

We are IntechOpen, the world's leading publisher of Open Access books Built by scientists, for scientists

6,900

Open access books available

186,000

International authors and editors

200M

Downloads

Our authors are among the

154

Countries delivered to

TOP 1%

most cited scientists

12.2%

Contributors from top 500 universities



WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com



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

Jun Cao, Liang Qin, Aibing Yu, Haibo Huang, Guoping Li, Zhongwei Yin and Huiyu Zhou

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].

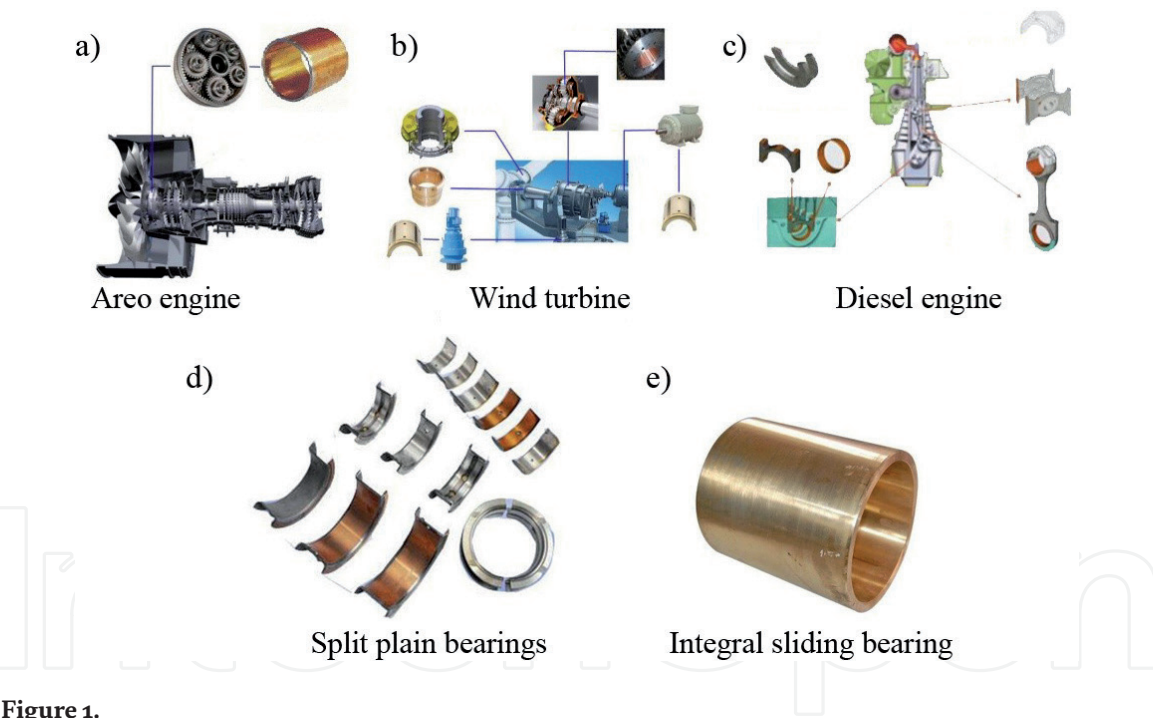


Figure 1.
The applications of plain bearings and their structures.

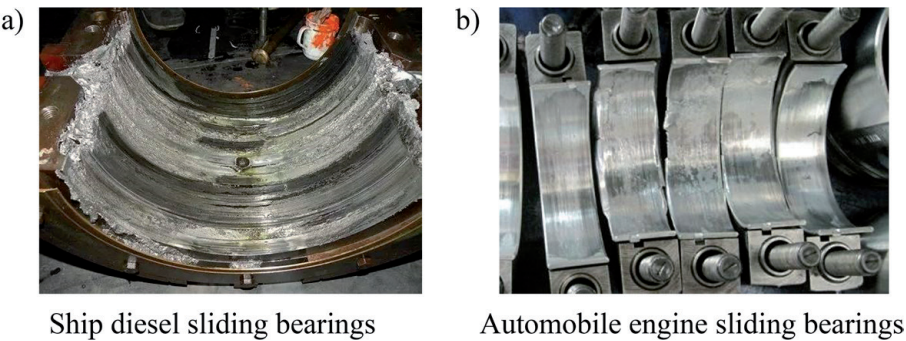


Figure 2.
Friction damage of sliding bearings.

