General Situation of Solid Lubricant Coatings

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Abstract: Lubricant is one of the important supporting materials in modern industry and national defense industry. The purpose of using lubricant is to reduce friction and wear, reduce or avoid material damage. Lubricating oil and grease are traditional lubricating materials, but they have their own application limitations. Solid lubricating materials, especially their lubricating coating, can meet high temperature, high pressure, high vacuum and other harsh conditions, and they are more and more widely used in various industries. Based on a large number of literatures at home and abroad, the properties, application characteristics and preparation technology of solid lubricant coating are reviewed, and the research trend of solid lubricant coating is prospected.

1. Introduction

With the development of advanced technologies such as aviation, aerospace and nuclear power, many mechanical parts are faced with severe service environment such as heavy load, high vacuum, low temperature and high speed. In order to prolong service life and save materials and energy, it is urgent to solve the problems of friction, wear and lubrication protection in many fields [1].

The operating temperature range of lubricating oil and grease is generally -60 °C ~ +350 °C. Beyond this temperature range, lubricating oil and grease will be powerless, while solid lubricating materials can give full play to their effectiveness. Generally, solid lubricating materials are used in the form of powder, film, surface coating, integral material or composite material. Among them, the solid lubricant coating is to disperse various solid lubricants, reinforcing fillers, etc. in the organic or inorganic bonding system to form a special coating, and then form a certain thickness of coating on the surface of components by spraying, brushing or dip coating and other similar coating processes, and finally form a solid coating after natural drying or heating curing. The coating can improve the lubrication state of mechanical components, reduce friction and wear of components, and extend the service life of components [2]. In recent years, solid lubrication coating has greatly broken through the use limit of traditional materials in performance, and has been widely used in high-tech fields such as electronics, biology, aerospace and aviation [3], which is the most promising direction in the field of lubrication.
2. Basic structure of solid lubricant coatings

According to the structure, solid lubrication coating materials mainly include single-layer single component coating materials, single-layer multi-component composite structure coating materials, multi-layer structure coating materials, gradient structure coating, adaptive intelligent coating, etc. [4]. Single layer single component coating mainly includes Ag, MoS₂, WS₂, diamond, DLC, etc. Single component coating is suitable for a narrow range of working conditions and temperature, and it has certain limitations. Ren Siming et al. [5] prepared multi-component composite coating by adding Pb and Ti to MoS₂. It was found that the mechanical properties and tribological properties of the coating were improved after adding other elements to the coating. In the multi-component composite coating, the components give full play to the synergistic advantages, which make the microstructure of the coating compact, the stress distribution reasonable and the high temperature tribological performance excellent. Multilayer structure coating can improve the compactness, hardness and life of the coating. Xu Lufeng et al. [6] prepared TiSiCN single-layer coating and TiSiCN / TiSiN multi-layer coating on the surface of titanium alloy by multi-arc ion plating technology. The research shows that compared with TiSiCN single-layer coating, TiSiCN / TiSiN multi-layer coating has better hardness, adhesion with matrix and friction and wear properties. Gradient structure coating is a kind of coating structure with continuous changes in composition, structure, density and functional characteristics from substrate to coating. Adaptive intelligent coating means that the coating can change with the change of application conditions or external environment to meet the requirements of special environment.

Due to the single component solid lubricant coating, its lubrication temperature range is narrow, generally only in a certain temperature range or a certain environment can have the effect of friction reduction and wear resistance. With the development of machining technology, multi-component solid lubricant coating can play a unique lubrication effect in a relatively harsh lubrication environment, and get rapid development and wide application. The multi-component solid lubricant coating is mainly composed of base phase, reinforcement phase and lubrication phase. According to the different basic phases, the solid lubricant coatings can be divided into metal-based solid lubricant coatings, polymer-based solid lubricant coatings and ceramic-based solid lubricant coatings.

