different environments, such as high vacuum, water, the atmosphere, cryogenic temperatures, high temperatures, or dust. Therefore, the successful use of materials as solid lubricants requires understanding their material and tribological properties and knowing which solid lubricant formulation is best for a chosen application. Issues such as substrate surface pretreatment, materials compatibility, the mating counterpart material, and potential debris generation must be taken into account during the design and application of a lubricated device or of moving mechanical assemblies.

Cross-References

- ▶ Asperities
- ▶ Bonded Solid Lubrication Coatings, Process and Applications
- ▶ Bonding at Surfaces/Interfaces
- ▶ Diamond-Like Carbon Coatings
- ▶ Engine Lubricants
- ▶ Solid Lubricants for Space Mechanisms
- ▶ Solid Lubricants, Ceramic-Based Self-Lubricating Materials
- ▶ Solid Lubricants, Graphene
- ▶ Solid Lubricants, Layered-Hexagonal Transition Metal Dichalcogenides
- ▶ Solid Lubricants, Polymer-Based Self-Lubricating Materials
- ▶ Solid Lubrication in Fretting
- ▶ Solid-Like Lubricating Films, Self-Assembled Films

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Solid Lubricants and Applications

▶ Bonded Solid Lubrication Coatings, Process, and Applications

Solid Lubricants Based on MoS_x

▶ MoS_x Coatings by Closed-Field Magnetron Sputtering

Solid Lubricants Based on Soft Metals

▶ Solid Lubricant: Soft Metal

Solid Lubricants for Gas Bearings

▶ Gas Bearing Materials

Solid Lubricants for Rolling Bearings

▶ Rolling Bearing Lubricants

Solid Lubricants for Space Mechanisms

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Synonyms

Dry lubricants for space mechanisms; Oil-less lubricants for space mechanisms

Definition

"Solid lubricants for space mechanisms" refers to solid-state materials (particles, thin films, coatings, and bulk materials) that can be used as lubricants to reduce friction and wear of contacting and coupling surfaces in relative motion in a space environments.

Scientific Fundamentals

Requirements of Solid Lubricants for Space Mechanisms

"Solid lubricants for space mechanisms" is a branch of solid lubricants that guarantees reliable operation of moving components in various providing stable the friction and low wear rate. Effects of space environments – including high-vacuum, elevated-temperature, cryogenic temperature, solar and/or cosmos radiation (such as high-energy particles, X-rays, ultraviolet), sand-dust, and chemical corrosive environments (such as atomic oxygen in low earth orbit) – on reliability of solid lubricants must be take into account in space mechanisms. Thus, solid lubricants for space mechanisms simultaneously feature low friction coefficient, stable operation state, good wear resistance, and excellent space environmental adaptability. The significance of solid lubricants for space mechanism can be clarified just from Jost's statement: "… even a small tribological failure can clearly lead to catastrophic results…" (H. P. Jost 1990).

Early application of solid lubricants aimed to resolve tribological problems (friction, wear, and lubricant) under space operating conditions, where as conventional liquid lubricants were liable to fail under the same conditions. With the progress of space exploration (such as long-term space stations and lunar rovers), demand for lubricants for space mechanisms has grown rapidly. A challenge is to match the lubricant with the key function and operating environment for each mission. Generally, space mechanisms that require lubrication including solar array drivers, momentum, reaction, and filter wheels, tracking antennas, slip rings, scanning devices, sensors, rover wheels, robotic arms, antenna arrays, gearboxes/harmonic drivesr, and actuators among others. Each mechanism has unique hardware and requirements based on operating environments, thus requiring unique lubrication.

Different from liquids, solid lubricants are considered the most appropriate choice for space applications. Most of the solid lubricants are applied as thin films (less than one micrometer in thickness) and thick coatings (thickness is from 1 to over 10 μm). The most commonly used solid lubricating coatings for space mechanisms include lamellar solids, soft metals, polymers, and other low shear strength and/or super-hard inorganic lubricating materials, such as DLCs and nano-structured and multi-layered thin films. Lamellar solid lubricants include transition metal dichalcogenides, such as MoS_2 and WS_2, etc. Soft metals include Ag, In, Au, and Pb, etc. Polymers include polyimides (PI) and polytetrafluoroethylene (PTFE), etc. Sputtering and ion-plating are the preferred fabrication methods for these lubricants. Another common method is bonded coating, in which solid lubricant particles are mixed with an organic binder and form a coating to the surface by spraying or dipping. Self-lubricating polymers and polymer-based composite are also utilized. These materials are mostly used as a retainer of rolling bearing or as a bushing. The most successfully applied solid lubricants for space mechanisms are various forms of sputtered MoS_2 based composite films and ion-plated soft metal films. The advantages of solid lubricants for space mechanisms over liquid lubricants are summarized as follows (W. R. Jones 2000).