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 antifric-tion, 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 WS₂, and the friction coefficient of surface liner under dry friction was about 0.05–0.06 [12]. Fabrics were treated with rare earths CeO₂, LaCl₃, La₂O₃ and CeF₃ 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 inlaid 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]. MoS₂/Sb₂O₃ mixed powders were produced to form solid

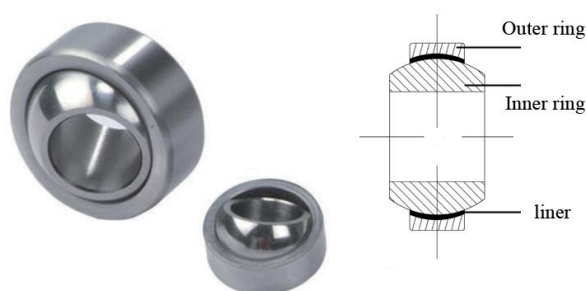


Figure 3.
 Joint bearing with self-lubricating liner.

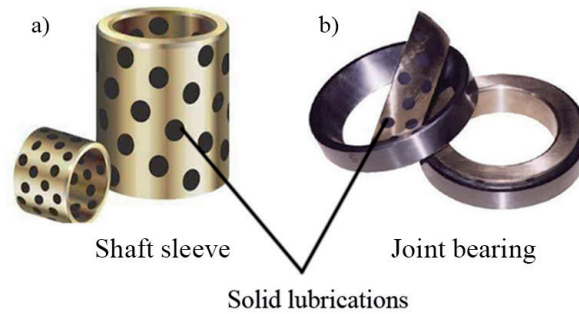


Figure 4.
Plain bearing inlaying with solid lubrications.

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

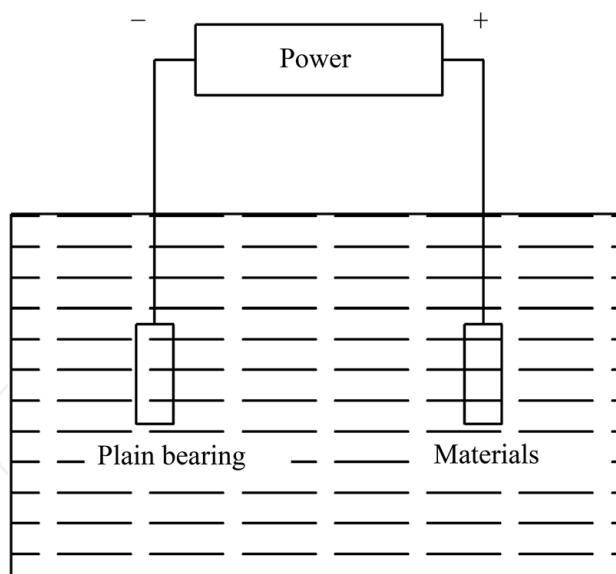


Figure 5.
 Technology of electroplating of bearings.

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

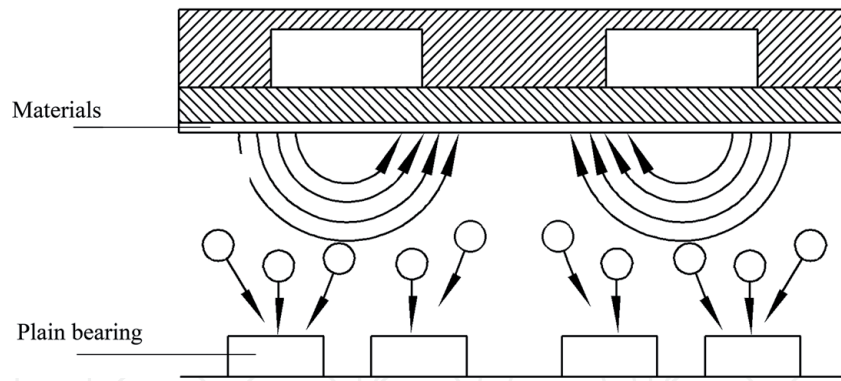


Figure 6.
Technology of magnetron sputtering.

sputtering. In the existing research, bearing alloy composite films such as Ti/Cu/N Cu_xSn_y , TiN/Cu had been prepared, and adhesion 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 .

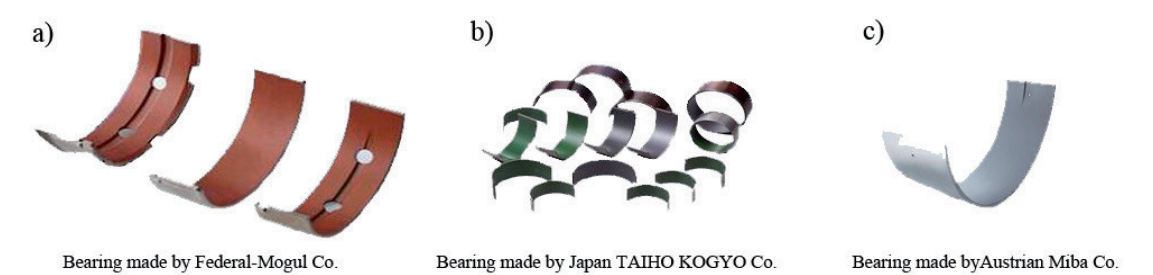


Figure 7.
Plain bearings with dope coating of overseas.

