

Design and application of friction pair surface modification coating for remanufacturing

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Received: 12 June 2017 / Accepted: 11 August 2017

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Abstract: Friction, wear, and contact fatigue are the main causes of energy loss, material waste, and equipment failure. The aim of remanufacturing is to repair and modify the damaged equipment surface, and the surface coating is the major material that allows the remanufactured parts to be used in a new round of operation. Thus, the design and preparation of surface coatings are very important to repair, strengthen, or modify the friction pairs, in order to ensure long-term operation of the remanufactured parts. Recently, a lot of research on designing and preparing friction pair surface modification coatings has been conducted by the National Key Laboratory for Remanufacturing (NKLR). The research conducted achieved the following goals: the mechanism of micro/nano multilayer surface modification coatings with long-term efficacy life was revealed, and the corresponding design considerations and preparation methods of nanocrystalline micro tribological coatings were innovatively developed. A series of new “two-step” processes to prepare sulfide solid lubricating coatings were developed. The competitive failure mechanism of the surface coating in simultaneous wear and fatigue conditions was revealed, and some composite coatings with dual properties of wear resistance and fatigue resistance were prepared. Based on the stress distribution of friction surface contact areas and the piezoelectric effect, a failure warning intelligent coating is designed and developed. These coatings have been successfully applied to critical friction components, such as the spindle of large centrifugal compressors, engine cylinder piston components, and driver gear pairs.

Keywords: remanufacturing; surface coating; solid lubrication; contact fatigue; intelligent sensing coating

1 Introduction

Friction and wear of relatively moving components cannot be avoided. Significant economic loss and energy waste can be caused by wear [1]. Remanufacturing practices also show that wear is considered as a major damage form of workblanks for remanufacturing (old equipment or parts). Additionally, it has been reported that many remanufactured parts failed due to oversized components, surface cracking, or plastic deformation caused by friction, wear, and contact fatigue in their new round of service. China's independent innovative remanufacturing engineering has developed surface

coating techniques that are capable of not only repairing the surface damage to recover the original shape and size of parts, but also using the newest surface treatment processes and applying high performance materials to the remanufactured part surface, in order to achieve excellent tribological properties [2].

Recently, the equipment remanufacturing practice has paid considerable attention to the tribology issue related to key kinematic pairs. The National Key Lab for Remanufacturing (NKLR) adopts the structure-function integrated approach to design and deposit surface modifying coatings on friction pair surfaces. This approach facilitates monitoring and improvement

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of the performance of the friction pair surfaces in terms of their self-lubrication, wear resistant, anti-fatigue, and friction pair service conditions. Based on the related theory of tribology, material, and surface science, the theoretic and technical problems of structural design, preparation technology, and performance evaluation of the coatings are conquered by restraining the thermodynamic condition and controlling the dynamic process of the coating forming process. Currently, the developed coatings have been successfully applied to modify the surface performance of moving parts and to remanufacture key heavy vehicle components, engineering machinery, and other kinds of industrial equipment.

2 Design, preparation, and application of friction pair surface performance modification coatings

2.1 Design, preparation, and application of solid lubrication coatings

Having been conducting the relative studies for more than ten years, our laboratory comprehensively applies various surface technologies such as vacuum infiltration, magnetron sputtering, thermal spraying, sol-gel, etc. Most of the common problems (low adhesive strength, complex producing process, low content of lubricant phase, and short lifespan) of traditional solid lubrication coatings were addressed by combining the structure, technology, and function of the applied coatings. Furthermore, using these technologies facilitates the deposition of solid lubrication coatings with a wide range of thicknesses onto a variety of friction surfaces. This enables us to examine the tribological behavior and performance evolution mechanism of solid lubrication coatings, and significantly promotes the operating performance, service life, and reliability of the moving parts under extremely harsh operating and weather conditions [3].

2.1.1 Composite nano-multilayer lubrication film of transition metal sulfide prepared by plating-penetrating

The key friction pairs of diesel engine in heavy vehicles, i.e., cylinder/piston, crankshaft/connecting rod, valve components, etc., chronically operate under high

temperature, speed, and contact stress conditions. Further, the surface accuracy and dimension tolerance requirements of the friction pairs are very strict. Serious accidents, starting difficulty, and power failure may occur if the main components of the engine suffer serious damage like scuffing, adhesion, and fatigue spalling [4]. Reliable lubrication is important to address the above friction failure problems. However, the traditional lubrication methods (oil/grease) are not sufficient to satisfy the lubrication demand for heavy equipment operating with high intensity for a long time under severe conditions.

