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Analysis of Nanocarbon Effect on Polymer Composite Tribological Properties

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Abstract

Present work aims to analyze the effect of including carbon-based nano materials in the thermosetting polymer based composite in terms of their tribological properties based on critical assessment of several literature data in this field of research. In particular, nanocarbon materials such as carbon nano tubes (CNT), graphene oxides (GO), and graphene are effectively being incorporated in to various polymers as a reinforcement agent to develop polymer nanocomposite based brake pad material. Phenolic and epoxy resins are found to be the most popular thermosetting polymers in practice and research for brake pad material development. Accordingly, the role of nanocarbon which is responsible for the stable coefficient of friction and reduced wear rate due to its inclusion in to phenolic and epoxy resins-based polymer composite have been studied in the present work. As per the present meta-analysis of tribological properties for nanocarbon based phenolic and epoxy resins polymer composite, the analyses showed that an average of around 65% specific wear rate reduction using 5 wt% graphene inclusions in the phenolic based polymer composite as compared to the 5 wt% graphite-based phenolic polymer composite. While in other case a wear rate reduction of 70%, 85%, and 94% were also achieved using 1.5 wt% CNT, 5.3 wt% graphene, and amino treated 0.2 wt% GO respectively in epoxy resin-based polymer composite as compared to pure epoxy resin in all the cases. Moreover, nanocarbon potential in reduction of wear rate for both phenolic and epoxy resin based nanocomposites are found practically evident while maintaining the stable coefficient of friction. Finally the nanocarbon found to be highly potential in affecting the tribological properties with limited amount addition in both phenolic and epoxy polymer composites, while at the same time it is also found that the nanocarbon effect may not pop up in same way when many ingredients added in the phenolic and epoxy polymer composites.

Keywords: Nanocarbon, phenolic resin, epoxy resin, COF, wear rate

1. Introduction

Tribology deals with the science and engineering of the contact mechanics of interacting surfaces in relative motion for moving devices, which is basically a concerned phenomenon of friction, wear and lubrication [1]. Tribology in brake pad material (BPM) is a phenomenon of interacting surfaces in relative motion between brake pads and the counterpart brake disc in the disc brake system, and similarly relative motion between brake pads and drum in the drum brake system. But in present study only disc brake system is emphasized and discussed, so BPM is a key component in disc brake system which is a crucial component in transportation systems as well as industrial equipments for the function of decelerating the system motion or stopping the relative motion in the system entirely through friction created between the two mating parts interfaces in presence or absence of lubricant, which is a known tribological phenomenon. Friction is the resistance to motion of a system generally occurred at the sliding interface between brake pads and disc during the application of brake. To create friction in the system, normal applied load is needed to push brake pads against the rotating disc, once they come into contact the torque is generated at the brake pad/disc friction interface and due to that frictional force comes into picture which potentially acts in the opposite direction to the disc motion as per the relation in Eq. 1, and Fig. 1 shows the schematic illustration of the situation. The torque capacity per brake pad can be computed using following equation:

$$T = \mu F_N r_e = F_F r_e \quad (1)$$

where T= Torque in (Nm), μ is coefficient of friction (COF) created at pad/disc interface, F_N is the actuating force, which is the same as normal force, F_F is frictional force, and r_e is the effective radius of rubbing path and can be computed using Eq. 2, where r_i is the inner radius of the rubbing path and r_o is outer radius of rubbing path.

$$r_e = \frac{r_i + r_o}{2} \quad (2)$$

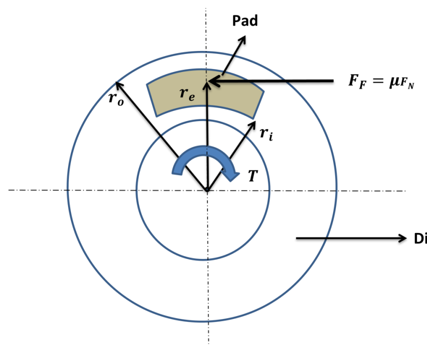

Fig. 1 Illustration of brake torque and COF at the brake pad/disc interface

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The friction created at the interface can be quantified by a numeric parameter based on a measure of friction property called COF, which is determined by a ratio of frictional force (F_F) and normal applied load (F_N) acting on the specimen as per the relation in Eq. 3 [2].