2.1. Metal-based solid lubricant coatings

Metal-based solid lubricant coating is a composite material formed by adding solid lubricant as a component into the metal matrix. It has both the characteristics of the base metal and the tribological characteristics of the solid lubricant. It is suitable for use in different atmospheric environment, chemical environment, electrical environment, high temperature, high vacuum and other special environmental conditions. At present, there are many researches on self-lubricating coatings of Ni based, Co based and Ni-Cr Based Superalloys [7]. Wu Xiangqing et al. [8] studied the properties of Ni-SiC composite coating by adding different surfactants; Cai Yufei et al. [9] prepared Ni/WC-Co based composite coating by laser cladding; Zhang Baoku et al. [10] prepared Co-Ce-NiCr based infrared radiation coating by plasma spraying. Above all, Mai et al. [11] prepared Ti₃C₂-copper(Cu) based composite coating by electrodeposition, and Fan xiangjuan et al. [12] prepared Ni₃Al based self-lubricating composite coating by plasma spraying, and the research shows that its tribological performance is good.

2.2. Polymer-based solid lubricant coatings

Polymer-based solid lubricant coating is widely used for sliding parts in non-lubrication (dry condition), water lubrication, vacuum, low temperature or corrosive atmosphere. Generally, it has a variety of ductility and mechanical properties. It has become a new kind of lubrication and wear-resistant coating material instead of traditional metal based lubrication coating. Polymer lubricating materials have the following advantages.

- It has good toughness, can absorb vibration, has no noise and does not damage dual material.
- Its chemical stability is good, and its friction and wear have little dependence on atmosphere, so it can also be used in seawater.
It has good low temperature performance and can still play a lubricating role under the ultra-low
temperature conditions of liquid ammonia, liquid hydrogen and vacuum.

At present, the common polymer solid lubricating materials are mainly PTFE, PI, PEEK, PS and
POM [13]. For example, M Zalaznik et al. [14] prepared MoS2-PEEK based composite coating by low
temperature sintering. Graphite-PDA-PTFE composite coating prepared by Samuel Beckford et al. [15]
Jason et al. [16] prepared Ni-PTFE composite coating by electrodeposition. The results show that they
all have good self-lubricating properties.

However, the mechanical strength, heat resistance and heat transfer performance of polymer
materials are not ideal. In the condition of severe friction, polymer materials with low heat transfer
performance are prone to local temperature rise and reach the heat-resistant limit, so polymer based solid
lubrication coating is not suitable for high temperature, high speed, heavy load and other working
conditions.

2.3. Ceramic-based solid lubricant coatings
Ceramic-based solid lubricant coating is based on hard ceramics, which is mainly used to improve the
high temperature adaptability of the coating due to its high hardness, low density and high temperature
strength stability. Ceramic materials are widely concerned because of their high hardness, high
temperature strength, wear resistance and chemical corrosion resistance. They have become the first
choice to replace metal and polymer materials in extreme conditions.

Self-lubricating ceramics include cermet and non-metallic ceramics. Cermet includes Al2O3 [17],
ZrO2, etc. Yin Yansheng et al. [18] prepared FeAl/Al2O3 ceramic gradient coating on Q235 steel by
plasma spraying, while Zhang Fabi et al. [19] prepared Al2O3 ZrO2 ceramic coating. Non-metallic
ceramics mainly include carbides, borides, nitrides and silicides (SiC, WC, BN, Cr2C3, etc.) [20].
Carbide ceramics are commonly used in anti-corrosion and wear-resistant coatings and are commonly
used materials for thermal spraying, while nitride ceramics have high hardness and mechanical strength,
which can well support the matrix material.

Ceramic materials generally have high friction coefficient (0.4-1.0) under dry friction conditions and
are difficult to achieve self-lubrication [21]. Therefore, self-lubrication of ceramic materials by adding
suitable solid lubricants has become an effective way to solve the problems of lubrication and wear
resistance. Mimaroglu [22] added a small amount of Cr2O3 and SiO2 to alumina ceramics, which reduced
the high-temperature wear rate to 10-8mm3/Nm; Ouyang J.H. [23] added CaF2 and Ag as lubricants to
ZrO2 ceramics, and the composite coating exhibited good high-temperature self-lubrication properties
from room temperature to 800 centigrade. Zhang [24] studied ZrO2 (3Y) - Al2O3/ZrO2 (3Y) laminar
gradient composites with graphite, calcium fluoride, barium sulfate and other lubricants. The results
showed that the dispersed lubricants made the composites have continuous lubricating properties in a
wide temperature range.

3. Preparation technology of solid lubricant coating
At present, the preparation technology of solid lubrication coating materials mainly includes: scratch
coating method, adhesion method, electrochemical deposition method, powder metallurgy method, laser
cladding method, vapor deposition method and thermal spraying method. Laser cladding, vapor
deposition and thermal spraying are commonly used.

