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Improving the wear and friction properties of racing sports automotive gears using SiC@Ag nanoparticles in lubricating oils

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Abstract. In this study, the effects of Ag-doped silicon carbide nanoparticles on improving lubricating properties and reducing wear rates in racing automotive gears were investigated. At high temperatures and pressures, SiC@Ag nanoparticles enable the creation of a strong and durable lubricating layer by combining the lubricating properties of silver metal with the high hardness of silicon carbide. Using SiC@Ag nanoparticles until the optimal concentration is reached dramatically reduces the wear rate and friction coefficient, according to tests conducted on steel gears using nano-oils containing different concentrations of these nanoparticles under various loading and speed conditions. The formation of a thin, uniform lubricating layer with anti-stick properties was further confirmed by surface analysis of the samples. These findings demonstrate that adding SiC@Ag nanoparticles as a novel additive is an effective approach to enhance the efficiency and durability of power transmission systems in sports and automotive applications.

Keywords: friction reduction; nano-oils; nanolubricants; racing automotive gears; SiC@Ag nanoparticles; surface analysis

1. Introduction

The automotive field, especially in the competitive area of racing vehicles, is fast-paced and unpredictable. It faces many challenges, with one of the biggest being how to achieve optimal performance, efficiency, extended life, and reduced friction in powertrain systems (Meheux *et al*. 2010). This is especially true for gearboxes and gears, where the performance is determined by extremely severe conditions (Charoo and Wani 2016). These components undergo significantly high loads at high temperatures and extremely high speeds, which can ultimately lead to severe wear and failure (Bond *et al*. 2024). Common failure modes are surface fatigue, micro-cracking, and ultimate material failure. Additionally, excess friction leads to reduced efficiency and a loss of output power in the vehicle (Nabhan *et al*. 2025). The lubricants, accompanied by additives, remain critical in maintaining and enhancing the functionality of the drive system's components under severe conditions (Zhao *et al*. 2021). The lubricants provide a stable, uniform, and durable lubricant film on the contacting surfaces, which helps prevent direct wear in the components while significantly reducing friction (Garcia Tobar *et al*. 2024). This reduces wear on components, enhances system efficiency, and improves the vehicle's overall performance. Therefore, selecting appropriate lubricants and employing high-quality additives are key factors in ensuring the durability and reliable operation of gearboxes and gears in racing cars (Liu *et al*. 2022).

In recent years, nanotechnology has garnered considerable interest as a promising and novel avenue for enhancing lubricant performance. Adding nanoparticles as an additive to lubricating oils has become an effective approach to enhance lubricant properties as well as functional performance (Kumara *et al*. 2017). Molecules in lubricant operating conditions experience significant changes in surface interactions by dispersing nanoparticles, while reducing friction and wear at extreme conditions with the formation of ultra-thin protective films (Chinnachamy *et al*. 2022). Reductions in friction and wear are critical as they directly result in an improved service life of mechanical components, while increasing overall system efficiency (Puchý *et al*. 2024). The outstanding performance of nanoparticles as lubricants is mainly due to their nanoscale size and extremely high surface-area-to-volume ratio, which allows nanoparticles to diffuse into contact regions between opposing metal surfaces, while facilitating the formation of uniform, continuous protective layers to optimize operating conditions (Duan *et al*. 2023, Venkatesh *et al*. 2023). Such nanostructured films prevent direct metal-to-metal contact, which reduces surface damage, wear, and even corrosion. Due to these unique benefits, nanoparticle-based additives are being increasingly recognized as a new class of lubricant additives across many engineering applications (Cai *et al*. 2024).

Their use is rapidly expanding in key industries such as

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automotive, aerospace, and power generation, where durability, reliability, and energy efficiency are critical (Erdi Korkmaz and Kumar Gupta 2024). Silicon carbide (SiC) is one of the most commonly applied nanoparticles in this area. This ceramic material can be a superior candidate for lubricants because of its very high hardness, good wear resistance, and thermal stability (Bakhtiarifard and Nayebpashaee 2025). However, SiC alone may generate surface scratches on the surface of other materials due to its hard and brittle nature under certain conditions (Biswal and Sahoo 2024). Therefore, recent studies have combined SiC with metals like silver (Ag) to utilize the high hardness of SiC while using the lubricant and anti-friction characteristics of silver (Ismail 2015). Fig. 1 illustrates a conceptual view of a high-performance racing vehicle in which the gearbox is lubricated with oils containing SiC@Ag nanoparticles. This image highlights how integrating nanotechnology into lubrication systems can enhance efficiency and reliability under extreme mechanical stress.

Silver is one of the metals that has been known for quite some time in various industries to have appropriate lubricating characteristics (Chen *et al*. 2023). It can develop a soft and slippery layer on surfaces under high-temperature and high-pressure conditions, thereby preventing subsequent contact between metal surfaces (Guan *et al*. 2025). Therefore, the combination of SiC nanoparticles with Ag can lead to a synergistic effect, where the hardness and abrasion resistance of SiC are combined with the lubricating characteristics of silver, ultimately resulting in the development of a robust, homogeneous, and durable protective film (Jin *et al*. 2024, Li *et al*. 2025a).

Recent laboratory experiments have confirmed that incorporating SiC@Ag composite nanoparticles into lubricating oils significantly decreases friction and lowers wear rates (Peng *et al*. 2024). Aside from developing strong lubricating layers, these nanoparticles exhibit antifriction properties and help prevent localized surface welding (Kharb *et al*. 2021). Moreover, these materials retain seamless stability under dynamic loading and varied speeds, making them especially important under extreme conditions, particularly within a gearbox on a racing car (AlAnazi *et al*. 2017).

