Research Article GU J Sci, Part A, 13(1): 404-418 (2026) 10.54287/gujsa.1883856

Gazi University
Journal of Science
PART A: ENGINEERING AND INNOVATION
http://dergipark.org.tr/gujsa

Enhancing the Tribological Performance of Diesel Engine Oil Using Boron Carbide Nanoparticles

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Keywords

Boron Carbide
Nano Particle Additives
Engine Oil
Wear

Abstract

In recent years, the use of nanoscale additives to diminish the coefficient of friction and regulate wear mechanisms in engine lubricants has emerged as a growing study field. In this study, the tribological performance of 15W-40 diesel engine oil was investigated by adding four different concentrations (25, 50, 100, and 200 ppm) of dispersed boron carbide (B4C) nanoadditive to 25 mL of oil. Friction and wear tests were performed under limiting lubrication conditions using a tribometer (20 N load, 500 m sliding distance). SEM/EDS analyses were conducted to evaluate the coefficient of friction, wear rate, and surface topography. The results show that the base oil exhibited the lowest average COF (0.112), friction force (2.24 N), and wear loss (0.0055 mm3), whereas the B4C-containing lubricants showed higher average COF (0.129-0.197), friction force (2.58-3.94 N), and wear loss (0.0285-0.0355 mm3) with increasing additive concentration from 25 to 200 ppm. Under the present test conditions, B4C addition did not improve the tribological performance of the base oil; instead, increasing B4C concentration led to progressively higher friction and material loss.

Cite

Orman, R. Ç. (2026). Enhancing the Tribological Performance of Diesel Engine Oil Using Boron Carbide Nanoparticles. *GU J Sci, Part A*, *13*(1), 404-418. doi:10.54287/gujsa.1883856

Author ID (ORCID Number)

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Article Process

Submission Date 06.02.2026
Revision Date 26.02.2026
Accepted Date 23.03.2026
Published Date 31.03.2026

1. INTRODUCTION

Internal combustion engines are one of the many methods used in modern transportation systems and energy production. Friction and wear losses between moving metal surfaces are one of the limiting factors that play a major role in the overall efficiency of internal combustion engines (Wang et al., 2021). A significant amount of fuel energy is converted into heat by factors such as mechanical friction around the piston ring and cylinder bore areas, the crankshaft bearings, the camshaft, the valve train, and auxiliary drive components, resulting in reduced efficiency and increased fuel consumption (Priest & Taylor, 2000). In terms of the lifespan of engine parts, maintenance intervals for these losses become important for energy efficiency (Wong & Tung, 2016).

Lubrication in internal combustion engines is highly complex and includes complicated hydrodynamic lubrication conditions (Kumar et al., 2018). Especially in single-cylinder engines, suddenly changing pressure, variable speed, changes in oil film thickness during operation and temperature increase cause the oil film to thin in some areas leading to slugging or transition to the lubrication system (Chu et al., 2023). Under these

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conditions, a significant portion of the stress is transmitted directly through surface roughness contact; therefore, adhesive and abrasive wear mechanisms, as well as undesirable tribological processes such as surface tearing and oxidative occur more frequently (Williams, 2005). Therefore, the rheological properties of engine oil, its chemical composition, and the interactions between surfaces in contact with additive components become fundamental parameters that determine friction and wear behavior (Alqahtani et al., 2022).

In recent years, stringent fuel economy and emission regulations have encouraged engine manufacturers to propagate the use of low-viscosity lubricants in order to minimize pumping losses and hydrodynamic friction (e.g., Euro 6/7 and EPA standards) (Blanco-Rodríguez et al., 2024). However, with the reduction in viscosity, there is an increase in the tendency for metal-to-metal contact, especially under boundary lubrication conditions, requiring enhancements to the performance of additive systems used in the formulation of lubricants. Conventional lubricant additives like antiwear and friction-reducing agents include zinc dialkyldithiophosphate (ZDDP), molybdenum-based friction modifiers MoDTC and many organic compounds, which have been used for decades in engine oils. However, they all have significant disadvantages, such as limited chemical stability at high temperature, undesirable interactions with either other additives or oxidation products of the base oil itself and negative impact on exhaust after-treatment systems (e.g., three-way catalytic converter and diesel particulate filter) through catalyst poisoning or filter blockage (Hong et al., 2023; Spikes, 2025).

Due to the increasing stringency in the enforcement of environmental regulations with respect to reductions of SAPS contents (sulfated ash, phosphorus, sulfur) in engine oils, the use of conventional additive systems has become more restricted (Bednarski et al., 2025). This situation is accelerating research into alternatives for environmentally friendly and long-lasting additives that maintain stable performance under high temperatures and loads. In this regard, nano-scale lubricants constitute one of the key research areas in modern tribology (Garcia Tobar et al., 2024). The high specific surface area of nanoparticles, their ability to form strong physical and chemical interactions with surfaces, their potential to improve load-carrying properties through better load distribution between micro-roughnesses, and their contribution to tribofilm formation make them highly suitable for use as additives in engine lubricants (Chen et al., 2019; Jiang et al., 2024).

Adding nanoparticles such as hBN, graphene, MoS_2, WS_2, Al_2O_3, SiO_2, ZnO, among others, in lubricating oils has been extensively reported to be able to promote the formation of a lubricious surface film; decrease micro-adhesion; reduce depth and width of wear scars; improve roughness of the surface and in some cases, to provide the micro-surface improvement mechanism known as the “mending effect” (Zhao et al., 2021). These additives can perform like load-bearing elements in areas where the oil film locally thickens, thereby reducing metal-to-metal contact and improving tribological performance depending on the coefficient of friction and wear rate. However, since each nano additive has different crystal structures, hardness, chemical stability, and surface characteristics, their behavior in engine oils must be examined separately through regular and comprehensive experimental studies (Zhao et al., 2021; Htwe et al., 2024).

