Chapter

A Review of Surface Treatments for Sliding Bearings Used at Different Temperature

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Abstract

The boundary lubrication and dry friction of plain bearings at different work temperature are unable to be avoided under the start and stop condition. The poor lubrication is one reason of bearing broken. In order to improve the tribological properties and select the best treatment for different bearings used at different temperature, the studies of different treatment technologies are reviewed in this paper. The review shows that the shortages of bonding fiber woven materials, inlaying solid lubricating materials, electro plating and magnetron sputtering are poor temperature resistance, low load capacity, environment pollution and low production efficiencies respectively. Based on the analyses and summaries, the liquid dope spraying and thermal powder spraying are suggested to deposit coating on the surface of bearing which working temperature is lower than 200 and above 800°C respectively. However, the technology processes, the mechanisms of spraying and self-lubrication materials should be studied further and deeply.

Keywords: plain bearing, surface treatment, wide range temperature, lubrication materials, technology process

1. Introduction

1.1 Background of the research review

Sliding bearings are widely used as the basic components in marine power, aerospace, water conservancy and hydropower industries. As shown in **Figure 1**, the sliding bearings are divided into integral sliding bearings and split sliding bearings according to their structures. They have some features, such as low noise, stable work operation, compact structure and heavy load bearing capacity [1]. With the advancement of science and technology, the automotive, marine, electric power transportation and some other industries are developing into 'serious conditions' such as high speed and high load, making the sliding bearing under a wide temperature environment. For example, the work temperature of engine rises from room temperature to about 140°C during different operating conditions, such as starting, accelerating, constant speed, deceleration and shutdown. From the research data, the temperature even rises up to 200°C at the time of bearing broken [2]. The work temperature of some bearings is high, for example, the working temperature of the socket bearing of missile launching mechanism exceeds 800°C. Under high temperature conditions, grease and lubricating oil fail, and unlubricated bearings will quickly be broken under the action of high friction coefficient and wear. Ordinary sliding bearings are normally lubricated due to lubricating oil with the hydrodynamic lubricating oil film. Under normal conditions, sliding bearings can generally satisfy the requirements of long-term service. However, the reasons of ablation and friction damage of the bearings 12.5% are due to poor lubrication the investigation.

As shown in **Figure 2**, the sliding bearing damage quickly due to the lacking of self-lubricating properties of bearing, and the mixed lubrication and even dry contact friction at the start-stop stage of engine [3]. Therefore, researching and improving the friction mechanical properties of the bearing under dry friction conditions is one of the key technologies for improving the bearing life of at start-stop stage. In the case of large dust, high temperature and no lubricating oil or grease, the life of the sliding bearing will be drastically reduced. For example, the working environment temperature of rolling steel rolling mill is about 200°C, and the maximum service life of the bearing is no longer than 3 months. In order to avoid the bearing damage and improve the service life of the sliding bearing at the dry friction stage, it requires the sliding bearing should have self-lubricating property to reduce the high torque requirement and tribology at the stages of start-stop under different temperature conditions [4].

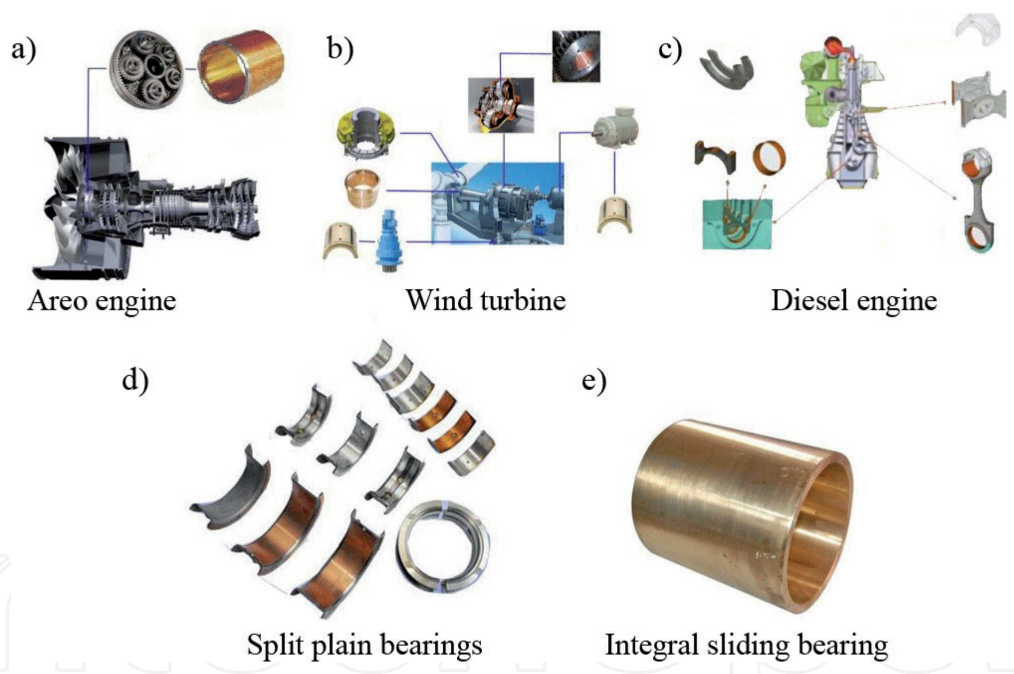

Figure 1.
The applications of plain bearings and their structures.

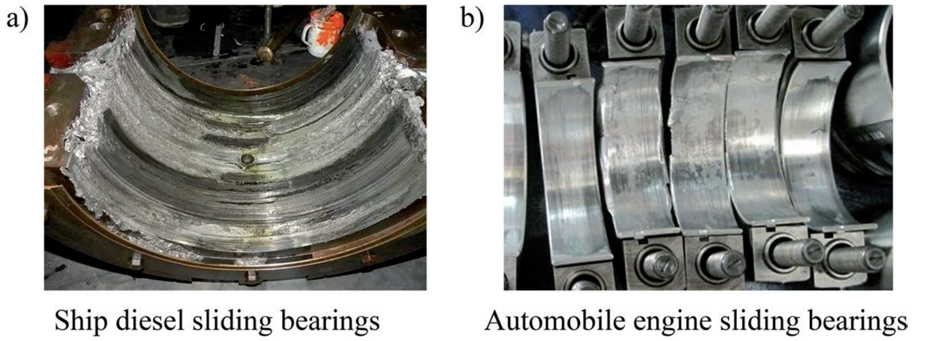

Figure 2.
Friction damage of sliding bearings.

The self-lubricating treatment technology of sliding bearings in China is still backward. Bearings with self-lubricating properties at different temperature conditions are still very rare. Compared with the advanced bearings of European and North American, the sliding bearings of China have short life, low carrying capacity, poor self-lubricating performance and overcapacity. High-performance sliding bearings such as, self-lubricating, high-load, and long-life are relied on import. The lack of high-performance sliding bearings restricts the development of China's basic manufacturing industry, especially the military industry. Therefore, the self-lubricating performance of the sliding bearing during in wide temperature range should be improved, and the different lubricating methods for different bearings at different temperature should be selected.