The integration of nanotechnology into tribological systems has catalyzed transformative advances across various fields, including energy, mechanical engineering, and even sports-related applications. Nanoparticle-enhanced lubricants now offer viable pathways to mitigate friction and wear under extreme conditions, such as those encountered in high-performance racing gearboxes (Wang *et al*. 2025a). This development resonates with broader efforts to reconcile energy demands, environmental constraints, and material durability through nanoscale interventions (Jia *et al*. 2023). Concurrently, theoretical frameworks rooted in nonlocal elasticity and strain gradient theories have enabled the refinement of modeling nano-structured components, particularly porous and functionally graded systems, under thermal, mechanical, and dynamic loads (Ehyaei *et al*. 2017, Mirjavadi *et al*. 2017, Wang *et al*. 2022, Zhang *et al*. 2023a). These models have proven essential not only in conventional structural contexts but also in emerging domains, such as sports engineering, where stability, weight, and dynamic response govern performance (Dai *et al*. 2022, Wang *et al*. 2024a, b, Xia *et al*. 2025).

Beyond structural mechanics, nanomaterials are increasingly deployed for corrosion inhibition, bio-compatibility, and smart functionality. For instance, green-synthesized silver nanoparticles have demonstrated efficacy in protecting subsurface oil and gas infrastructure from microbiologically induced corrosion (Zhang *et al*. 2023c), while surface-engineered titanium implants highlight the role of nanoscale design in biomedical integration (Omidi *et al*. 2013). In civil engineering, elastic nano-composites are being leveraged to enhance seismic resilience (Dong *et al*. 2025a), and in textiles, microfiber mechanics are being redefined through nano-reinforcement (Liu *et al*. 2025a). Even physiological processes, such as hemodynamic responses during exercise or protein stability in athletic tissues, are now analyzed using size-dependent mechanical models informed by nanomechanics (Chang *et al*. 2025, Chen *et al*. 2025a, b). Furthermore, innovations in metamaterials (Lin *et al*. 2025), nanocomposite sports equipment (Xiao *et al*. 2025, Yang *et al*. 2025), and smart sensors for athletic performance (Daichang *et al*. 2025, Liu *et al*. 2025d, Xu *et al*. 2025) illustrate a growing convergence between nanoscience and real-world functional optimization. Together, these diverse yet interconnected advances underscore the versatility of nanotechnology as a cross-disciplinary enabler, extending from automotive tribology to human performance, and affirm its pivotal role in next-generation engineering solutions.

The pursuit of enhanced tribological performance in high-stress mechanical systems has catalyzed a broad spectrum of innovations, ranging from nanomaterial design to intelligent diagnostics and adaptive control. In the realm of advanced lubrication, the synergistic pairing of hard ceramic phases with soft metallic coatings, as exemplified by SiC@Ag core–shell nanoparticles, offers a compelling route to simultaneously suppress wear and reduce friction under extreme thermo-mechanical loads (Yi *et al*. 2024). This approach resonates with recent demonstrations of macroscale superlubricity achieved through hydrated alkali metal ions (Han *et al*. 2018) or engineered amorphous–crystalline interfaces (Zhu *et al*. 2024), both of which underscore the pivotal role of interfacial chemistry in minimizing energy dissipation (Han *et al*. 2022). Concurrently, the incorporation of two-dimensional nano-materials, such as boron nitride nanosheets, into synthetic base oils has shown marked improvements in film strength and thermal resilience (Liu *et al*. 2025f). Meanwhile, metal-free brake formulations leveraging andalusite highlight a parallel drive toward environmentally sustainable tribo-materials (Zheng *et al*. 2025). On the mechanical side, refined gear geometries, such as herringbone planetary configurations, have been shown to mitigate stress concentrations and enhance dynamic stability under high-speed operation (Liang *et al*. 2025), and the durability of such components is further informed by advanced fatigue

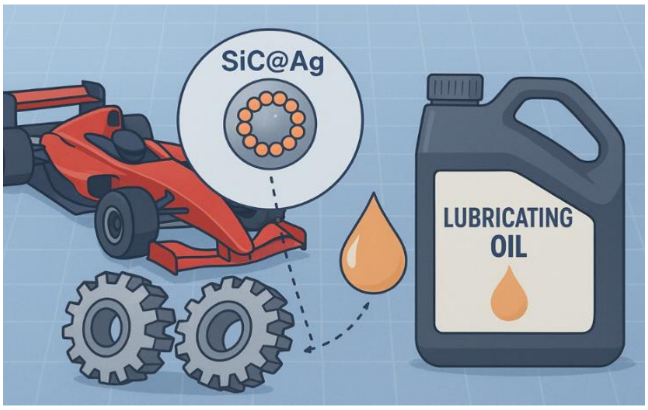

Fig. 1 Schematic of a high-performance racing vehicle oil containing a nanoparticle

load spectrum editing techniques that account for multi-axis stress states in automotive structures (Liu *et al.* 2024). These mechanical insights are increasingly augmented by intelligent monitoring frameworks. Data-efficient machine learning models now enable compound fault diagnosis in gearboxes, even under limited operational data (Wan *et al.* 2025a), and multi-scale convolutional architectures facilitate robust condition assessment across diverse operating regimes (Wan *et al.* 2025b). Such diagnostic capabilities are further supported by physics-informed models of rotor–bearing dynamics that explicitly account for elastohydrodynamic lubrication effects (Liu *et al.* 2025b) and interdependent degradation pathways in rolling elements (Li *et al.* 2025b). Complementing experimental tribology, computational approaches such as discrete element modeling (DEM) have been refined through advanced calibration of contact parameters, particularly in particulate systems, offering transferable methodologies for simulating wear particle interactions in lubricated contacts (Wang *et al.* 2025c). Moreover, the emergence of multifunctional tribovoltaic coatings that enable self-powered in situ sensing while maintaining exceptional tribological robustness illustrates a growing convergence between lubrication science and smart materials engineering (Wang *et al.* 2025d).