To address this issue, a composite multilayer solid lubrication coating with a bimetal matrix and multiphase lubricants is designed and deposited through composite surface engineering technologies, such as a combination of physical vapor deposition and low temperature ion sulfurizing technologies [5]. First, nanoscale multilayer metal films (Fe/Mo, Fe/W, W/Mo, etc.) are alternately deposited by dual-target magnetron sputtering technology. Subsequently, various lubricating phases (FeS/MoS₂, FeS/WS₂, WS₂/MoS₂, etc.) are generated in multilayer films using low temperature ion sulfurizing technology. Thus, the composite multilayer solid lubrication coating with transition metals (Fe, Mo, W, etc.) as the matrix combined with diverse lubricants (FeS, MoS₂, WS₂) was formed accordingly [6]. Figure 1 shows the surface topography and the element distribution with depth of FeS/MoS₂ multilayer films.

The effect of precursor metal film structure on the following sulfurizing process, and the “sputtering etching” effect of ion bombardment on the film surface during sulfurizing have been studied. Based on the thermodynamics conditions analysis, such as the diffusion law and reaction temperature, it is found that the precursor film made of transition metallic elements (Fe, Mo, W, etc.) must form metal-sulfides during the following sulfurizing process, and S in the film can only exist in the form of an intermetallic compound. The reaction kinetics factors, which can promote the generation of sulfides, and the reaction of transition metal film (Mo, W, etc.) with S have been summarized. Moreover, the effects of the structure and mechanical properties of the Fe/Mo, Mo/W multilayer films, and mono-metal films with different thicknesses on the follow-up sulfurizing process and tribology

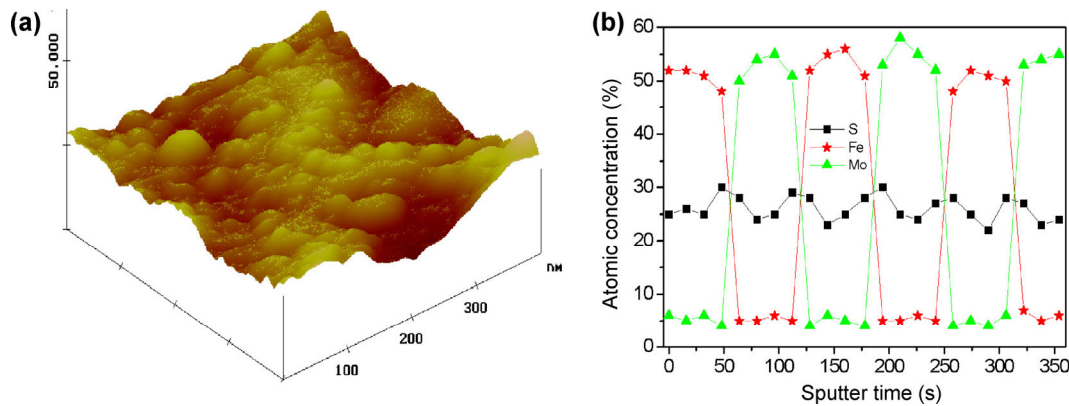


Fig. 1 Surface morphology of FeS/MoS₂ nano multilayer film (a) and the element distribution with surface coating of FeS/MoS₂ multilayer films (b) [6].

behavior of the films have been studied. The effects of the microstructure properties, i.e., ultra-fine grain, multiple interface, and high stress, on the performance of antifriction, wear-resistance, and anti-scratch characteristics of the multilayer films (such as FeS/MoS₂ and WS₂/MoS₂), have also been analyzed [7, 8].

The distinct advantages of this solid lubricating coating are that the assemble mode of the sublayers can be adjusted based on the material of the substrate, which contributes to the best matchup of material properties between the substrate and coating. The high-density layer boundary inside the coating can form an ideal channel for the diffusion of S during sulfurizing. Additionally, the nanoscale multilayer structure can attain stress adjustment between film-to-substrate interface and layer-to-layer. There are more than two kinds of lubricating phases inside the coating. Further, the abundant S at the boundary of the layers can react with the matrix metal under the influence of friction high-temperature, and generate new lubricating phase. Thus, this kind of solid lubricating coating exhibits distinct advantages, such as high bond strength, high content of lubricants, strong bearing capacity, and long service life. Such properties are suitable for applications that involve surface modification of key precise friction pairs, which operate under harsh conditions including high temperature, high speed, and high stress conditions.