$$COF = \mu = \frac{F_F}{F_N} = \frac{T}{F_N r_e} \quad (3)$$

The friction created at the sliding interface is a principal cause of another phenomenon of tribology called as wear. Wear is the surface damage or removal of material from brake pad surface during frictional interaction with rotating disc. In general, wear analysis performed using a relation given by Archard, and is often known as Archard wear equation or Archard law as presented in Eq. 4 [3].

$$V = k\frac{F_N S}{H} \quad (4)$$

Where V is the wear volume (mm^3), k is an Archard proportional constant or Archard wear coefficient, S is sliding distance (m), F_N is the normal applied load (N), and H is the hardness of the sample (Pa).

Furthermore, the wear of the material can also be determined by measuring the weight difference before and after the material tests for the friction event, known as wear loss in gram (gm). However, the most popular wear property measurement is expressed by a measure of material removal through numerical quantification known as specific wear rate, for which the relation is presented in Eq. 5 [4].

$$W = \frac{m_1 - m_2}{\rho F_N S} \quad (5)$$

Where W is the specific wear rate (mm^3/Nm), m_1 is the initial mass of the specimen (kg), m_2 is the final mass of the specimen (kg), ρ is the density of the composite (kg/mm^3), F_N is the normal applied load (N), and S is the sliding distance of specimen (m).

Moreover, the practical objective of tribology in BPM is to reduce the wear as much as possible and keeping moderately high COF value range with stability under the system operating conditions for the intended application. It is a misconception that every frictional application based material should have lower COF and lower wear rate, actually it depends on the type of practical applications. For instance, BPM should have critical combination of COF and wear rate properties which can provide high friction and low wear at the same time as compared to other frictional applications as illustrated in Fig. 2 [5,6].

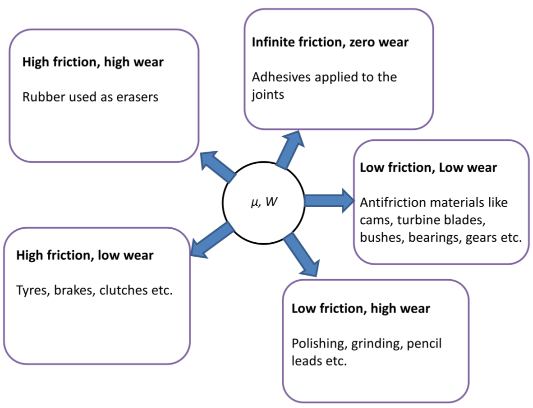

Fig. 2 Frictional-applications with desired combinations of friction and wear.

In order to provide the required tribological performances of BPM during the real application, its material selection and development is a crucial aspect to be considered in the beginning. BPM based on polymer composite have multiple ingredients and each ingredient properties have significant contribution in overall property of the polymer composite. The polymer binder materials, due to their light weight, resistance to corrosion, lower energy consumption, ease of manufacturing, better for less noise, and low cost have important research value in the development of polymer composite based BPM as compared to metallic and ceramic matrix composites [7,8].

Among polymers, thermosetting polymers commonly phenolic resin found as a good historical and current research utility material for BPM development and other frictional application such as clutches and bearings [9,10]. Additionally, another thermosetting polymer, epoxy resin has also received a great attention from researchers due to its potential prospect to be used for friction based applications.

2. Current Industry Challenges and Research Gap

Pure resins alone for frictional components including BPM remains a challenge due to their inherent disadvantages, as it is not satisfying the current functionality needs in the field of BPM development. The pure resin material have compromised properties such as low mechanical strength and high brittleness for the case of phenolic resin, low resistance to heat for epoxy resin, and generally they possess worse tribological properties, makes them unfit for frictional component development [11]. As a consequence, the resins are incorporated with other multi constituents, where resins act as a binder and multi constituents may include various classes of fiber reinforcements, functional and inert fillers, abrasives and lubricant modifiers [12]. The current industry challenges and research gap is to design and optimize material for friction components which can provide stable COF and reduced wear rate with enhance self-lubricating capabilities using polymer-based asbestos free material. Therefore through present meta-analysis work it is tried to provide comprehensive insights for the capability of nanocarbon as a property enhancer with its low percentage inclusion in the phenolic/epoxy resin-based nanocomposites. Polymers alone have its own characteristics which are not satisfactory for BPM and hence its composite form with certain additive materials found to be beneficial for BPM development as shown in Fig. 3. The specific drawback can be tackle separately such as inclusion of fiber for low strength and inclusion of modifiers and fillers for low frictional and thermal resistance.