The development, manufacturing and processing capabilities of sliding bearing materials of China should be improved. At present, the main production technologies sliding bearings are centrifugal casting and alloy powders metallurgical. However, most bearings have no surface lubrication and will be quick broken. For example, more than 90% of the bearing bushes prepared by powder metallurgy in the automotive industry are not subjected to surface self-lubricating treatment such as electroplating and magnetron sputtering. Powder metallurgy technology of sliding bearing preparation has high production efficiency and low cost. The sliding bearing prepared by metallurgical process has high porosity without centrifugal force. In addition, the bearing alloys such as copper, aluminum and tin are easily oxidized at high temperature during the metallurgy preparation of sliding bearing, and metallographic organization is not uniform [5]. Centrifugal casting is another common production process for sliding bearings. The integral and thick-walled plain bearings are usually produced by centrifugal casting. However, most of the sliding bearings produced by centrifugal casting process are not subjected to inert gas protection or vacuum environmental protection, therefore, the bearing alloys are oxidized and the alloy grains size are not uniform [6].

With high dry friction coefficient and low load bearing capacity of bearings, the common methods are the surface treatments which improve the bearing life effectively. The electroplating, magnetron sputtering, self-lubricating liner antifriction, and inlaying self-lubricating materials are the main surface treatments for bearings. The lubrication and mechanical properties of the sliding bearing surface are changed by one or several electro-plating alloy layers. However, the plating solution is highly polluted, and electroplating technology of sliding bearings is seeking alternative process technology [7].

The magnetron sputtering is one of the most advanced technologies for the preparation of sliding bearings. Compared with electroplated bearings, magnetron sputtering bearings have better bonding strength and surface lubricity. However, magnetron sputtering requires a process such as pumping, vacuuming, and sputtering to form a uniform film. The magnetron process needs long production time and high production cost, and its target materials utilization rate are lower than 40%, which cannot satisfy the requirements of large-scale production. What is more, due to the constraints such as size and structure, just small bearings are able to be prepared by magnetron sputtering [8]. At present, it is an urgent problem to find a mass production of sliding bearing to satisfy the requirements of self-lubrication at wide temperature range, and having good lubricity under special working conditions such as start-stop, lean lubrication or even dry friction. The materials of electroplated plain bearing are mainly babbitt alloy, ternary and quaternary indium alloys which friction coefficient is large under dry friction conditions, and it does not have wide temperature range self-lubricating performance. The Kevlar aramid fiber modified with nano-solid lubricants, and pasted on the surface of the sliding bearing that is the liner anti-friction technology. The liner and pasted glue cannot be used at high temperature conditions, and it does not have self-lubricating properties at wide temperature. The sliding bearing inlaid solid self-lubricating materials such as graphite, MoS_2, WS_2 and so on, and they are punched on the working surface of the sliding bearing. With self-lubricating materials, the self-lubricating materials are crushed to form a self-lubricating film to reduce the friction coefficient of the bearing. However, single-phase self-lubricating material such as graphite and MoS_2 cannot satisfy the requirements of wide temperature range self-lubrication, and the inlaid holes will reduce the mechanical strength and load capacity of the bearing. The temperature environment of the joint bearing, machine tool and electric equipment sliding bearings is room temperature environment; the working temperature of the sliding bearing for hot-burning furnace, gas pump and rolling steel rolling roller is about 200°C; the working temperature of the bearing socket for aviation is above 800°C, and they require self-lubricating materials at different temperature environments. Studies have shown that the use of coating lubrication technology improves the friction and wear, impact resistance, high temperature and longevity of the sliding shaft without changing the bearing matrix structure and composition [9]. Therefore, bearing surface coating technologies are one of the most critical and feasible methods to improve the overall technology of the domestic sliding bearing industry.

1.2 Significance of the research review

Due to the higher requirements of high-speed, high-load and high-temperature, the lubrication of sliding bearings under different temperature conditions and different load conditions will directly determine the working state and service life of the bearings and the whole machine. Many scholars have studied the self-lubricating methods of sliding bearings such as electroplating, magnetron sputtering, inlaying solid lubricants, and adhesive self-lubricating liner. However, these traditional sliding bearing self-lubricating methods have some defects. With the improvement of environmental protection requirements, the sliding bearings prepared under large-scale and high-volume production conditions have excellent self-lubricating properties under different temperature conditions, which are the keys of the current research. One of the current advanced treatment technologies for self-lubricating sliding bearings is liquid coating technology, but the theoretical calculation of bearing spraying is litter. The phenomenon of bearing sag and leveling has not been studied deeply. The optimum thickness of coating, the best surface roughness of the substrate, and coating the optimum curing temperature and optimum cooling temperature of the layer also lack of relevant details and theoretical analysis. The studies of sliding bearings with wide temperature range self-lubricating coating materials under different temperature conditions are lacking.

2. Reviews of self-lubricating sliding bearing

The traditional self-lubricating sliding bearing production and preparation processes are mainly electroplating, magnetron sputtering, inlaying solid lubricants, and adhesive self-lubricating liner and so on. The self-lubricating bearing processes and their performances are summarized as follows.

2.1 Review of self-lubricating sliding bearings at room temperature

In the severe conditions such as large dust, high pollution, high load bearing, lacking of lubricating oil and grease, sliding bearings only rely on their own lubrication to improve work performance. For example, in the automobile manufacturing, cement production and coal mining industries, the inlaying solid lubricants and adhesive self-lubricating liner are the common methods of the joint bearings and bushing sleeves.

2.1.1 Adhesive liner for self-lubricating bearing

The friction coefficient of the bearing is reduced, the wear resistance is improved and the working life is prolonged through the modified liners for sliding bearings. Braided liners are generally composed of Kevlar aramid fiber materials (KEVLAR), polytetrafluoroethylene (PTFE), modified carbon fiber materials, and nano-additives [10]. The structure of sliding bearing with liner is shown in **Figure 3**. In order to obtain a small shear force and a large bonding strength, the fabric liner is bonded on the bearing surface through the adhesive glue. The frictional coefficient is decreased by changing the metal to metal contact to metal to liner contact. Aderikha studied the friction and wear properties of the liner based on PTFE and plasma treated polymer fibers. The results showed that the friction coefficient was 0.15–0.2 under different loads [11]. Li studied the friction and wear properties of nano-materials SiC and WS_2, and the friction coefficient of surface liner under dry friction was about 0.05–0.06 [12]. Fabrics were treated with rare earths CeO_2, $LaCl_3$, La_2O_3 and CeF_3 by Shen, Zhan and some scholars, and their friction, wear properties and bonding properties of the joint bearings with the modified rare earths were studied. The results shown that the bonding strength was higher under the action of rare earths, the film formation is faster, and the coefficient of friction is generally less than 0.1 [13–16]. Liners and adhesive glue as the main component cannot be used at medium and high temperatures, and the bonding liner method is generally applicable to small thick-walled sliding bearings, which has certain limitations for medium and large sliding bearings.

