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Improving the wear resistance of guides: tribological analysis, surface texture and lubricants

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Abstract

The article considers the main failure modes of guides, in particular wear and contact fatigue, which depend on friction between contact surfaces. The influence of tribological parameters, in particular surface roughness and lubricating structures, on the operational characteristics of linear guides is studied. Particular attention is paid to the dynamic behavior of guides, which determines the accuracy and stability of mechanical systems. To predict wear, mathematical models based on the Archard and Hertz theories were used, which allow estimating load distribution and contact deformations. The influence of lubricants, in particular molybdenum disulfide and hexagonal boron nitride, on reducing the friction coefficient and improving antifriction properties was separately studied. The prospects for using new materials, such as cubic boron nitride, to increase the wear resistance of guides are considered. Methods for optimizing the load between rolling elements, which contributes to increasing the durability of guides, are proposed. The results obtained can be used to improve the designs of high-precision mechanical systems and reduce operating costs.

Keywords: wear, friction, contact fatigue, stiffness, lubricating structures, guideway dynamics, load optimization

Introduction

Guideways are one of the key components of mechanical systems that ensure the accuracy and stability of movement in various technical devices. They are widely used in industrial machines, lathes, conveyor systems, and other high-precision mechanisms. One of the main issues that arises during the operation of guideways is wear, which largely depends on the friction between the contact surfaces. As a result of prolonged use, guideways can experience significant deformation, reducing their efficiency and requiring frequent maintenance or replacement.

One of the key factors affecting wear is the surface texture of the contacting elements, as well as the choice of lubricating materials. Inadequate surface roughness parameters and improper lubricant selection can increase the friction coefficient, which, in turn, accelerates wear. However, optimizing the surface texture and using specialized lubricating materials can significantly reduce this effect. Therefore, one of the priority areas of research is the analysis of the impact of various factors on the tribological characteristics of guideways, which allows the development of new methods for improving their wear resistance.

In particular, studies have shown that using composite lubricants containing molybdenum disulfide, hexagonal boron nitride, and other promising additives can significantly improve friction and wear resistance of guideways. At the same time, optimizing the geometry of the contact surfaces and controlling the lubrication process are necessary to achieve maximum efficiency of mechanical systems.

Thus, the problem of wear resistance of guideways and optimizing their characteristics is relevant and requires further scientific development, which will contribute to increasing their lifespan and improving the reliability of mechanical systems.

Main material

The most common failure modes of the guide are wear and contact fatigue, which are significantly affected by the friction properties of the contact surfaces. In the paper [1], the parameters of the three-dimensional rough surface are investigated for the evaluation of the guide. First, an effective three-dimensional surface model is achieved using the wavelet transform method and reverse engineering software. Second, the influence of the parameters of the functional surface on the friction force, average pressure and friction coefficient is studied using the computational fluid dynamics modeling method, and a regression model is built to predict the friction force. Third, the combinations of optimal surface parameters are analyzed considering the friction index and the simulation results are compared. The results show good agreement between the experimental results and the simulation. This study provides theoretical guidance for the fabrication of the guide.

Roller linear guide is a type of precision linear motion component that is widely used [2]. Stiffness and wear directly affect the performance and service life of roller linear guides. Therefore, the study of stiffness and wear is important for optimizing the design and improving the performance of roller linear guides. The study analyzes the contact mechanics between the roller and the raceway and the deformation of the roller. Using Archard's wear theory, the wear process of roller linear guides is analyzed. A calculation model of the slider movement, which is related to the wear loss of the slider's raceway during its reciprocating motion under load, is developed to predict the wear of roller linear guides. The effectiveness of the proposed models in predicting the contact stiffness and wear is verified through simulation and experiments on a specialized test system.

