TRIBOLOGICAL EVALUATION OF 2D NANOMATERIALS AND THEIR HYBRID IN BIOLUBRICANTS

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By

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Chapter 8 : Conclusion and future scope

Extensive tribological investigations were conducted on nanolubricants to optimize friction and wear properties. Functionalized 2D and hybrid nanomaterials were studied to assess the stability of biolubricants and address lubrication challenges. The following major conclusions were drawn from various tribological studies.

8.1. Major conclusion

1. **Hybrid nanolubricants and tribological enhancements**

- The study on spherical hybrid silica-molybdenum disulfide (SiO_2-MoS_2) in castor oil demonstrated exceptional antifriction and antiwear properties. At an optimal concentration of 0.05 wt%, the coefficient of friction (COF) reached a minimum of 0.03236, reflecting a ~46% reduction, while wear volume decreased by 58%. The synergistic interaction between spherical silica and MoS_2 played a pivotal role in tribofilm formation, ensuring superior lubrication and enhanced wear resistance.

- Images of worn surfaces, combined with debris analysis of nanolubricants, offer deeper insights into nanoparticle lubrication mechanisms. A circular mark on the surface with radially outward patterns suggests hybrid sphere braking, as confirmed by SEM analysis of the collected debris.

- A study on graphene-zinc oxide (AZnOGO) hybrids demonstrated a 48% reduction in wear volume at a 0.0625 wt% concentration, while a higher concentration of 0.1 wt% led to a more significant reduction in the coefficient of friction (COF), emphasizing the influence of nanoparticle concentration on the lubrication performance of castor oil.

- The coefficient of friction (COF) is statistically modelled and optimized using the response surface technique. The lubrication phenomenon is influenced by factors such as applied load, sliding speed, lubricant temperature, and nanolubricant concentration. Among these, COF is most significantly impacted by concentration, followed by temperature and sliding speed.

2. **Functionalized nanostructures**

- MXene, a new class of 2D materials, has been successfully synthesized from a Ti_3AlC_2 precursor and functionalized to serve as a lubricant additive for castor oil.
- Functionalization enhances the stability of MXene over time and demonstrates superior antiwear and frictional properties compared to pristine MXene.
- By improving the interaction between the metal surface and the additive, functionalization increases the surface activity of the nanolubricant. This, in turn, enhances the formation and retention of nanomaterials. Furthermore, this property has been explored by utilizing base oil as a functionalizing agent.
- The investigation of Karanja oil (KO) and its epoxidized variants highlights the potential of vegetable-based oils for sustainable lubrication. Functionalized hexagonal boron nitride (fh-BN) combined with epoxidized KO improved load-bearing capacity by over 100% while significantly reducing wear and friction. The tribological benefits of fh-BN arise from its lamellar structure and ability to form a thin, durable tribolayer.

- Polymerized silica-coated hexagonal boron nitride, functionalized with modified Karanja oil (MKO) fatty acid hybrid lubricants, was blended with Karanja oil as a base lubricant, utilizing the principle of 'like dissolves like.' Even a minimal dose of the hybrid lubricant resulted in a 107% improvement in load-bearing capacity.

- Functionalization enhances the robust film formation characteristics of nanolubricants, improving surface activity and enabling the formation of a strong, durable film capable of withstanding high loads during prolonged testing.

- MXene a new class of 2D materials is been successfully prepared from Ti_3AlC_2 precursor and functionalized to act as a lubricant additive for castor oils.

- Functionalization improves the stability of the MXene over the period of time and demonstrate better antiwear and frictional properties than pristine MXene.

- Functionalization improves surface activity of the nanolubricant by improving interaction between metal surface and additive. Thus, forming and retention of nano materials are improved by functionalization. This property is further explored to use base oil as a functionalizing element.

- The exploration of Karanja oil (KO) and its epoxidized variants demonstrated the viability of vegetable-based oils for sustainable lubrication. Functionalized hexagonal boron nitride (fh-BN) combined with epoxidized KO improved load-bearing capacity by over 100% and significantly reduced wear and friction. The tribological advantages of fh-BN stem from its lamellar structure and ability to form a thin, durable tribolayer.