Nowadays the real frictional component development uses around 10 to 15 ingredients to produce satisfactory application based component [6]. On the other hand, this much variety of constituents in friction material development potentially remains a paramount concern due to its balance in optimized composite formulations, which can yield desired tribological and other required properties.

Following the increasing demand for better tribological properties, several ingredients were introduced to enhance the required properties in the past, and still there is continuing search of new multifunctional nanomaterials as an effective additive in the polymer-based composites for various polymers including phenolic and epoxy resins. Moreover, it is found that the introduction of carbon nanomaterials as an additive in polymer-based composites have preferred potentials for tribological property enhancements such as better COF stabilization and wear rate minimization capability, because of its inherent properties including large surface area, high mechanical strength, and better thermal stability [13]. Therefore, in present study the current scientific advances developed to enhance COF and minimize wear rate properties using nanocarbon in phenolic and epoxy resins based nanocomposite materials have been analyzed and presented here onwards in the next sections.

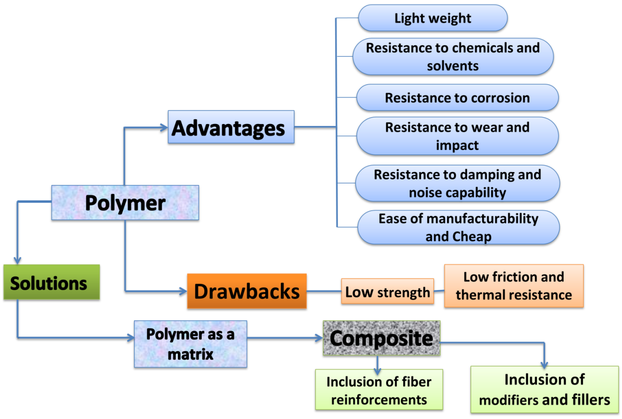

Fig. 3 Advantages, disadvantages and recommended solutions to overcome drawbacks of potential polymers.

3. Nanocarbon Effect on Phenolic Composite Tribological Properties

Nanocarbon materials such as CNTs, GO and graphene incorporation in phenolic resin-based composite found to have significant impact on wear rate reduction and COF stabilization. Hwang and coworkers investigated the tribological properties of a developed BPM through addition of multi walled carbon nano tubes (MWCNT) in phenolic resin binder with other ingredients, and on analyzing the results they found that a decrease of COF from 0.53 (for 0 wt% MWCNT) to 0.38 (for 8.5 wt % MWCNT) with better stability. Simultaneously, the specific wear rate was reduced from $3.3 \times 10^{-3}\, mm^3/Nm$ to $1.7 \times 10^{-3}\, mm^3/Nm$ using 8.5 wt% MWCNT as compared to that of the composite without MWCNT [14]. Zhang et al. have also confirmed that addition of 6 wt% of CNT in phenolic composite achieved the reduction of COF and wear rate by around 20% and 40% respectively compared to carbon fiber reinforced phenolic composite [15]. The addition of CNT nano additive in phenolic resin based composite can potentially increase the strength and surface hardness, which can play crucial role in supporting higher load as that provides reinforcement effect, and helps to reduce wear rate of the part made by this kind of composites significantly. Moreover, higher thermal conductivity value of CNT can also increase the thermal conductivity value of the phenolic based composite material, thereby improve the heat dissipation capability generated during friction process at the interface of sliding materials, so that the wear of the material decreases and at the same time it can also improve COF stability at elevated temperatures [13].