Advantages of Solid Lubricants for Space Mechanisms

- More stable operation state than liquid lubricants while applied under elevated temperature, cryogenic temperature, ultra-high vacuum, high-radiation, and corrosive environments.
- Maintains more lasting adequate lubrication under intermittent loading, wide range of loads and speeds (especially low speed), and rerunning after a long rest.
- High resistance to abrasive wear in sand-dust environments due to successful development of super-hard lubricating films.
- Complex sealing systems for liquid lubricants are not needed for solid lubrication. So, replacement of liquid lubricants by solid lubricants reduces weight of spacecraft and benefits extension of functions and maneuverability of a mission.
- Provides reliable operation under high radiation, maintaining a relative stable friction coefficient and high wear resistance.

Disadvantages of Using Liquid Lubricants in Space

- Liquid lubricants would evaporate under ultra-high vacuum and contaminate devices such as optical and electrical units.
- Most liquid lubricants would decompose or be oxidized at elevated-temperature. Proper solid lubricants can extend the operating temperature with relatively low friction coefficients.
- Liquid lubricants would be frozen, thereby becoming ineffective.
- Liquid lubricants would decompose under solar and/or cosmos irradiation when exposed to space environments.
- Liquid lubricants tend to pick up dust, forming a grinding paste, causing abrasive wear to damage equipment under sand-dust conditions.

- Liquid lubricants become unstable even ineffective or under intermittent operating conditions.

Design Proposals for Solid Lubricants for Space Mechanisms

Based on future requirements of solid lubricants for space environment applications, several design proposals are summarized below (K. Miyoshi 2007):

- For high-accuracy moving components that need stable and precise lubrication, low friction coefficient solid lubricating films should be selected, such as modified sputtered MoS_2-based composite films, ion-plated soft metal films, PTFE, DLCs, diamond films, multi-layered nanocomposite films (MoS_2/WS_2/C and MoS_2/WS_2), and functionally graded, multilayered inorganic films (TiCx/C).
- For wide-range temperature cycling environments, an interlayer between a substrate and a solid lubricating film should be created by controlling chemical composite and microstructure, minimizing mismatches of thermal expansion coefficient, lattice parameter, and differences in mechanical properties, strengthening chemical attraction and adhesion (e.g., a Ti or Cr interlayer on a metal substrate, a Si interlayer on a ceramic substrate, or a Zn interlayer on a polymer substrate).
- For high speeds, high loads, and other applications where heat dissipation is required, high thermal conductive solid lubricating films should be constructed, such as carbon nanotubes, nanocrystalline diamond films, metal doped diamond and DLC films, and soft metals (Au, Ag, Cu, Pb) and their alloys films.
- For a sand-dust environments, such as a lunar rover would encounter, hard solid lubricating films should be applied, such as ceramic films, including BN, BC, VC, AlN, CN, TiO_2, SiC, Si_3N_4, and SiO_2, nano- and micro-crystalline diamond, and DLC films.
- For advanced controlling mechanisms, self-adaptive hard and tough solid lubricating films should be employed. These films include multiphase composite films (WC/C, WS_2/WC/DLC, and TiC_x/C), multilayered composite films (MoS_2/DLC, WS_2/DLC, MoS_2/WS_2 and TiC_x/C), and functionally graded films (Ti-TiC_x-DLC).