- Polymerized silica coated hexagonal boron nitride functionalized by modified Karanja oil (MKO) fatty acid hybrid lubricants are mixed with Karanja oil as base lubricant utilizing the principle of like dissolve like. The load bearing capability after minute doze of hybrid lubricant found to be improved by 107%.
- The robust film formation characteristic is improved by the functionalization which improves the surface activity of nanolubricants and forms a strong film that can withstand high load under prolonged tests.

3. **Sustainability**

- The environmental benefits of using biodegradable vegetable oils as a base stock were emphasized. Modifications such as epoxidation enhanced load-bearing capacity and addressed issues related to unsaturation in fatty acid chains. These advancements make vegetable-based nanolubricants a viable alternative to traditional mineral oils.
- Blending modified oil with pristine vegetable stock oil is an effective approach to improving the load-bearing capacity of base oils. Depending on the application, it can also serve as a viscosity modifier.
- The environmental benefits of using biodegradable vegetable oils as a base stock were underscored. Modifications such as epoxidation improved load-bearing capacity and addressed issues related to unsaturation in the fatty

acid chains. These advances make vegetable-based nanolubricants a viable alternative to traditional mineral oils.

Comparison of performance

Table 8.1 Comparison of different performance parameters of 2D hybrid additives

Properties	SiO_2-MoS_2	AZnOGO	fMXene	fh-BN
Base Oil	Castor oil	Castor oil	Castor oil	Karanja Oil
Stability (hour)	120	168	288	144
Friction Reduction (%)	46	42	34	14
Wear volume reduction (%)	58	48	65	67
Optimum Concentration (wt%)	0.05	Wear: 0.0625 COF: 0.1	0.025	0.025
Change in Weld Load	No change	No change	No Change	No Change

The comparison of different hybrid nano-additives highlights distinct advantages across various performance aspects. In terms of base oil compatibility, SiO_2-MoS_2, AZnOGO, and fMXene are used with castor oil, while fh-BN is paired with Karanja oil. Regarding stability, fMXene exhibits the highest stability (288 hours), followed by AZnOGO (168 hours), fh-BN (144 hours), and SiO_2-MoS_2 with the lowest (120 hours).

For friction reduction, SiO_2-MoS_2 performs best with a 46% reduction, followed by AZnOGO (42%), fMXene (34%), and fh-BN (14%). However, in terms of wear volume reduction, fh-BN leads with a 67% reduction, closely followed by fMXene (65%), SiO_2-MoS_2 (58%), and AZnOGO (48%).

Regarding optimal concentration, fMXene and fh-BN require the lowest amounts (0.025 wt%), making them more efficient than SiO_2-MoS_2 (0.05 wt%) and AZnOGO (which requires 0.0625 wt% for wear reduction and 0.1 wt% for COF reduction). Lastly, none of the additives showed any change in weld load.

Implications of the study

- This research validates the potential of hybrid and functionalized 2D nanolubricants in enhancing the efficiency, durability, and sustainability of mechanical lubrication systems. These materials exhibit superior load-carrying capacity while significantly reducing friction and wear, making them ideal for critical applications in automotive, aerospace, and industrial machinery.
- The findings highlight the importance of integrating material science and tribological principles to address environmental concerns. By utilizing biodegradable oils and innovative additives, this research contributes to global efforts to minimize the environmental footprint of lubricants.

8.2. Future directions

- **Scaling and Industrial Application:** Future efforts should focus on scaling up the synthesis of hybrid nanolubricants for commercial applications. Real-world testing in engines, gear systems, and other mechanical components is essential to validate laboratory findings.

- **Long-Term Stability Studies:** The long-term dispersion stability and compatibility of nanolubricants with existing machinery must be thoroughly evaluated.

- **Eco-Friendly Approaches:** Continued emphasis on sustainable processes, including the use of renewable feedstocks and green synthesis methods for nanomaterials, is crucial.

- **Reducing Carbon Footprint:** The carbon footprint can be minimized by optimizing process parameters to reduce energy consumption and streamline synthesis steps.

In conclusion, this study establishes a strong foundation for the development of advanced nanolubricants, paving the way for more efficient and sustainable lubrication technologies. The integration of hybrid 2D nanomaterials, functionalized nanostructures, and biodegradable oils offers a transformative solution to the challenges of modern tribology.