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.

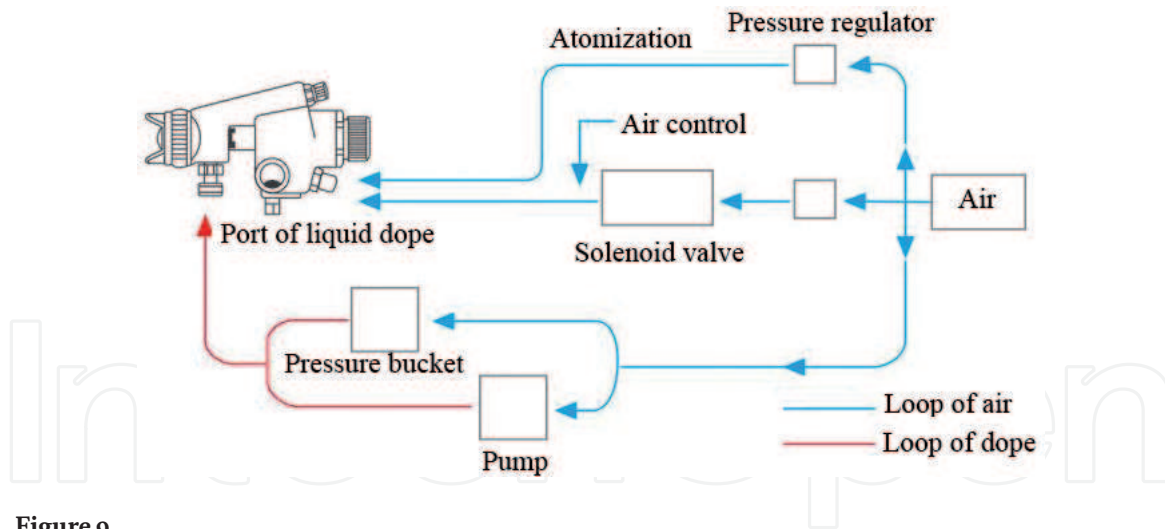


Figure 9.
Work principle of coating dope spraying

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 soaking 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 MoS₂ is generally lower than 0.1 under room temperature. The oxidations of Mo element will be generated if MoS₂ working temperature exceeds 200°C, that the self-lubricity of MoS₂ is reduced. The MoS₂ lubrication performance will be further reduced and the self-lubricating effect will be lost if the temperature exceeds 350°C. In **Table 1**, B₂O₃ produced by BC₄ under high temperature has self-lubricity, and its friction coefficient is from 0.10 to 0.30, while the BC₄ 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 BaSO₄, BaCrO₄, 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 CaF₂, BaF₂ 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 Ti₂AlC 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 Ti₆Al₄V 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 Ti₆Al₄V 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
	TaS ₂	PbO	BN	BC ₄
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].

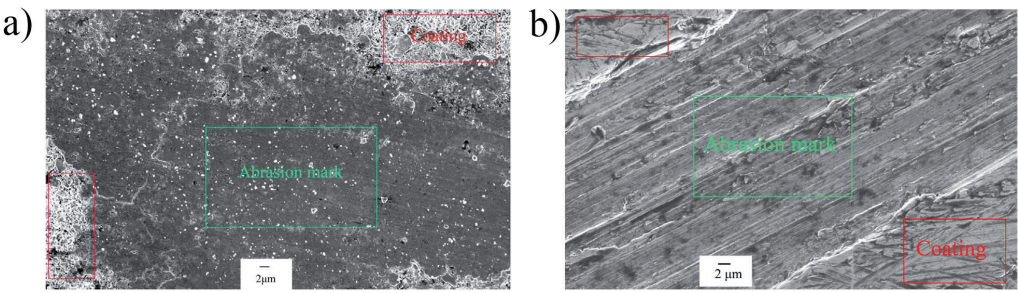


Figure 10.
Structure and abrasion marks of Ti_2AlC coating at different temperature: (a) room temperature; (b) 800°C .

