction under high loads. Consequently, the specimens became softer, more compressed, and deformed. The adhesive slip of the specimens due to the significant delayed frictional forces caused the generation of adhesive layers on the worn surface. Additionally, the PALF dispersion in the NR matrix exhibited a random orientation. Several fibers were drawn from the surface during the wear process. At elevated temperatures, PALF tips exhibited wear and breakage. Therefore, it can be concluded that the attachment of multiple debonded PALF to the wear surface of the NR composite is the primary cause of abrasive wear during the friction and wear processes. As sliding continued, slight fatigue wear occurred.[43]

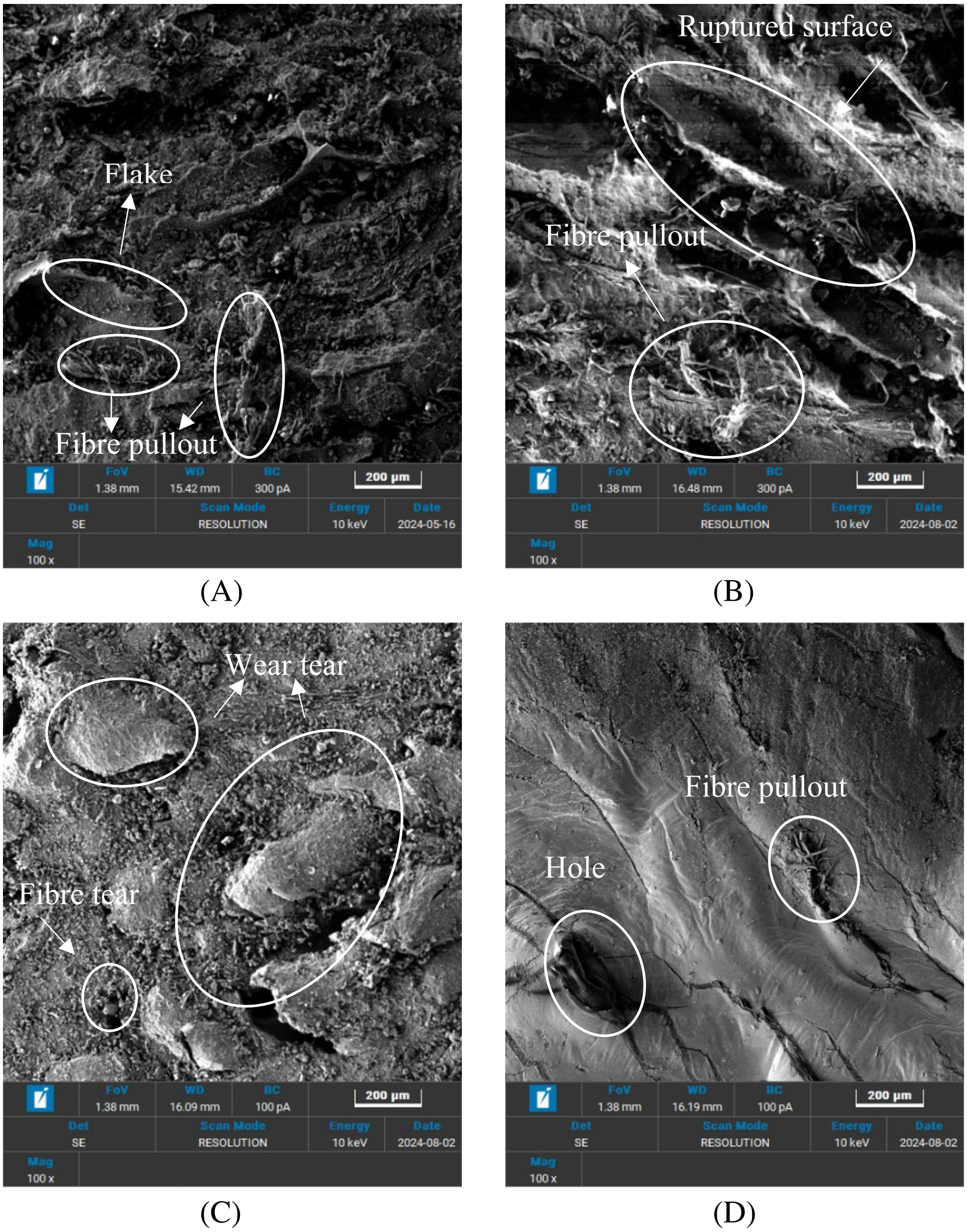

FIGURE 7 Worn surface morphologies of NR/30PALF under 15 N at (A) RT, (B) 40°C, (C) 60°C, and (D) 80°C.