The above technologies have been applied to repair and strengthen the main components of diesel engine, such as the cylinder, crankshaft, connecting rod, and camshaft. After depositing the FeS/MoS₂ solid lubricating

film on the key friction pairs, the reliability and performance of the engine has been significantly improved, its smoke level has been reduced by about 40%, the output power has been increased by 2%–5%, the fuel consumption has been reduced by 5%, and the active time of the repaired heavy vehicle has been doubled. These technologies have also been applied for modifying the surface of forming equipment, such as closure rails of precision machine tools, bending molds of hydraulic plate bender, hobbing cutters, and hydraulic rubber cutters. The results show that the rails wear-resistance and the performance accuracy of machine tools both have been obviously improved, the service life of the bending molds subject to high load and intense temperature has been doubled, the sticky rate of hot forging mould has been reduced to 80% and the lifetime of this mold has been doubled, the lifetime of cutters has been extended 50%, the anti-abrasion property of hobbings has been significantly improved, and the lifetime of cutters has been trebled.

2.1.2 A series of “two-step” process for preparation of iron-based sulfide lubricant coatings

In the past decades, a series of “two-step” preparation technologies for iron-based sulfide lubricant coatings have been developed. The hardness, fatigue strength, and wear resistance of friction pair surfaces can be greatly improved through preprocesses such as nitriding, carbonitriding, shot blasting, supersonic fine particles bombarding, etc. Then, a self-lubricating surface that is rich in sulfide lubricants can be generated *in-situ* using sulfurizing technology. This special

composite surface has a soft outside layer of low shear strength and good lubricating performance, and a hard subsurface with high strength and toughness and high load-carrying capacity, which can achieve a synergetic effect to improve durability and lubrication properties. As shown in Fig. 2, the nitrided-sulphurized surface layer, which is formed by the two-step composite chemical heat treatment of “carbonitriding/nitriding and ion sulfurizing” has much better abrasive-resistance and load-carrying capacity compared to the traditional nitriding layer. Moreover, it has more durable and stable antifriction property compared to the direct sulphurized surface layer. Thus, the combination of the two technologies conducted multiple

improvements in the surface tribological properties [9]. This technology has already been applied to the tribological modification of large compressor rotating shafts and main rotors of rubber mixing machine.

An innovative ion sulphurizing process assisted by surface mechanical treating has been studied in-depth. The steel surface was pretreated using shot blasting and supersonic fine particles bombarding, respectively. This can form martensite phase transformation hardening layer, high density interface layer, and high surface activity nanocrystalline layer on the workpiece surface of sulfurizing, which also increased the substrate hardness and sulfurizing layer thickness (as shown in Fig. 3) [10]. Thus, the antifriction and wear resistance

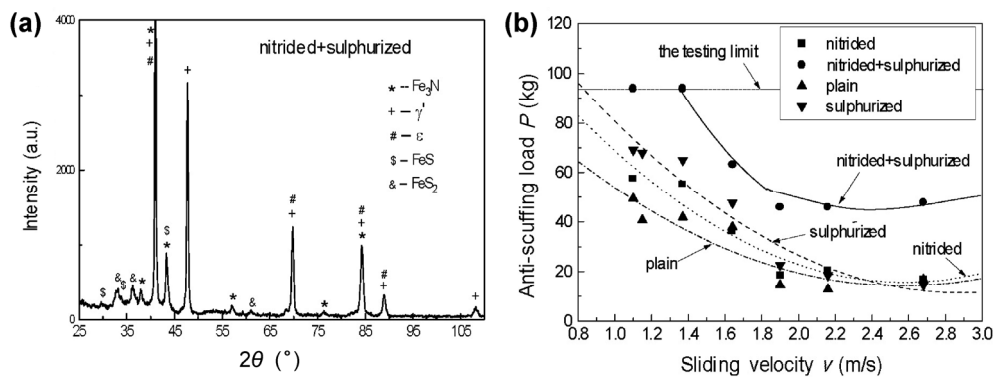


Fig. 2 Phase structure diagram of nitriding+sulfurizing surface (a) and P - V diagram under oil lubrication condition (b) [9].