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 ₃ Al-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 ₃ C 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 MoSi₂ 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% Cr₃C₂ added with 34% NiCr and 12% CaF₂/BaF₂ 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 AgSnO₂/Cu coating prepared by Chong, Al-Si coating prepared by Wu, and Cu(In, 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 Laval 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

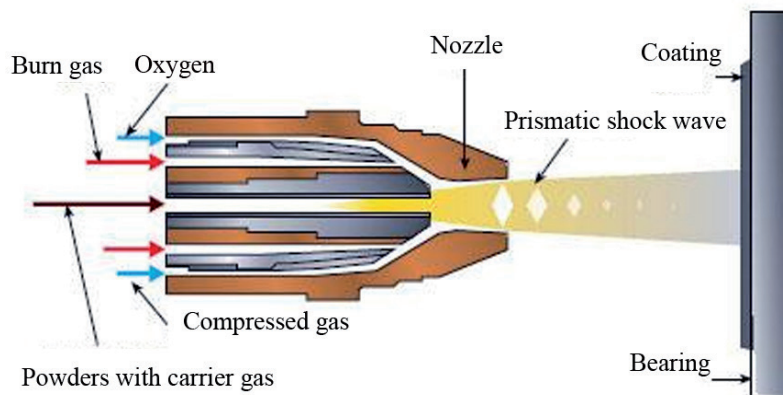


Figure 11.
Principle of supersonic flame spraying.

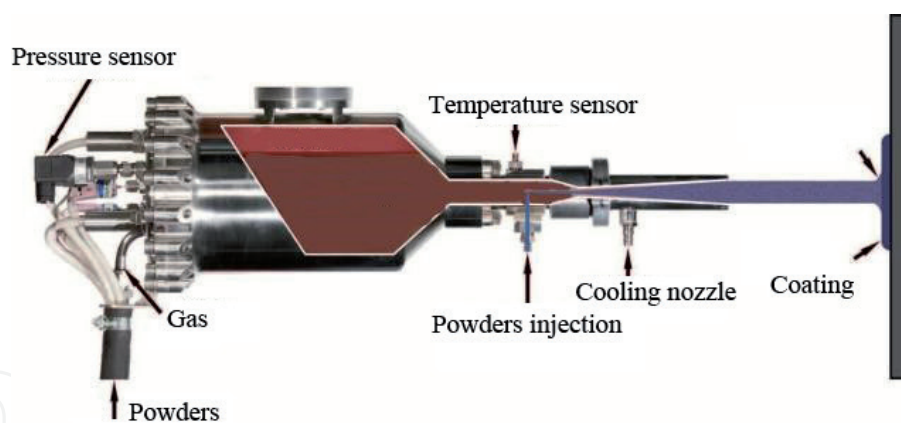


Figure 12.
 Principle of supersonic cold spraying.

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 $10\ \mu\text{m}$. 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.

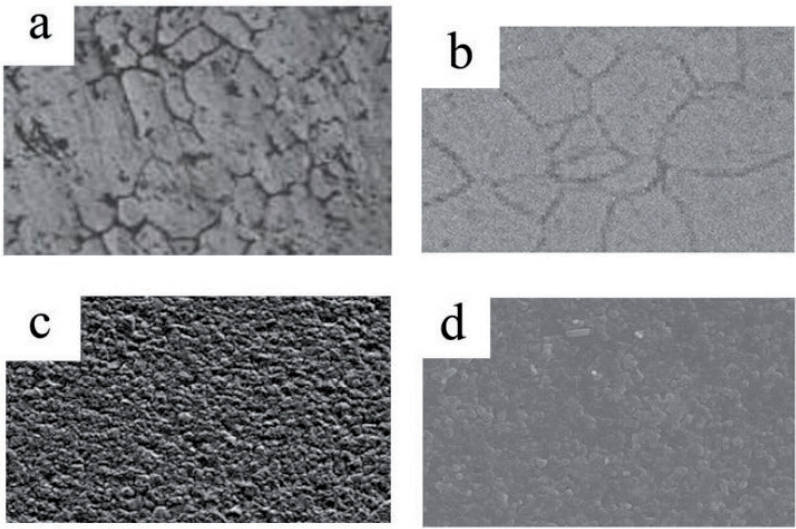


Figure 13.
Microstructure of Cu-Sn alloy of different manufacturing technologies: (a) centrifugal casting; (b) sintering; (c) electroplating; (d) magnetron sputtering.

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 copper 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 MoS₂, 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.

Acknowledgements

This research was supported by Shanghai Xiangsheng beco engine bearing Co, Ltd. and its chairman of Shengxiang Zhu.

Author details

Jun Cao^{1,2*}, Liang Qin³, Aibing Yu^{1,2}, Haibo Huang^{1,2}, Guoping Li^{1,2}, Zhongwei Yin³ and Huiyu Zhou⁴

1 School of Mechanical Engineering, Ningbo University, Ningbo, China

2 Part Rolling Key Laboratory of Zhejiang Province, Ningbo, China

3 School of Mechanical Engineering, Shanghai Jiaotong University, Shanghai, China

4 School of Natural and Applied Science, Northwestern Polytechnical University, Xi'an, China

*Address all correspondence to: caojun@nbu.edu.cn

IntechOpen

© 2019 The Author(s). Licensee IntechOpen. This chapter is distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/3.0>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited. 