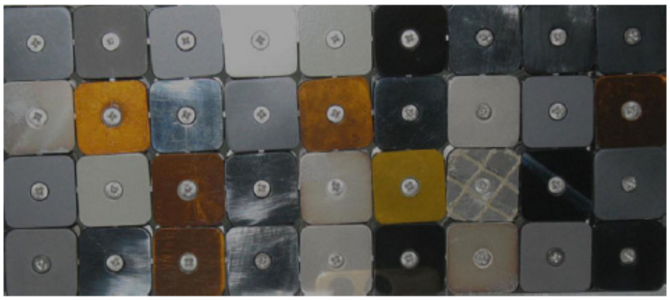
Key Applications

Overview

Historically, solid lubricants for space applications can be traced to the early 1960s when the demands of space mechanism moved lubricants from liquids to solids in order to adapte to space environments. Various routes for fabrication and application of solid lubrication systems were developed. These techniques did contribute to successful. Thus, most work in this area ceased in the early 1970s. Renewed interests in lubricants for space mechanisms grew during the late 1980s and early 1990s with the emerging demands of new space missions as well as the rapid developments in advanced material science. These included novel solid lubricating films and coatings with cryogenic friction coefficient and high wear resistance, light-weight materials for moving components of spacecraft mechanisms, lubricating systems for long-term spacecraft, and retainers for bearings running in ultra-low temperature. The coming requirements of solid lubricants include stable, reliable, and long-term operation in space environments. For example, the expected endurance life of a future long-term space-station as currently under development is more than 15 years. National Aeronautics and Space Administration's (NASA) objectives for deep space exploration are human exploration of and permanent human presence on the Moon and Mars (K. Miyoshi 2007). These are critically dependent on the reliable operation of many moving mechanisms, and need advanced solid lubricant selection and fruitful efforts in applications where liquid lubricants are ineffective and inappropriate. Numerous moving components will be directly exposed to space environments during space docking and planet exploration. The effects of space environments on the tribological properties of such lubricants may pose potential threats to the overall performance of spacecraft. Thus, the environmental effects of space must be regarded when designing and selecting the required long-term space solid lubricants. Advanced solid lubricants are required to meet these operating requirements. Sand-dust wind storms on the surface of the deep space planets provide additional challenges to explorers, such as the Lunar rovers and the Martian rovers. In low earth orbits, the effects of atomic oxygen and ultraviolet irradiation should not be ignored. To explore the low earth orbit environment effects on performance degradation and failure mechanism of solid lubricants, ten solid lubricant samples (see Fig. 1) of eleven materials of three different types of solid lubricants were selected for an in-orbit, outside-cabin exposure experiment on China's Shenzhou VII manned spacecraft.

Space Mechanisms Requiring Solid Lubrication

Almost all space mechanisms have moving components require lubrication. The space mechanisms usually to require solid lubrication are listed as follows (W. R. Jones 2005).



Solid Lubricants for Space Mechanisms, Fig. 1 Section of the solid lubricants samples for in-orbit, outside-cabin space exposure experiment on China's Shenzhou-VII spacecraft (Photo provided by the State Key Laboratory of Solid Lubrication, Lanzhou Institute of Chemical Physics, Chinese Academy of Sciences)

Electrical contact ring assemblies (ECRAs) are a typical example with unique lubrication requirements. Excessive electrical noise, usually due to surface contamination, is the most common failure mechanism in ECRAs. Thus, low speed operation and electrical conductivity are the two key factors that affect lubricant selection. Proper selection of lubricants and the electrical properties of degradation products are significant for reliable ECRA operation.

Gyroscopes, which are used to measure changes in orientation, operate at high speed with high accuracy. Waves in the bearing reaction torque, noise, and excess heat generation can cause a null position loss in the gyroscope, making the bearings a vital gyroscope component. The proper lubricants for a gyroscope should provide a high level of wear protection, and minimal friction, and they should also have low evaporation rate.

Momentum and reaction wheels have similar requirements of lubricant selection. The momentum wheels typically operate at a speed of 3,000 and 10,000 r/min. Therefore, lubricants are usually become more serious due to creep and degradation subjected to higher operating temperatures and stresses. Reaction wheels operate at low speeds. To support bearings with good lubrication, the lubricants must have good boundary lubrication characteristics. Control moment gyroscopes (CMGs) combine the aspects of gyroscopes and moment wheels to provide spacecraft attitude control. Therefore, both groups must be considered when selecting a CMGs lubricant.

Sensor bearings are used by many spacecrafts that contain rotating or dithering components for support. Correct lubricant selection is important to guarantee that the sensor bearings are operating in the regular state to complete mission life and adapt environmental requirements.