Graphene inclusion in polymer composite also provides outstanding behavior in reduction of wear and COF fluctuation. Wang and coworkers exhibited a decreased wear rate using graphene nanomaterial reinforced phenolic resin based composite from $0.375 \times 10^{-6}\, mm^3/Nm$ to $0.268 \times 10^{-6}\, mm^3/Nm$ compare to that of phenolic composite without graphene [16]. Rajan et al. study revealed that there is a significant wear rate reduction from $16.5 \times 10^{-6}\, mm^3/Nm$ to $5.5 \times 10^{-6}\, mm^3/Nm$ at higher load of 50N by using 5 wt% graphene additives in phenolic resin based composite as compared to the same amount of micro graphite filled phenolic resin based composite as presented in Fig. 4 [17].

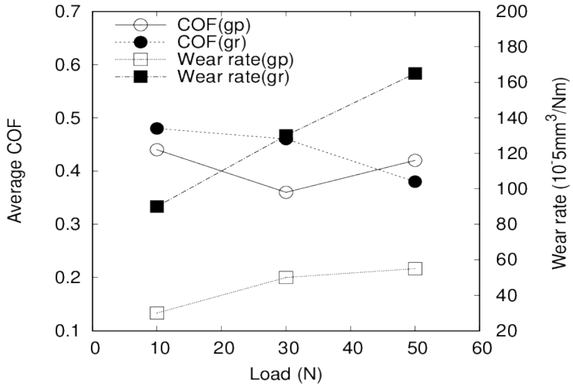

Fig. 4 Average COF and wear rate versus applied load for 5 wt% graphene (gp) and 5 wt% graphite (gr) in phenolic composite [17].

From there study, it is also found that in average around 65% specific wear rate reduction is possible using 5 wt% graphene instead of 5 wt% graphite inclusions in the phenolic based polymer composite. Besides 5 wt% graphene included phenolic based polymer composite maintained better COF stabilities at different operational stages with respect to temperature variation, such as improved COF stability by 41.7% up to 289°C, by 16.48% up to 345°C, and even the fade resistance property also found to be improved by 40.14% up to the mentioned higher temperature. It is also found that the COF of graphene based polymer composite is decreases initially for the loads of 10N and 30N, and then slightly increases for the load of 50N when compared to graphite based polymer composite as presented in Fig. 4. Graphene based polymer composite wear particle creation at lower load is minimum due to its strong reinforcement effect. However, when the applied load increases, more particles can be created at the friction interface, that might be happened due to the presence of graphene bundles created at the contact zone, which has a potential to increase surface roughness, leads to upward trend of COF at 50N as shown in Fig. 4 for the test condition of 3m/s speed, 6000m sliding distance and average temperature 140°C. Finally from the study of Rajan et al. it can be inferred that the 5 wt% graphene based phenolic polymer composite have suitable value of COF with very significant value of wear rate reduction for all loads [17].

This result is attributed due to the graphene specific properties such as high mechanical strength, high fracture toughness, high surface area, high interfacial interaction and dispersion capability, which can potentially contribute much higher reinforcing and load carrying capacity in the composite leading to lower wear rate compared to graphite-based composite. Even though with these many better properties, if processing of graphene mixing not done properly in polymer composite then there may be chance of unstable tribological properties. Graphene has also better thermal conductivity than graphite, which can be contributed to higher heat dissipation capability of polymer composite with graphene, thereby reduces wear rate and improves COF stability.

Overall it can be inferred that the addition of various nanocarbons such as MWCNT, CNT, and graphene have significant contribution towards tribological properties of phenolic based polymer composite and can be further investigated for better results. Similar to this, it is also found that the addition of nanocarbon in epoxy based polymer composite have the same type of effects on their tribological properties as presented here in the next section.

4. Nanocarbon Effect on Epoxy Composite Tribological Properties

In addition to phenolic resin, it is also found that the incorporation of nanocarbon in to epoxy resin can enhance the tribological properties such as better COF stability and wear rate minimization. In the work of Sakka and coworkers in 2017, they examined the tribological properties of CNT reinforced epoxy composite, and found that the addition of 1.5 wt% CNT greatly reduced wear rate from $22.1 \times 10^{-5}\, mm^3/Nm$ to $6.5 \times 10^{-5}\, mm^3/Nm$, and from $22.1 \times 10^{-5}\, mm^3/Nm$ to $3.37 \times 10^{-5}\, mm^3/Nm$ at the same time using amino treated 1.5 wt% CNT, which are about 70% and 85 % lower wear rate when compared to the neat epoxy resin, while at the same time 28% of COF reduction was recorded for amino treated 1.5 wt% CNT [18]. Neat epoxy possesses relatively high COF and wear rate when compared to nanocarbon based composite forms as shown in Fig. 5 under testing condition of 4N applied load, 400 rpm sliding velocity, 4000 second test duration, and 25°C temperature.

