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Bolted Joints

► Bolted Connections

Bonded Solid Lubrication Coatings, Process, and Applications

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Synonyms

Solid lubricants and applications

Definition

Bonded solid lubrication coatings are composed of one or more solid lubricants (e.g., MoS_2, graphite, PTFE) and other additives dispersed in an organic or inorganic binder, diluted with a solvent, then sprayed, dipped, or brushed onto a substrate, and cured to form a "bonded" solid film lubricant.

Scientific Fundamentals

Introduction

Bonded solid lubrication coatings came about in the late 1940s with the development of the aircraft industry. Their use accelerated in the early 1950s with the birth of the space program. Almost all of the original bonded solid lubrication coatings were composed of molybdenum disulfide (MoS_2), graphite, phenolic resin (binder), and a suitable solvent, and were cured at a temperature of +150°C. The majority of development work on bonded solid lubrication coatings occurred during the 1950s and 1960s. Since then, there have been many changes or revisions to the original products. The binders have been expanded to include inorganic components such as sodium silicates, phosphates, and ceramics. The lubricating pigments have been expanded to include polytetrafluoroethylene (PTFE), antimony trioxide (Sb_2O_3), silver, and gold. Cure temperatures have been expanded to +1,000°C or higher. In recent decades, bonded solid lubrication coating technology has grown considerably and is now applied in a wide variety of industrial, automotive, military, and aerospace applications (Clauss 1972; Campbell 1972; Fusaro 1978). Today, bonded solid lubrication coatings are an attractive alternative to fluid lubricants for minimizing friction and preventing seizing and galling, especially in harsh environments where conventional oils and greases no longer meet the performance and durability needs of advanced mechanical systems (Lancaster 1984; Gresham 1997).

Mechanisms

Bonded solid lubrication coating has inherent lubricating properties because of the presence of solid lubricants. The solid lubricants are generally composed of lamellar solids (e.g., MoS_2, WS_2, graphite), polymers (e.g., PTFE, phthalocyanine), and soft metals (e.g., In, Sn, Pb, Ag, Au, Pt, Sn) (McMurtrey 1985).

Each type of solid lubricant has different lubricating properties. Lamellar solids crystallize with a layered structure in which interatomic bonding between the layers is weaker than that within them. Thus, these materials have low shear forces between their crystalline lattice layers. When present between sliding surfaces, the crystalline lattice layers can align themselves parallel to the direction of relative motion and slide over one another with relative ease, thus providing low friction. In addition, strong interatomic bonding in each layer is thought to help reduce wear damage (Farr 1975; Erdemir 2001).

PTFEs can also provide lubrication, although they do not have a layered crystal structure. The low friction of

PTFE is attributed to the smooth molecular profile of the polymer chains, which, after orientation in early stages of sliding, can then slip easily along each other, similar to lamellar structures (Pooley and Tabor 1972).

The soft metals can provide low friction on sliding surfaces mainly because of their low shear strengths and rapid recovery as well as recrystallization. Soft metals have crystal structures with multiple slip planes and do not work-harden appreciably during sliding contact. Dislocations and point defects generated during shear deformation are rapidly nullified by the frictional heat produced during sliding contact.

When present at a sliding interface, initial smoothing of the surface of the bonded solid lubrication coating takes place as a result of the relative movement of the opposing surfaces. A partial discharge of materials from the solid film lubricant layer creates a "transfer" film on the opposite surface. The build-up of lubricating film between the two surfaces leads to a reduction in the coefficient of friction.