References

- [1] Zeng ZQ, Wang YK, Wang ZH. 2D simulation of the aerodynamic micro air journal bearing for micro gas turbine engine. *Applied Mechanics and Materials*. 2012;**121-126**:3087-3091
- [2] Han QL, Li GD, Zhao WX. Bearing of high speed of rail failure analysis at rising temperature. *Electric Drive for Locomotives*. 2017;**1**:115-117
- [3] Summer F, Grüna F, Offenbecher M, Stuart T. Challenges of friction reduction of engine plain bearings—Tackling the problem with novel bearing materials. *Tribology International*. 2019;**131**:238-250
- [4] Sander DE, Allmaier H. Starting and stopping behavior of worn journal bearings. *Tribology International*. 2018;**127**:478-488
- [5] Lu ZC, Zeng MQ, Gao Y, Zhu M. Significant improvement of wear properties by creating micro/nano dual-scale structure in Al–Sn alloys. *Wear*. 2012;**296**(1-2):469-478
- [6] Liu TS, Guo YS, Song YH, Sun SW, Zhou WX. Defect analysis and elimination of $ZCuSn_{10}Zn_2$ products by centrifugal casting. *Physical Testing and Chemical Analysis Part A: Physical Testing*. 2013;**49**(1):52-54
- [7] Novak M, Chrastny V, Sebek O, Maetinkova E, Curik J, Veselovsky F, et al. Chromium isotope fractionations resulting from electroplating, chromating and anodizing: Implications for groundwater pollution studies. *Applied Geochemistry*. 2017;**80**:134-142
- [8] Huang SY, Qu FQ, Miao Y, Meng ZK. Development of cylindrical rotating magnetrons with high target utilization rate. *Journal of Vacuum Science & Technology*. 2000;**20**(2):123-125
- [9] Liu HT, Li ZX, Wang JM, Sheng CX, Liu WL. Wear resistance properties reinforcement using nano-Al/Cu composite coating in sliding bearing maintenance. *Journal of Nanoscience and Nanotechnology*. 2018;**18**(3):2152-2157
- [10] Tang ZQ, Liu XJ, Pang MH, Liu K. Surface texturing design and frictional experiment of friction pair of grease lubricated spherical plain bearings. *Transactions of the Chinese Society of Agricultural Engineering*. 2016;**32**(12):61-67
- [11] Aderikha VN, Shapovalov VA. Mechanical and tribological behavior of PTFE–polyoxadiazole fiber composites effect of filler treatment. *Wear*. 2011;**271**:970-976
- [12] Li HL, Zeng FP, Yin ZW, Huo YJ. A study on the tribological behavior of hybrid PTFE/Kevlar fabric composites filled with nano-SiC and/or submicron- WS_2 fillers. *Polymer Composites*. 2016;**37**(7):2218-2216
- [13] Li YC, Qiu M, Miao YW. Bonding behavior and tribological property for self-lubricating spherical plain bearings with PTFE/Kevlar woven liners. *China Mechanical Engineering*. 2016;**27**(2):222-229
- [14] Zhan SH, Bai YX, Qiu M. Effects of liners modification on tribological properties of self-lubricating spherical plain bearings. *Bearing*. 2013;**(2)**:33-35
- [15] Shen JT, Top M, Pei YT, Hosson JD. Wear and friction performance of PTFE filled epoxy composites with a high concentration of SiO_2 particles. *Wear*. 2015;**322-32**:171-180
- [16] Zhang ZZ, Xue QJ, Liu WM, Shen WC. Effect of rare earth compounds as fillers on friction and wear behaviors of PTFE-based composites. *Journal of Applied Polymer Science*. 2015;**72**(3):361-369