Guides adapt to the movement of tools or workpieces, and their dynamic behavior and associated sliding effects have a great influence on accuracy, stability, and productivity [3]. During machining, guides are subjected to oscillatory excitations due to cutting forces, which requires consideration of their pre-slip behavior along with the sliding characteristics to compensate for the associated tracking errors by the position control system. The study [3] considers the friction effects in the pre-slip and sliding modes of lubricated linear roller guide systems to provide an accurate dynamic model of the machine tool element. To simulate the dynamic characteristics of the frictional contact in a lubricated linear roller guide, which is commonly used in the machine tool positioning control system to estimate the compensating driving force, a modified approach is used to consider the contact physics of rollers and tracks and the dynamics of the lubricating film. The proposed model also includes the effects of the coupling between normal and tangential forces in the contact (Fig. 1).

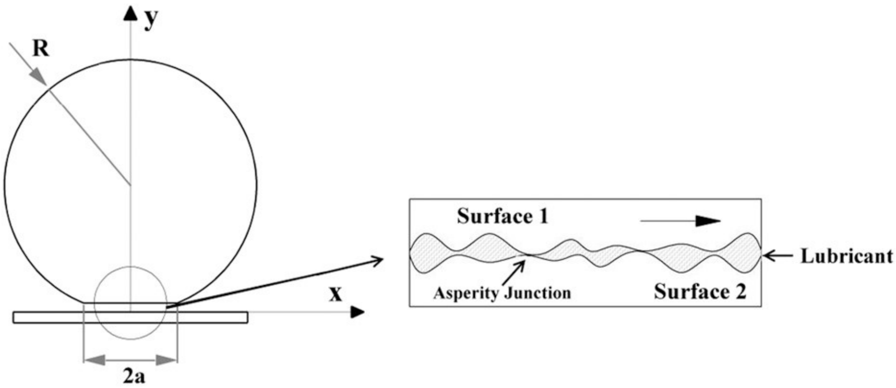

Fig. 1. Schematic representation of an elastohydrodynamic lubricating contact in a mixed lubrication mode [3]

Experimental studies were conducted on a lubricated linear roller guideway to verify the performance of the proposed modified model. The experimental observations illustrate the dynamic behavior of friction in a lubricated linear guideway. Comparison of experimentally measured data and the proposed modified samples shows that the model can accurately predict the dynamic behavior of the frictional contact.

To optimize the sliding phenomenon under low speed and high load conditions, a composite lubrication structure is used [4]. The optimal response surface design method establishes a quadratic mathematical model for the multi-stage parameters of the composite lubrication structure, including creep time and average friction coefficient. The optimal combined parameters of the multi-stage composite lubrication structures are determined. The optimal ratio of lubricant to molybdenum disulfide was identified, and a composite lubrication structure was proposed to improve the sliding phenomenon and friction efficiency of sliding guide rails under medium speed and medium load conditions. The results of these studies show that when low speed and high load are present, the creep time and friction coefficient first decrease and then increase as the width, distance, and cycle length of the sinusoidal texture and the diameter of the hexagonal pit expand. Under the circumstances of medium load and speed, the multi-stage composite lubrication structures exhibit superior friction performance. These data can guide the design of multi-stage composite lubrication structures on the surface of slideways.

In order to improve the sliding of guides [5], the design of a composite lubricating structure on the surfaces of sliding guides and the characteristics of the friction force were investigated step by step. The composite lubricating microtexture was prepared by the high temperature and high pressure mosaic method based on the laser ablation microtexture. The general scheme of the formation of structured surfaces by laser is shown in Fig. 2.