Beyond rotating machinery, emerging manufacturing techniques such as wire-based friction stir welding and additive processing have demonstrated the ability to produce high-integrity joints in aluminum alloys, despite assembly gaps or layer discontinuities, which are critical for lightweight automotive structures (Dong *et al.* 2025b, Sun *et al.* 2025). Even in seemingly peripheral domains, such as intelligent soil compaction using coupled roller–subgrade models (Tang *et al.* 2025), wear prediction in percussive drilling via MBD–DEM simulation (Wang *et al.* 2025b), or geochronological constraints on fluid overpressure in shale formations (Zhang *et al.* 2025a), the underlying emphasis on interfacial durability and real-time performance assessment aligns closely with the challenges inherent in racing gear contacts. At the systems level, the integration of adaptive control strategies has become increasingly vital, not only for maintaining stability under uncertainty but also for compensating for modeling errors and external disturbances in nonlinear mechanical systems (Cai *et al.* 2025). This control-theoretic perspective is further extended through event-triggered sliding mode frameworks (Liu *et al.* 2025c, Wang *et al.* 2025e) and observer-based navigation for underactuated marine systems (Wu *et al.* 2025a, Zhang *et al.* 2025b). In parallel, resilient coordination strategies for multi-agent systems have been developed to address actuator faults and false data injection attacks using adaptive neural and event-triggered secure control schemes (Cao *et al.* 2025, Huang *et al.* 2025). Complementary approaches based on dynamic programming and distributed protocols further enhance robustness under denial-of-service threats and intermittent failures (Liu *et al.* 2025e, Wu *et al.* 2025b), illustrating how system-level intelligence can amplify the benefits of advanced materials. Together, these developments form a cohesive ecosystem in which nanolubricants like SiC@Ag operate not in isolation, but as integral components of a broader architecture encompassing material science, mechanical design, fault diagnostics, and autonomous adaptation, particularly vital in the demanding context of high-performance automotive powertrains.

The importance of this challenge becomes evident in racing cars, where small reductions in friction and increased power transmission efficiency can dramatically influence the car’s performance and ultimate success in competition (Ali *et al.* 2024). Increasing parts’ durability and leading to maintenance delays are also critical technical and economic factors for racing components, especially when considering the overall maintenance of racing gearboxes (Jiang *et al.* 2023). Ultimately, the innovations of additive products such as SiC@Ag within lubricating oils offer an opportunity for an advancement in lubrication science and could increase durability in high-load systems (Pownraj and Valan Arasu 2021).

Recent analytical and numerical studies have further refined the prediction of structural response in nano- and micro-scale systems, particularly through Eringen’s nonlocal elasticity theory and advanced computational frameworks applied to rotating or thermally loaded functionally graded beams and plates (Ebrahimi and Shafiei 2016, Ghadiri *et al.* 2017). Complementing these efforts, hybrid approaches that couple artificial neural networks with classical mechanics (Liang *et al.* 2024), or account for environmental effects such as humid-thermal conditions on wave propagation in cylindrical panels (Yuanchao *et al.*), alongside high-fidelity simulations of fluid, structure interactions (Mousavı *et al.* 2017) and static analyses of porous nanotubes using higher-order beam theories (Zhang *et al.* 2023b), continue to expand the predictive capabilities of nano-engineered systems under complex operational scenarios. In light of this information, the current work studies the impact of SiC@Ag nanoparticles on the friction and wear performance of a steel gear (36G) operating under simulated racing car conditions. In this study, oils containing different concentrations of nanoparticles were studied, and their performance was analyzed in cases of friction reduction, wear, and lubricant film formation. The primary objective is to develop an understanding of the mode of action of nanoparticles and assess their suitability as next-generation additives in industrial lubricants, ultimately for use in high-speed vehicles.

2. Experimental section

2.1 Preparation of SiC suspension in polyol

To produce SiC@Ag nanoparticles, the initial step involves dispersing 1 g of silicon carbide powder with an average diameter of 50 to 200 nm in 100 mL of ethylene glycol in a 3-neck flask equipped with a magnetic stirrer. In order to achieve a homogeneous distribution of SiC and avoid particle association, the solution was ultrasonicated for 10 to 15 min at 30 s on and 10 s off cycles. The next step involved adding 0.5 to 1 mL of oleylamine or 0.2 to 0.5 mL of oleic acid to the suspension to provide the organic functional groups, enhancing dispersion in the base oil via adsorption onto the SiC surface.

2.2 Addition of silver precursor and in situ reduction

Subsequently, a silver precursor solution was created by dissolving 0.5 g of silver nitrate in 10 to 20 mL of ethylene glycol, which was then slowly added to the SiC suspension over a 15- to 20-minute period. The reaction temperature was held between 120 to 160 °C to regulate the reduction of silver ions. For the adjustment of the rate of reduction and uniformity of the silver shell coating, 0.1 to 0.3 g of sodium citrate or small amounts of ascorbic acid were added to the system. The reaction was held at a temperature between 140 to 160 °C for either 1 to 3 hours to achieve a uniform coating of silver on the SiC surface. The color change from a pale yellow to a grayish-brown solution indicated the formation of metallic silver. After the working period, the system was cooled, and the product was separated by centrifugation at either 8000 to 10000 rpm for 10 minutes. The precipitate was washed three times with isopropyl alcohol or ethanol and once with hexane to remove excess solvent and unreacted ligand.