2.1.2 Bearings with inlaid solid self-lubricating materials

The self-lubricating materials are inlayed on the surface of bearing. As shown in **Figure 4**, the solid lubrications will be expanded when sliding bearing subjected to load, and the bulged out lubrications are ground to tiny wear debris. With the sliding movement of bearing, the frictional coefficient is decreased with the formation of lubricating film from the debris. The inlaid materials are generally the solid lubricant materials such as graphite, molybdenum disulfide and PTFE. Wei prepared a new self-lubricating material consisted of PTFE, graphite and glass fiber. The results showed that the friction and wear properties of self-lubricating materials prepared by 40% PTFE + 20% graphite + 20% lead powder + 20% glass fiber were the best [17]. MoS_2/Sb_2O_3 mixed powders were produced to form solid

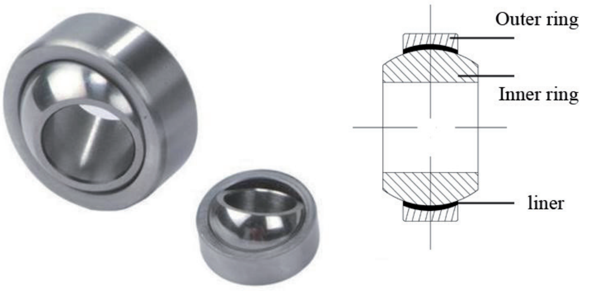

Figure 3.
Join bearing with self-lubricating liner.

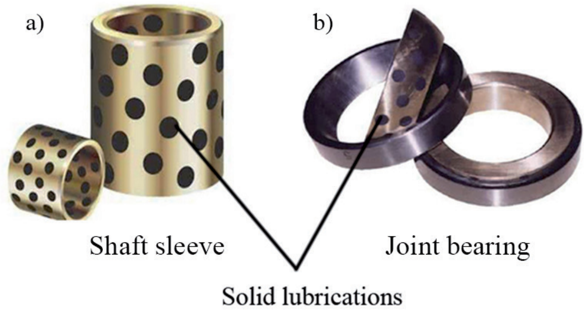

Figure 4.
Plain bearing inlaying with solid lubrications.

lubricant by Zabinski with thermosetting bonding method. The results pointed out that MoS_2 and Sb_2O_3 have synergistic antifriction effect on friction work, and Sb_2O_3 can prevent MoS_2 from oxidizing [18]. Li prepared FeS/copper-tin alloys as the inlaying materials by powder metallurgy. The research showed that the increase of FeS content reduce the friction coefficient. When the FeS content is 10%, the friction coefficient is 0.15 [19]. The research studies of inlaid solid self-lubricating materials showed that the working conditions of the prepared materials were mostly room temperature environment, and the studies of medium and high temperature self-lubricating materials were few. Therefore, the working conditions of sliding bearings embedded with solid self-lubricating materials on the market are mostly room temperature environments. In addition, the inlaid structure will reduce the strength of the bearing, resulting in low bearing capacity.

Sliding bearings prepared by modified liner technology and inlaid solid self-lubricating technology satisfy the self-lubricating requirements of room temperature conditions, but the fiber fabric materials cannot be used at high temperature. However, there are few studies of solid self-lubricating materials that satisfy the self-lubricating under the wide temperature range. Generally, bearings with inlaying solid materials are used at room temperature environment, and the structural strength of the bearing will be reduced by this technology.

2.2 Review of self-lubricating sliding bearing at medium temperature condition

2.2.1 Electroplating

The working temperature of bearing bush, plain bearing of rolling mills near to furnace and sleeves is from 100 to 200°C. At the start and stop stages, the automobile bearing bush is under a boundary lubrication or even a dry friction state because the lubricating oil film is not formed at start stage or broken at stop stage. However, the sliding bearings of rolling steel and the bearings in the heating furnace may cause the lubricating oil and grease to fail due to the high working environment temperature. In order to improve the performance of the bearing and prolong its service life, bearings need to be self-lubricated. The most common self-lubricating treatment methods for plain bearings represented by bearing bushes are electroplating and magnetron sputtering. As shown in **Figure 5**, one or more layers can be prepared on the surface of the bearing to improve bearing lubrication and improve bearing fatigue strength and service life. Wang studied Ni/SiC and Ni/Al_2O_3 electroplating techniques, and ceramics such as SiC and Al_2O_3 were added to the coating material, which improve the wear resistance of the bearing [20]. Li studied the friction and wear behavior of nano-Ni-PTFE composite coating on steel substrate. The results showed that the coating friction coefficient range was 0.05–0.15 under different loads [21]. Zhang prepared a MoS_2 coating containing

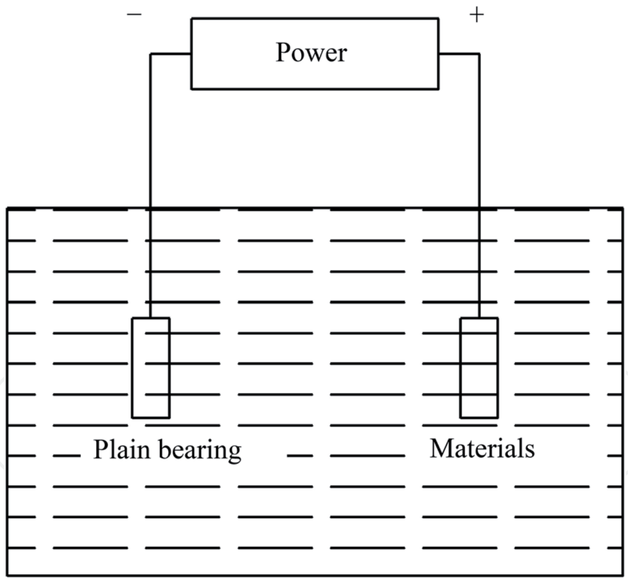

Figure 5.
Technology of electroplating of bearings.

nano-graphite particles by electroplating brush, and tested the friction coefficient was from 0.05 to 0.15 [22]. However, the plating prepared by the electroplating brush is not uniform, and the bonding strength is not as good as that of chemical electrophoresis. Studies had shown that metals such as In, Ni, and W improve the wear resistance of sliding bearing coatings [23, 24]. The addition of rare earth metals such as La, Ta, Nb significantly improved the frictional mechanical properties of the sliding bearing coating [25–27]. The friction coefficient of electroplated copper-tin alloy, aluminum-tin alloy and babbitt alloys under dry friction conditions is generally 0.3–0.6, which needs to be combined with lubricating oil and grease to satisfy the lubrication requirements [28]. Electroplated plain bearings are currently the most widely used preparation methods, but the plating solution is highly polluting and does not satisfy environmental production requirements.