One of the nanomaterials with superior physical and chemical properties is boron carbide (B_4C), an advanced ceramic material. This nanomaterial has very high hardness (~30 GPa) and low density (Cheng et al., 2017; Reddy et al., 2018). Due to these properties, B_4C has been used in armor systems, abrasive powders, nuclear applications, high-temperature components and it has also attracted considerable interest for tribological applications. Thanks to their high hardness and good wear resistance, B_4C particles can behave as micro-scale "load-bearing areas" on the surface and redistribute stresses over a wider contact area. In addition, the chemical inertness and oxidative stability of B_4C allow it to stay stable even under a high-temperature and reactive environment, offering huge advantages for long-time operation of lubricant systems (Švec, 2025).

The addition of nano-scale B_4C particles to lubricating oils is expected to (i) mechanically strengthen the tribofilm on the surface, (ii) fill the micro-roughness, (iii) increase the load-carrying capacity, and (iv) reduce metal-to-metal contact. Additionally, when an appropriate particle size and dispersion are achieved, B_4C particles exhibit a "semi-bearing" effect that reduces the coefficient of friction by providing lubrication under sliding conditions (Lai et al., 2023; Aithal et al., 2025). On the other hand, at high additive concentrations or under poor dispersion conditions, B_4C particles may exhibit a agglomerate; in such cases, the resulting agglomerates can cause three-body abrasive wear mechanisms. This is a factor that should never be underestimated, as it is at least as important as the others. Therefore, with regards to the real behavior of B_4C within lubricant systems, appropriate additive concentrations and dispersion parameters have to be determined (Dai et al., 2016; Jiang et al., 2024).

Although there are numerous studies in the literature on the use of B_4C additives in industrial lubricants, the number of studies comparing the tribological behavior of commercially available diesel engine oils modified with B_4C and having different viscosity grades is limited (Zhang, 2021). In particular, 15W-40 diesel engine oils can be expected to respond differently to B_4C addition than gasoline engine oils due to their different base oil compositions, viscosity, and working conditions. Whereas gasoline engines operate at higher speeds and relatively lower torque conditions that are more favorable for hydrodynamic lubrication diesel engines typically operate under lower speeds and higher torque, both contribute to more significant limits and mixed lubrication conditions. These differences could result in the same concentration of B_4C additive giving different tribological results in gasoline and diesel engine oils (Menacer & Bouchetara, 2020).

Furthermore, many studies cited in the literature have been carried out on model tribological test systems like pin-on-disc, four-ball tribometers or block-on-ring configurations, while investigations using samples acquired from real engine components remain few (Kamimura et al., 2007). However, real engine surfaces develop specific micro-topographical features, residual stress and surface defects resulting from manufacturing processes like casting and machining. Thus, the study of B_4C enhanced lubricants for their tribological effects using specimens cut from real engine blocks will more likely provide results that are meaningful and relevant to applications (Yue et al., 2018).

In this study, the influence of boron carbide (B_4C) nano-additive on the tribological behavior of diesel engine oil is explained with real engine surfaces using different additive concentrations. In this context, four distinct B_4C concentrations corresponding to an oil volume of 25 mL were chosen, and the nanoparticles were uniformly distributed in the oil utilizing an ultrasonic dispersion technique. Consequently, wear tests were performed under continual sliding load circumstances on samples derived from single-cylinder diesel engines utilizing motor oils enhanced with B_4C nano additives. The coefficient of friction, wear, and wear mechanisms were examined through SEM analyses, which results in a thorough evaluation of B_4C's application as an additive in engine lubricants.

2. MATERIAL AND METHOD

2.1. Preparation of B_4C-Enhanced Lubricant Formulations

This study utilized a commercial 15W-40 base oil, often employed in diesel engines, with boron carbide (B_4C) nanoparticles selected as an addition to improve the tribological properties of the lubricant. The morphology and size of the B_4C nano-additive used in this study were characterized prior to lubricant preparation. As shown in Figure 1, the B_4C powder exhibits an irregular particle morphology with localized agglomeration. Particle size analysis indicated a median particle size of D_{50} = 0.0532 µm (≈53.2 nm), confirming that the additive is in the nanoscale range. In accordance with the experimental design, four distinct additive concentrations were established within the context of the chosen 25 mL of oil; additionally, the additive quantities were quantified in ppm. The prepared oil B_4C mixes were made to include approximately 25, 50, 100, and 200 ppm of B_4C. Homogeneous dispersion of nanoparticles within the oil phase can be considered as one of the most important stages of the preparation of B_4C enhanced lubricants. Therefore, at the beginning, each additive quantity was first mixed mechanically at low speed with the oil to ensure the initial transfer of particles into the oil, followed by a 3-hour ultrasonic dispersion process to minimize the probability of agglomeration and is shown in Figure 2, which allows the suspension behavior to be stable and the B_4C particles to remain well dispersed and suspended within the lubricant.

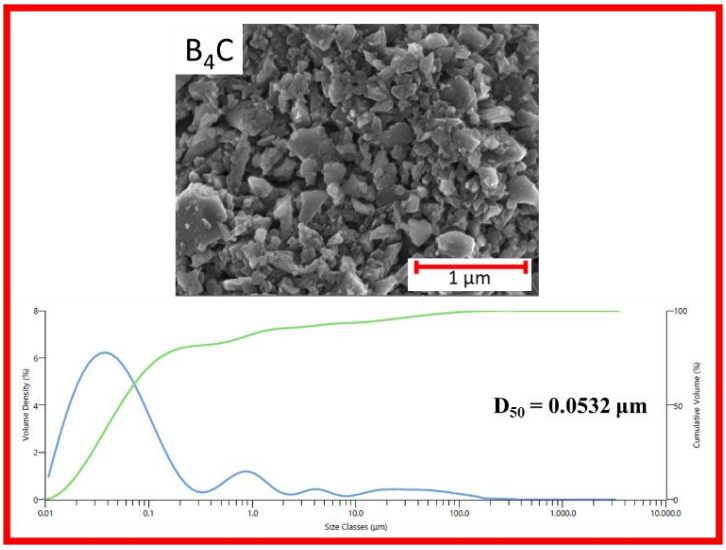

Figure 1. *SEM micrograph of the B_4C nano-additive and particle size distribution curve of the B_4C powder*