Actuators and gearboxes are not in continuous operation for long terms, however, high stresses may be produced within long rest periods. The mechanisms cannot be re-lubricated between missions and also may be stored on ground for a long periods. Because examination and re-lubrication is often an expensive, complicated, and time consuming process, understanding the reaction between the selected lubricants and the actuator components during storage and rest time is a significant issue for ensuring the correct operation state of the actuators and gearboxes.

Planet rovers have many components that need lubrication and have unique lubrication requirements. During space travel, the lubricant is subject to low pressure and controlled temperature of the spacecraft, but once deployed, it will be exposed to extreme planet surface environments, including ultra-high vacuum, wide temperature ranges, various gaseous atmospheres, irradiation, and other environmental conditions, such as sand-dust and solid contaminants. Rover mechanisms include robotic arms to deploy instruments and manipulate the environment, mast assemblies to hold cameras and viewing devices, solar arrays to provide power, antennas and communication equipment masks, and a mobility system consisting of wheels, legs, and other moving components. In addition to the rover, the associated landing craft also has many lubricated mechanisms.

One-time operated mechanisms include satellite solar arrays or antenna deployments. Not all mechanisms require long-term lubrication, but even such one-time operated mechanisms require critical lubricant selection. If these mechanisms fail to deploy, functions of the spacecraft will be partially or completely lost. Failure to fully understand the system, its dynamics, build-up, testing, and final operating environment effects can lead to disastrous results, as evidenced by the high gain antenna failure on the Galileo spacecraft (K. Miyoshi 1999). These mechanisms have unique lubrication demands because they only operate once, are low-speed applications, may have long rest periods before moving, and may be exposed to space environments. Generally, solid lubricants are the best choice for such mechanisms due to their low friction coefficient and ability to reside in the contact section.

Other mechanisms used in space also require lubrication. Some examples of such include solar array drives (SADs), which rotate solar arrays of spacecraft, ball, roller, and acme screw drives, and many types of gears and transmission assemblies, such as harmonic drives.

Most Applied Solid Lubricants for Space Mechanisms

Numerous solid lubricants have been developed for space mechanisms in the past decades. The most commonly applied ones in space mechanisms are as follows (W. R. Jones 2005):

Sputtered molybdenum disulfide (MoS_2) based films are widely used as lubricants in space mechanisms due to their ultra-low friction coefficients and long durability for rolling and sliding tribo-components in ultra-high vacuum. The distinct characteristic of MoS_2 is its highly anisotropic crystal layer structure, which consists of a layer of molybdenum atoms arranged in a hexagonal array. Each molybdenum atom is surrounded by equal distance of six sulfur atoms placed at the corners of a triangular prism. The distance between the layers of molybdenum and sulfur atoms is 0.154 nm, which is smaller than the distance between the adjacent sulfur atoms layers, which is 0.308 nm. Thus, the inter-lamellar layer attractions between the adjacent lamella are weak and consist basically of van der Waals force. However, the chemical bonds between molybdenum and sulfur atoms within the lamellae are much stronger covalent ones. Thus, macroscopic MoS_2 crystals easily shear along the van der Waals space between the lamella. The weak inter-lamellar bonding contributes to the low shear strength during sliding, which is reflected in the low friction coefficient (T. Spalvins 1982). Environmental factors obviously affect the friction coefficient and endurance life of MoS_2 films. In ultra-high vacuums, films that are one micrometer or less in thickness exhibit ultra-low friction coefficient (less than 0.01) (C. Donnet et al. 1996). Under normal vacuum, the friction coefficients of the films may range from 0.01 to 0.04 and exhibit exceptionally low wear rates and long endurance lives. It is well known, however, that most components of spacecrafts/space mechanisms have to be subjected tests in air, especially in moist air, before lunching. So the resistance to oxidation of the MoS_2-sputtered film in moist air needs to studies further more. As (D. Yu et al. 1997) reported, after storage in moist air for 15 days, the substrate (440C bearing steel) surface which MoS_2-sputtered corroded badly with lots of corroded spots on the disc surface, which are about 0.30–0.40 nm in diameter and 0.002–0.013 mm deep in the substrate, microcracks in the neibghboring zones and some peeled parts of the MoS_2-sputtered film. On the contrary, the substrate with MoS_2-LaF_3 cosputtered on it were not corroded at all, looks like the same as that of the as-deposited samples, even after being stored for two months in the moist air with the same humidity (~100% RH). Some metal elements, including Ti, Ni, Au, Pb, and Sb, were added to enhance the endurance life of MoS_2 based films. An adhesion interlayer and gradient layer(s) can be used to increase the wear life of most films (T. Spalvins 1982).