Characteristics

Bonded solid lubrication coatings have some unique properties compared with conventional fluid lubricants (oils and greases). The major characteristics of bonded solid lubrication coatings are as follows (Chen et al. 1994):

1. The thickness of the bonded solid lubrication coatings is normally thin (several microns). This makes it possible for them to be applied to many tribological parts and components without changing the size.
2. Bonded solid lubrication coatings can work efficiently in many harsh environments, such as high temperatures, ultra-low temperature, ultra-high vacuum, strong radiation, strong redox, and other extreme environmental conditions where conventional fluid lubricants (oils and greases) do not work properly. The load-bearing capacity of a bonded solid lubrication coating with good pressure resistance is several times or even a hundred times higher than that of oils and greases. In addition, they does not pollute the environment like conventional fluid lubricants do.
3. Bonded solid lubrication coatings neither age over time nor are flowable. This makes them suitable for lubricating mechanical parts that are started frequently and function intermittently but reliably between long periods of inactivity. In addition, bonded solid lubrication coatings can be used in combination with oils and greases to guarantee additional safety through emergency lubrication and to optimize the running-in performance of highly stressed components.
4. Solid film lubricants adhering to a workpiece not only provide good corrosion resistance and dynamic sealing performance but also prevent mechanical vibration and the occurrence of "stick-slip" and thus reduce noise.
5. In addition to lubricating metal parts, bonded solid lubrication coatings are suitable for the surface lubrication of a number of other materials (plastics, elastomers, ceramics, glass, etc.), on which oils and greases usually function with difficulty.

Classification

An enormous number of bonded solid lubrication coatings have been developed to date; some of the widely used constituents are listed in Table 1. These coatings can be categorized into several subclasses. Based on the composition of binders, the bonded solid lubrication coatings are commonly categorized into two different classes: organic bonded solid lubrication coatings and inorganic bonded solid lubrication coatings.

Organic Bonded Solid Lubrication Coatings

Organic bonded solid lubrication coatings are most comprehensively and widely used in tribological parts. More than 80% of bonded solid lubricants are organic bonded solid lubrication coatings. Commonly used organic resins include alkyd, polyurethane, polyacrylate, epoxy, phenolics, silicone, polyimide and its modified products, aromatic heterocyclic polymers, and other thermoplastics. With the combination of different solid lubricants and organic binders, bonded solid lubrication coatings with different performances have been successfully developed. In addition, special organic resins can be synthesized for use as binders to satisfy specific requirements. However, most organic resins are only stable below about 300°C. This property limits the application of organic bonded solid lubrication coatings at higher temperatures.

Inorganic Bonded Solid Lubrication Coatings

Using inorganic salts (silicate, phosphate, borate, etc.) and ceramics (silica, B_2O_3, hydrated Al_2O_3, etc.) as binders is classified as inorganic solid lubricant coating. The main advantages of inorganic solid lubricants are their wide temperature range, low vacuum outgassing, and good compatibility with liquid oxygen compared with organic bonded solid lubrication coatings. However, these coatings also have some shortcomings, including high brittleness, poor load-bearing capacity, and relatively inferior tribological properties. Therefore, most inorganic bonded

Bonded Solid Lubrication Coatings, Process, and Applications, Table 1 Typical composition of bonded solid lubrication coatings

Binders	Solid lubricants	Other components
1. Organic resins	MoS_2	Corrosion inhibitors
Room-temperature curing	WS_2	Sodium phosphite
Cellulosics	Graphite	Stannous chloride
Acrylics	$(CF_x)_n$	Lead phosphite
Heat curing	PTFE	
Alkyd	Phthalocyanine	Solvents
Phenolic		
Vinyl butyral		Water
Epoxy	CaF_2/BaF_2	Isopropyl alcohol
Silicone	PbO	Toluene
Polyimide	PbS	Amyl acetate
	Sb_2O_3	Ethyl acetate
		Naphtha
2. Inorganic salts		
	Au	
Sodium silicate	Ag	
Aluminum phosphate	In	
Sodium phosphate	Pb	
Potassium silicate		
Sodium borate		
Titanates		
CaF_2/BaF_2		
3. Inorganic ceramics		
Silica		
B_2O_3		
Hydrated Al_2O_3		