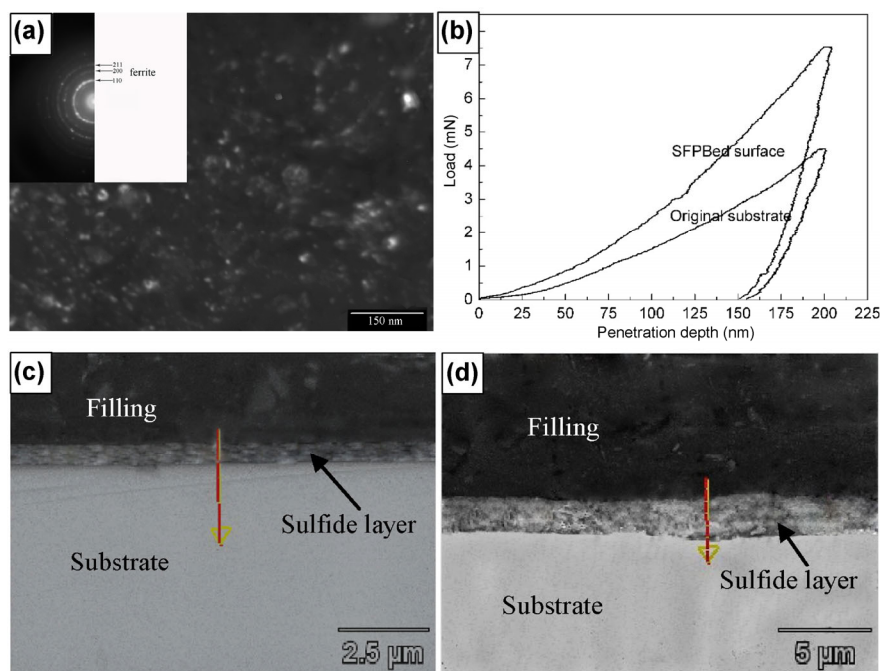


Fig. 3 Morphology (a) and hardness (b) of surface nanocrystalline layer on 1Cr18Ni9Ti steel obtained by supersonic fine particles bombarding; comparison of sulphurized layer without (c) and with (d) pretreatment.

properties of the sulfurizing film were remarkably improved.

The conventional plasma sulphurizing technology is mainly used for the surface modification of iron-based bulk materials. Considering that the thermal spraying technology has no special material constraints for both coating and substrate, a two-step combination technology of “spraying iron-based coating and ion sulfurizing” has been developed, which successfully deposited sulfide films on the surface of all kinds of non-ferrous metal materials. A solid lubricating coating which is rich in FeS lubricant and micropores for oil storage has been formed by spraying iron-based coatings with a porous structure (FeCrBSi, 3Cr13, etc.) on the surface of key friction pairs, and subsequent sulfurizing [11]. The porous structure not only provides micro-channels for the diffusion of S atoms during the sulfurizing process and promotes the synthesis of high density solid lubricating phase, but also has the essential properties of oil storage and wear debris gathering. The solid lubricating phase can adapt to work conditions in which traditional lubricants cannot effectively work, such as dense sand, high temperature, and arctic conditions. Moreover, in the severe conditions that involve heavy load, high impact, and dry friction, oil stored in the micropores will enter the friction interface to form an oil film, which effectively improves the lubricating conditions. This technology has been successfully applied to the cylinder components of heavy vehicles and engineering machinery, while also being used in surface modification to improve the running mechanism of crawler equipments. Real

heavy vehicle testing has proved that composite solid lubricating coatings represented by 3Cr13/FeS coating can minimize abrasive wear and scuffing of cylinders operating in dry conditions. It can double the lifetime of cylinder body, and reduce the engine failure rate by 20%. The oil-storage function of the composite coating successfully solved the starting up difficulty in armored engineering vehicles operating under starved-oil and severe cold conditions, and improved the success rate of one-time startup to 85% under the extremely cold temperatures of -35°C . This series of composite coatings have also been applied to the surface tribology properties modification of the moving parts of crawler equipments, which doubled the lifetime of their vulnerable parts, such as creeper treads, dowels, and driving wheels.