3.1. Laser cladding method
The working principle of laser cladding is to add cladding powder material to the surface of the substrate,
and then we use high-power and high-density laser beam to heat the cladding material and the surface
of the substrate, so that it can undergo metallurgical fusion and rapid condensation at the same time,
forming a high-strength and corrosion-resistant cladding layer [25]. Wu Hongliang [26] used CO2 laser
to clad Ni-based alloy on TA2 titanium alloy surface, which increased the hardness of cladding layer by
4 times than the original matrix itself. Song et al. [27] cladded Fe/SiC nanocomposites, which showed
753 Mpa higher tensile strength compared with pure iron samples. Majumdar et al. [28] doped 20% and
5% SiC particles in 316L stainless steel powder by laser cladding technology, and the surface hardness and wear resistance of the cladding layer were significantly improved.

3.2. Vapor deposition method
Vapor deposition technology refers to the formation of functional or decorative metal, non-metal or compound coatings on the workpiece surface by utilizing the physical and chemical processes occurring in the vapor phase. According to the film-forming mechanism, vapor deposition technology is mainly divided into chemical vapor deposition and physical vapor deposition. In recent years, the technology of preparing solid self-lubricating coatings by chemical vapor deposition has developed rapidly [29]. Yang Gangyi et al.[30] used TiCl₄, CH₃SiCl₃, H₂ as reaction gases, Ar as carrier gas and dilution gas to deposit Ti-Si-C ternary system coatings under low pressure, and studied the formation rule of Ti₃SiC₂ prepared by chemical vapor deposition at different temperatures. Compared with other preparation methods, chemical vapor deposition method has the advantages of low temperature, high degree of density and uniformity of coating, and the prepared coating has a high purity. However, up to now, the coating prepared by chemical vapor deposition method still has a small amount of other impurities, and its raw material composition range is relatively narrow [31][32].

3.3. Thermal spraying method
Thermal spraying is a metal surface processing method that sprays the molten spraying material on the surface of parts by high-speed airflow to form a coating. The plasma spraying technology is widely used. Plasma spraying uses plasma arc as heat source, heating the powder material to the melting or semi-melting state, and spraying to the pretreated substrate surface at high speed to form a solid self-lubricating coating. Mao jinyuan et al. [33] prepared ZrB₂-MoSi₂ composite coating by plasma spraying, and Du sanming et al.[34] prepared nano-Al₂O₃ coating. However, in terms of high temperature self-lubricating coatings, plasma spraying technology produces relatively low bonding strength and high residual stress, which limits its application.

4. Conclusion and prospect
On the basis of the existing work, the following issues deserve attention and further study.

- Develop new super wear-resistant materials. The traditional solid lubricants, such as graphene [35] and MoS₂ [36][37], will degrade at high temperature. Recently, a new family of two-dimensional early transition metal carbides and carbonitrides, named mxenes[38][39]. This kind of material has the characteristics of low shear strength, high mechanical strength and self-lubricating property [40] [41]. In recent years, we have paid more attention to the tribological properties of the material, and the tribological properties of the material as a solid lubricant added to the lubricating coating deserve attention.

- The composite friction coating in wide temperature range was studied. With the rapid development of high and new technology, the requirements of lubricating materials are higher and higher, such as engine parts. Although the normal working temperature is in the high temperature section, the temperature in the start-up and shutdown stage is a gradual evolution process from room temperature to high temperature or from high temperature to room temperature. It is required that its components have good lubricating effect from room temperature to high temperature, that is, wide temperature range lubrication [4]. The continuous lubrication problem from room temperature to 1000 °C or even higher temperature has become the neck of high-tech development.

- Study on solid lubrication gradient coating material. In recent years, "gradientation" [42] as a design idea and structure control method of materials, its application scope has been greatly expanded to many fields such as aviation, aerospace, machinery, chemical industry, atomic energy and medicine, especially in heat-resistant, wear-resistant and corrosion-resistant structural materials, which is still a research hotspot in the future.
Research on modified lubricating materials. The research on the modification of inorganic nanoparticles, graphene, molybdenum disulfide [43] and other solid lubricating materials is also a hot spot in the future.

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