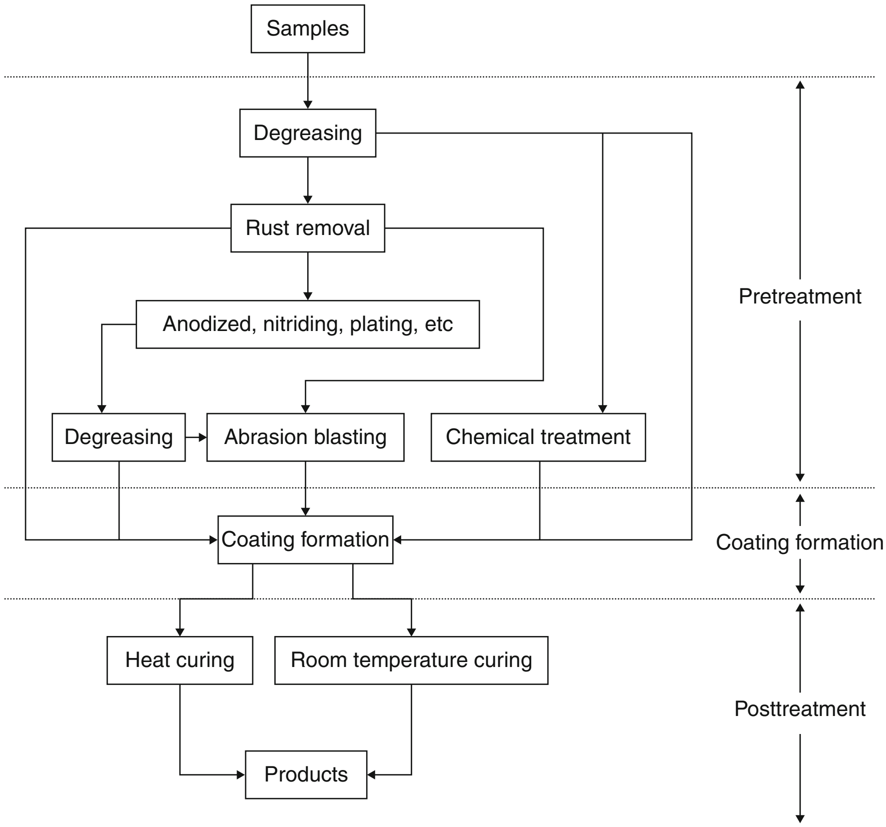
solid lubricant films are currently confined to use in several specific conditions, such as in a liquid oxygen environment, extra-high temperatures, and organic vapor-free satellite machineries.

In addition to organic and inorganic bonded solid lubrication coatings, bonded solid lubrication coatings using organometallic compounds as binders have also been developed. The application performance of this type of bonded coatings is between the organic and inorganic bonded solid lubrication coatings.

Preparation Process

Generally, there are three steps for the preparation process of bonded solid lubricant coatings: pretreatment, coating formation, and post-treatment. The scheme of the preparation process is shown in Fig. 1 (Chen et al. 1994).

Pretreatment of the parts to be coated plays an important role during the preparation process of bonded solid lubrication coating. Good adhesion and, therefore, long lifetime can only be achieved with a pretreatment that is customized for the particular part and solid film lubricant. For non-metallic parts (plastics and ceramics), degreasing or degreasing followed by blasting is the most common pretreatment process. Chemical treatments are also used in some cases. For metals, rust and scale must be chemically removed through pickling in acids or lyes. Further treatments, such as anodizing, plating, nitriding, chemical oxidation, vulcanizing, and phosphating are sometimes



Bonded Solid Lubrication Coatings, Process, and Applications, Fig. 1 Scheme of the preparation process of bonded solid lubrication coatings

necessary to improve adhesion of the solid film lubricant onto the metal surface.