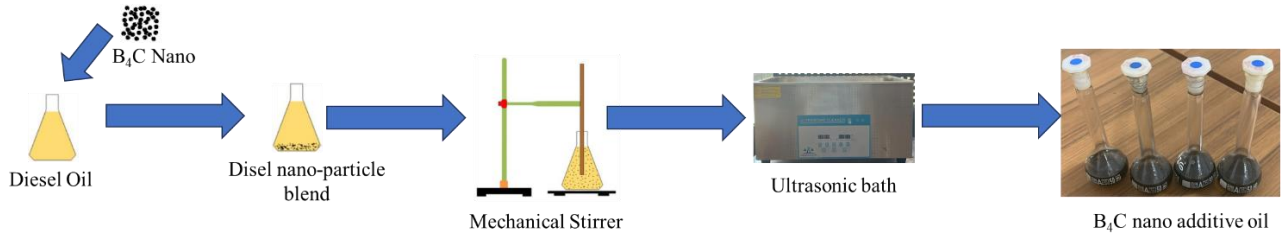

Figure 2. *Preparation of B_4C Lubricant Formulations*

2.2. Physicochemical Characterization of Lubricant Formulations

The density of the base and B_4C-formulated lubricants was measured using an Anton Paar SVM 1101 viscometer-density meter prior to tribological testing. This measurement was conducted to evaluate the effect of B_4C addition on the commercial SAE 15W-40 diesel engine oil.

2.3. Preparation of Test Specimens

Test specimens for the wear experiments were prepared by cutting materials obtained from single-cylinder diesel engine blocks into dimensions of 30 × 30 × 5 mm using a precision cutting machine. Representative photographs of the single-cylinder diesel engine block and the prepared test specimens are provided in Figure 3. To ensure that all specimens possessed comparable initial surface characteristics, a multi-stage grinding process was applied by going through coarse and fine steps. In this regard, SiC abrasive papers of grit sizes ranging between 120 and 1200 were used. After the mechanical surface preparation, an ultrasonic cleaning process was carried out in an alcohol to eliminate residual abrasive particles, oil, metallic debris, or micro-contaminants on the cleaned surface. Following the cleaning process, the specimens were dried with compressed air at room temperature and then prepared for the tests.

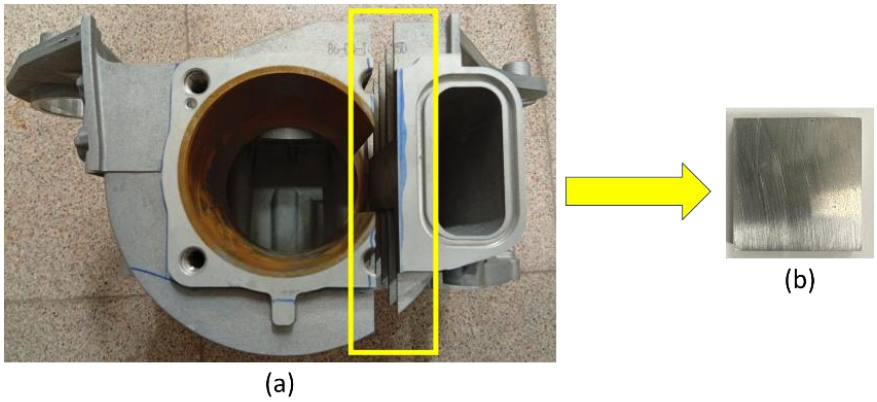

Figure 3. *(a) The single-cylinder diesel engine block used as the source material and (b) test specimen prepared in dimensions of 30 × 30 × 5 mm*

2.4. Tribological Testing Procedures

The tribological performance of the surfaces of samples treated with B_4C nano-additive engine oil was evaluated using the Anton Paar TRB3 tribometer. Separate tests were conducted for each additive concentration on samples prepared under the same working conditions. The load applied in the tests was 20 N and the total sliding distance was kept constant at 500 m and is shown in Figure 4. The sliding speed and

applied load parameters represent the boundary and mixed lubrication typically occurring in single-cylinder engines. Therefore, this test was performed in a controlled and repeatable manner on the samples to allow the investigation of the effect of B_4C nano-additive oils on sample surface interactions, tribofilm formation, and wear mechanisms.

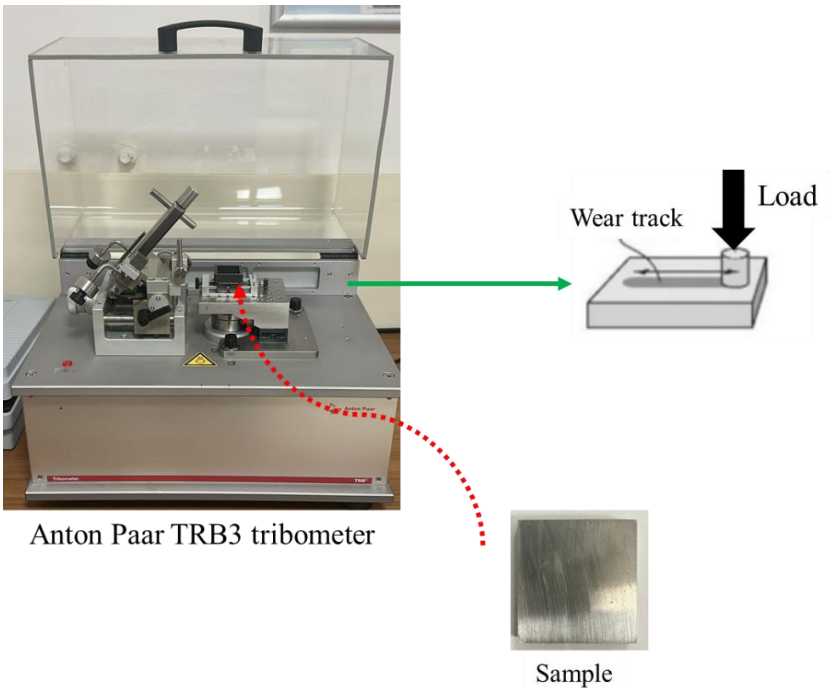

Figure 4. *Tribological Testing Procedure*

2.5. Surface Characterization After Tribological Testing

After the wear test, the sample surfaces were first examined using an optical microscope to evaluate the tribological effects, and the wear scare width, surface defects, and wear severity were assessed. For a more detailed examination of the sample surfaces after wear testing, SEM analyses were performed using JEOL JSM-6060LV, and wear types were examined, including microcracks, layer separation areas, and features indicative of abrasive and adhesive wear. Subsequently, a FILMETRICS 3D optical profilometer was used for 3D topographic mapping of the sample surface, providing precise measurements of the wear scare depth, area and determining the wear scare roughness parameters.