2.2.2 Magnetron sputtering

Unlike electroplating, magnetron sputtering does not cause environmental pollution. The magnetron sputtering process shown in **Figure 6** has a dense film, and the thin metallographic structure in a vacuum environment makes the performance of the sliding bearing superior to that of the electroplated production. Li prepared a Babbitt Cu-Sn-Sb film on a steel substrate by magnetron sputtering. The friction coefficient was from 0.1 to 0.25 after dry friction experiment of 4000 rpm [29]. The Max- phase Ti_3SiC_2 material was sputtered during magnetron sputtering of Cu film. It studied by Li, and results showed that the physical and mechanical properties of Cu film were significantly improved after adding new materials [30]. Guo studied the metallographic properties and hardness of the magnetron sputtering bearing of AlSn20 material, and the experimental results reached the international advanced level like Miba bearings [31]. Song prepared AlSn20Cu thin films by magnetron sputtering. The hardness of the tested films was 120 HV, and the friction coefficient was less than 0.1 under oil lubrication [32]. Although the high hardness film improves the bearing capacity of the bearing, it also reduces the adhesion of the bearing. However, if the surface hardness of bearing is less than 50 HV will have better embedding performance [33].

The different compound films can be synthesized and synthesized because maximum as eight targets can be sputtered simultaneously from magnetron

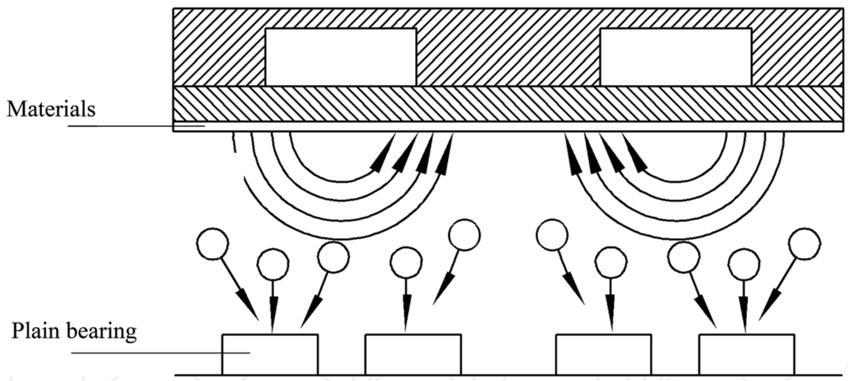

Figure 6.
Technology of magnetron sputtering.

sputtering. In the existing research, bearing alloy composite films such as Ti/Cu/N Cu_xSn_y, TiN/Cu had been prepared, and adhesin strength of these films is excellent [34, 35]. However, the tribological properties of above materials are the same as the bearing materials such as AlSn20 and AlSn20Cu. The friction coefficient is higher under dry friction conditions and mixed lubrication conditions, which cannot satisfy the self-lubricating performance requirements at wide temperature.

To improve the tribological and mechanical properties, the noble metal materials such as indium or rare earth materials are used during the electroplating plating process. However, the plating solution is a strong acid or a strong alkali substance, which is likely to cause serious environmental pollution. Magnetron sputtering equipment is expensive to manufacture. Many magnetron sputtering equipment only produce small test specimens in a laboratory environment, and cannot be mass-produced or mass-produced for large-sized sliding bearings. The utilization rate of magnetron sputtering target is generally less than 40%, and the working time is long and the production efficiency is not high when vacuuming, injection and depositing materials [36]. Therefore, it is necessary to find a new technology to prepare a self-lubricating sliding bearing.

2.2.3 Liquid dope of spraying

The most advanced surface treatment method available today is the surface spraying coating method. Compared with traditional surface treatment processes such as electroplating and magnetron sputtering, it has the advantages of environmental friendliness, high production efficiency, coating processing, and good coating lubrication performance. Spraying sliding bearings are characterized by high speed and high efficiency. It takes only several seconds to spray lubricating liquids, and large-scale and large-scale production will be realized if solidification furnaces and cooling furnaces are enough. For example, an automatic spraying production line of Shanghai Federal-Mogul company produces more than 12 million bushings with spraying coating (**Figure 7** and **Figure 9**).

The north Americans first began to study the coating technology of sliding bearing coatings and applied for related technology patents. For example, in the 1970s, Campbell used MoS_2 and Sb_2O_3 as solid fillers and epoxy resin as a binder to prepare self-lubricating coating, which was applied to sliding bearings [37]. The bearing coating prepared from materials such as MoS_2, Sb_2O_3 and epoxy resin has the advantage of low friction coefficient, but the ordinary epoxy resin working temperature generally does not exceed 140°C, which does not satisfy the long-term use requirements of temperature conditions above 200°C.

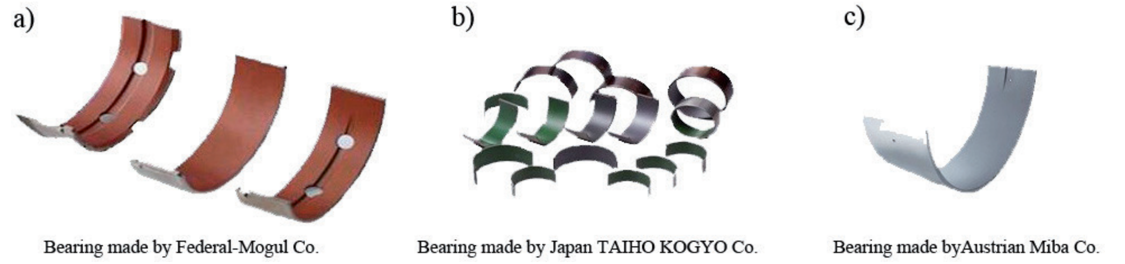

Figure 7.
Plain bearings with dope coating of overseas.

After several decades of development, the of plain bearings with self-lubricating coating made from liquid spraying have been large scale produced by developed companies such as Federal-Mogul Co., Austrian Miba Co., Japan TAIHO KOGYO Co. However, there are few research materials on self-lubricating coatings in China. In the year of 1983, the first MoS_2 self-lubricating coatings prepared by liquid dope was studied by Liu of the Institute of Coatings, however, the coatings were not applied to sliding bearings [38]. The sliding bearing surface coating technology of China started late, and it is still a new technology. In recent years, many bearing research institutes and manufacturers in China have begun to study the coating technology of sliding bearing made by liquid spraying. As shown in **Figure 8**, bearings with MoS_2 lubricating coating made by liquid spraying, and prepared with Zhejiang CSB Co. and the ZYNP Co.

The widely used coating dopes in China are MoS_2 and PTFE dopes, which wear resistance and temperature resistance are poor, and the tribological properties of composition elements such as resin and auxiliary are lower than that of Dow Corning D7409 and Kawanori of Japan. However, self-lubricating coatings for bearings under the medium (200°C) and high temperature (800°C) dopes are lacking of. The special lubricating materials of coating dopes of American D7409 and Kawanori of Japan did not particularly be selected according to the special alloys of bearing likewise the different aluminum alloys, copper alloys, and babbitt alloys, and these coatings drop easily if the temperature varies with time. Therefore, it is important to develop new coating dope for special alloys at different temperature.

The coating spraying technology includes coating dope preparation, liquid dope spraying through spraying gun and solid coating formation. The coating dope consists of self-lubricating materials, anti-wear materials, resins, auxiliaries and solvents. The different lubrications and anti-wear materials easily mixed together due to the liquid solution, and the coating made from dope will have the excellent tribological properties. The principle of paint spraying is shown in **Figure 9**. There are two ports on the spray gun connected to the spraying gas and dope respectively.