- [17] Wei Q, Zhou BY, Chen SK. Investigation on friction and wear properties of new-type inlay self-lubricating bearing materials. *Material and Heat Treatment*. 2009;**38**(14):81-84
- [18] Zabinski JS, Donley MS, Mcdevitt NT. Mechanistic study of the synergism between Sb_2O_3 and MoS_2 lubricant systems using Raman spectroscopy. *Wear*. 1993;**165**(1):103-108
- [19] Li JG, Yin YG, Zhang GT, Tang HY. Investigation on friction and wear properties of FeS/copper matrix composite. *Bearing*. 2015;**12**:34-37
- [20] Wang S, Wei W. Characterization of electroplated Ni/SiC and Ni/ Al_2O_3 composite coatings bearing nanoparticles. *Journal of Materials Research*. 2003;**18**(7):1566-1574
- [21] Li WH, Zhou XY, Xu Z, Yan MJ, Wei GR. Friction behavior of brush electro-plated Ni-PTFE nano-composite coating. *Tribology*. 2005;**25**(6):520-524
- [22] Zhang S, Li GL, Wang DH, Xu BX, Ma GZ. Tribological properties of electric bush MoS_2 -C combination plating. *Journal of Materials Engineering*;2013(1):85-90
- [23] Tang WH, Jiang YX, Ba JZ, Li J, Wu WH, Tang JK. Preparation of indium-tin alloy electrode by plating and its property in electroreduction of CO_2 . *Electroplating & Metal Finishing*. 2013;**32**(6):1-4
- [24] Zhou ZP, Zhao GP, Hu YH, Gan ZJ. Preliminary study of nickel-tungsten alloy plating process. *Electroplating & Metal Finishing*. 2010;**29**(4):5-7
- [25] Klochko NP, Khrypunov GS, Volkova ND, Kopach VR, Lyubov VM, Momotenko OV, et al. Electrodeposition of Cu-In-Se precursors for chalcopyrite solar cells. *Functional Materials*. 2011;**18**(3):328-334
- [26] Li Y, Tao Y, Ke D, Ma YF, Han SM. Electrochemical kinetic performances of electroplating Co-Ni on La-Mg-Ni-based hydrogen storage alloys. *Applied Surface Science*. 2015;**357**:1714-1719
- [27] Li BS, Lin A, Gan F. Improvement of stability of trivalent chromium electroplating of Ti based $\text{IrO}_2 + \text{Ta}_2\text{O}_5$ coating anodes. *Rare Metals*. 2006;**25**:645-649
- [28] Chen DC, Zhao ZY, Zeng P, Xie GR, Zhong GM, Xu XD. Study on heat treatment and tribological properties of electro-brush plated high-tin copper-tin alloy coating. *Electroplating & Metal Finishing*. 2015;**34**(24):1385-1391
- [29] Li CS, Wang F, Hu ZL, Sun JR, Tang H. Preparation and tribological properties research of magnetron sputtered Sn-Sb-Cu Films. *Lubrication Engineering*;2013(9):1-5
- [30] Li A, Zhou Y. Joining of Ti_3SiC_2 by magnetron sputtering a layer of Cu or Zr followed by heat treating at relatively low temperatures. *Journal of the American Ceramic Society*. 2011;**94**(9):3072-3077
- [31] Guo YJ, Li QF, Yin ST, Ren ZY, Wang J. New bearing material for magnetron sputtering coating. *Journal of Harbin Engineering University*. 2001;**22**(6):93-96
- [32] Song H, Liu ZY, Tang WH, Yang RT, Ling GP. Effect of deposition parameter on properties of AlSn20Cu coating prepared by magnetron sputtering. *Ordinance Material Science and Engineering*. 2017;**40**(6):26-29
- [33] Lv TS. Experiments of bearing bush. *Internal Combustion Engine Parts*. 1982;(3):64-69
- [34] Kelly PJ, Li H, Benson PS, Whitehead KA, Verran J, Arnell RD, et al. Comparison of the tribological

and antimicrobial properties of CrN/Ag, ZrN/Ag, TiN/Ag, and TiN/Cu nanocomposite coatings. *Surface & Coatings Technology*. 2010;**205**(5):1606-1610

[35] Li JX, Zhang HQ, Fan AL, Tang B. Tribological properties characterization of Ti/Cu/N Thin films prepared by DC magnetron sputtering on titanium alloy. *Surface & Coatings Technology*. 2016;**294**:30-35

[36] Iseki T. Target utilization of planar magnetron sputtering using a rotating tilted unbalanced yoke magnet. *Vacuum*. 2009;**84**(2):339-347

[37] Campbell ME, Walker WD. Polyphenylene sulfide bonded film lubricant. US Patent 23337009. 1975

[38] Liu QX, Zhu EX, Ding SZ. Study on wear resistance lubricating past for the bed plate of HZt13-3 rail switches. *Tribology*. 1983;**3**(4):25-31

[39] Guo PR, Qiu M, Li YC, Li QL. Effect of MoS₂ on tribology and adhesion properties of polytetrafluorethylene base bonded solid lubrication coating. *Materials for Mechanical Engineering*. 2015;**39**(7):82-85

[40] Cao XG, Su YS, Wang N. The Analysis for influence of spraying distance on utilization efficiency of coatings. *Shanghai Coating*. 2011;**49**(9):40-42

[41] Yang J, Zhang L, Zhang YC. Preparation and application of PTFE aqueous dispersion modified waterborne polyurethane self-lubrication coatings. *China Rubber Industry*. 2018;**65**(7):752-755

[42] Li YG, Rui MA. Elimination of porosity in heavily rare-earth doped sol-gel derived silicate glass films. *Journal of Sol-Gel Science and Technology*. 2012;**61**(2):332-339

[43] Lins VFC, Cecconello ES, Matencio T. Effect of the current density on morphology, porosity, and tribological properties of electrodeposited nickel on copper. *Journal of Materials Engineering and Performance*. 2008;**17**(5):741-745