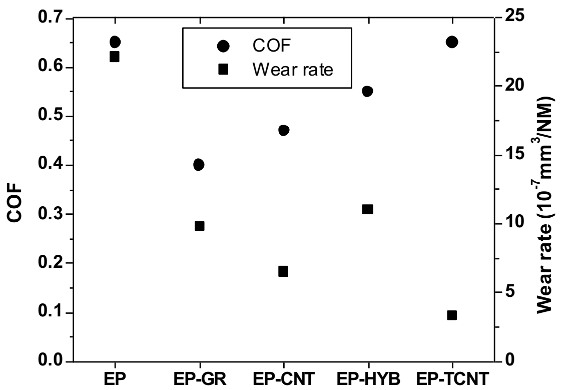

Fig. 5 COF and wear rate of neat epoxy (EP), epoxy-1.5 wt% graphite (EP-GR), epoxy-1.5 wt% CNT (EP-CNT), epoxy-1.5 wt% hybrid of graphite and CNT (EP-HYB), and NH_2 (amino) treated 1.5 wt% CNT (EP-TCNT) composites [18].

In case of neat epoxy and disc pair during tribological test, the interface between the soft neat epoxy specimen and hard steel based counter face disc potentially increases strong adhesion and deformation, which can increase the adhesion force between the two interacting parts and further becomes the cause of increase in wear rate and COF. The problems are addressed and the epoxy based composite potentially improved by mechanism of nano additive such as CNT in epoxy binder. Due to inherent properties of CNT such as having high strength, high thermal conductivity, better thermal stability, high surface area, better interfacial interaction etc., and with its uniform dispersion within epoxy can significantly reduce the wear rate when compared to neat epoxy and macro graphite based epoxy polymer composite.

B. Tianjiao and coworkers in 2021 investigated the COF and wear rate of the pristine epoxy and its composites using GO and amino treated GO, and from their results it is found that amino functionalized 0.2 wt% GO composite could reduce wear rate from $9.11 \times 10^{-6}\, mm^3/Nm$ to $0.55 \times 10^{-6}\, mm^3/Nm$, which is around 94% wear rate reduction compared with pure epoxy resin [19] as shown in Fig. 6 under testing condition of 5N normal applied load, 0.1m/s speed, and 3600 second testing time duration. The untreated GO epoxy composite achieved around 47% wear rate reduction, which is lower compared to the treated one with the same constituent amount in the composite. Treating of GO with polyethermine groups found to be good for homogeneous dispersion and excellent interfacial interaction with the epoxy resin, which results in better reduction of wear rate compared with neat epoxy and GO epoxy composite.

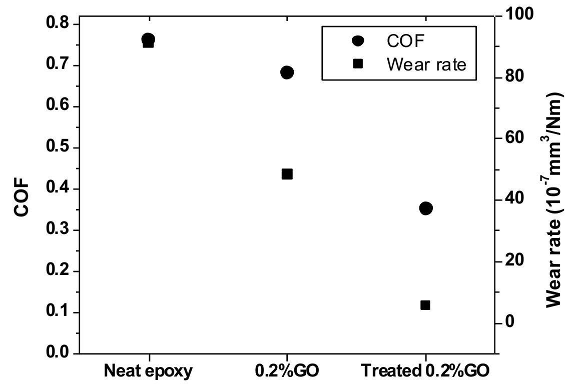

Fig. 6 COF and wear rate of neat epoxy, 0.2 wt% GO, and treated 0.2 wt% GO composites [19].