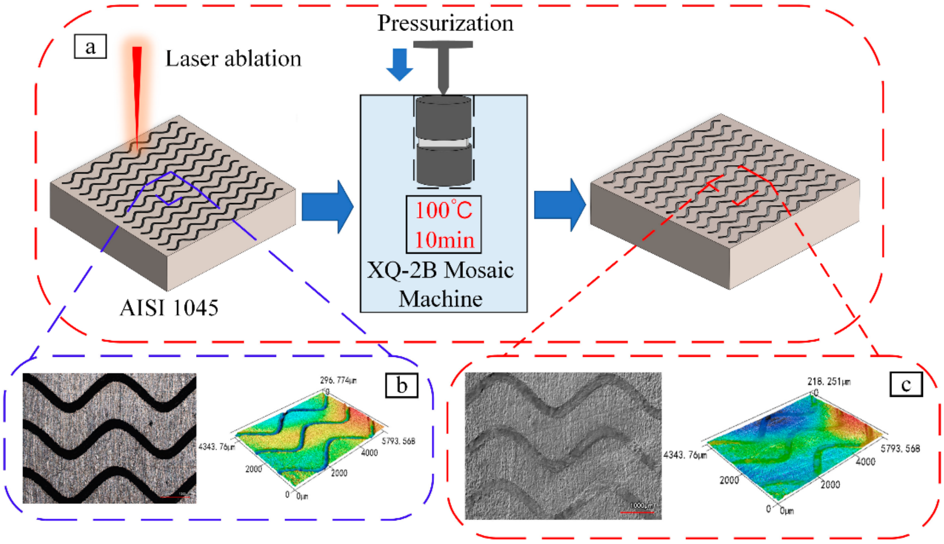

Fig.. 2. Schematic diagram of specimen preparation: (a) Laser ablation diagram. (b) Micro-texture before filling. (c) Micro-texture after filling [4]

The friction force characterization methods were proposed step by step by friction tests. The effects of different composite lubricant structures on the friction characteristic parameters of each stage were investigated. Theoretical models of composite lubricant structures for improving the creep phenomenon were established, and composite lubricant structures with the best characteristics for reducing the influence of the creep phenomenon were found. The results show that the surface microtexture only affects the sliding and rising stages of the friction force, while the composite lubricant texture has a significant effect on the entire starting stage. The multi-stage composite lubricant texture with a combination of sinusoidal grooves and hexagonal pits filled with molybdenum disulfide was the most effective in improving the surface contact conditions and suppressing the creep phenomenon (Fig. 3).

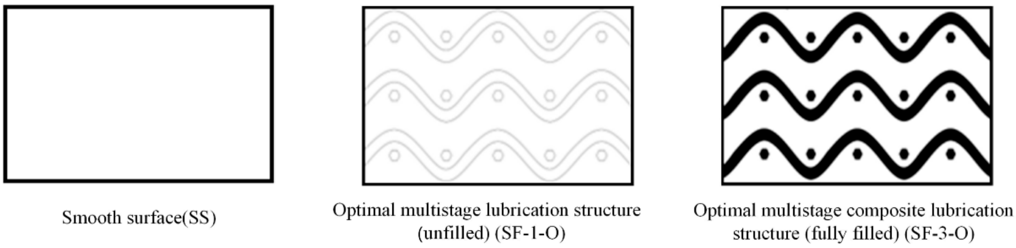

Fig. 3. Diagram of different grease textures

To study the effect of different surface treatment methods on the antifriction performance of Babbitt-Steel 45 alloy pair, hexagonal boron nitride was encapsulated in the surface texture, and composite lubricating structure surfaces were prepared [6]. The disc wear test was carried out with lubricant, and the wear process was separated by quantitative analysis. The antifriction performance of composite lubricating structure surfaces during running-in and normal wear was investigated. The results show that the composite lubricating structure surfaces have a lower friction coefficient and that the antifriction performance is better than that of the texture surface alone. Compared with the surface without texture, the average friction coefficient of the composite lubricating structure surfaces decreases by 77% during the running-in period and 68% during the normal wear period. Composite lubricating structure surfaces with larger texture pore diameter have better antifriction performance and shorter running-in period. Both textured surfaces and composite surfaces of the lubricating structure have more significant anti-friction characteristics at higher speeds. It has been found that the lower the friction coefficient of different surfaces during the break-in period, the lower the corresponding friction coefficient after entering the normal wear period.