[44] Yoo JH, Ahn SH, Kim JG, Lee SY. Influence of target power density and substrate bias voltage on the electrochemical properties of type 304 SS films prepared by unbalanced magnetron sputtering. *Surface & Coatings Technology*. 2002;**157**(1):47-54

[45] Wang CY, Ren YX, Li QX, Li Z, Wang XX, Huang XY, et al. Preparation technology of high refractive index anatase TiO₂ film by low temperature magnetron sputtering technique. *Surface Technology*. 2017;**46**(5):177-183

[46] WU YP, Leng YX, Gui X, Sun H, Huang N, Zhu SF, et al. Porosity ratio and anti-corrosion properties of Cr/CrN films synthesized by unbalanced magnetron Sputtering. *Materials Science Forum*. 2009;**610-611**:647-651

[47] An QL. Study on the formation optimization and performance of epoxy resin powder coating [master dissertation thesis]. Shandong University; 2012

[48] Mao JY, Peng RS. Study on new PPS composite coating preparation and performance. *Development and Application of Materials*. 2014;**29**(1):36-40

[49] Song XF, Huang ZR, Li QM. Preparation of polyamide-imide self-lubricating composite paint and evaluation of performance of composite coating made of the paint. *Material Protection*. 2013;**46**(3):18-21

[50] Gao JM, Li HY, Zhou L, Hou B, Hou LW. Study on preparation and anticorrosive properties of polyamide-imide special coatings. *Paint and Coatings Industry*. 2014;**44**(9):31-36

- [51] Li K. Study on preparation and properties of PTFE lubricant coating [master dissertation thesis]. Yanshan University; 2016
- [52] Chen JM, Lu XW, Li HX, Zhou HT. Progress of solid self-lubricating coating over a wide range of temperature. *Tribology*. 2014;**34**(5):592-600
- [53] Shi MS. Solid Lubricating Materials. China: Chemical Industry Press; 2000
- [54] Hu ZB, Li HJ, Fu QG, Xue H, Sun GL. Fabrication and tribological properties of B₂O₃ as friction reducing coatings for carbon-carbon composites. *New Carbon Materials*. 2007;**22**(2):131-134
- [55] Wu F, Wang LS, Zhang JS, Fan Y, Liu BW, Gao Y. Friction and wear properties of self-mated hot-pressed boron carbide pair. *Tribology*. 2001;**21**(3):214-217
- [56] Ouyang JH, Sasaki S, Murakami T, Umeda K. Spark-plasma-sintered ZrO(YO)-BaCrO self-lubricating composites for high temperature tribological applications. *Ceramics International*. 2005;**31**(4):543-553
- [57] Zhen J, Li F, Zhu S. Friction and wear behavior of nickel-alloy-based high temperature self-lubricating composites against Si₃N₄ and Inconel718. *Tribology International*. 2014;**75**(5):1-9
- [58] Cao J, Yin ZW, Li HL, Gao GY, Zhang XL. Tribological and mechanical properties of Ti₂AlC coating at room temperature and 800°C. *Ceramics International*. 2018;**44**:1046-1051
- [59] Xu L, Wu J, Liu YY, Lei JF, Yang R. Densification and properties of Ti-5Al-2.5Sn alloy prepared by using HIP. *Titanium*. 2011;**28**(4):19-23
- [60] Chen XB, Fan JZ, Liu YQ. Measurement of micro-nonuniformity of 50% Si/Al composites and its influence on mechanical properties. *Chinese Journal of Rare Metals*. 2016;**40**(10):1008-1014
- [61] Ding HT. Reason and solution of oxidation and decarbonization of iron base P/M parts during sintering. *The Powder Metallurgy Industry*. 2008;**18**(5):36-39
- [62] Cao YK, Zeng FP, Liu B, Liu Y, Lu JZ, Gan ZY, et al. Characterization of fatigue properties of powder metallurgy titanium alloy. *Materials Science and Engineering A*. 2016;**654**:418-425
- [63] Li JL. Study on tribological properties of novel solid lubricating material and coatings at elevated temperature [doctoral dissertation thesis]. Nanjing University of Technology; 2009
- [64] Kong LQ, Bi QL, Niu MY, Zhu SY, Yang J, Liu WM. High-temperature tribological behavior of ZrO₂-MoS₂-CaF₂ self-lubricating composites. *Journal of the European Ceramic Society*. 2013;**33**(1):51-59
- [65] Niu MY, Bi QL, Yang J, Liu WM. Tribological performance of a Ni₃Al matrix self-lubricating composite coating tested from 25 to 1000°C. *Surface & Coatings Technology*. 2012;**206**(19-20):3938-3943
- [66] Zhen JM, Li F, Zhu SY, Ma JQ, Qiao ZH, Liu WM, et al. Friction and wear behavior of nickel alloy based high temperature self-lubricating composites against Si₃N₄ and Inconel 718. *Tribology International*. 2014;**75**(5):1-9
- [67] Yang MS, Liu XB, Fan JW, He XM, Shi SH, Fu GY, et al. Microstructure and wear behaviors of laser clad NiCr/Cr₃C₂-WS₂ high temperature self-lubricating wear-resistant composite coating. *Applied Surface Science*. 2012;**258**(8):3757-3762