2.1.3 Preparation of inorganic solid lubricant coatings by other surface technologies

The brush plating technology has many advantages as it involves using simple devices and flexible processes to obtain fast plating rate and high bond strength that can be used in wide range of applications [12]. Recently, a lot of research on brush plating of soft metal self-lubricating coatings (Ag, Sn, Zn, In, etc.) has been carried out by NKLR. Specifically, the Ni/In composite plating exhibits well adaption in vacuum space environment, in which it can rapidly form stable transfer film on the friction pair surface, resulting in relatively excellent resistance to adhesive-wear and good antifriction performance, as shown in Fig. 4.

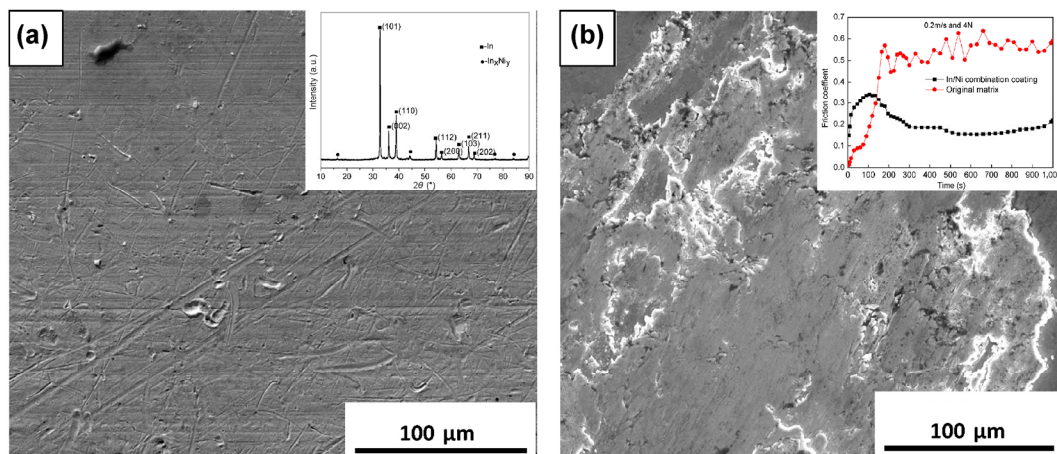


Fig. 4 Microstructure and tribological properties of Ni/In composite coating (a) coating and (b) wear spot.

Furthermore, the $n\text{-Al}_2\text{O}_3/\text{Ni}$ functional layer is introduced, which exhibits good load-bearing and wear resistance properties under the Ni/In coating, and thus an $n\text{-Al}_2\text{O}_3/\text{Ni}/\text{In}$ composite multilayer coating is formed. The multifunctional space tribology experiment system is used to test the friction and wear properties of this coating under four kinds of environmental conditions, including atmosphere, vacuum, atomic oxygen erosion, and ultraviolet radiation, as shown in Fig. 5. It is found that the $n\text{-Al}_2\text{O}_3/\text{Ni}/\text{In}$ composite coating is composed of granular asperities of approximately $2\ \mu\text{m}$ diameter. In addition, the coating is flat and smooth at the macro level, without relatively high porosity, nodule and local coarse structure, and exhibits good antifriction properties in all of the above-mentioned environmental conditions.

Further, the Zn/FeS and Zn/graphite coatings were deposited using “sol-gel” technology, and the effect of the content and wettability of the lubricant particles on the bond strength and tribological properties of the coatings were analyzed. Additionally, an iron-based solid lubricating coating was prepared with FeS and FeS_2 powder by plasma spraying technology and high-speed flame spraying technology, respectively. The melting, decomposition, oxidation, and regeneration phenomena of the spraying powder during spraying of the iron-based multiphase composite coating were studied. A Ni/ MoS_2 composite coating was also deposited by plasma spraying technology, and the effects of its microstructure, cohesive strength, and bond strength on wear-resistance and anti-scuffing properties of the coating were analyzed.

2.2 Design, preparation, and application of wear-resistance & anti-fatigue integrative coating

Wear and contact fatigue are considered as the most important damage mechanisms of key friction pair components. The focus of the existing surface strengthening modification technologies is often limited to improving the wear resistance of components [13]. Particularly, the coating has contrary and uniform characters of high-free-energy and multiple interfaces, so its wear resistance and anti-fatigue properties show a competitive rule of interplay and interaction. Thus, the forming method and evaluation technique of wear-resistant and fatigue-resistant integrative coatings were studied in-depth, and the service life and reliability of the key friction components of the equipments were improved.