2.3 Final drying and surface modification

The final precipitate was dried in a vacuum or oven at a temperature below 60 °C. A final surface modification step was also conducted to improve particle compatibility with the base oil. In this step, the dry particles were heated in an organic solvent, such as hexane or toluene, with 0.5 to 1 wt% of ligands, such as oleylamine or oleic acid, for 30 to 60 minutes. They were then rehardened by centrifugation and drying. These steps improved particle dispersion or stability in the lubricating oil.

2.4 Dispersion of nanoparticles in oil (preparation of nano-oil)

To fabricate the nano-oils, the modified particles were dispersed in synthetic base oil (either PAO or synthetic ester) at concentrations of 0.01, 0.05, 0.1, 0.5, and 1 wt%. The nanoparticles were first combined with the oil using a low-intensity magnetic stirrer to ensure uniform dispersion of the sample, and then sonicated with an ultrasonic processor using pulsed waves for 15 to 30 minutes. The samples were monitored for temperature during sonication and cooled in an ice bath if the temperature rose to undesired levels. To maintain the stability of the suspensions, a small amount of oil-compatible dispersant (0.01 to 0.1 wt%) was added, such as polyisobutylene succinimide.

2.5 Four-ball test

In order to determine the friction coefficient and anti-wear properties of oils, we used a four-ball apparatus according to ASTM D4172. In this test, three steel balls are fixed under load while one ball is rotated in contact with the stationary balls. The test was performed at a load of 392 N, a speed of 1200 rpm, and at a temperature of 75 °C for 60 minutes. The wear diameter was measured using an optical microscope for the balls, then averaged.

2.6 Weld load test

The weld load test, as specified in ASTM D2783, was conducted to determine the maximum load that the lubricant can withstand before the lubricant layer fails. In this test, as the load applied to the wear balls increased, the weld load was recorded when the lubricant film failed sufficiently to weld the balls together. A comparison between the base oil and the nano-oils revealed that SiC@Ag yields the highest weld load and maximum load capacity of the lubricant.

2.7 Friction coefficient measurement

Throughout the entire test, the friction coefficient was measured continuously. The samples containing nanoparticles at the optimum concentration (0.1 to 0.5 wt%) showed a decrease in the coefficient of friction, even when compared to the virgin base oil.

2.8 Viscosity and suspension stability

The rheological properties of the nano-oils were determined using a viscometer at varying temperatures (40 °C and 100 °C). The stability of suspension was assessed by a sedimentation test and the turbidity of the solution over a 30-day time period. The results suggested surface modification of nanoparticles was effective in preventing sedimentation and maximizing stability over time.

3. Results and discussion

X-ray diffraction (XRD), Fourier transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM), X-ray photoelectron spectroscopy (XPS), and transmission electron microscopy (TEM) confirmed that SiC@Ag nanoparticles can be attributed to the structure of core-shell material with uniform Ag coating and surface modification with organic ligands. This coating enhances wear reduction properties and decreases friction and wear by creating a stable tribofilm that provides better oil resistance under harsh tribological conditions such as extremely high temperatures and high pressure. Surface modification with organic groups promotes long-term dispersion in the base oil and inhibits particle sedimentation, a critical factor for racing applications.

3.1 Four-ball Test – Friction and Wear

The performances of the four-ball test for base oils and nano-oils containing SiC@Ag are shown in Table 1. The addition of SiC@Ag nanoparticles significantly reduced wear diameter and friction coefficient. For instance, grease with a concentration of SiC@Ag nanoparticles at 0.1 wt% reduced the wear diameter from 15 µm (base oil) to 8 µm and the friction coefficient from 0.12 to 0.08. When the concentration was increased to 0.5 wt%, it further reduced wear and COF. However, a concentration of 1 wt% only slightly improved, possibly due to the slight aggregation of SiC@Ag in the oil. Hence, the reduction in friction and wear coefficient can be attributed to the formation of a uniform tribofilm resulting from the presence of Ag on SiC. SiC maintains surface hardness, and Ag as a lubricant reduces friction. This pairing also enhanced the mending and polishing effect, preventing direct metal-to-metal contact.

3.2 Weld Load Test – Load Carrying Capacity

The weld load test results indicated that adding SiC@Ag nanoparticles improved the weld load considerably (Table 2). The weld load was 980 N in the base oil, whereas the nano-oil with 0.5 wt% SiC@Ag exhibited a weld load of 1350 N, attributed to an increase in the lubricating layer's ability to resist mechanical failure. The higher welding load is attributed to the development of an Ag/SiC protective layer on the metal surface, which enhances the pressure distribution and avoids the occurrence of cold welding and direct contact.

3.3 Viscosity and suspension stability

The rheological measurements of the nano-oils indicated that the viscosity at both 40 and 100 °C was approximately equivalent to the base oil, and that introducing SiC@Ag at concentrations less than 0.5 wt% had minimal impact. The 30-day sedimentation study demonstrated that modifying the surface with organic ligands (oleic acid/oleylamine) was successful in keeping the particles suspended and thereby promoting long-term stability. Nano-oils remained uniform and translucent, which is crucial for use in racing applications.