- [68] Zhu CC, Wang MY, Hou BY, Ren XJ. Application of HVOF with WC-10Co-4Cr on high sluice valve. *Journal of Thermal Spray Technology*. 2013;**5**(1):11-15
- [69] Tang CY, Chen RF, Shen ZX, Zhu R, Yang F, Su FS. Investigation on WC-Co wearable coating on the surface of screw substrate prepared by HVOF spraying. *Journal of Yangzhou University*. 2008;**11**(1):34-37
- [70] Wu H, Li HJ, Lei Q, et al. Effect of spraying power on microstructure and bonding strength of MoSi₂-based coatings prepared by supersonic plasma spraying. *Applied Surface Science*. 2011;**257**(13):5566-5570
- [71] Xue QZ, Zhang JP, Ma L, Wang W. Study on the fluorination high velocity oxy-fuel spraying coating. *New Technology & New Process*. 2010;**2010**(7):80-83
- [72] Hou YF, Shen CJ, Zhang H, Hu WX. The tribological performance of HVOF Tin bronze steel bimetal material. *Lubrication Engineering*. 2011;**36**(1):70-73
- [73] Fu C, Jiang FY, Du ZM. Preparation and characterization of AgSnO₂/Cu contact material by supersonic plasma spraying. In: 2010 International Conference on Mechanic Automation and Control Engineering, MAC. 2010. pp. 3442-3445
- [74] Wu JW, Yang JG, Fan HY, Yoon SH, Lee CH. The bond strength of Al-Si coating on mild steel by kinetic spraying deposition. *Applied Surface Science*. 2006;**252**(22):7809-7814
- [75] Guo XP, Zhang G, Li WY, Gao Y, Liao HL, Coddet C. Investigation of the microstructure and tribological behavior of cold-sprayed tin-bronze-based composite coatings. *Applied Surface Science*. 2009;**255**(6):3822-3828
- [76] Li JF, Agyakwa PA, Johnson CM, Zhang D, Hussain T, McCartney DG. Characterization and solderability of cold sprayed Sn-Cu coatings on Al and Cu substrates. *Surface & Coatings Technology*. 2010;**204**:1395-1404
- [77] Guo XP, Zhang G, Li WY, Dembinski L, Gao Y, Liao HL, et al. Microstructure, microhardness and dry friction behavior of cold-sprayed tin bronze coatings. *Applied Surface Science*. 2007;**254**(5):1482-1488
- [78] Ning XJ, Kim JH, Kim HJ, Lee CH. Characteristics and heat treatment of cold-sprayed Al-Sn binary alloy coatings. *Applied Surface Science*. 2009;**255**(7):3933-3939
- [79] Ning XJ, Jang JH, Kim HJ, Li CJ, Lee CH. Cold spraying of Al-Sn binary alloy: Coating characteristics and particle bonding features. *Surface & Coatings Technology*. 2008;**202**(9):1681-1687
- [80] Deforce BS, Eden TJ, Potter JK. Cold spray Al-5% Mg coatings for the corrosion protection of magnesium alloys. *Journal of Thermal Spray Technology*. 2011;**20**(6):1352-1358
- [81] Cao J, Yin ZW, Li HL, Gao GY. Research progresses and suggestions of manufacturing technologies of engine bearing bushes. In: IOP Conf. Series: Materials Science and Engineering. Vol. 272. 2017. p. 012005
- [82] Tsega M, Kuo DH, Dejene FB. Cu₂ZnSnSb(S, Se, Te)₄ film formation from selenization of sputtered self-prepared single ceramic target. *Thin Solid Films*. 2015;**589**(8):712-717
- [83] Gabbittas BL, Ariff TF, Cao P. Synthesis of pewter alloy from tin-copper-antimony powder mixtures by microwave and conventional sintering. *Powder Metallurgy*. 2011;**54**(4):488-496

[84] Meinshausen L, Bhassyvasantha S, Majumdar BS, et al. Influence of indium addition on whisker mitigation in electroplated tin coatings on copper substrates. *Journal of Electronic Materials*. 2016;**45**(1):791-801

[85] Vahda SE. Tin-copper-lead alloy produced by horizontal centrifugal casting. *Archives of Foundry Engineering*. 2016;**16**(1):131-137

IntechOpen

IntechOpen