Figure 8.
Plain bearings with dope coating of China.

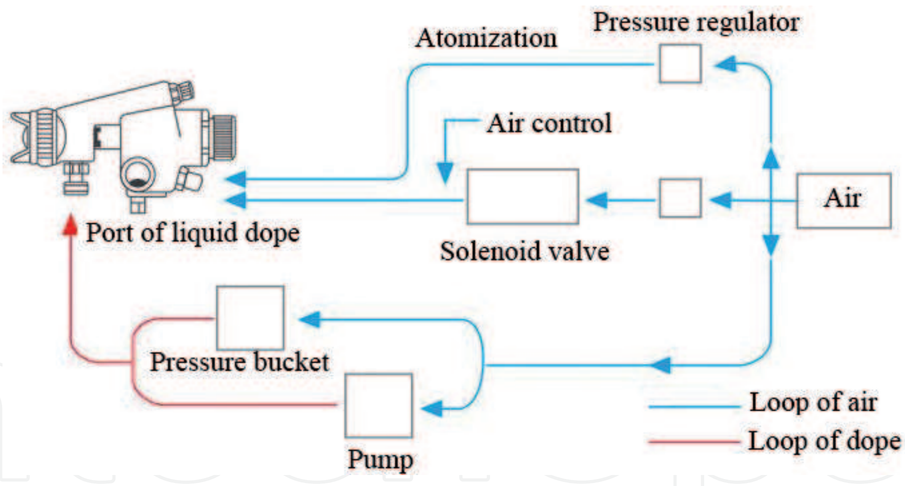

Figure 9.
Work principle of coating dope spraying

The paint dope is in a pressure tank with automatic stirring. It is driven into the spraying gun by the action of the pump to adjust the size of the gas source, liquid flow rate and spraying distance to control the amount of spraying dope.

2.2.3.1 Coating formation

Guo used epoxy resin as the binder, and MoS_2 and PTFE were used as the main lubricating materials to prepare the antifriction coating. The friction mechanical properties of the coating were studied at different curing temperatures. The results showed that the coating performance was the best when the coating formation temperature was 120°C. The coefficient of friction is 0.125, and the adhesion is 16.73 N [39]. However, ordinary epoxy resins have poor temperature resistance, and the coating thus prepared cannot be operated for a long period of time at 200° C. Cao studied the spraying distance effects on coating spraying efficiency and coating thickness uniformity. He pointed out that reducing the spraying distance improves the adhesion between the coating and the substrate. However, the shorter the distance was, the worse the coating thickness uniformity could be [40]. Yang used sagging as the object of assessment, and studied the spraying distance and spraying temperature during the PTFE coating preparation, but the principle and theory of sag phenomenon had not studied [41].

2.2.3.2 Porosity

The heating temperature of the coating to form a coating is generally from 120 to 220°C. Under the action of materials such as resin and polyimide, the liquid coating has a sealing effect on the solid coating process which leads to low coating porosity. Li uses rare earth materials and a rapid thermosetting method to prepare a coating, and the porosity of coating is just only 0.35% [42]. The porosity of sliding bearing produced by the powder metallurgy and electro-plating is high. Lins et al. studied the effect of current density on the porosity of nickel deposited with copper substrates. The porosity of nickel coatings was 6.22% according to different current magnitude tests [43]. The films prepared by magnetron sputtering are relatively dense, and the porosity is generally from 0.5 to 5% [44, 45]. If 1–2% reduction in porosity, the fatigue strength of the workpiece will increase from 10 to 30%, so low porosity is one of the necessary conditions for sliding bearings [46].

2.2.3.3 Bond strength

The initial state of the coating prepared on the surface of the bearing is liquid. In order to avoid sagging of the coating, the coating thickness should not be too thick. The optimum coating thickness of the coating method is less than 20 μm, and the infiltration method and the brushing method are prepared. The thickness of the coating should not exceed 120 μm. The bonding strength of the coating to the substrate is influenced by surface roughness of the substrate, the type of coating adhesive, the preheating and the curing temperature. Therefore, it is particularly important to study the coating forming process to improve the bonding strength of the coating. An used epoxy resin and polyvinyl butyral as binder to prepare coating with TiO_2 as filler. The bond strength of the steel matrix is from 9 to 12 MPa [47]. Mao prepared a coating of made by graphite, MoS_2, PPS (polyphenylene sulfide) and PES (polyethersulfone resin) by regression test. The optimum bonding strength of the tested coating was 42 MPa [48]. The self-lubricating coatings with polyamide-imide used as the binder, and the main lubricants were MoS_2 and PTFE. The adhesive strength studied by Song according to the GB9286-88 paint film rating test of China is poor as level 1, which does not reach the optimal bonding strength [49].

2.2.3.4 Lubrication properties

Self-lubricating coatings are mainly composed of solid lubricating fillers such as MoS_2, PTFE, WS_2, graphite, and some additives such as polyimide, epoxy resin, phenolic resin, leveling agent, dispersing agent, defoaming agent, etc. Gao used PAI (polyamide-imide polyamide-imide) as a binder, and the coating prepared by mixing 8% MoS_2, 5.4% PTFE and 1.5% graphite had the best performance. The coating had not changed which was tested at 80°C and −40°C, and it was not changed for socking in 10% HCl over 3 months [50]. Li made PTFE coating which added MoS_2 and graphite as the solid lubricants. The PTFE used as the main component, and PEEK (polyether ether ketone), PI (polyamide) and PPS as binders. The coefficient of friction of the PTFE coating was 0.12 [51]. The studies of self-lubricating sliding bearing coatings are mainly concentrated in recent years, so there are few researches of self-lubricating coatings which used at wide-temperature. Ordinary epoxy resins and polyimide materials are generally used in coatings, however, they cannot work for long under condition of 200°C. In addition, the sagging and leveling phenomenon of the sprayed sliding bearing have not been studied in detail. The theory of optimal thickness of coating, optimum roughness of the substrate, optimum curing temperature of the coating and cooling temperature of the coating are also very few.

Compared with the self-lubricating sliding bearings prepared by electroplating and magnetron sputtering, the paint-coated bearings have the advantages of environmental protection and high production efficiency. The review of coating research shows that the development of self-lubricating coatings under different temperature is one of the best technologies for preparing sliding bearings due to the excellent wear resistance and low friction performance.

2.3 Review of self-lubricating sliding bearing at high temperature

The work temperature of socket bearings in the missile launcher mechanism is higher than 800°C. Materials such as resins used as components in dope coating cannot be operated under ultra-high temperature conditions. At present, the maximum working temperature of grease-based lubricating materials generally do not exceed 200°C, and the maximum using temperature of polymer-based self-lubricating materials (single-phase) generally does not exceed 400°C [52]. The ranges of optimum lubrication for single-phase materials are shown in **Table 1**.