3.4 Discussion – Optimization

The findings indicate that the ideal concentration of SiC@Ag is approximately 0.5 wt%. Below this concentration, the effect on friction reduction is minor, above this concentration, there may be aggregation of the particles alongside a likely increase in viscosity. The effect of the accumulated hardness of SiC and the lubricity of Ag contributes to overall wear reduction, alongside an increase in weld load, thereby improving the stability of the lubricant film. This finding aligns with other studies from the tribology literature and demonstrates the significant potential of similar core-shell nanoparticles to improve the performance of racing oil.

Table 1 Tribological performance of base oil and nano-oils (Four-ball Test)

Sample	SiC@Ag Concentration (weight%)	Average Wear Scar Diameter (µm)	Coefficient of Friction (COF)
Base Oil	0	15	0.12
Nano-oil	0.01	12	0.10
Nano-oil	0.1	8	0.08
Nano-oil	0.5	6	0.06
Nano-oil	1.0	5.8	0.059

Table 2 Weld load (load carrying capacity) of base oil and nano-oils

Sample	Weld Load (N)
Base Oil	980
Nano-oil 0.1 wt%	1150
Nano-oil 0.5 wt%	1350
Nano-oil 1.0 wt%	1380

3.5 X-ray Diffraction (XRD)

As shown in Fig. 2, the XRD pattern of SiC@Ag nanoparticles showed characteristic peaks corresponding to the SiC phase (β-SiC) at $2\theta \approx 35.6°$, 41.4°, and 60.0°. In addition, the characteristic peaks of metallic silver were also observed at $2\theta \approx 38.1°$, 44.3°, and 64.5°, confirming the successful formation of the Ag shell on SiC. No additional side peaks were detected, indicating that the final product was pure and free from impurities.

3.6 Fourier Transform Infrared Spectroscopy (FTIR)

The FTIR spectrum of the altered nanoparticles (Fig. 3) exhibited the characteristic absorptions associated with $–CH_2$ units at approximately 2920 cm^{-1}, $–CH_3$ at roughly 2850 cm^{-1}, and Si-C at around 1000 cm^{-1}. These absorptions are associated with organic ligands, such as oleylamine or oleic acid, that were adsorbed onto the SiC@Ag surface. The evidence of organic units verifies that successful and stable dispersion of the particles in the base oil was achieved following the modification process.

3.7 X-ray Photoelectron Spectroscopy (XPS)

Based on the XPS analysis shown in Fig. 4, we determined that the silver element was present in its metallic state (Ag^0) on the surface of the nanoparticles. The Ag $3d_{5/2}$ and Ag $3d_{3/2}$ peaks were qualitatively observed at 368.2 and 374.2 eV. The surface ratio of silicon to carbon was fairly close to 1:1, indicating that the SiC structure was maintained. The XPS spectra did not show significant peaks corresponding to silver oxide, indicating that silver was deposited in a thin and uniform layer on SiC.