3. RESULTS AND DISCUSSION

3.1. Density of the Formulated Lubricants

The density values of the neat and B_4C nano-additive lubricant formulations are presented in Table 1. Since density is one of the basic physicochemical parameters affecting lubricant flow and film behavior, it was measured to determine whether the addition of B_4C altered the bulk characteristics of the base oil.

As shown in Table 1, only limited variation was observed in the density values of the nano-additive lubricants compared with the base oil. This result indicates that the incorporation of B_4C at the studied concentrations did not cause a substantial change in the bulk density of the commercial SAE 15W-40 diesel engine oil.

Table 1. *Measured density values of base and B_4C nano-additive SAE 15W-40 diesel engine oil.*

sample	B_4C concentration (ppm)	Measured density (kg/m^3)
base oil	0	872.05
B_4C-25	25	872.064
B_4C-50	50	872.079
B_4C-100	100	872.107
B_4C-200	200	872.164

3.2. Coefficient of Friction Results

Boron carbide (B_4C) is an advanced ceramic material characterized by extremely high hardness (≈30 GPa), a sharp-edged crystalline morphology, and an inherently abrasive nature. These features position B_4C to function by a fundamentally different tribological mechanism than that of low shear resistance layered solid lubricants such as graphene or hexagonal boron nitride (hBN). Even in nanoscale dimensions, the hard and angular morphology of B_4C particles can exacerbate micro-cutting and micro-ploughing during sliding between contacting surfaces. This has been considered one of the main mechanisms responsible for the rise in coefficient of friction under the boundary and mixed lubrication systems.

The coefficient of friction slip distance curves, as shown in Figure 5, demonstrate that the concentration of B_4C nano-additives has a significant and non-linear effect on tribological behavior. The specimen tested with the base oil showed the lowest and most stable COF values within the whole duration of the tests, thus representing the reference behavior. Among the oils containing B_4C, the oil with 25 ppm B_4C nano-additive showed the lowest COF values and friction behavior nearest to base oil. This was followed by additive ratios of 50 ppm, 100 ppm, and 200 ppm according to the increasing amount of COF; particularly high additive concentrations showed significantly high and more fluctuating COF values. At high concentration ranges such as 200 and 100 ppm, the irregular and unstable distribution of B_4C particles within the contact area prevented the formation of a sufficiently effective lubricating layer between surface roughnesses, and friction increased. When the concentration decreases 50 ppm, a significant decrease in COF is achieved, which means a relatively more continuous tribofilm at the contact interface and a partial decrease in resistance. At the lowest additive concentration of 25 ppm, the intense concentration of B_4C particles within the contact region behaved like a layer that promoted sliding despite their further reducing the coefficient of friction. The slightly increasing COF profile at 25 ppm should not be regarded as contradictory behavior; rather, it indicates a concentration-dependent transition in friction evolution, where the lower additive dosage provides a less stable lubricating film during sliding compared with higher concentrations. These results have shown that the effect of B_4C nano-additives on COF is not only determined by surface protection mechanisms but also by the dynamics of third bodies and particle interface interactions.

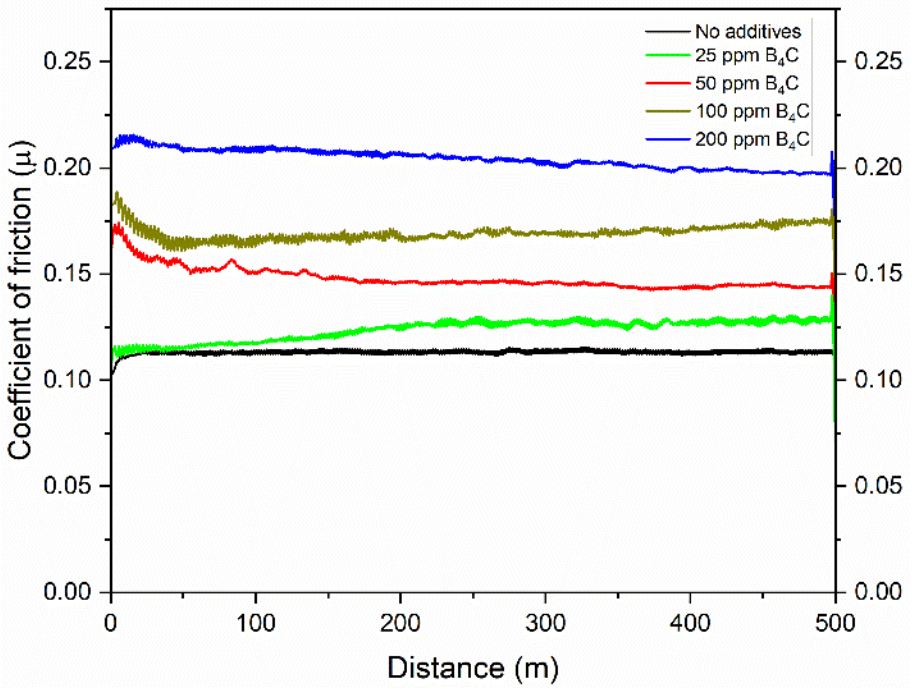

Figure 5. *Friction coefficient (COF) values of the neat oil and the oils containing four different B_4C additive concentrations.*

3.3. Quantitative Comparison of Wear Loss and Friction Force

The quantitative tribological results obtained under different B_4C concentrations are summarized in Table 2. In addition to the wear loss values measured after the tests, the corresponding friction force values were calculated from the average coefficient of friction under the constant applied load of 20 N. This comparison provides a clearer numerical evaluation of the effect of B_4C concentration on both frictional response and material removal behavior.