Ion-plated soft metallic films of Ag, Au, or Pb is solid lubricants selected for precision spacecraft mechanisms, where wear debris formation is critical and high reliability requirements must be satisfied (Spalvins and Buzek 1981). Ion-plated soft metallic films have three improvements over ordinary vapor-deposited films: increased endurance life, lower friction coefficient, and avoidance of catastrophic failure. The increased endurance life is attributed to superior adherence, lower friction coefficient (due to the dense, cohesive, small crystalline size), optimum film thickness, and gradual increase in the friction coefficient, which attributed to the formation of the graded interface in the film, after the film has been worn off.

Diamond-like carbon films (DLCs) are made of sp^2- and sp^3-hybridized carbon atoms and may contain some hydrogen ranging from less than 1% to about 50%, which affects not only their structures but also their properties. The great variety of DLC structures and compositions leads to a wide range of friction coefficients in various conditions. The friction coefficient and wear rate can be adjusted through preparation methods, incorporated alloying elements, and a variety of multilayer structures. Some DLCs exhibit friction coefficients below 0.01 in vacuum and show promise for future space applications.

Polymers have been successfully used in many applications. Many polymers can be used in vacuum and at cryogenic temperatures due to their low friction coefficients, low densities, excellent corrosion resistance, and machinability. Commonly used polymers are introduced as follows.

- Polyimide (PI)

  Polyimide (PI) is widely used in spacecraft mechanisms because of its favorable tribological performance at high gearing pressures and sliding speeds, excellent mechanical properties, and high thermal stability at temperatures up to 315°C. PI possesses some extraordinary characteristics such as excellent mechanical and insulating properties, good thermal stability and chemical inertness, high wear resistance, and radiation resistance (S. Bahadur and V.K. Polineni 2001). Certain additives (such as graphite, MoS_2, fluoride graphite, PTFE fiber, and so on) can improve the mechanical strength and the lubrication performance of PI. The incorporation of carbon fiber and solid lubricants in PI can greatly decrease the friction coefficient and wear rate in sliding against stainless steel. The combination of micro SiO_2 and carbon fibers and graphite can improve the tribological properties of the PI composites. The fillers of nano-Si_3N_4 and short carbon fibers and graphite can also improve the tribological properties of the PI-based composites.
- Polytetrafluoroethylene (PTFE)

  PTFE is a commonly used polymer solid lubricant that provides a dry sliding friction coefficient lower than 0.2 sliding against stainless steel (Gregory Sawyer et al. 2003). The low friction coefficient of PTFE has been attributed to its low adhesion to the mating surface, the low shear stress needed to overcome adhesion at the interface, and to its ability to transfer on bare surfaces resulting in PTFE versus PTFE contact. PTFE can also be applied as thin sintered or resin-bonded films on metal and ceramic substrates. They have stable tribological behavior in vacuum. PTFE fibers and woven fabrics containing cotton or glass fibers are commonly used in bearings, gaskets, and seals applications.
- Polyamide-imide (PAI)

  PAI is a kind of thermoplastic resin, and has very good high-temperature properties (approaching those of polyimides), good wear and radiation resistance, inherently low flammability and smoke emission, and the highest strength of any unreinforced thermoplastic. Applications include parts for internal combustion and jet engines, bearings and thrust washers, and mechanical, electrical, and electronic components.
- Ultra-high molecular weight polyethylene (UHMWPE)

  UHMWPE exhibits excellent impact and abrasion resistance, which makes it useful for bearings, gears, bushings, and other sliding components. UHMPWE is widely used for low precision gears in space mechanisms. It has the highest sliding abrasion resistance and highest notch impact strength of any commercial polymers (Abdul Samad and Sinha 2010). In its bulk form, UHMWPE is highly wear resistant compared to many other polymers, such as polyetheretherketone (PEEK), polyethylene (PE), polystyrene (PS), etc. The outstanding characteristic of UHMWPE is that they can be operated from −269°C to 90°C, and even higher for short time. Since it does not liquefy at its softening point of 138–142°C, it retains excellent dimensional stability at temperatures up to 200°C.
- Polyoxymethylene (POM)