2.2.1 High quality forming of wear-resistant and anti-fatigue integrative coatings deposited by plasma spraying

The plasma sprayed coatings have exhibited excellent wear resistance properties in moving parts. However, the deposition process of the coating that determines its microstructure involves a lot of interfaces. This induces coating invalidation that co-affected by wear and fatigue under the practical service condition. The key to improve the wear resistance and fatigue resistance properties of the plasma sprayed coatings synchronously is to enhance the bond strength and cohesion strength of the coatings. After long-term study, a series of methods are proposed to extend the

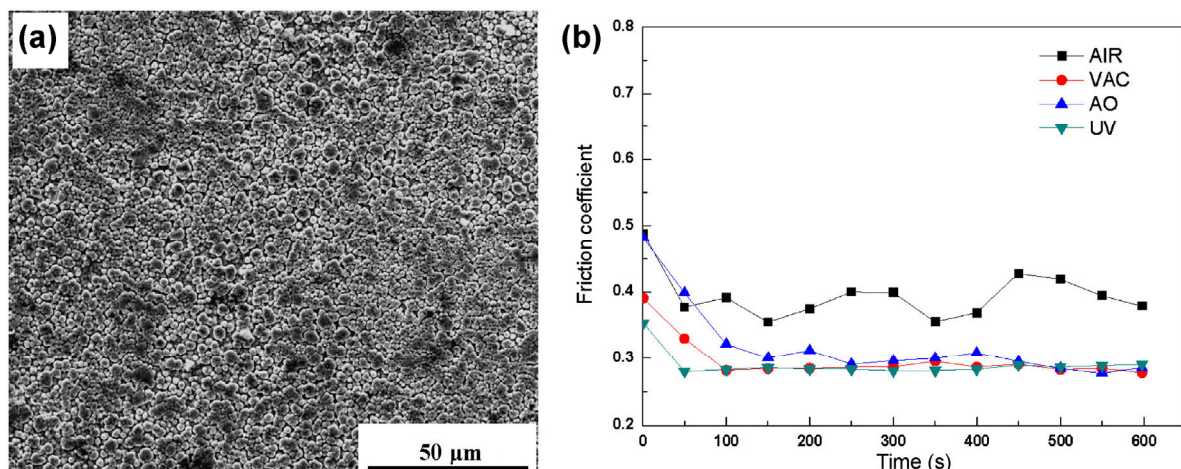


Fig. 5 Surface morphology (a) and friction coefficient under space environment (b) of $n\text{-Al}_2\text{O}_3/\text{Ni}/\text{In}$.

contact fatigue lifetime of plasma sprayed coatings. The proposed methods are summarized as follows: (1) the coating forming parameters can be optimized and the cohesion strength of the coating can be greatly enhanced by the state monitoring of spraying particles and the temperature field of the plasma beam; (2) the micro interlock bond strength of the interface can be improved by using the laser micromachining technology to make the coating/substrate interface textured; (3) the cohesion strength and bond strength of the coating can be considerably increased by using post-processing technologies such as re-melting and hot isostatic pressing, to eliminate the micro-defects in the coating and interface, and to release the stress adequately. In this way, the high quality forming of metal-based coatings (Fe-based and Ni-based), cermet coatings (NiCr-Cr₂C₃ and WC-Co), and composite ceramic coatings (Al₂O₃-TiO₂ and Cr₂O₃-Al₂O₃) are achieved (as shown in Fig. 6 that illustrates the micro-morphology of plasma spraying Al₂O₃/40 wt% TiO₂ (AT40) coating) and successfully applied to various equipment components [14, 15].

The NiCr-Cr₂C₃ cermet coating is successfully used for modifying the surface of wheel ball bearings of certain overloaded vehicles turret rotation mechanism. The wear-resistant and anti-fatigue performance of the components after strengthening has been significantly enhanced, and their service life has been tripled. The NiCr-Cr₂C₃ coating and Al₂O₃-TiO₂ composite ceramic coating are also widely applied to modify the performance of key friction pairs of oil and gas drilling equipments. After spraying the NiCr-Cr₂C₃ hard coating

on the cemented carbide wear plate, its hardness and wear resistance are greatly increased. The practical drilling application shows that the cemented carbide wear plate strengthened by the above technology can effectively eliminate the wear failure of the centering guide, and significantly extend its service life. Meanwhile, the Al₂O₃-TiO₂ composite ceramic coating can improve the wear resistance and corrosion resistance of the oil drill pipe and screw to a great extent, and extend its service life by 1.5 times. The Fe-based self-fluxing alloy coating greatly enhances the wear resistant and anti-fatigue performance of the key friction pairs of industrial equipments, such as the roller of rolling machine, compressor vane, and tools used in rubber molding. Both the service life and product quality of the equipment have been considerably improved.