According to Du et al, graphene has also shown good tribological property enhancements in the epoxy composite, and the tribological test result indicated that the reduction of wear rate from $7.6 \times 10^{-5}\, mm^3/Nm$ to $1.1 \times 10^{-5}\, mm^3/Nm$ and reduction of COF from 0.68 to 0.26 compared to the neat epoxy [20]. In one study, Ige and coworkers developed an epoxy based polymer composite using carbon nano sphere (CNS) and other ingredients for brake pad application and further studied their tribological properties using pin-on-disc tribometer. The result exhibited $0.95 \times 10^{-8}\, gm/N\,m$ wear rate and 0.55 COF with 0.3 wt% CNS inclusion in the epoxy based polymer composite. The wear rate is reduced by 51% when compared to 0.1wt % CNS composition in the epoxy based polymer composite as shown in Fig. 7 under 30N normal applied load, with 0.7m/s speed, and 2168m of total sliding distance [21].

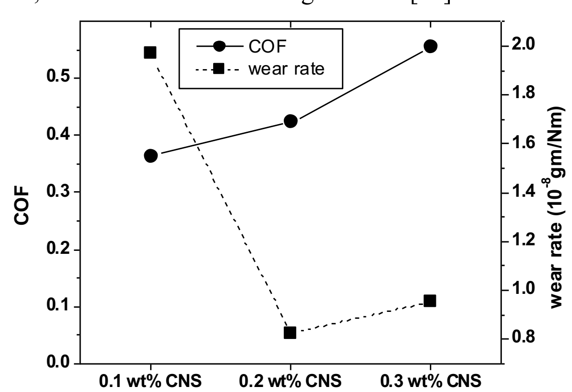

Fig. 7 The effect of carbon nano sphere (CNS) on wear rate and COF properties incorporated in to epoxy resin binder at 0.1 wt% CNS, 0.2 wt% CNS, and 0.3 wt% CNS [21].

In an another study by Ige and Inambao, they investigated the effect of CNS on the properties of epoxy resin based hybrid nanocomposite BPM containing graphite and steel nanoparticles also, and reported a stable COF value of 0.41 in average and reduced wear rate of $1.07 \times 10^{-8}\ gm/Nm$ when 2 wt% of CNS added in the mentioned nanocomposite as shown in Fig. 8 under 30N normal applied load, with 0.7m/s speed, and 2168m of total sliding distance [22].

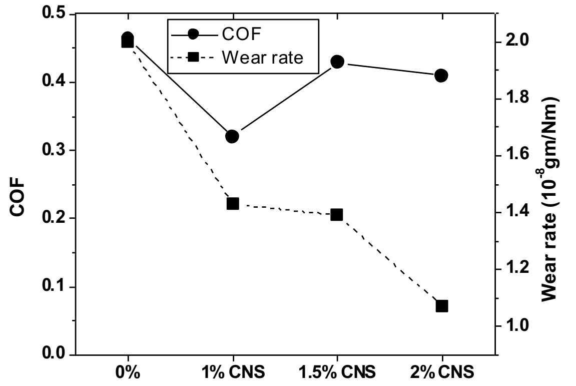

Fig. 8 The effect of carbon nano sphere (CNS) on wear rate and COF properties incorporated in to epoxy resin binder at 0 wt% CNS, 1 wt% CNS, 1.5 wt% CNS, and 2 wt% CNS [22].