The frictional coefficient of MoS_2 is generally lower than 0.1 under room temperature. The oxidations of Mo element will be generated if MoS_2 working temperature exceeds 200°C, that the self-lubricity of MoS_2 is reduced. The MoS_2 lubrication performance will be further reduced and the self-lubricating effect will be lost if the temperature exceeds 350°C. In **Table 1**, B_2O_3 produced by BC_4 under high temperature has self-lubricity, and its friction coefficient is from 0.10 to 0.30, while the BC_4 friction coefficient is from 0.35 to 0.40 at room temperature [55]. Single coatings are difficult to maintain self-lubricating performance over a wide temperature range. Ouyang used $BaSO_4$, $BaCrO_4$, Ag as the main materials to prepare self-lubricating materials. The results of friction and wear tests showed that the friction coefficient was from 0.38 to 0.55 when the temperature was from room temperature to 800°C [56]. Zhen studied a self-lubricating material mainly consisted of CaF_2, BaF_2 fluoride and noble metal Ag, and the frictional coefficient of the composite material is from 0.24 to 0.3 at the temperature from room temperature to 800°C [57]. The physical and phase change will vary with temperature, for example, the structure and tribological properties of Ti_2AlC coating made by thermal spraying are different at room temperature and 800°C [58]. The coating shown in **Figure 10a** is spongy and many pores, however, the coating was oxidized and became dense at 800°C.

2.3.1 Powder metallurgy sintering

In order to make the bearings have self-lubricating performance under ultra-high temperature conditions, the common method is to prepare self-lubricating coating by powder metallurgy method. In the powder sintering method, the self-lubricating powders often mixed with some functional powders, and placed together in a high-temperature furnace to prepare a self-lubricating composite material. In the preparation of self-lubricating composites by powder metallurgy, local unevenness will be generated due to uneven powder mixing, uneven laying, uneven powder size or incomplete sintering of the powder during sintering [59].

Chen studied the uneven microstructure of AlSi alloy powder. The study showed that when the mass fraction of AlSi alloy powder is 50%, it can effectively reduce the unevenness of the product and improve the stability of the alloy [60]. Ding studied the powder metallurgy oxidation behavior at different temperatures, different processes and different atmospheres, and results pointed out that the amino atmosphere was more protective than nitrogen [61]. Cao prepared Ti_6Al_4V coating by sintering 23 μm Ti particles and 40 μm Al-V powder. The powder was cold pressed to 180 MPa before sintering, and then sintered at 1250°C in vacuum to prepare Ti_6Al_4V coating. The layer porosity was only 3.5% [62]. Studies had shown

	Graphite	**MoS_2**	**WS_2**	**WSe_2**
Frictional coefficient	0.05–0.15	0.05–0.20	0.08–0.20	0.09–0.20
Max using temperature	300°C	340°C	450°C	450°C
	TaS2	**PbO**	**BN**	**BC4**
Frictional coefficient	0.05–0.20	0.07–0.20	0.06–0.20	0.10–0.30
Max using temperature	550°C	700°C	900°C	1200°C

Table 1.
The best frictional coefficient of single material [53, 54].

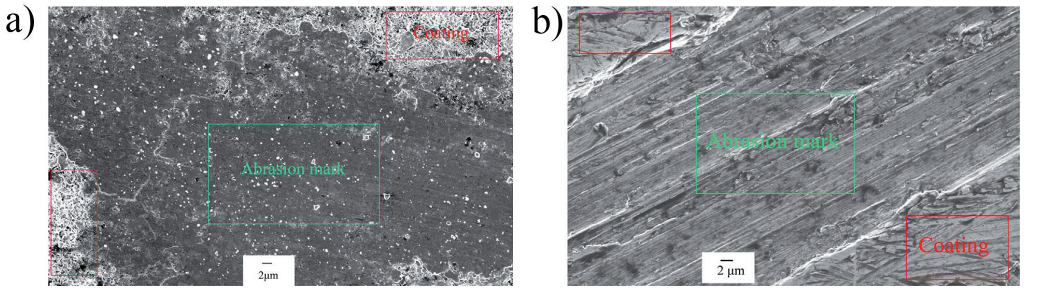

Figure 10.
Structure and abrasion marks of Ti_2AlC coating at different temperature: (a) room temperature; (b) 800°C.

that increasing pressure during powder metallurgy preparation of products, and using an atmosphere to protect the environment or vacuum environment is conducive to the reduction of porosity.

As shown in **Table 2**, the frictional coefficient of self-lubricating materials prepared by the powder sintering method is from 0.26 to 0.8 under different temperature conditions. Although self-lubricating materials at wide temperature domain had achieved some success, they had not been applied to sliding bearings. Most of the results were in the laboratory stage, and the self-lubricating composite materials prepared by powder sintering had defects such as high oxidation and high porosity. In **Table 2**, in order to reduce the high temperature frictional coefficient, a highly toxic fluoride material under high temperature conditions was used, which was not conducive to safe production.

The CoFs (coefficients of friction) of self-lubricating materials studied in **Table 2** is high and at 800°C. In order to satisfy the requirements of self-lubrication of sliding bearings used at wide temperature range, the new process and method should be used.

2.3.2 Thermal spraying

The solid self-lubricating powder particles are heated and molten by thermal spraying, and then directly sprayed onto the surface of the sliding bearing to form a coating. Since there is no resin, the prepared coating can be applied to a super-high temperature working condition. The kerosene, propane, or hydrogen used as burn gas during the supersonic flame spraying, and the molten or semi-molten alloy powders are sprayed with high speed on the surface of substrate by flame spraying. The time of alloys contact with oxygen in the air is very short due to the high spraying speed of 500 m/s. Supersonic flame spraying technology widely used as surface additive processing technology, and have high production efficiency and good coating bonding strength. A variety of coatings had been successfully prepared by thermal spraying

Materials	Lubrications	CoF at room temperature	CoF at 600°C	CoF at 800°C
Ag-Pb-Cu-Sn [63]	Ag-Pb	0.35	0.3	—
ZrO_2-MoS_2-CaF_2 [64]	MoS_2-CaF_2	0.3	0.8	0.27
Ni_3Al-Ag-Mo-BaF_2/CaF_2 [65]	Ag, BaF_2/CaF_2	0.35	0.38	0.32
Ni-Ag-BaF_2/CaF_2 [66]	Ag, BaF_2/CaF_2	0.3	0.32	0.26
NiCr/Cr_3C_2-WS_2 [67]	WS_2	0.42	0.28	—

Table 2.
CoFs of self-lubricating composite materials at high temperature.

technology, and which also can be used as sliding bearing materials. Thus, the preparation of sliding bearing coatings in combination with thermal spraying technology is reliable. Supersonic flame spraying is shown in **Figure 11**. The self-lubricating powders enter the spraying gun firstly, then, with the action of prismatic shock wave, the molten powders are sprayed on the surface of substrate to form a coating.

High bonding strength is one of the advantages of supersonic flame spraying. The bonding strength of WC-10Co-4Cr coating made by supersonic flame sprayed and prepared by Zhu was 72.63 MPa, and the porosity was 1.5% [68]. WC–Co coating studied by Tang, and prepared on the surface of the screw material substrate had a bonding strength of 65 MPa [69]. The bonding strength of $MoSi_2$ coating prepared by Wu was only 14.5 MPa, indicating that the material and spraying parameters were important factors for the bonding strength of the coating. If bonding strength is low, the bonding strength can be improved by optimizing the spraying parameters [70].