2.2.2 Wear-resistant and fatigue-resistant integrative coatings deposited by brush plating and its engineering application

In terms of brush plating wear resistant/anti-fatigue coatings, the NKLR successfully developed a series of nanocomposite brush plating solutions and corresponding plating processes, such as n-Al₂O₃/Ni, n-ZrO₂/Ni, n-(Al₂O₃-ZrO₂)/Ni, n-(Al₂O₃-SiC)/Ni, n-(Al₂O₃-CNTs)/Ni, etc., which are used to remanufacture and repair heavy vehicle running gear parts, aeroengine compressor blades, automotive engine components, and machine parts [16]. In particular, the Ni-Co-based nanocomposite (n-Al₂O₃/Ni-Co) rotary brush plating technology, which has been successfully developed recently, can replace the hard chromium coating, and

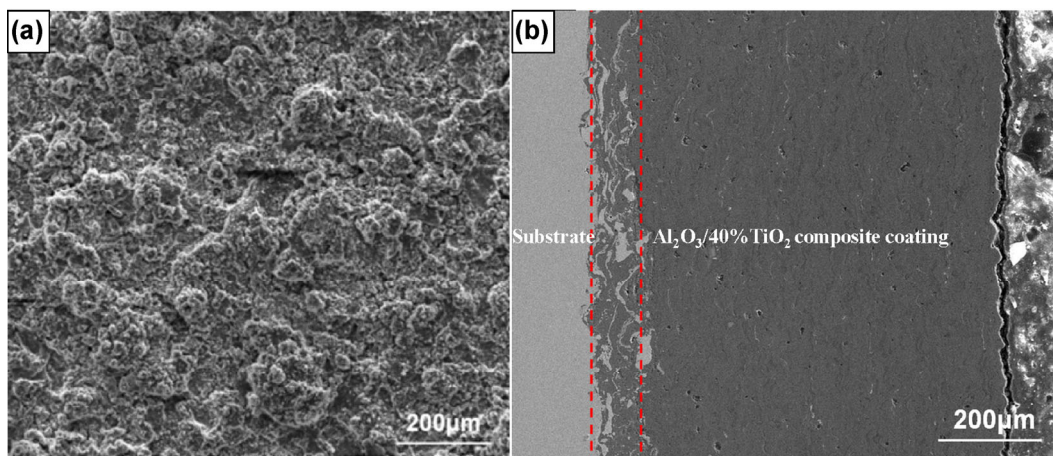


Fig. 6 Surface (a) and cross-sectional (b) morphology of AT40 coating deposited by plasma spraying [15].

can be used for the remanufacturing of gun barrels, hydraulic parts of aircraft landing gear, hydraulic cylinders, and piston rods. This technology can not only realize high quality repair of local and large area damages in chromium-plated parts at a lower cost, but also can eliminate the risk of environmental pollution by the traditional chrome-plating that contains Cr^{6+} solution. Brush plating by $\text{n-Al}_2\text{O}_3/\text{Ni-Co}$ composite coating was successfully used to repair serious local gouge in hydraulic rods. Further, the wear resistance of the composite coating is significantly higher than that of hard chromium plating. Although friction coefficient of the composite coating is equivalent to that of the hard chromium plating, its tribological properties are more stable during long-term operations [16].

2.3 Intelligent sensing coating with the function of in situ condition monitoring for friction moving components

The continuous accumulation of micro-damage in the key friction pairs in service can cause serious sudden accidents. Thus, it is necessary to monitor the surface condition of equipment components in order to recognize any damage instantly. However, the existing monitoring technologies that rely on embedding or attaching sensors to the monitored components have some disadvantages, for example: in some cases it is difficult to approach the contact interface to place the sensor. The sensor itself can be easily damaged during equipment operation, the surface integrity may be affected by external sensors, or the bond strength of the attached sensor is weak, and it is difficult to securely fix it to complex shaped surfaces.