5. Discussion

In summary the mechanisms of favorable effects in terms of tribological properties such as wear minimization and better COF using some nanocarbons such as CNT, GO, and graphene as an additive in phenolic and epoxy resins polymer based composites is completely practical. This betterment of tribological properties in nanocarbon phenolic/epoxy polymer based composite is attributed due to the nanocarbon high reinforcing effect, better interfacial interaction at lower inclusion, and better load carrying capacity thereby potentially restrain the deformation and adhesion of the binder during friction at the interface when braking process initiated. Additionally, nanocarbon can potentially enhance heat dissipation capability of the nanocarbon phenolic/epoxy polymer based composite as nanocarbon generally possess high thermal conductivity, and the effect of increasing thermal conductivity of nanocarbon phenolic/epoxy polymer based composite leading to reduce wear rate and COF fluctuation. For additional outlook in the field of nanocarbon effect on phenolic/epoxy resin based nanocomposite properties there are some literatures which can be referred [23-26]. Finally, some of the significant tribological property results of nanocarbon included phenolic and epoxy resin based nanocomposites are presented in Fig. 9 below. As indicated in Fig. 9, graphene phenolic composite (C3) shows higher wear rate value, the reason found as higher operational stages and more constituents to optimize the required properties of BPM which is a graphene phenolic composite. However, for C1 composite with three ingredients including 6 wt% CNTs, the tribological test result based inference is presented in Fig. 9 with tribological test condition of 500N load, 0.43m/s speed, room temperature, and 120 minutes test duration. C2 composite result were found for the tribological test condition of 150N applied load, 5m/min speed, room temperature, and 180 minutes test duration with grafting of graphene on carbon fiber and dispersed in phenolic matrix composite. C3 composite result found with nine ingredients including 5% graphene with tribological test condition of 3m/s speed, 6000m sliding distance, and 140°C average operational temperatures. C4 composite developed from 0.2 wt% GO and neat epoxy, and tested at 4N load, 25°C temperature and 64 minutes test duration. C5 composite was also tested at 50N load, 0.1m/s speed, room temperature, and 60 minutes test duration, in which the neat epoxy and 0.2 wt% GO were only the constituents. C6 composite is a with 5.3% graphene epoxy composite, whose tribological properties result were found with the tribological test consideration of 10N load, 2cm/s speed, room temperature, and 60 minutes test duration.

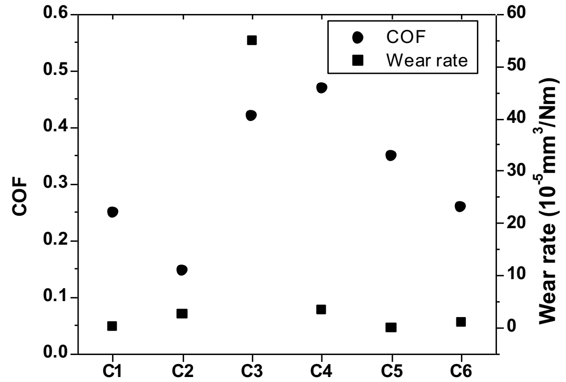

Fig. 9 COF and wear rate of composites, C1: phenolic-CNT composite [15], C2: phenolic- graphene coated carbon fiber composite [16], C3: phenolic-graphene composite [17], C4: epoxy-CNT composite [18], C5: epoxy-GO composite [19], and C6: epoxy-graphene composite [20].

In overall cases shown in Fig. 9, almost all the nanocarbon phenolic/epoxy polymer based composites are showing very less wear rate except C3 composite as that composite contains lots of ingredients and some ingredients may be responsible for this high value of wear rate, while the COF value is varying case to case.

In brief, the present work is a critical meta-analysis work on specific nanocarbon composition based polymer composite and its effect on the tribological property only, so those parametric combinations only were extracted from various literatures and primarily focused. So, this work planned in a very specific manner with the aim of bringing all nanocarbon composition based polymer composite and their specific tribological parameter in one platform so that audience in this or related field can have an outlook of all nanocarbon effect on specific tribological parameter respectively with its constituent limit and test conditions. Overall, this meta-analysis represents study on the analysis of nanocarbon effect on the phenolic and epoxy resin based composite tribological properties, which is contributed by the existing body of knowledge in the literature through systematic analysis of the effects on COF and wear properties against the quantified compositions including weight percentage and size of the nanocarbon filler in considered polymer composite from the available evidences. This study can be a better guide for future research in enhancing the polymer composite tribological properties and advancing their practical applications.

5.1 Potential Applications and Implications of the Current Findings

The inherited characteristics of nanocarbon includes high surface area, good mechanical strength, better thermal stability, good frictional stability, low wear rates and high lubrication capability [27-30] which surface out its potential capabilities, and whenever this will be added to polymer composite which can surpass the performance of both phenolic and epoxy polymers matrix based conventional components. In specific the tribological properties of polymer (phenolic/epoxy) composite when incorporated with nanocarbons, it contributes to the enhancement in the properties and perform better in intended applications by addressing the upcoming requirement of advanced engineering material in the fields of various industries including automotive, aerospace, and frictional components manufacturer by providing stable COF, reduced wear rate, and improved solid lubrication capabilities. The present work also aimed to provide an understanding of the capability of nanocarbons in tribological property enhancements of polymer (phenolic/epoxy) composite, which mainly encompasses COF and wear rate of developed frictional components as per the industrial applications related to these property domains. Fig. 10 presents a brief highlight of neat resin tribo-limitation and consecutively the tribology enhancement mechanism using nanocarbon filler in considered resins and the significant enhancements in tribological properties might be offered, which is the implication of present research in this field.

