Chapter 13
The Role of Two-Dimensional Materials in Superlubricity on Friction and Wear-Prone Surfaces

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ABSTRACT

Moving mechanical systems create a lot of friction; therefore, a lot of the energy produced is used to overcome it. It is vital to find unique ways to develop lubricants that allow for more effective control or decrease friction to reach a sustainable future. High friction, if not efficiently reduced or controlled, can result in higher wear losses and, as a result, shorter system life and lower reliability. Two-dimensional (2D) materials have distinct friction and wear properties from their three-dimensional (3D) counterparts. They can be used as additives in oils and composites to reduce stiction, friction, and wear, even though they are ultra-thin even with numerous layers. The role of these materials in superlubricity on surfaces prone to friction and wear is discussed in this chapter. These materials are solid two-dimensional lubricants that can address developing needs in mechanical systems in motion in current and emergent real-world applications.

INTRODUCTION

One of the issues that mankind faces is reducing energy losses due to friction and wear, which for roughly 20% of the total energy produced worldwide (Holmberg, 2019). The use of novel materials in lubricants to develop more efficient systems could cut these losses by as much as 40%. These materials should be used as low-shear-resistance coatings to reduce frictional forces and hence improve tribological performance. Furthermore, these additives must be non-toxic and environmentally beneficial. They

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may be exposed to radiation, function at high temperatures, or work in a vacuum or under ultra-clean conditions (Rosenkranz, 2020).

Without the addition of additives, base fluids such as mineral oil and synthetic goods cannot meet the standards of a high-performance lubricant (Braun, 2017). Synthetic substances that can increase the qualities of lubricants are known as additives. They serve three purposes in base fluids: to enhance existing properties, inhibit unwanted qualities, and introduce new properties. Lubricants typically comprise at least 90% mineral oil and no more than 10% additives. Tribology divides additives into two categories: 1) those that affect the physical and chemical properties of base fluids, and 2) those that affect metal surfaces by altering their physicochemical qualities. The additives examined in this chapter are those that are designed to reduce friction, support severe pressures, and protect surfaces from wear. The lubrication system operates in a mixed friction event when two components of equipment in contact move and hydrodynamic lubrication has not been formed, or when high stress and powerful pressures are applied. Antiwear (AW) and extreme pressure (EP) additives are necessary for metalworking fluid, motor oil, hydraulic fluid, or lubricating grease in this scenario to prevent moving parts from wearing out. These additives have a polar structure that forms layers on the metal surface through adsorption or chemisorption, ensuring their instant availability through the formation of a coating. As the temperature rises, these additives react with the metal surface, generating tribochemical reaction layers (such as phosphides, sulfides, sulfates, oxides, and/or carbides) that keep the sliding metals from making direct contact. Friction modifiers (FM) are layers that are physically adsorbed and have only moderately high or poor pressure support qualities. The coefficient of friction and viscosity is reduced by these modifiers. They perform at high temperatures with low sliding speeds, substantially increased loads, and low viscosities. By lowering friction forces, these reduce stick-slip oscillations and noise.

The newly introduced additives, which are based on finely ground powders of two-dimensional materials and their dispersions, are utilized as solid additions because of their outstanding circulation capabilities and high thermal stability when the oil supply fails. Because they minimize friction and increase the anti-friction capabilities of basic oil, two-dimensional materials can be used as developing lubrication additives (Yang, 2014). These even multi-layer materials are ultra-thin and can be used as additives in oils to reduce stiction, coefficient of friction ($0.0001 < CoF < 0.01$), and wear in mechanical systems with oscillating, rotating, and sliding contacts. Ultra-low shear strength, high specific surface strength, in-plane strength, poor layer-to-layer interaction, and surface chemical stability are all physical properties of two-dimensional materials that are important for superlubricity (Liu, 2019). Graphene and its derivatives were the first two-dimensional materials to be utilized as oil additives, and when applied in small amounts, they considerably reduced the friction and wear of steel parts. Other two-dimensional materials have been developed to optimize tribological performance with positive results due to their simple chemistry and the weak van der Waals bond between graphene layers. Molybdenum disulfide (MoS_2), tungsten disulfide (WS_2), phosphorene or black phosphorus (BP), hexagonal boron nitride (*h*-BN), layered double hydroxides (LDH), graphitic carbon nitride ($g\text{-}C_3N_4$), metal-organic frameworks (MOFs), and MXenes are some of the other solid lubricants (Liu, 2019; Rosenkranz, 2020; Wang, H., 2020). Additionally, these two-dimensional nanomaterials have a high elastic modulus, great strength, and ultra-low friction. Two-dimensional titanium carbide Ti_3C_2 can be used as a lubrication additive, either as a single layer or stacked in many layers, to reduce friction and anti-friction qualities of the base oil when increased to 1% by weight (Yang, 2014). Film-forming, self-healing, and ball-bearing lubrication mechanisms are used in these lubricants. Lubricant additives, nanoscale lubrication films, and aeronautical lubrication materials are the major uses (Liu, 2019).