To tackle the above issues, we developed an intelligent sensing coating, which integrates the friction modification and condition monitoring of friction pairs based on the force-electric mapping relation of piezoelectric materials. Figure 7 shows the structure of the intelligent sensing coating and its layers from outside to inside are surface work layer, piezoelectric sensor layer, transitional insulating layer, respectively: (1) the surface work layer, which is composed of alloy material (FeCrBSi , NiCrBSi), is used to resist wear and fatigue, and also acts as an electrode for the sensor layer; (2) the piezoelectric sensor layer, which consists of piezoelectric ceramic material (PZT , BaTiO_3), is used to recognize any change in the stress state of the surface work layer when damage occurs [17] to be converted into current signals and transferred through the piezoelectric effect; (3) the transitional insulating layer is composed of an intermetallic compound and ceramic ($\text{NiAl-Al}_2\text{O}_3$), which not only improves the bond strength between the coating and substrate but also prevents the charge loss. In general, the new type of intelligent sensing coating can electronically monitor the degree of damage and stress state of the part surface in real time, and overcome the past limitation of relying on the post analysis monitoring technology such as change of libration, torque and friction coefficient, or variation in oil composition [18].

The abovementioned intelligent sensing coating has successfully passed the evaluation carried out in a tank engine bench test. The performed test proved that the coating can maintain low friction for a long time under high temperature and high stress conditions, and can predict most (about 80%) fatigue peeling and heavy wear. This research can provide pivotal technical

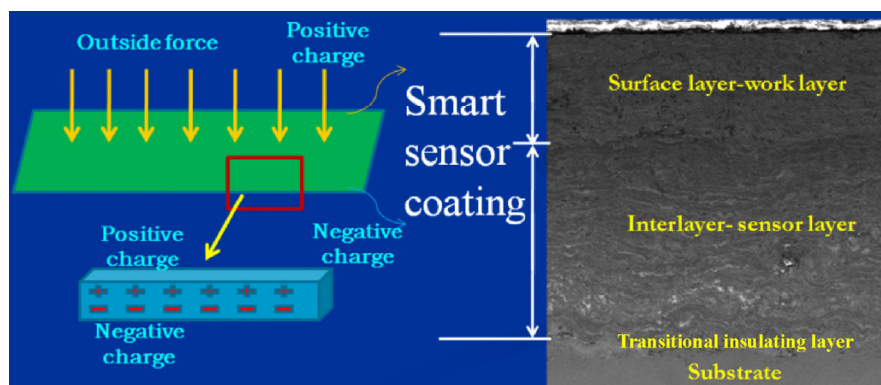


Fig. 7 Schematic diagram and Microstructure of PZT intelligent sensing composite coating.

support for developing intelligent friction pairs. The intelligent sensor coating technology has also been broadly applied to relevant tribology testers. The technology facilitated achieving a dynamic warning for fatigue/wear failure and accurate calculation of the coating's remaining service life, and thus promoted the development of intelligent testers with high resolution, efficiency, and automation.

3 Conclusion

Friction, wear, and contact fatigue are the main causes of energy consumption, material waste, and equipment damage. Thus, developing an appropriate method to reduce wear, alleviate fatigue, extend service life, and improve operational reliability is a major technical challenge to guarantee long-term service life of friction moving components. Based on the surface science theory and structure-function integration design approach, the latest achievement in surface engineering technology was comprehensively applied to design surface modification coatings that can endow the functions of solid lubrication, anti-fatigue, wear resistance, and automatic sensing to the surface of key friction pair. The relevant basic-research findings are reviewed to complement and enhance the basic tribology theory. In addition, it is found that the design, deposition, and evaluation technology of the developed friction pair surface modification coatings can significantly improve the working performance properties, extend the service life, and allow real-time monitoring of the service condition of the equipment key moving components. Further, the technologies discussed in this study have been successfully applied to remanufacture, strengthen, and repair key moving components of heavy equipment engines, machining and forming tools, oil, and gas drilling equipment, etc. In general, these technologies can provide theoretical and technical support for surface modification, strengthening, and remanufacturing of key friction pairs.

Acknowledgements

The authors are grateful for the financial support by NSFC (Nos. 51675531 and 51535011) and NSF of Beijing

(No. 3172038), and the Tribology Science Fund of State Key Laboratory of Tribology (No. SKLTKF16A05).

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