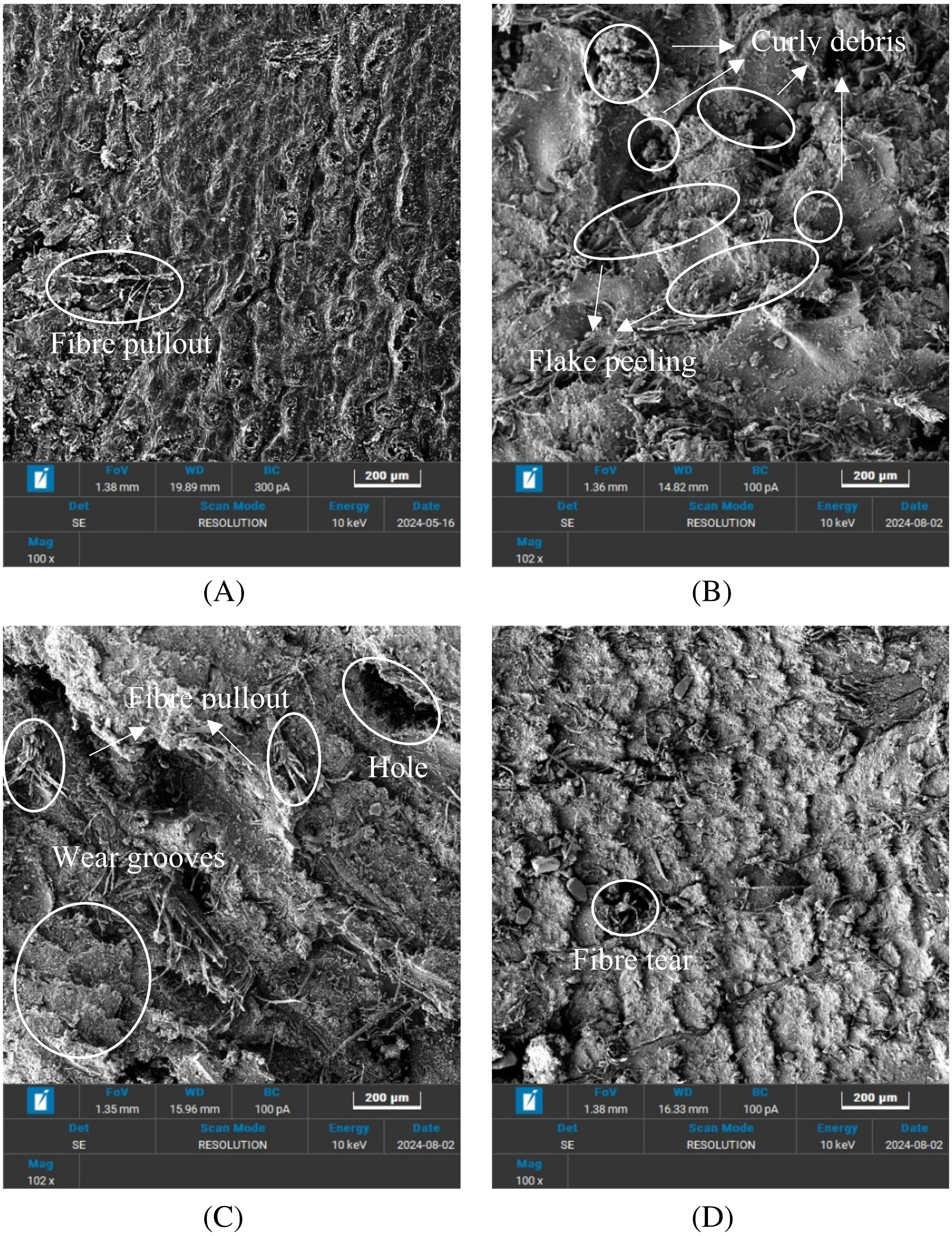

FIGURE 8 Worn surface morphologies of NR/30PALF/MWCNT under 15 N at (A) RT, (B) 40°C, (C) 60°C, and (D) 80°C.