Reducing sliding wear and friction in guide bearings can bring both economic and environmental benefits, including longer service life, lower operating costs, and higher efficiency. In a study [7], the effect of stainless steel countersurface roughness on the tribological behavior of three bearing materials used in hydropower was evaluated using linear reciprocating motion at high contact pressure and low sliding speed. Surface roughness was measured using white light interferometry. The results of this study show that surfaces that are too smooth lead to greater friction and wear of the countersurface, while rougher surfaces negatively affect polymer wear (Fig. 4).

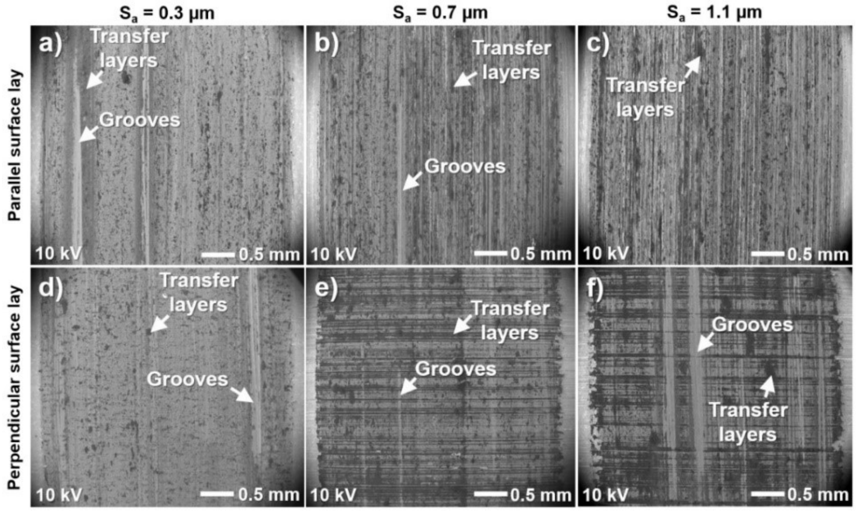

Fig. 4. SEM micrographs of transfer layers formed on polished stainless steel closer to the center of the wear track after sliding on fiber-reinforced thermoset [7]

The best surface coverage by protective transfer layers is found on steel surfaces with perpendicular stacking and is accompanied by a lower coefficient of friction compared to parallel stacking. The dominant wear mechanism of the bearing materials changes from delamination wear to abrasive wear between the lowest and intermediate roughness of the steel surfaces with parallel stacking. It is concluded that the relief of the opposing surface has a significant effect on the tribological behavior of these bearing materials and that the effect differs between self-lubricating polymer composites.

In [8-9], an experimentally validated numerical approach to the evaluation of linear guideway wear is presented, taking into account the associated vertical and horizontal movements and taking into account the lubrication starvation. The results show that the lubrication starvation has a pronounced effect on the thickness of the lubricating film, friction and the applied load at contact up to 30%. The localized pressure values can vary. The course of the starvation effect depends on the frequency. It was also found that the starvation effect can be controlled by the magnitude of the preload on the linear guide.

Based on the theory of point contact elastohydrodynamic lubrication, a model of free vibration of a contact pair is presented for qualitative analysis of the influence of vibration on film characteristics [10]. Models of film stiffness and damping coefficient under elastohydrodynamic lubrication are constructed to study the influence of operating conditions on dynamic parameters. Complete numerical solutions are obtained using multi-grid techniques. It is found that there is damping from the decay of pressure fluctuations and film thickness in a lubricated ball linear guide. In addition, high load or low speed operating conditions can lead to an increase in film stiffness at the steel ball-guide contact, but there is a tendency for the film damping coefficient to vary inversely. The study [11] studies the contact stiffness of linear rolling guides due to the effects of friction and wear during operation. The initial and final contact stiffness models were established. As a confirmation of the predicted variable stiffness, an experimental modal analysis was performed on a specialized linear guide system. The results show that the contact stiffness of linear guides decreases with the increase of the friction path, and the entire stiffness decline can be divided into two different stages depending on how the thermal effect and wear effect affect the contact deformations of the balls at different rolling distances.