The 54% Cr_3C_2 added with 34% NiCr and 12% CaF_2/BaF_2 mixed powders, and sprayed as coating was studied by Xue. The frictional coefficient of coating was 0.75 and 0.37 at room temperature and 500°C respectively [71]. Hou used supersonic flame spraying process to prepare aluminum bronze alloy coating on steel substrate, and the frictional coefficient of coating was from 0.08 to 0.12 under different oil lubrication conditions [72]. Copper alloy and aluminum alloy materials are also suitable for supersonic spraying to prepare coatings. The studies like $AgSnO_2$/Cu coating prepared by Chong, Al-Si coating prepared by Wu, and Cu(ln, Ga)(S, Se)2 coating prepared by Park [73, 74].

2.3.3 Cold spraying

Cold spray technology is a new spray technology developed from thermal spray technology in recent decades. The obvious spraying characteristics are low temperature and high speed. As shown in **Figure 12**, under the action of high pressure gas, the powder particles are supersonic flying through the Lava tube and deposited directly on the surface of the plain bearing to form a coating by the pure plastic deformation.

The sliding bearing materials are generally copper alloys, aluminum alloys and tin alloys. These metal materials have an ability of excellent plastic deformation during the formation of coating by cold spraying. Guo, Li and some scholars studied the coating properties of bearing alloy materials such as CuSn6, CuSn8, Cu5Sn95, AlSn5, AlSn10 and AlSn20 made by cold spraying, and the frictional coefficient of bearing alloy materials under dry friction conditions were generally

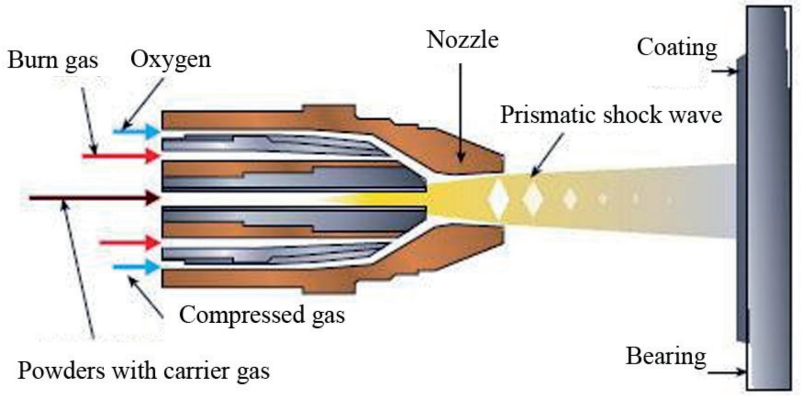

Figure 11.
Principle of supersonic flame spraying.

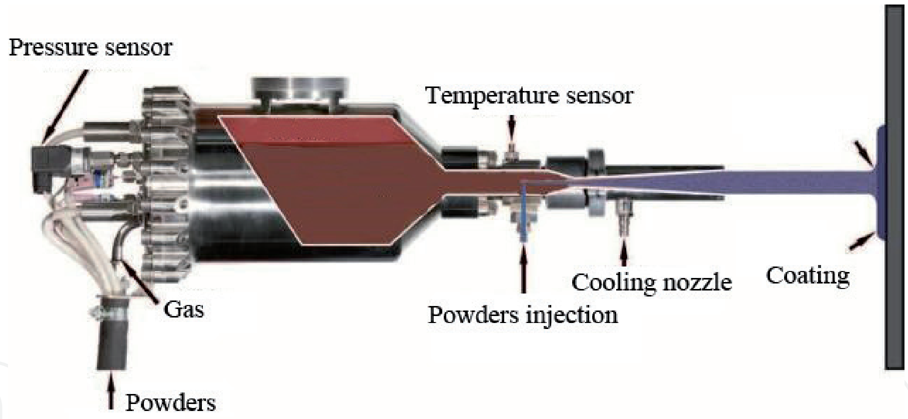

Figure 12.
Principle of supersonic cold spraying.

higher than 0.5 [75–79]. The preparation of supersonic cold spray coating is mainly based on the plastic deformation ability of powder particles, so the material should have excellent elastoplasticity [80]. The self-lubricating powder materials such as MoS_2, graphite and h-BN have poor elastoplastic deformation ability, and they are difficult to deposit on the bearing to form a coating.

The material frictional tests of coatings made by powder sintering, supersonic thermal spraying and supersonic cold spraying showed that the supersonic flame spraying and cold spraying are the desired methods to prepare coating used at high temperature. However, many materials lack of plastic deformation ability that the liquid dope spraying is the best method to deposit coating used at temperature lower than 200°C.

3. Comparisons and characteristics of different self-lubricating treatment methods

According to the studies of self-lubricating sliding bearing and self-lubricating composite materials at room temperature, medium temperature and high temperature, bearings with self-lubricating liners and bearings inlaying with solid lubricating materials are used at room temperature commonly. Bearings treated by electroplating, magnetron sputtering and liquid spraying are used at the temperature lower than 200°C. However, there are no bearings that have the continue self-lubricating performance from room temperature to 800°C, though the coating made by powder sintering, supersonic thermal spraying and cold spraying.

The production efficiency, oxidation rate, coating thickness, porosity and bonding strength compared and shown in **Table 3** according to the different surface treatments and bearing using temperature. As shown in **Table 3**, the coating thicknesses prepared by electroplating, magnetron sputtering and liquid dope spraying is thin. The electroplating is environment polluting.

The production efficiency of film produced by magnetron sputtering is low. It takes more than 20 h to prepare a film which thickness is 10 μm. The film of large sliding bearing cannot be prepared due to the structure limit. The self-lubricating liner that added on the surface of bearing has low temperature resistance due to the fail of adhesive glue and fiber braid. The structure strength is decreased as the structure of bearing changing with inlaying solid materials. The oxidation and high porosity of bearing will be generated by the method of powder sintering. The structure of materials used for thermal and cold spraying should be spherical, and the materials used for cold spraying should have plastic deformation performance.

Technologies	Production efficiency	Oxidation	Coating thickness	Porosity	Adhesive strength	Shortages
Electro-plating	Middle	Low	<15 μm	Middle	Low	Pollution
Magnetron sputtering	Low	Low	<15 μm	Low	High	Less utilization of target
Fabric liner	Low	—	—	—	High	Woven fabric invalid at high temperature
Supersonic flame spraying	High	Middle	<1 mm	Low	High	Spherical powders
Cold spraying	High	Low	>1 mm	Low	High	Powders need plastic deformation ability
Powders sintering	High	High	>1 mm	High	High	High oxidation
Inlaying lubrications	Low	Low	—	—	—	Structure strength is decreased
Liquid dope spraying	High	Low	<20 μm	Low	Middle	—

Table 3.
Comparisons of different self-lubricating methods.