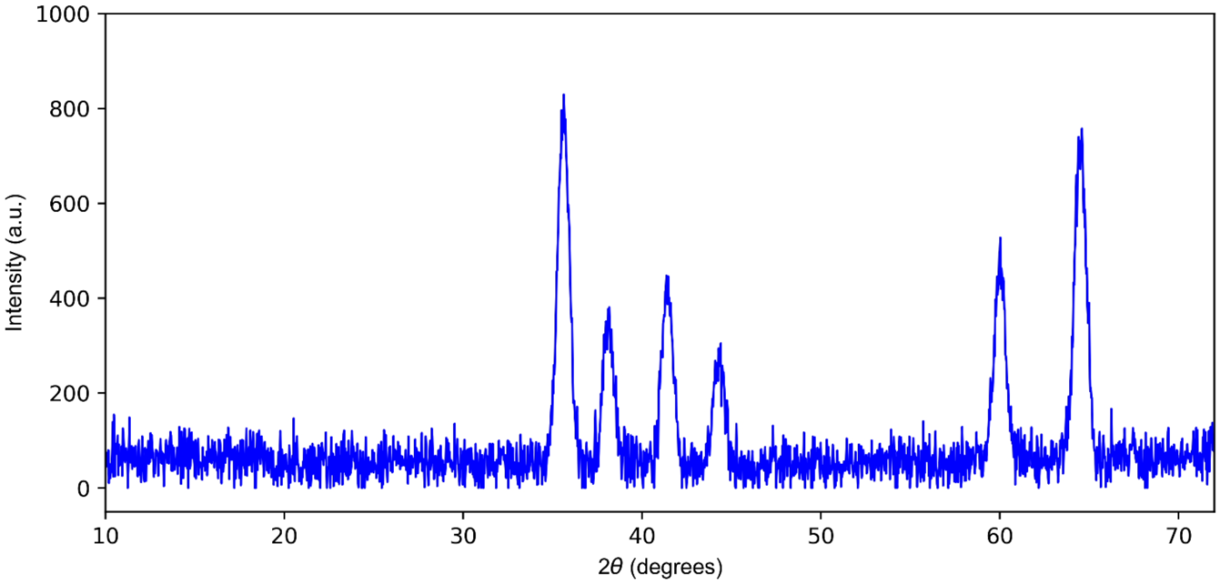

Fig. 2 XRD pattern of SiC@Ag nanoparticles

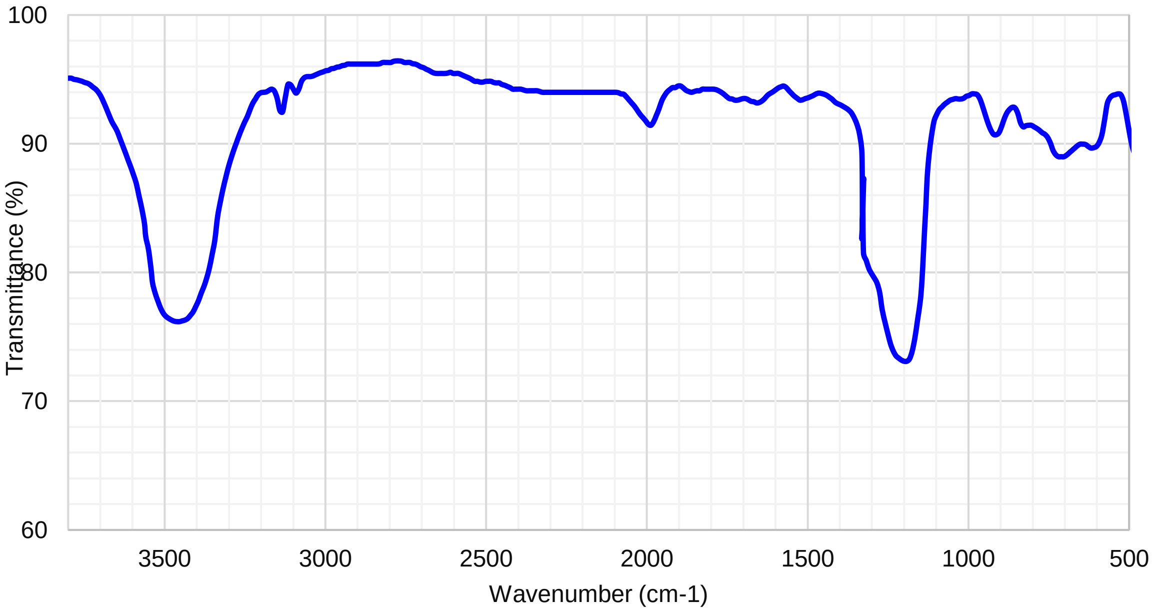

Fig. 3 The FTIR spectrum of the modified nanoparticles

3.8 Transmission Electron Microscopy (TEM)

The TEM image revealed that the SiC particles were nearly spherical nanostructures with a size between 50–200 nm and the Ag coating was deposited as a uniform layer that was about 5–10 nm thick. The core-shell configuration explains the mechanism of friction reduction and wear resistance due to the nano-oils (Fig. 5).

3.9 Scanning Electron Microscopy (SEM)

The SEM images revealed that the SiC particles were almost spherical, with diameters ranging from 50 to 200 nm, and that the silver (Ag) coating remained uniformly deposited on their surface. The width of the Ag shell was estimated to be ~5-10 nm. The particle distribution was even, and no significant agglomeration was apparent, indicating that core-shell synthesis was successful (Fig. 6).

3.10 Energy Dispersive Spectroscopy (EDS)

The EDS analysis confirmed the uniform distribution of Ag (silver) and Si (silicon) elements on the surface of the particles studied (Fig. 6). The analysis results indicate that the silver and silicon components were indeed distributed uniformly on the surface of the particles. A closer examination of the EDS analysis results reveals an approximate ratio of 1:10 between the elements Ag and Si.

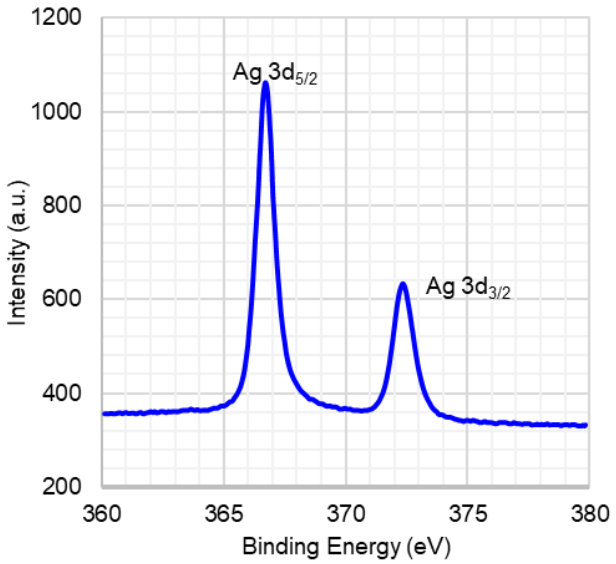

Fig. 4 XPS analysis of SiC@Ag nanoparticles

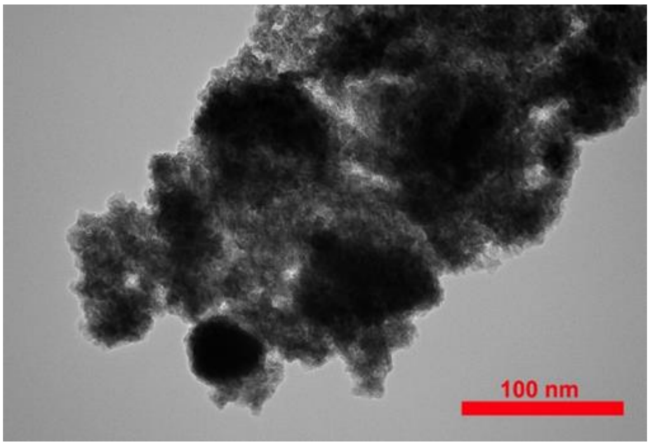

Fig. 5 TEM image of SiC@Ag nanoparticles

This Ag:Si ratio of 1:10 indicates that the particles were properly coated with silver. This ratio also indicates that the consumption of silver during the coating process was optimal and useful silver was not lost. In other words, the amount of silver used to coat the silicon particles was adequate and economically beneficial.