The aim of [12] is to establish a simplified model of a closed hydrostatic guideway for rapid analysis of static and dynamic characteristics. In addition, the effects of compressibility and dynamic frequency are taken into account in the new dynamic model. The new model is based on the second type of Lagrange equation. In this model, a closed hydrostatic guideway is supported by 10 gaskets, and each oil gasket is equivalent to a nonlinear spring-damper system. The equivalent spring coefficient and the damper coefficient of the oil gasket are considered by three different equivalent methods. Verification experiments of the step load response and dynamic stiffness are carried out on the hydrostatic guideway.

Most studies on linear rolling bearings usually assume that the contact load between the ball and the raceway is uniform, which leads to deviations from the actual conditions. The study [13] aims to establish a load distribution model based on the Hertzian contact theory with combined ball obstacles that are transformed from the preload, the center distance error of the ball raceway. The reliability of the proposed model is verified by numerical methods for load distribution and deformation analysis. The result shows that the proposed approach is in better agreement with the experimental results compared with the preload effect alone. This work can be an important starting point for studying the friction and wear of equipment guide elements.

Hydrostatic guides have been used as an important element of precision engineering in numerous applications requiring high-precision motion and positioning with significant load capacity. Hydrostatic guides provide good operational performance, especially in terms of high rigidity and damping characteristics, but also its high load capacity combined with excellent motion accuracy. However, a comprehensive review of hydrostatic guides has not been reported so far. The paper [14] aimed to present an informative literature review of research and engineering developments on hydrostatic guides, describing their basic operating principles and applications in precision machines, defining and characterizing hydrostatic guide concepts, briefly reviewing motion error modeling and compensation types, discussing the impact characteristics, and further discussing emerging issues of sliding guides and their engineering applications.

In [15], in order to expand the production of machine tools that use precision-machined slideways, cubic boron nitride was implemented as an alternative machining process to conventional surface grinding. While higher material removal rates can be achieved with a milling strategy, the use of a defined cutting edge results in surfaces with irregularities. These sharp peaks wear quickly during sliding contact, leading to unacceptable changes in the bearing surface of the guide. This paper investigates the use of a spindle-mounted abrasive disk tool to fabricate a functional surface. The optimal process parameters were investigated using 2D profile measurements and then compared using an analysis of ground, milled and polished surfaces. Polishing was found to reduce both the height and volume of irregularities on the milled surface, resulting in contact characteristics that were more similar to those of conventional surfaces currently used for slideways.

For economic, environmental and even technical reasons, there has been a trend for several years towards the introduction of self-lubricating materials for cylindrical slideways. This makes it possible to eliminate external lubricants, simplify the design and reduce maintenance costs. Among self-lubricating materials, the so-called engineering plastics are of increasing importance. Unfortunately, data on their friction and wear characteristics are very different, and there is often a lack of a common understanding of the physical mechanism of their action. In the article [16], some types of oil-filled engineering plastics are experimentally investigated using small-scale reciprocating tribotesting. The dependences for the coefficient of friction for such types of materials are shown in Fig. 5.

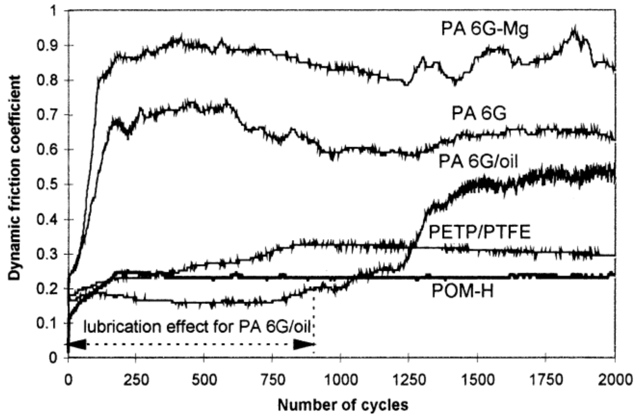

Fig.. 5. Dynamic friction characteristic of polymers against smooth steel surface [16]

Tribological behavior is explained in relation to the chemical and mechanical properties of materials. The main failure processes are described for light wear conditions as well as for overload conditions.

