
Abstract

The growing demand for sustainable and eco-friendly lubrication solutions has brought vegetable-based oils into focus as potential alternatives to conventional lubricants. However, their limited thermal stability, poor oxidative resistance, and suboptimal tribological properties necessitate the development of advanced hybrid additives to enhance their performance. This investigation highlights the effect of different types of hybrids nanolubricants made from 2D materials. A structural hybrid composed of spherical silica and lamellar MoS₂, which combine to form a sphere, was used as an antifriction and antiwear additive in vegetable oil for steel-on-steel tribo-pairs. These nanohybrids demonstrated improved dispersion stability due to the lightweight silica on the surface of hydrothermally prepared 2D MoS₂ sheets. The concentration of the nanohybrid was optimized to achieve optimal lubricant performance, and the optimal test space is detailed in this study. At the optimum concentration, the coefficient of friction was decreased to 0.03236, with an average wear volume of $2.16 \times 10^{-12} \text{ m}^3$. The synergistic interaction of the particles significantly reduced both friction and wear. The collision of hybrid spheres with the surface was found to have an immediate impact. Scanning electron microscopy revealed broken spheres in the wear debris, suggesting that the lubrication mechanism begins with the rolling of hybrid spheres and transitions to the rolling and sliding of silica and MoS₂ particles.

The next research focuses on the developing and characterizing of a novel lubricant containing hybrid composite nano-additives of graphene and zinc oxide (AZnOGO) for enhanced antifriction performance. This study considers the benefits of the combined sliding rolling mechanism achieved in the previous work. 2D graphene oxide sheets are attached to spherical zinc oxide particles, in which graphene oxide helps form a tribolayer, whereas spherical particles support rolling. A central composite design model

was employed to analyse the effects of key parameters, including sliding speed, applied load, temperature, and nanohybrid particle concentration, using response surface methodology (RSM). The study revealed that nanoparticle concentration is the most critical factor in lubricant design, as minor changes in concentration significantly affect the performance of lubricants. Other important factors include sliding speed and operating temperature, while applied load had the least effect within the selected range. A quadratic model was found to be the best way to predict output within the surrounding region. Incorporating 0.1 wt% AZnOGO resulted in considerable improvements, including enhanced thermophysical properties and a 24% reduction in the coefficient of friction.

Two-dimensional (2D) layered MXene nanosheets have gained significant attention in tribology due to their remarkable physicochemical and mechanical properties. However, their use has been limited because of poor dispersion stability in the oil. In this work, MXene was synthesized using the MAX phase (Ti_3AlC_2) by selectively etching aluminium with a combination of lithium fluoride and hydrochloric acid. The synthesized MXene was further functionalized with trichloro(octadecyl)silane to enhance its dispersion stability in the base oil. The MXene and functionalized MXene (fMXene) were characterized using FTIR, XRD, and TEM techniques. Functionalization effectively reduced agglomeration and improved the dispersibility of MXene in the oil. Tribological testing in the boundary lubrication regime demonstrated a 27 and 30% reduction in the coefficient of friction with 0.025 wt% MXene and fMXene, respectively. The improved dispersibility and reduced agglomeration enhanced the performance of fMXene, as evidenced by the increased fractal dimension of the worn surface. Functionalization also increased the surface activity of MXene, promoting tribofilm formation and the mending effect depicted by a reduction in valley height in the bearing ratio curve, which ultimately improved the wear and friction performance of the base lubricant.

Further studies were conducted on lubricants derived from Karanja seed oil (*Pongamia pinnata*) through chemical modification, combined with hexagonal boron nitride (h-BN), to enhance load-bearing performance. The tribological properties of pure Karanja oil, chemically modified Karanja oil (MKO), and blends containing fatty acid-functionalized h-BN (fh-BN) were evaluated. Initial tests assessed essential lubricating properties, and a 50% chemically modified oil blend showed the best performance at sliding speeds between 0.05 and 0.3 m/s. The key parameters measured includes frictional loss, failure load, wear volume, and the coefficient of friction for both modified blends and fh-BN nano-lubricants. The 100 % chemically modified oil blend (100% MKO) demonstrated a 114 % higher load-bearing capacity before failure, while the addition of fh-BN enhanced load capacity by 107% compared to pure Karanja oil. After the run-in phase, frictional work loss was similar between 100% MKO and pure oil under lubricant starvation conditions. However, blends of 50% MKO with 0.025 wt% h-BN and fh-BN exhibited reduced frictional work loss. The fatty acid layer on the functionalized fh-BN surfaces facilitated the formation of a thin tribolayer, which significantly enhanced the lubrication performance.