3.11 Brunauer–Emmett–Teller Surface Area Analysis (BET)

The surface properties and porosity of SiC@Ag nanoparticles were evaluated by the BET method (as shown in Fig. 8). The bare SiC nanoparticles exhibited approximately 45 m²/g specific surface area. Surface functionalization with organic ligands (oleylamine or oleic acid) and silver coating resulted in a slight reduction in the surface area to 38 m²/g, suggesting that a reasonably uniform Ag shell was created while still providing adequate exposed surface for tribological interactions. SiC@Ag had a pore volume of 0.12 cm³/g and an average pore size of 12 nm, confirming the existence of mesoporous structures, which is favorable for performing as effective lubricants.

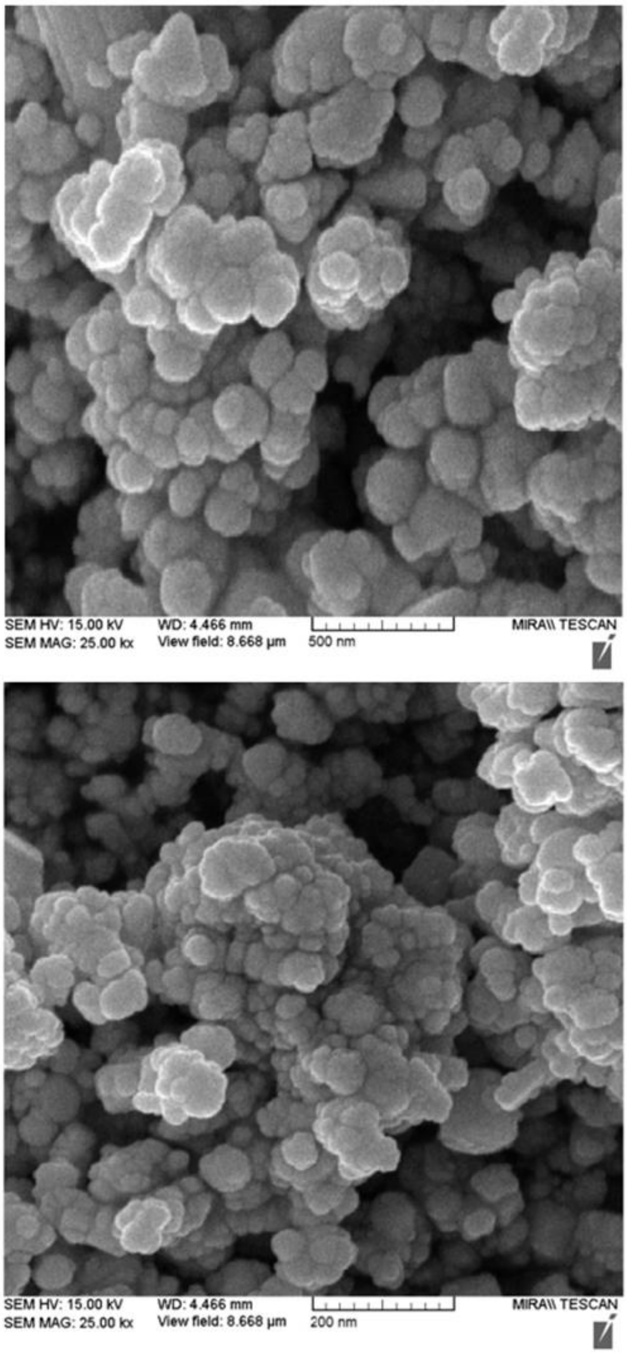

Fig. 6 SEM images of SiC@Ag nanoparticles

3.12 Thermogravimetric Analysis (TGA) Test

Thermogravimetric analysis (TGA) provided information on the thermal stability and organic content of the nanoparticles’ surfaces (Fig. 8). A modest weight loss of approximately 1.5 wt% occurred below 150 °C, attributed to the elimination of residual solvents and adsorbed moisture. A larger weight loss of about 3.0 wt% was detected between 250 and 450 °C, corresponding to the degradation of the organic ligands with surface attachment. Above 600 °C, there was no substantial weight change, confirming the thermal stability of the SiC@Ag core–shell nanoparticles. These findings suggest that the nanoparticles