Table 2. *Quantitative comparison of average COF, friction force, and wear loss for base oil and B_4C-formulated lubricants under different additive concentrations.*

sample	B_4C concentration (ppm)	Average COF (μm)	Friction force (N)	Wear loss (mm3)
base oil	0	0.112	2.24	0.0055
B_4C-25	25	0.129	2.58	0.0285
B_4C-50	50	0.144	2.88	0.0311
B_4C-100	100	0.174	3.48	0.0332
B_4C-200	200	0.197	3.94	0.0355

As shown in Table 2, the base oil exhibited the lowest average COF (0.112), the lowest friction force (2.24 N), and the lowest wear loss (0.0055 mm3), indicating the best overall tribological performance among all tested conditions. In contrast, the addition of B_4C nanoparticles led to a progressive increase in all three parameters with increasing additive concentration. The wear loss rose from 0.0285 mm3 at 25 ppm to 0.0355 mm3 at 200

ppm, while the friction force increased from 2.58 N to 3.94 N over the same concentration range. These results indicate that, under the present experimental conditions, B_4C addition did not improve the tribological behavior of the base oil; instead, increasing B_4C concentration resulted in higher frictional resistance and greater material loss. This suggests that the hard B_4C particles may have acted as abrasive third bodies rather than providing an effective protective tribological mechanism in the studied system. The tribological behavior observed in the present study can be explained mainly by the interfacial action of hard B4C particles during sliding. Although B4C is intrinsically a hard and wear-resistant ceramic, under the selected test conditions its addition did not generate a beneficial protective mechanism in the lubricant system. Instead, the particles likely entered the contact as hard third bodies and contributed to abrasive interaction between the sliding surfaces. In the absence of a sufficiently stable and continuous protective tribo-layer, these particles may have promoted localized ploughing and micro-cutting effects, thereby increasing both friction and material removal. As the B4C concentration increased, the number of hard particles present at the interface also increased, which likely intensified particle–surface and particle–particle interactions and made the contact more unstable. This concentration-dependent increase in abrasive interfacial action is consistent with the observed increase in average COF, friction force, and wear loss.

When compared with previous wear-test studies on nano-lubricants, the present results reveal an important material-dependent difference in tribological response. In many studies involving layered or low-shear nano-additives such as graphene-derived materials or hBN, reductions in friction and wear have been commonly associated with the formation of protective tribofilms, surface mending effects, and the prevention of direct asperity contact (Marlinda et al., 2023). By contrast, the B_4C-based lubricant system examined here did not show an improvement in wear performance relative to the neat base oil, and both friction and wear increased with increasing additive concentration. This indicates that the tribological role of B_4C in the present system was fundamentally different from that of softer solid-lubricant-type nano-additives. Owing to its high hardness and angular particle morphology, B_4C appears to have acted more as an abrasive third body than as a friction-reducing interfacial film-forming additive under the selected test conditions. Although some studies have reported beneficial effects for B_4C-containing nano-lubricants at optimized concentrations and under favorable dispersion conditions (Liu et al., 2022; Çanakçı et al., 2024), the present findings suggest that, in commercially available 15W-40 diesel engine oil tested on real engine-derived surfaces, the dominant response was an increase in frictional resistance and wear. Therefore, the present results highlight that the tribological effectiveness of nano-additives cannot be generalized solely by additive type, and must be interpreted together with particle hardness, morphology, dispersion state, and contact configuration.

3.4. Surface Morphology

Figure 6 presents the SEM images obtained after the wear tests and shows that the surface morphology and the prevailing wear mechanisms are strongly dependent on the B_4C nano-additive concentration. For the specimen tested with base oil, continuous deep grooves and homogenous abrasive tracks, aligned parallel to

the sliding direction, were observed. This morphology is indicative of a dominating two-body abrasive wear mechanism, dominated by the contact of the substrate material directly with the Al_2O_3 counter-body under boundary lubrication conditions.