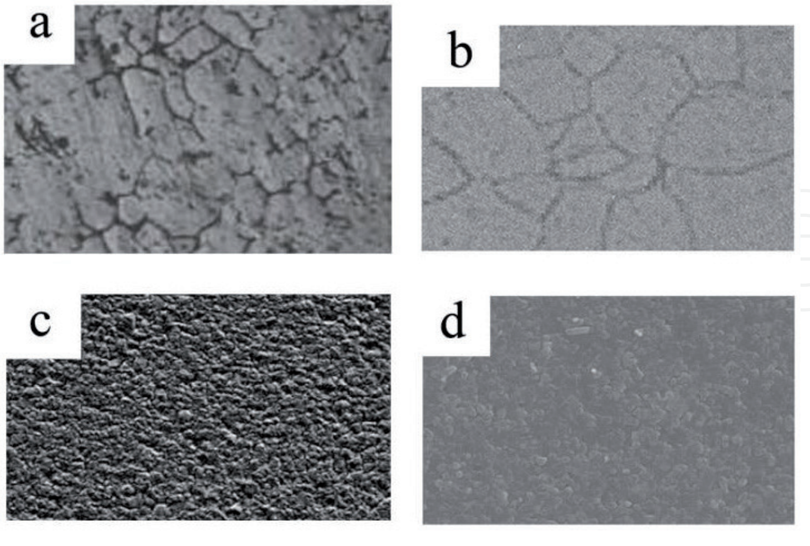

Figure 13.
Microstructure of Cu-Sn alloy of different manufacturing technologies: (a) centrifugal casting; (b) sintering; (c) electroplating; (d) magnetron sputtering.

The ceramic materials such as WC, SiC, h-BN are limit to use by the thermal spraying and cold spraying. The coating made by liquid dope spraying has the advantages of high production efficiency, green materials and good lubricity. The thickness more than 1 mm of coating on bearing prepared by supersonic flame spraying can be obtained, and it has the advantages of low porosity, good bonding strength and high production efficiency. Therefore, low- temperature and medium-temperature self-lubricating coatings should be prepared by liquid dope spray method, and ultra-high temperature wear-resistant anti-friction coatings should be prepared by thermal spraying.

The micro structure of tin and cooper coating made by different manufacturing technologies are shown in **Figure 13** [81–85]. The obvious cracks can be found in **Figure 13a, b** which manufactured by centrifugal casting and powder metallurgy sintering respectively. The coating made by magnetron sputtering is more smooth than that of electroplating, and the porosity of coating made by magnetron sputtering is little than that of electroplating. The tribological and mechanical properties of alloy coating made by centrifugal casting and powder metallurgy sintering are poor from the results shown in **Figure 13**. However, the shortages of electroplating and magnetron sputtering are the pollutions and low efficiency respectively. The new coating formation technologies such as liquid dope spraying and supersonic flame spraying should be applied for sliding bearings.

4. Current problems of self-lubricating plain bearings

The traditional self-lubricating treatments of sliding bearings are mainly electroplating, magnetron sputtering, bonding self-lubricating liners and inlaying solid self-lubricating materials. The new self-lubricating preparation technologies of sliding bearings are mainly the liquid dope spraying and supersonic flame spraying. The problems of sliding bearings are listed as follows through above investigations and discussions.

1. High friction coefficient and low fatigue life

   Most of the sliding bearings have not been surface treated, and these bearings have high dry frictional coefficients, low fatigue strength, low life and low bearing capacity. The frictional coefficient of copper alloy, aluminum alloy and tin alloy of sliding bearings is generally higher than 0.5 under dry friction condition, and it does not have self-lubricity under a wide temperature range. The traditional copper alloys of sliding bearings contain Pb metal, which is polluting and harmful to human. The self-lubricating materials at ultra-high temperature are still in the laboratory research stage, and the sliding bearing with self-lubricating cannot be produced on a large scale.

2. Environmental pollution and low production efficiency

   The usage of acid, alkali and heavy metal solutions during the production of self-lubricating sliding bearings will cause serious environmental pollution. Magnetron sputtering takes long time during vacuuming and injection processes, and the efficiency of depositing thin films is lower than other processes. The utilization efficiency of target materials of magnetron sputtering is generally less than 40%. The multiple modification treatment processes and bonding processes are required for preparing self-lubricating bearings using of bonding self-lubricating fabric liners and bearings with inlaid solid self-lubricating materials. The punching holes and inlaying solid lubricating materials are required during the production. The production efficiency of inlaying solid lubrications is low, which cannot satisfy the requirements of large-scale mass production.

3. The theory of spraying process for sliding bearing is not deep enough

The liquid dope spraying method is one of the best methods for preparing self-lubricating sliding bearings which used at room temperature and medium temperature. However, the spraying mechanisms such as leveling and sagging coating on bearing surface have not been studied. The optimum thickness of the coating, the optimum surface roughness of the substrate, the optimum curing temperature of the coating, and the optimum cooling temperature of the coating were not studied in details.

4. Poor tribological properties

The wear-resisting and self-lubricating performances of coatings are poor, and their service life under the medium temperature (200°C) is short. There are no special materials which have low difference of thermal expansion and similar physical properties with the given materials of bearings. The self-lubricating materials used at high temperature are currently in the state of laboratory research stage, and have not been prepared for bearings at large production scale.

5. Conclusion

The processing technologies and material properties of self-lubricating sliding bearings made by electroplating, magnetron sputtering, bonded self-lubricating liners, and embedded solid self-lubricating materials are studied and summarized in this paper. The advantages and disadvantages of self-lubricating bearings made by different technologies are shown. The widely surface treatment of sliding bearing is electro-plating, however, the bond strength is lower than magnetron sputtering, supersonic flame spraying, cold spraying and powder sintering technologies, and the solutions of electro-plating is pollution and harmful to human. The properties of thin film made by magnetron sputtering is excellent, however, the production efficiency is too low due to the vacuum and deposition process. The large-scale size of bearings such as bearings used in ship diesel engine cannot be deposited due to the structure limit of magnetron sputtering machine. The porosity of bearing made by powder sintering is high, and the alloys are oxidized at the high sintering temperature. The mechanical properties of cold spraying are better than thermal spraying, however, the materials of cold spraying should have excellent plastic deformation ability, that the materials such as MoS_2, C, h-BN and many ceramics materials are not able to be deposit on the surface of bearing.

Through comparative analysis, liquid dope spraying method is suggested to be adopted as the surface treatment process for bearing using at room temperature and medium temperature. The solid powder thermal spraying is suggested to be used for preparation of bearings working at high temperature. The liquid dope spraying is used in the advanced sliding bearing manufacturing companies, and the materials of liquid dope should be improved due to the wide range temperature variation at start and stop stage. The self-lubricating coating at high temperature is lacking, and the tribological properties of bearings at high temperature are poor. There were few materials that had continuous self-lubricating properties at the wide range temperature. According to the review, the lubrication materials used at high temperature mostly were the fluorides which were poisonous at high temperature. According to the summaries of self-lubricating treatments, the green materials, coating formation mechanisms, technology processes and tribological properties of liquid dope spraying and supersonic flame spraying for sliding bearings should be studied further.

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