In the article [17] a new experimental apparatus is presented, suitable for wear tests of reciprocating guides at elevated temperatures (Fig. 6).

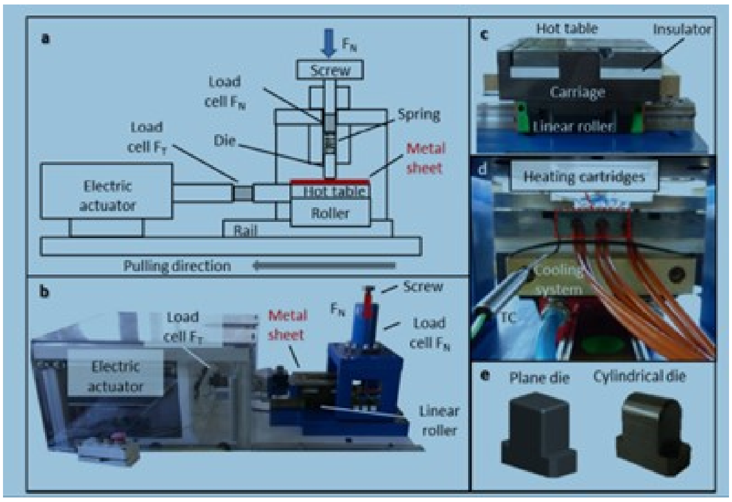

Fig. 6. (a) Schematic representation of flat strip drawing test and (b) the real version; (c) Details of the linear roller guideway; d) Details of the hot table heating system, thermocouple to control temperature and the cooling system; e) Plane and cylindrical die shape usable in the machine [17]

It consists of a linear slide rail connected to an electric drive and equipped with a heating plate for heating the metal sheets. The solid frame incorporates a screw device used to apply the normal load. Thermocouples placed on both the plate and the sheet sample are used to monitor the temperature during the test. The machine is also equipped with two strain gauges to record the normal and tangential loads. High-strength steel was chosen as the reference material for testing the machine. The results showed the operational capability of the new equipment and good stability of the mechanical and thermal state during the tests.

In recent years, sliding guides have been re-examined as linear motion guides for machine tools due to the demand for machines with good dynamic characteristics, which is vital in machining difficult-to-machine materials. While the traditional approach to manufacturing the sliding surface is grinding. In [18-20], an alternative manufacturing approach based on cubic boron nitride using Al and Mg additives in the cast iron material for better machinability of sliding guides was investigated. The machining results showed a significant improvement in machinability, especially in terms of tool wear under certain cutting conditions using cleaned hardened cast iron and cubonite tools. During experimental analysis, it was found that oxide films of the additives were created on the cutting edge of the tool to protect the tool from wear. By reducing tool wear, a stable surface roughness can also be achieved. The case study also demonstrated the effectiveness of a manufacturing approach based on milling slideways with cleaned cast iron and found high-speed cutting conditions.

The characteristics between the rolling balls and the raceways are key to studying the linear rolling guide. In [21-22], the contact stresses with non-standard sized balls, which include the change of contact angle, are given by the established joint model (Fig. 7).

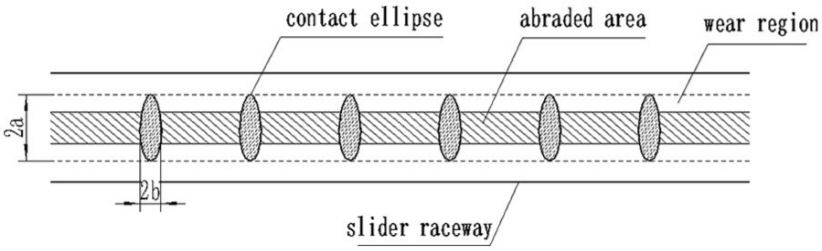

Fig. 7. Contact mechanism between the balls and the carriage raceway [22]

In addition, the influence of the location, number and degree of deviation of non-dimensional balls on the stress distribution is studied. The contact stress distribution between the ball and the raceway is analyzed for different location cases. The effectiveness of the contact stiffness and wear prediction model is verified by simulation and analysis.