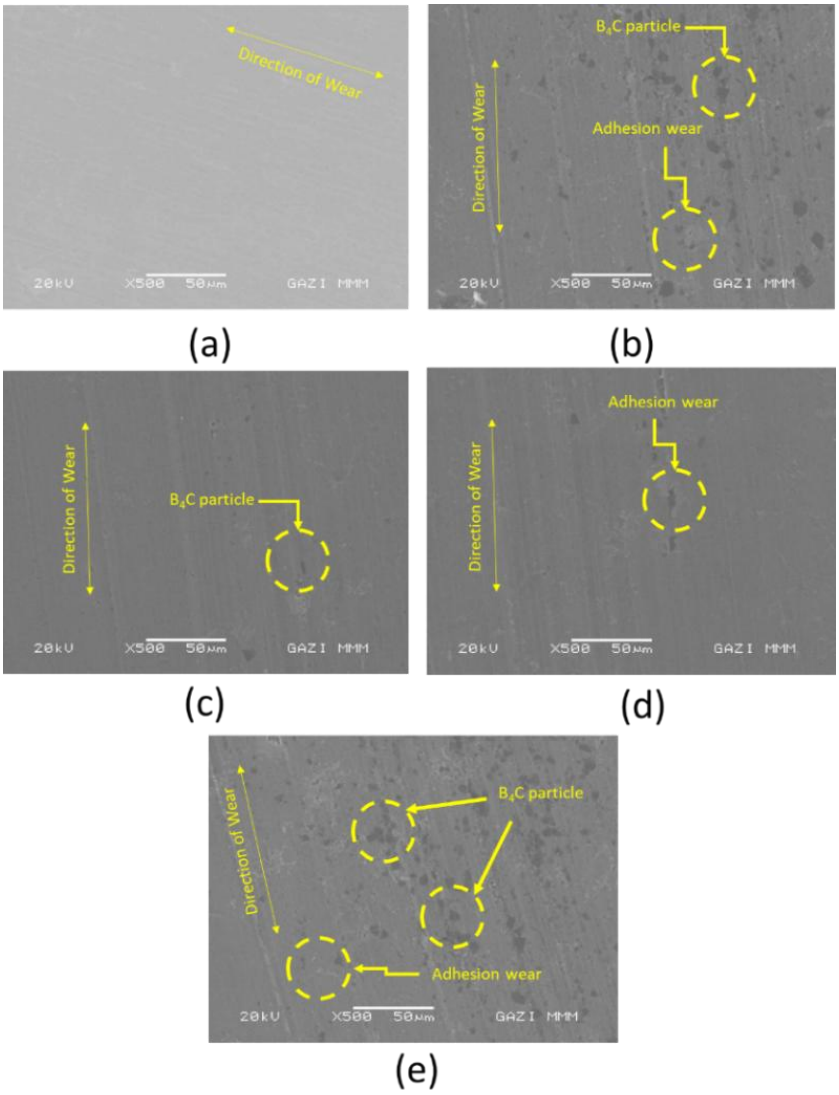

Figure 6. *SEM images of wear surfaces obtained at different concentrations of B_4C nano-additive: (a) additive-free oil, (b) 25 ppm B_4C additive, (c) 50 ppm B_4C additive, (d) 100 ppm B_4C additive, and (e) 200 ppm B_4C additive samples.*

In the specimen lubricated with 200 ppm B_4C (Figure 6b), An increase in the density of wear tracks was observed, along with scattered irregular micro-pits on the surface. This behavior suggests that at high additive concentration, the B_4C particles could not form a stable lubricating layer on the surface, resulting in enhanced friction at the localized contact points. This is in good agreement with the relatively high values of COF measured at this concentration. The SEM images taken at the 50 ppm B_4C level show that in Figure 6c, the depth of the wear scare partially increase and the morphology of the worn surfaces becomes closer to homogeneity, but signs related to localized micro-tearing and interaction traces of particles are still visible. Thus, it can be explained that though the friction-reducing effect of the particles starts to appear, a continuous and stable tribofilm has not been fully developed yet. In the case of a specimen lubricated with 100 ppm B_4C

(Figure 6d), one can observe that the morphology of the worn surface is considerably smoother, characterized by more surface scratches and more regular wear traces in the direction of sliding. This observation indicates that B_4C particles at this concentration function as contact interface elements between surface irregularities and create more balanced and stable wear tracks. SEM images reveal dense particle agglomerations along wear tracks and scattered third-body structures on the surface at the highest additive concentration of 200 ppm (Figure 6e). The accumulated particles form a third-body layer that provides slip at the interface and thus increase the coefficient of friction, and gives the highest COF values among the samples in B_4C nano-additives oil. On the other hand, the same hard and sharp B_4C particles locally induce micro-shear effects that increase roughness in the wear scar. Overall SEM results indicate that the nano-additive B_4C affects both friction and wear behavior simultaneously but with different effects. low and medium concentrations ensure partial or complete protection of the surface, while high concentrations are associated with a more complex wear scare due to particle surface interactions, leading to higher friction through the third-body effect.

3.5. Tribological Performance under Boundary and Mixed Lubrication

The 3D optical profilometry results for all specimens are shown in Figure 7 and demonstrate a strong, but nonlinear dependence on B_4C nano-additive concentration with regards to wear scar size and roughness.

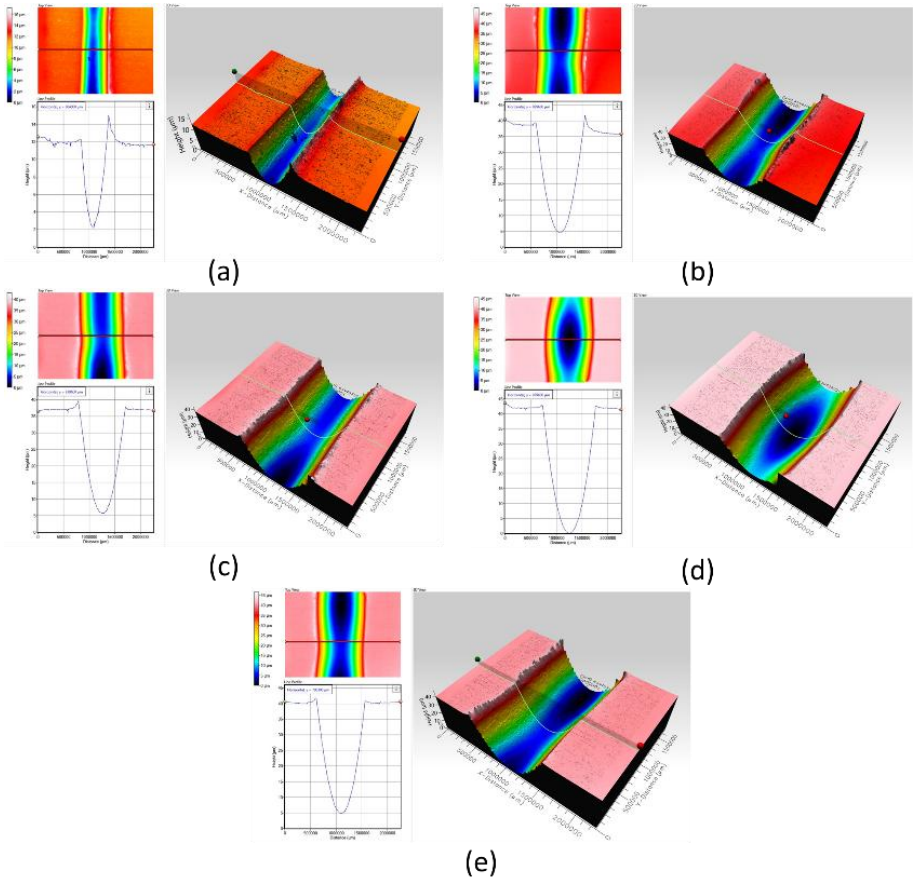

Figure 7. *3D profilometer images of wear surfaces obtained at different concentrations of B_4C nano-additive: (a) additive-free oil, (b) 25 ppm B_4C additive, (c) 50 ppm B_4C additive, (d) 100 ppm B_4C additive, and (e) 200 ppm B_4C additive samples.*