In the pretreatment process, thorough removal of all grease residues, dust, dirt, rust, and scale is a fundamental step in the pretreatment of the workpiece surface. The quality of degreasing significantly affects further pretreatment processes and finally the adhesion between solid lubrication coating and part. The most common degreasing methods include alkali cleaning, pickling, solvent cleaning, emulsion cleaning, and electrolytic cleaning. One or two of these methods can be applied for the specific materials. For many technical standards of preparation of bonded solid lubrication coatings (for example, the US military standard "MIL-L-8937D"), strict regulation of the procedure for degreasing have been created due to its critical effects on final performance (MIL-L-8937D 1982).

The coating formation process of the bonded solid lubrication coatings is similar to the traditional painting process. Spraying, dipping, and brushing are most widely used in the coating formation processes. Electrochemical deposition, powder metallurgy, and other methods can also be applied. In all these methods, dipping is widely used because of its low cost, but spraying is usually the most consistent method. As a result, spraying techniques have been rapidly developed. Many new spraying devices, such as automatic sprayers and painting robots, have been developed to improve further the quality of bonded solid lubrication coatings.

Post-treatment processing of bonded solid lubrication coating includes curing and finishing. Different curing processes, such as room temperature curing, heating curing, light curing, electron beam curing, and water curing, can be used according to the components of the bonded system. In general, overall performance of bonded solid lubrication coatings prepared by heat curing is better than that produced using room-temperature curing.

Key Applications

Bonded solid lubrication coatings are widely used in the following circumstances due to their unique characteristics (Sliney 1993; Miyoshi 1996):

1. Components for which high- or low-temperature lubricants are needed. The application temperature of oils and greases is normally less than 300°C. As illustrated above, one of the major characteristics of the bonded solid lubrication coating is its wide temperature range. As a result, bonded solid lubrication coatings have been widely used to lubricate the sliding parts working in high-temperature conditions, such as rocket, plane, and automobile engines, afterburner and anti-thrust systems in planes, bores of long-range cannons, molds for metal thermal processing, some components in atomic reactors, and high-temperature ablation-resistant screws (Sliney 1993). Typical application examples at low temperatures include the turbo-pump gear of hydrogen-oxygen rocket engines and sliding parts of superconducting devices.
2. Parts that may be stored for long periods of time. Many devices, for example, ejection seats, canopy links, and joysticks in aircrafts, are usually inactive for long periods and are not used frequently. In such cases, bonded solid lubrication coatings can ensure that such devices function reliably and flexibly in an emergency.
3. When sealing is desired, bonded solid lubrication coatings between tribological couples (for example, piston and cylinder) not only provide lubrication but also act as seals to prevent leakage after running-in.
4. When fretting and galling is a problem. In the assembly clearances for some mechanical joint surfaces, such as splines, universal joints, and keyed bearings, fretting and galling can be caused by vibration if lubrication is not sufficient. The use of solid film lubricant can prevent abrasion and prolong service life (Xu et al. 2004).
5. Parts that are subject to frequent disassembly. Some parts, such as trapezoidal nuts, lead screws, and injection molds of PVC are subject to frequent disassembly. Wear and tear on these parts can be effectively avoided when they are pre-coated with solid film lubricants.
6. Parts that will be operated in corrosive atmospheres. The solid lubrication coatings usually provide excellent corrosion protection to the substrate in addition to low friction and wear. In fact, the corrosion resistance of some bonded solid lubrication coatings is similar to some anti-corrosion paints. Many bonded solid lubrication coatings also contain special rust inhibitors that offer exceptional corrosion protection in harsh environments. As an example, rusting of the screws and connectors in chemical machinery can be prevented under heating, oxidation, and corrosion conditions when rust inhibitors containing solid lubrication coating are applied.
7. Where operating pressures exceed the load-bearing capacities of oils and greases. The load-bearing capacity of bonded solid lubricant coatings is much higher than that of oils and greases. Lubrication under high load conditions, for example, the turbine/worm components of torpedo steering rods, bearing pedestals of bridges and flyovers, machine tool chucks, and cold working molds of metals, can be achieved using bonded solid lubrication coatings.
8. Other special circumstances. For example, bonded solid lubrication coatings have been widely used to lubricate devices subject to radiation, vacuum, and other extreme environmental conditions in space programs, such as drive systems of satellite antennas, solar panel systems, drive and temperature-controlled systems of optical instruments, satellite and rocket separation systems, and satellite-carried machineries. Application of bonded solid lubricant coatings in household vacuum machines has also increased (Hiraoka 2001).