Figure 7A–D illustrate the worn surface morphologies of the NR/30PALF composites under a 15 N load at elevated temperatures. Owing to the adhesion and cyclic shearing actions, the NR matrix gradually loses its resistance to shearing activities throughout the sliding process, and fine fatigue fractures continually develop on the surface. Under continuous cyclic friction, the fine cracks spread and eventually connect. This resulted in the formation of wear debris.[42] The NR was torn and plastically deformed by continuous sliding, which eventually caused the materials to peel, illustrated in Figure 7A,C. Subsequently, the continuous erosion exhibited by the NR matrix under frictional stress results in surface rupture, as shown in Figure 7B.[43] Cracks developed uniformly on the specimen's surface when the temperature was elevated to 80°C, as observed in Figure 7D. This suggests that significant wear occurred on the surface during sliding.[48]

Figure 8A–D illustrate the worn surface morphologies of the NR/30PALF/MWCNT composites under a 15 N load at elevated temperatures. An almost neat surface morphology can be observed in Figure 8A. This was associated with the inclusion of MWCNTs, which promoted the generation of continuous transfer films between the contacting surfaces. The lubricant film protects the material from additional wear loss by reducing the direct contact area.[33,48] The wear surface presented typical curly wear debris and a few flake materials due to the severe abrasive wear during the deformation process, as shown in Figure 8B. The abrasive action that occurred during the sliding process resulted in localized material removal, creating holes in the wear surface, as shown in Figure 8C.[43] At higher temperatures (80°C), the NR matrix softened as a result of friction-heat accumulation followed by the formation of a series of parallel ridges on the surface of the specimen, as observed in Figure 8D. This suggests that the specimens underwent fatigue and adhesive wear throughout the friction process.[42]

The NR/30PALF/MWCNT composites exhibited a better-worn surface morphology than the NR/30PALF composite at elevated temperatures. The NR/30PALF/MWCNT composites exhibited a lighter degree of wear due to the reinforcing effect of the MWCNTs. The MWCNTs act as a solid lubricant, promoting the generation of continuous transfer films between the contacting surfaces. The ability of the MWCNTs to lubricate themselves contributes to a smoother wear surface. The developed lubricating layer further decreased the contact area and shielded the material from additional wear loss. The inclusion of the MWCNTs provided several conduction paths for heat diffusion, which reduced the softening effect of the NR matrix at higher temperatures. Subsequently, the excellent thermal conductivity of the MWCNTs played a role in heat dissipation and prevented heat accumulation, which deteriorated the NR matrix. This enhanced the thermal stability and decreased the thermal degradation of the NR matrix at elevated temperatures.[33,41,43]

In contrast, the microscopic analysis underscores the critical role of MWCNTs in enhancing the tribological performance of PALF-reinforced NR composites, especially under elevated temperatures. The inclusion of MWCNTs enhanced the wear performance of the NR composite due to its exceptional hardness, excellent thermal conductivity, and self-lubricating ability. These factors collectively contributed to the superior wear resistance and surface quality of the NR/30PALF/MWCNT composites under high-temperature conditions, making them suitable for high-temperature applications requiring reliable wear performance.

4 | CONCLUSION

In this study, the wear and frictional properties of NR composites reinforced with 30 phr PALF and MWCNTs were studied at elevated temperatures. This study highlights the enhanced wear and frictional performance of PALF-reinforced NR composites with the inclusion of MWCNTs under elevated temperatures. The COF and frictional force gradually decreased as the temperature increased at all applied loads. With the inclusion of MWCNTs, the frictional force and COF were more stable at higher temperatures, with values converging more closely. The SWR of the composites with MWCNTs decreased under all conditions. Because MWCNTs possess high thermal conductivity, this contributes to the successful heat dissipation of the NR matrix. Thus, the reinforcement of MWCNTs in the NR composites enhanced their wear and frictional properties. These results imply that the NR/30 PALF/MWCNT composites are more suitable for high-temperature applications, where consistent frictional behavior and resistance to wear are critical. This work offers insightful information into the potential of hybrid reinforcements in improving the wear performance of NR composites.

The scalability of the composite fabrication method for industrial applications is an important consideration. While MWCNTs are relatively costly, their loading in the composite is optimized to balance performance enhancement and cost-effectiveness. Additionally, advancements in large-scale MWCNT production and dispersion techniques are progressively reducing their cost, making their use in industrial applications more feasible. Furthermore, the processing techniques used in this study are compatible with conventional rubber composite manufacturing methods, ensuring that the fabrication process remains scalable.

AUTHOR CONTRIBUTIONS

M. J. M. Ridzuan, Yeo Yi Xuan, M. S. Abdul Majid, and M. T. A. Rahman designed the manuscript and performed all the tests and data analyses. Noraini Marsi and Mohd Hafis Sulaiman designed and revised the manuscript. All authors discussed the methods and results and reviewed the manuscript.

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FUNDING INFORMATION

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The datasets generated and/or analyzed in the current study are available from the corresponding author upon reasonable request.

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