Figure 7a illustrates that the wear scar of the sample lubricated with base oil exhibits a valley-like profile characterized by substantial dimensions and a pronounced base, together with evident plastic deformation on the edges. As a result, it can be argued that there is prominent direct contact between the substrate materials and the Al_2O_3 counter-face due to boundary lubrication conditions. Figure 7b represents a specimen lubricated with 25 ppm B_4C. Although there is some variation in the wear depth compared to pure lubrication, The amount and variability of geometry and height changes in the wear track are preserved. It can be inferred that at a low additive concentration, B_4C particles are ineffective at providing a stable loading support or developing a barrier on the surface. At a 50 ppm B_4C concentration (Figure 7c), there is an indication that there is a smooth valley and a reduction in abrupt changes at the bottom of the track. The wear scar remains high, and this shows that there is a discontinuity at a 50 ppm B_4C concentration. Figure 7d shows that with 100 ppm B_4C lubrication, the wear scar profile is more clearly defined, with a smoother cross-section at the bottom and more pronounced deformation at the edges. Based on these observations, it can be seen that with 100 ppm B_4C, the load distribution on surface roughness is more pronounced due to the higher number of particles. On the other hand, at the maximum additive amount with 200 ppm B_4C addition (Figure 7e), the wear scar depth and edge profiles become more pronounced once again. It should be noted that the higher friction coefficient at the 200 ppm measurement does not contradict the profilometry observations. This implies difficult cutting at the interface with the third layer formed by particles at high concentrations. At the same time, there are heightened micro-cutting action from the hard and corner-like B_4C particles. In general, based on 3D optical profilometry analysis data, it can be seen that the effect of B_4C nano additives on wear performance should not be limited to only a reduction in wear depth. Moreover, wear scar geometry and deformation characteristics should be factored into consideration.

4. CONCLUSION

In this study, the effect of B_4C nano-additives added to 15W-40 diesel engine oil on tribological properties was investigated in terms of determining the coefficient of friction, scanning electron microscopy, and 3D optical profilometry analyses. It would appear that B_4C additive concentration impacts on friction and wear effects as a decisive yet nonlinear factor.

The measured density values showed that the incorporation of B_4C nanoparticles caused only a slight change in the density of the base oil. This indicates that, despite the presence of the nano-additive, the formulated lubricants largely preserved the bulk physical characteristics of the commercial SAE 15W-40 oil within the studied concentration range.

The result for the friction coefficient shows that among all samples, base oil has the lowest and most stable value for the COF. Also, among the B_4C-added oil samples, it can be seen that with a higher amount of B_4C additive, there are higher values for COF and more similar friction characteristics approaching that of base oil. On the other hand, for higher additive concentrations (200 and 100 ppm), COF values was larger and more dispersed. A significant decrease in COF was observed from 50 ppm onwards; however, the smallest

coefficient of friction was obtained at 25 ppm. SEM results showed that the B_4C additive had a significant effect on the morphology of the worn surface. Pure lubrication led to large grooves characteristic of predominantly two-body abrasive wear, while low additive concentrations resulted in irregular micro-pits and random wear scares. However, at 50 ppm B_4C, a shows regularity and control in the wear track morphology was observed with less groove depth and equalized surface deformation, indicating better contact regulation and stress distribution. At a concentration of 25 ppm B_4C, the aggregation of small particles and the formation of a third body increased sliding and consequently reduced friction. Micro-cuts were formed due to the hard and sharp particles.

The results obtained from SEM and COF analyses were consistent with those obtained from 3D profilometry analysis, demonstrating that B_4C affects the size and geometry of wear tracks through different concentration-dependent mechanisms. Pure oil formed valley-shaped wear tracks with high symmetry and large size, while a concentration of 50 ppm produced more stable and controlled wear tracks. Despite the decrease in the coefficient of friction, irregularity in the wear geometry was present at a concentration of 25 ppm with deeper localized areas. Therefore, it can be concluded that at lower concentrations, the particles form a third layer that reduces friction but increases the complexity associated with the wear geometry. It was observed that the wear morphology became more stable at a B_4C additive concentration of 50 ppm, and friction was low and more favorable for a B_4C additive of 25 ppm. From these experiments, it can be seen that the tribological properties of B_4C nano-additives cannot be predicted based on separate factors such as coefficients of friction and wear depths. A lower coefficient of friction, especially at lower additive concentrations, is not solely related to lower wear values. The third-body effect becomes more pronounced at lower concentrations. Based on these experiments, an optimal amount of B_4C additive will be determined according to the required tribological properties. The current experiments provide a strong scientific basis for future engine-scale experiments using B_4C engine oil blends.

AUTHOR CONTRIBUTIONS

All human authors have read and legally accepted the final version under the CC BY-SA 4.0 framework.

CONFLICT OF INTEREST

The author declares no conflict of interest.

REFERENCES

Aithal, V. S., Khan, M. A., Shetty, A. R., Hanumantharaju, C. M., Aroor, G., Rai, R., & Navada, M. K. (2025). Revolutionizing Tribology: The Impact of Nanoparticle Coatings on Modern Engineering. *Journal of Bio-and Tribo-Corrosion*, *11*(4), 101. https://doi.org/10.1007/s40735-025-01020-w

Alqahtani, B., Hoziefa, W., Abdel Moneam, H. M., Hamoud, M., Salunkhe, S., Elshalakany, A. B., Abdel-Mottaleb, M., & Davim, J. P. (2022). Tribological performance and rheological properties of engine oil with graphene nano-additives. *Lubricants*, *10*(7), 137. https://doi.org/10.3390/lubricants10070137

Bednarski, M., Sikora, M., & Orliński, P. (2025). Analysis of the current lubricant requirements of the latest combustion engines. *Combustion Engines*, *204*(1), 192–199. https://doi.org/10.19206/CE-211331

Blanco-Rodríguez, J., Simón-Montero, X., Cortada-García, M., Maroto, S., & Porteiro, J. (2024). Modelling the impact of reducing lubricant viscosity on a conventional passenger car fuel economy and wear protection. *Results in Engineering*, *24*, 103159. https://doi.org/10.1016/j.rineng.2024.103159

Çanakçı, A., Karabacak, A. H., Çelebi, M., Özkaya, S., & Arpacı, K. A. (2024). A study on the optimization of nano-B4C content for the best wear and corrosion properties of the Al-based hybrid nanocomposites. *Arabian Journal for Science and Engineering*, *49*(11), 14625–14641. https://doi.org/10.1007/s13369-024-08736-w