Cross-References

► Graphite Solid Lubrication Materials
► High-Temperature Solid Lubricating Materials
► Solid Lubricant: Soft Metal
► Solid Lubricants
► Solid Lubricants for Space Mechanisms
► Solid Lubricants, Layered-Hexagonal Transition Metal Dichalcogenides
► Solid Lubricants, Polymer-Based Self-Lubricating Materials

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Bonding at Surfaces/Interfaces

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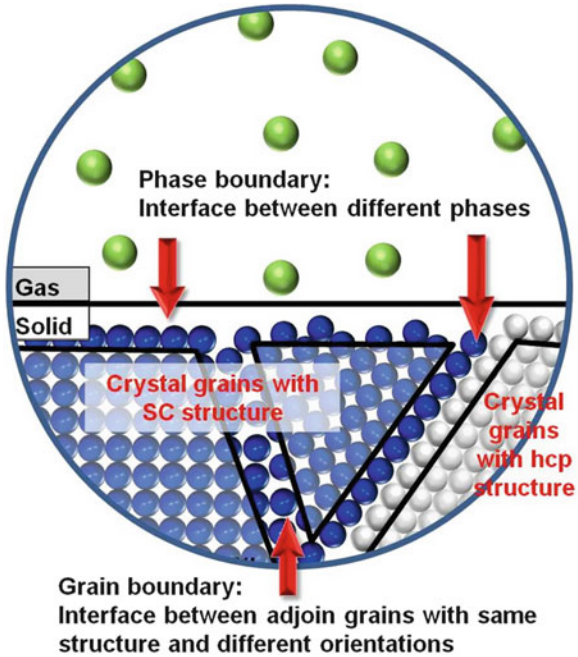
Synonyms

Contact angle for evaluating surfaces and interfaces; Interaction; Interface; Interface bonding; Surface and bonding

Definition

The common boundary between two different phases, or between adjoin crystal grains of different orientations, is generally called an interface (Fig. 1). According to the difference of physical state, an interface can be classified as gas–liquid, liquid-liquid, gas-solid, solid–liquid, and solid-solid. A surface can be defined as a face of a matter presenting freely without any contact with any other matter, which means that surface exists in the condition of absolute vacuum. Therefore, in the open air condition, there is no absolute surface present. Generally, people call the interface contacting with a gas, such as solid/gas or liquid/gas, a surface and the others an interface.



Bonding at Surfaces/Interfaces, Fig. 1 Interfaces: grain boundaries and phase boundaries

Interfacial bonding creates new bonds between two contacted matters, the core content of an interface reaction, which is related to the interface structure, interface bonding mechanism, and interface stability. Interface stability is directly relevant to the application and is determined by the interface structure. The interface bonding mechanism is the detailed process routine of interface bonding. The bonding mechanism of a special interface is determined by material properties and the technique process. Various techniques have different process conditions and thus different bonding mechanisms.

There are several kinds of bonds at surfaces or interfaces, including covalent bonds, hydrogen bonds, van der Waals forces, and electrostatic forces. As a form of chemical bond, a covalent bond is characterized by the sharing of electrons pairs between atoms. The hydrogen bond is the attractive interaction of a hydrogen atom in one molecule or chemical group with an electronegative atom (such as nitrogen, oxygen, and fluorine) in another molecule or chemical group, which means that hydrogen bonds can occur intra- or inter-molecularly. Van der Waals forces are interactions of dipoles (permanent, induced, and instantaneous dipoles), which exist in atoms and molecules. Electrostatic forces exist in charged particles, which can be in a molecule or between two molecules. In general, the energies of hydrogen bonds