  As a type of engineering plastic, POM exhibits good fatigue resistance and creep resistance, high impact strength and elastic modulus, good self-lubricant property, and wear resistance. Friction of POM with polydimethylsiloxane (PDMS) additive can be further reduced by the admixture of 5 wt% polytetrafluoroethylene (PTFE) additive (Laursen et al. 2009). POM filled with Cu exhibited increased friction coefficients and decreased wear weight loss compared with unfilled POM. POM can be widely applied as the rotation materials of mechanical and electromechanical fabricates electronic parts, automotives, precision instruments, etc.
- Filled polymer composite

  This is a modified polymeric lubricant where fibers (glass or carbon fibers) are dispersed into engineering polymers to enhance their mechanical and tribological performances. The fibers are typically 5–10 μm in diameter and can be continuous, milled, or chopped. Fiber size and orientation affect wear resistance and mechanical properties. Commonly specified fiber reinforcement materials are glass, aromatic polyamide (Kevlar), carbon, polyester, cotton, asbestos, graphite, and nylon. Carbon or glass-filled acetal and fiber-reinforced and filled PTFE (Rulon) are commonly specified for low-precision gears in space craft mechanisms. PTFE/chopped glass/MoS_2 composite is used as a retainer material for bearings. Solid particulate fillers, such as MoS_2, carbon, PTFE, PI, Ag, Cu, SiO_2, TiO_2, and Al_2O_3, are usually doped into polymers to improve their tribological properties.
- Polymer-based composite coatings

  These are bonded to a metal substrate to give them the necessary stiffness to perform a useful bearing function. PTFE- and PI-based self-lubricating coatings are widely used as bearing retainers for rolling and/or sliding surfaces in space mechanisms (M. J. Todd 1982). Vacuum pin-on-disk tests showed that the friction coefficients of ten different polymer-based lubricating coatings applied to 440 C steel substrates are less than 0.05, meanwhile their wear rate orders of magnitude are less than those in moist air (Fusaro 1988). PTFE films reinforced with glass fibers or bronze mesh are all suitable for use in vacuum, and are used for rod-end bearings and other applications in vacuum. This type of bearing finds widespread use in high loads with small movements.

Fabrication Methods of Solid Lubricants for Space Mechanisms

Many methods, such as plasma-based deposition, spray-bonded coatings, and chemical deposition, have been developed to successfully obtain solid lubricants for space mechanisms. Most of them are based on vacuum technologies, such as ion plating, sputtering, pulse laser deposition (PLD), ion beam assisted deposition (IBAD), or plasma enhanced chemical vapor deposition (PECVD). These methods result in strong adhesion between solid lubricant films and substrate materials. Recently, these advanced methods were combined with smart surface engineering practices, such as micro patterning or texturing, to achieve much improved tribological properties in applications. Ion plating and sputtering are the most basic forms of physical vapor deposition (PVD).

Ion plating is used for depositing soft metal films and achieving strong adhesion between substrate materials and films. In this technique, atoms of soft metal lubricants are thermally evaporated into argon plasma where they become ionized. The ions are then accelerated towards a negatively biased substrate where film growth occurs. The substrate bias also ensures that, during its growth, the film is continuously bombarded by argon ions and these help to reduce the contamination and loosely bound atoms in the growing film. Thus, ion plated metal films have high density, low porosity, high purity, and strong adhesion to substrates.

Sputtering is created by ion-bombardment of the source materials (targets). Direct current (DC), radio frequency (RF) and mid-frequency magnetron sputtering are three general sputtering modes for solid lubricants. Higher deposition rates are obtained by using magnetron sources. Sputtering is commonly employed for the deposition of MoS_2 and other metal dichalcogenide-based lubricating films.

Burnished films are obtained by rubbing dry lubricant powders onto a surface to be lubricated. It is the simplest method of applying solid lubricants in the form of thin films. Burnishing can be carried out by hand, using a burnishing cloth, but it is difficult to reproducibly obtain films of the required thickness with this technique. More refined methods have been devised in which the lubricant is applied in more a controlled manner by mechanical means.