Chen, Y., Renner, P., & Liang, H. (2019). Dispersion of nanoparticles in lubricating oil: A critical review. *Lubricants*, *7*(1), 7. https://doi.org/10.3390/lubricants7010007

Cheng, C., Reddy, K. M., Hirata, A., Fujita, T., & Chen, M. (2017). Structure and mechanical properties of boron-rich boron carbides. *Journal of the European Ceramic Society*, *37*(15), 4514–4523. https://doi.org/10.1016/j.jeurceramsoc.2017.06.017

Chu, N. R., Jackson, R. L., Ghaednia, H., & Gangopadhyay, A. (2023). A mixed lubrication model of piston rings on cylinder liner contacts considering temperature-dependent shear thinning and elastic–plastic contact. *Lubricants*, *11*(5), 208. https://doi.org/10.3390/lubricants11050208

Dai, W., Kheireddin, B., Gao, H., & Liang, H. (2016). Roles of nanoparticles in oil lubrication. *Tribology International*, *102*, 88–98. https://doi.org/10.1016/j.triboint.2016.05.020

Garcia Tobar, M., Contreras Urgiles, R. W., Jimenez Cordero, B., & Guillen Matute, J. (2024). Nanotechnology in lubricants: A systematic review of the use of nanoparticles to reduce the friction coefficient. *Lubricants*, *12*(5), 166. https://doi.org/10.3390/lubricants12050166

Hong, Y., Mo, Y., Lv, J., & Wang, J. (2023). Tribological properties of polymer friction improvers combined with MoDTC/ZDDP at different temperatures. *Lubricants*, *11*(5), 196. https://doi.org/10.3390/lubricants11050196

Htwe, Y. Z. N., Al-Janabi, A. S., Wadzer, Y., & Mamat, H. (2024). Review of tribological properties of nanoparticle-based lubricants and their hybrids and composites. *Friction*, *12*(4), 569–590. https://doi.org/10.1007/s40544-023-0774-2

Jiang, Z., Sun, Y., Liu, B., Yu, L., Tong, Y., Yan, M., Yang, Z., Hao, Y., Shangguan, L., & Zhang, S. (2024). Research progresses of nanomaterials as lubricant additives. *Friction*, *12*(7), 1347–1391. https://doi.org/10.1007/s40544-023-0808-9

Kamimura, H., Kubo, T., Minami, I., & Mori, S. (2007). Effect and mechanism of additives for ionic liquids as new lubricants. *Tribology International*, *40*(4), 620–625. https://doi.org/10.1016/j.triboint.2005.11.009

Kumar, V., Sinha, S. K., & Agarwal, A. K. (2018). Tribological studies of an internal combustion engine. In *Advanced engine diagnostics* (pp. 237–253). Springer. https://doi.org/10.1007/978-981-13-3275-3_12

Lai, C., Zhong, M., Xu, W., Yi, M., Wu, H., & Huang, M. (2023). Influences of B4C and carbon nanotubes on friction and wear performance of Cu base self-lubricating composite. *Tribology International*, *187*, 108726. https://doi.org/10.1016/j.triboint.2023.108726

Liu, W., Qiao, X., Liu, S., & Chen, P. (2022). A review of nanomaterials with different dimensions as lubricant additives. *Nanomaterials*, *12*(21), 3780. https://doi.org/10.3390/nano12213780

Marlinda, A. R., Thien, G. S. H., Shahid, M., Ling, T. Y., Hashem, A., Chan, K.-Y., & Johan, M. R. (2023). Graphene as a lubricant additive for reducing friction and wear in its liquid-based form. *Lubricants*, *11*(1), 29. https://doi.org/10.3390/lubricants11010029

Menacer, B., & Bouchetara, M. (2020). Parametric analysis of the effect of engine speed and load on the hydrodynamic performance of the lubricant in diesel engine. *Periodica Polytechnica Mechanical Engineering*, *64*(4), 299–306. https://doi.org/10.3311/PPme.15725

Priest, M., & Taylor, C. M. (2000). Automobile engine tribology—approaching the surface. *Wear*, *241*(2), 193–203. https://doi.org/10.1016/S0043-1648(00)00375-6

Reddy, P. S., Kesavan, R., & Vijaya Ramnath, B. (2018). Investigation of mechanical properties of aluminium 6061-silicon carbide, boron carbide metal matrix composite. *Silicon*, *10*, 495–502. https://doi.org/10.1007/s12633-016-9479-8

Spikes, H. (2025). Mechanisms of ZDDP—an update. *Tribology Letters*, *73*(1), 38. https://doi.org/10.1007/s11249-025-01968-3

Švec, P. (2025). Wear Resistance of B4C-TiB2 Ceramic Composite. *Lubricants*, *13*(1), 35. https://doi.org/10.3390/lubricants13010035

Wang, Z., Shuai, S., Li, Z., & Yu, W. (2021). A review of energy loss reduction technologies for internal combustion engines to improve brake thermal efficiency. *Energies*, *14*(20), 6656. https://doi.org/10.3390/en14206656

Williams, J. A. (2005). *Engineering tribology*. Cambridge university press.

Wong, V. W., & Tung, S. C. (2016). Overview of automotive engine friction and reduction trends–Effects of surface, material, and lubricant-additive technologies. *Friction*, *4*(1), 1–28. https://doi.org/10.1007/s40544-016-0107-9

Yue, C., Gao, H., Liu, X., & Liang, S. Y. (2018). Part functionality alterations induced by changes of surface integrity in metal milling process: a review. *Applied Sciences*, *8*(12), 2550. https://doi.org/10.3390/app8122550

Zhang, W. (2021). A review of tribological properties for boron carbide ceramics. *Progress in Materials Science*, *116*, 100718. https://doi.org/10.1016/j.pmatsci.2020.100718

Zhao, J., Huang, Y., He, Y., & Shi, Y. (2021). Nanolubricant additives: A review. *Friction*, *9*(5), 891–917. https://doi.org/10.1007/s40544-020-0450-8