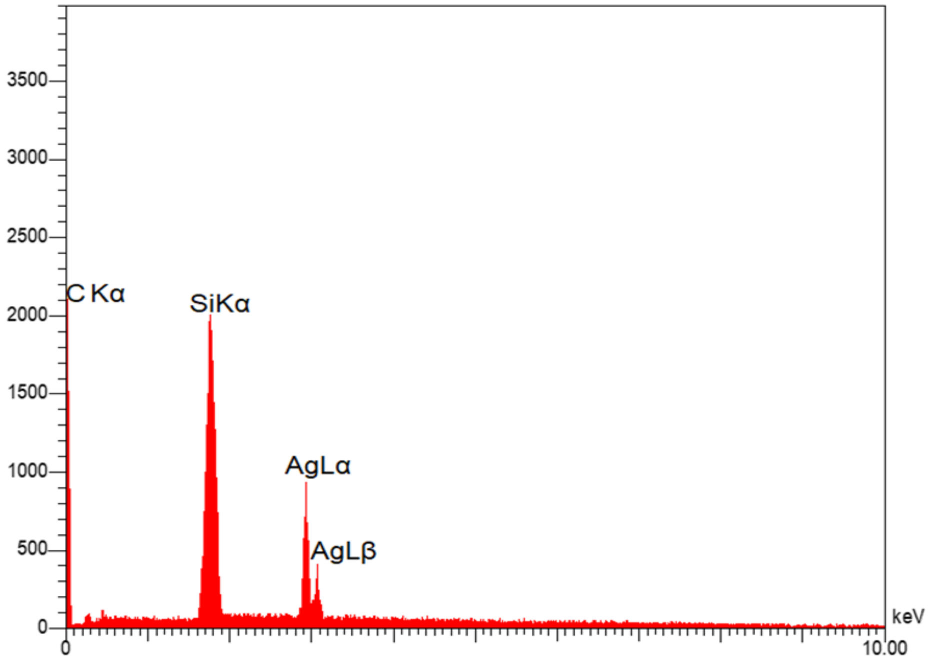

Fig. 7 The EDS analysis of SiC@Ag nanoparticles

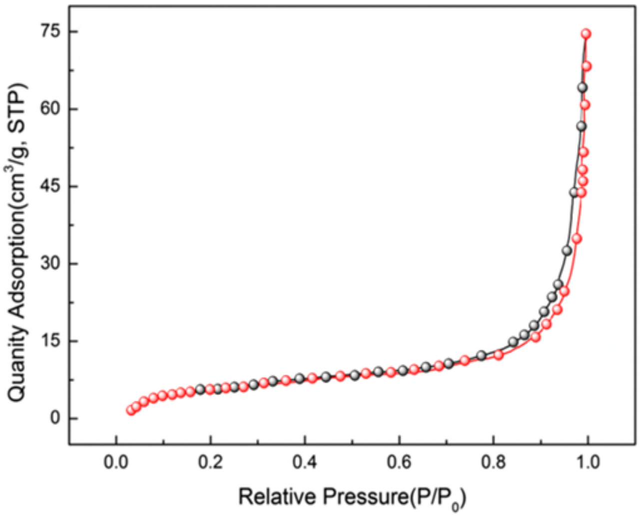

Fig. 8 BET analysis of SiC@Ag nanoparticles

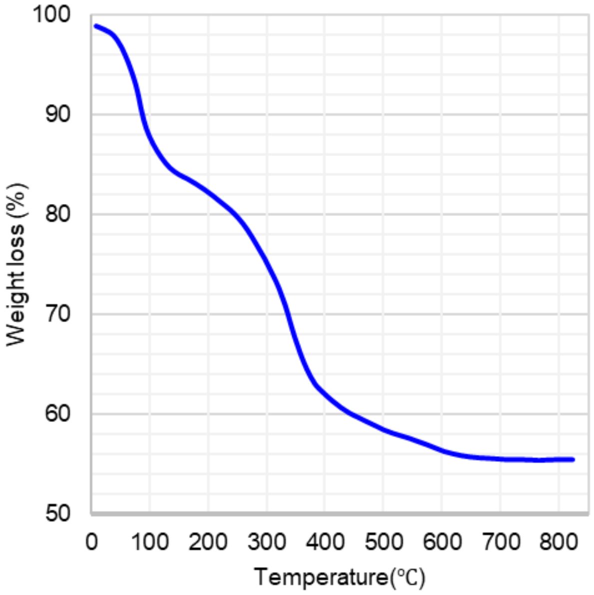

Fig. 9 TGA analysis of SiC@Ag nanoparticles

can withstand typical engine operating temperatures and that surface modifications will promote long-term dispersion stability in base oils.

4. Conclusions

In this investigation, the influence of SiC@Ag nanoparticles on the tribological properties and performance of base oils in racing gearboxes was studied. The core-shell nanoparticles were successfully synthesized using the polyol method, and the uniform silver coating on SiC particles was confirmed. The organic ligands used for surface modification improved compatibility and increased particle dispersion stability in the base oil. The SEM and TEM analyses revealed spherical SiC particles, sized between 50–200 nm, uniformly coated with Ag to achieve a coating thickness of 5–10 nm, with no significant agglomeration observed. The FTIR spectra confirmed the presence of organic groups, such as $–CH_2$, $–CH_3$, and C=O, additionally, XPS confirmed that Ag was deposited on the SiC surface in a metallic form without significant oxide formation. The four-ball test demonstrated that the addition of nanoparticles to the oil decreased the wear diameter from 15 to 6–8 µm with a 50% reduction in the friction coefficient. The weld load test indicated significant increases in the lubricant layer resistance, the welding load improved from 980 N in the base oil to over 1350 N in the 0.5 wt% nano-oil. The findings demonstrate that a hybrid SiC@Ag nanomaterial can substantially enhance the load-carrying capacity and durability of the lubricating film. The BET analysis indicated that the specific surface area of the particles after Ag coating was reduced to 38 m²/g, which is still sufficient for the essential physical dispersion of particles. TGA showed that the organic ligands were sufficiently stable and did not contribute to improved resistance to elevated engine operating temperatures. To summarize, the high hardness of SiC, coupled with the lubricating effect of Ag, can produce reduced friction, lower wear, and contribute to the formation of a reliable tribofilm. Additionally, the surface modification with organic ligands resulted in a favorable long-term dispersion and stabilization of the nanoparticles in the base oil. This study has demonstrated that hybrid SiC@Ag nanoparticles represent a novel additive technique for enhancing the efficacy and durability of powertrain engines in racing vehicles. The information gained from this work may lead to the development of new product formulations for advanced lubricants with superior performance under extreme temperatures and pressures, as well as provide new pathways for core-shell nanoparticles across the automotive industry and potentially other engineering industry applications.

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