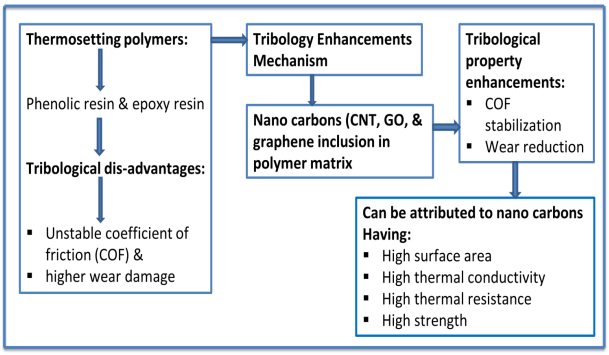

Fig. 10 An overview on resin tribo-limitation and potential enhancements with carbon nanofiller

5.2 Limitations and Insights for Future Work

In the field of frictional material development, the use of nanocarbon as filler in polymer composite have some critical issues related to its agglomeration and dispersion in the polymer matrix due to density difference during the composite processing. On the other hand, even though phenolic and epoxy resins are from same class of thermosetting polymers, they have basic property difference, where phenolic resin is inherently brittle but better in friction and wear resistance properties compared to epoxy resin. In polymer composite development nanocarbon filler in the pure resin have some limitations as stated above whereas some filler had been used in previous work didn't show those limitations by using macro carbon filler and modifier or reinforcement. It is also noticed that the variation of noncarbon type and its purity in the composition of polymer composite can also affect its overall tribological properties. The present meta-analysis work which considered different testing equipment, standards, testing methods and operational conditions showcase the polymer composite viability in various friction based applications.

The future research should consider such limitations and other listed variations to develop better polymer composite based frictional components using phenolic or epoxy resin specifically. Further the developed polymer composite with nanocarbon fillers must undergo related experimental testings in specific to used practical applications. This type of future work will provide better insight about various nanocarbon filler materials effect on the overall tribological properties of polymer composite. Finally, by addressing these limitations and pursuing these future research directions, a more comprehensive understanding of the nanocarbon effect on polymer composite tribological properties can be achieved, and can be advancing their practical applications where stable COF and higher wear resistant properties are required like in brake pads, brake linings, bearings and other frictional components.

6. Conclusions

The present work showcase the significant impact of carbon nanofillers on the tribological properties of phenolic and epoxy resin composite materials and also highlight the current state of research in this area. This meta-analysis of tribological properties data against phenolic and epoxy resin composites from multiple studies allow us to understand the impact of nanocarbon as filler in the considered resin based composite, and the findings are highlighted the potential of various nanocarbon fillers in enhancing the phenolic and epoxy resin composite tribological properties such as low and stable COF as well as reduced wear rate. It is completely clear that polymer composite with nanocarbon filler demonstrate the superiority in tribological properties as compared to pure phenolic/epoxy resin alone. It is also seen that the variants of carbon filler produces different effect on tribological properties, such as phenolic-(5 wt%) graphite composite experienced more wear rate (approximately three times) as compared to phenolic-(5 wt%) graphene composite at various loading conditions with similar COF values in both the cases, epoxy-(0.2 wt%) amino treated GO composite reduced the wear rate by 94% as compared to pure epoxy resin, and similarly epoxy-(2 wt%) CNS composite reduced the wear rate by 43% as compared to pure epoxy resin out of many presented cases. So as a concluding remark, the inclusion of nanocarbon filler led to significant enhancement of wear reduction of 50% and 80% with moderate COF for phenolic and epoxy resin-based nanocomposites respectively. Additionally, this meta-analysis identifies the gaps in the literature work and suggests directions for future work. Furthermore, the work highlights current limitations and future research and development perspectives. Overall, this work provides the researcher and BPM manufacturer an overview about nanocarbon based polymer composite, and may help to develop new material that can cater major problems in the present brake pad materials which is commercially available in the market.

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