Bonded coatings are kinds of lubricants in which lubricant powders (usually MoS_2, PTFE, or PI) are attached to the substrates by binder materials. In general, the binding agent and lubricant powder are suspended in a solvent and the resulting dispersion is applied to surfaces by spraying, painting or dipping. Resin-bonded lubricants require curing before application. Coatings utilizing cellulosic and acrylic resins are air-cured, while thermosetting resins need curing at high temperature. Resins in the latter category include epoxies, phenolics, polyimides, alkyds, silicones, and polyphenyl sulphide. Coating thicknesses are typically 25 μm. These coatings are improper for precision components since precise control over the coating thickness is difficult to achieve.

Plasma-sprayed is a type of coating technology in which lubricant particles are heated rapidly in a hot gaseous medium and projected at high velocity onto a surface to produce a coating. Several materials can be deposited simultaneously, and this capability has been exploited to produce multiphase coatings composed of a hard, wear-resistant matrix (e.g., Al_2O_3) with solid lubricants (e.g., MoS_2 and Ag). In space mechanism applications, this method has been used primarily for the development of high temperature coatings for use in re-entry vehicles.

Cross-References

- ► Cryogenic Solid Lubrication
- ► Diamond-Like Carbon Coatings
- ► Gear Lubricants
- ► MoS_x Coatings by Closed-Field Magnetron Sputtering
- ► PVD: Ion Plating
- ► Solid Lubricants
- ► Solid Lubricants, Layered-Hexagonal Transition Metal Dichalcogenides
- ► Solid Lubricants, Polymer-Based Self-Lubricating Materials
- ► Thin Film Lubrication

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Solid Lubricants, Ceramic-Based Self-lubricating Materials

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Synonyms

Ceramic-based/ceramic matrix self-lubricating coatings; Ceramic-based/ceramic matrix self-lubricating composites

Definition

Self-lubricating, an adjective, means "not requiring external application of lubrication to parts that experience friction because the lubricant is self-contained." Ceramic-based self-lubricating materials are composites, and the most important characteristic is self-lubricating behavior. They are normally composed of two basic components, ceramic matrix and solid lubricants. Advanced structural ceramics (alumina ceramics, zirconia ceramics, silicon nitride ceramics, and silicon carbide ceramics) are good candidates for the matrix because they usually have low density and possess good properties, e.g., high hardness, high compressive strength, retention of mechanical properties at elevated temperatures, and high resistance to chemical corrosion (Gangopadhyay et al. 1994). The above-mentioned properties enable these ceramics and ceramic-based self-lubricating materials to be applicable at high temperatures and in other harsh environments. Metal binders as well as the stabilizers are sometimes necessary and useful for constructing the ceramic matrix. Solid lubricants are an important component of ceramic-based self-lubricating materials and improve the tribological properties. Solid lubricants include precious metals, soft oxides, chemically stable fluorides, and a combination of various solid lubricants. Some carbides containing titanium, e.g., TiC and TiCN, are not solid lubricants, however, they can produce lubricous oxides on the frictional surface during sliding in an air or oxidizing atmosphere. In a broad sense, ceramic-based materials containing TiC or TiCN should be included in the category discussed here.

Scientific Fundamentals

Structural ceramics have high potential for application in tribological fields because of the particular properties mentioned above. However, it is reported that the coefficient of friction between ceramics is generally high under unlubricated conditions (Sliney and Dellacorte 1994), and it is not effective to use liquid lubricants when the ceramics are used under high temperature or vacuum environments. The high friction coefficients of these materials limit their uses as tribological components. To take advantage of the beneficial properties of the advanced structural ceramics, friction coefficient must be reduced. A strategy to improve the tribological properties of advanced ceramics is to fabricate ceramic-based self-lubricating materials. There are two or more benefits from the self-lubricating concept. The first is that the solid lubricants in the ceramic-based self-lubricating materials are reservoirs for a successive supply of the lubricating film on the frictional surface. The second is that material design can be simple because no supply of solid lubricants is needed.

Three aspects should be considered in fabricating ceramic-based self-lubricating materials: (1) material selection for the matrix and solid lubricant; (2) preparation, microstructure, and mechanical properties of ceramic-based self-lubricating materials; and (3) self-lubricating mechanism.

Material Selection for the Matrix and Solid Lubricant

Material selection of the matrix is based on two guidelines: (1) the working condition of the ceramic-based