In articles [23-24], favorable microdimples from the calculated results were fabricated on a guide using single-pulse process intervals with a specialized accuracy compensation method (Fig. 8).

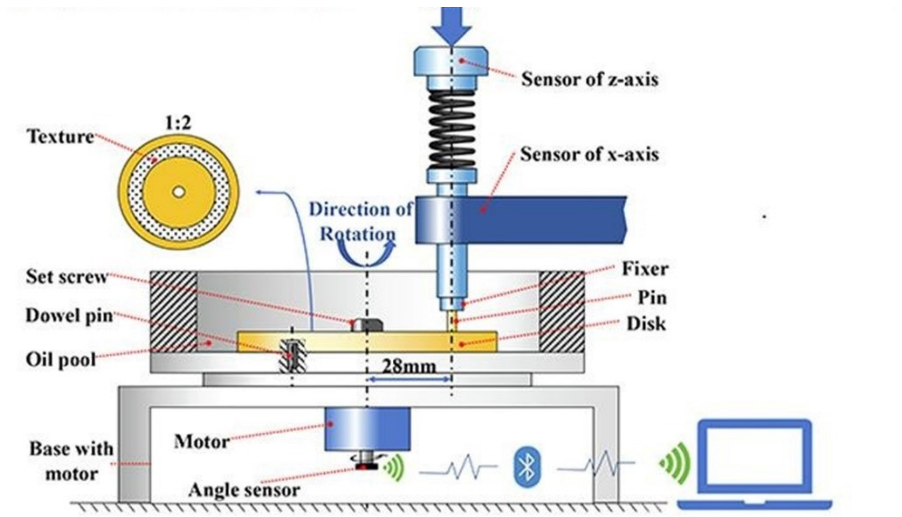

Fig. 8. Experimental setup for the formation and study of surface microprofiles [24]

Contrast tests were conducted to verify the anti-slip performance. The results showed that the favorable micro-dimple depth size could be 1-5 μm, and the area ratio was 11%~16%. The friction coefficient was reduced by 15%.

At present, the wear models and the prediction of the accuracy of the guide are established based on the elastoplastic mechanics of continuum media. These methods are limited to describing the process of accuracy reduction using the material characteristics determined based on the conditions of the macroscopic hypothesis. In [25-26], a multi-scale method based on the principle of a quasi-continuous medium is proposed to describe the degradation process of the linear accuracy of the guide using an exponential model. According to the distribution of the wear of the guide surface with the process of micromorphology evolution, the measurement value of the linear accuracy of the guide is systematically modeled. Using the quasi-continuous medium method instead of the continuum hypothesis, an exponential model of the guide wear is established. The exponential wear model uses a wear index to describe the wear state based on the measurement of linear accuracy, rather than long-term wear products. Information about the microtopography of the guide surface is obtained. Thus, the wear condition of the guide is checked under different loading conditions, and the validity of using the method to establish an exponential guide wear model is also verified.

Solid lubricants have been widely used in many fields. In [27-28], the influence of each component in composite solid lubricants on the tribological characteristics is investigated and the antifriction effect of different types of solid lubricants is compared to solve the problem of lubrication of cylindrical sliding guides (Fig. 9). Surface textures with pits were produced on the surfaces of bearing steel by solid-state laser. Composite solid lubricants filled the micropits with heat- and pressure-supported deposition products consisting of lubricating elements. The tribological characteristics of sliding friction for different types of lubricants with different grain sizes were evaluated using a ring-on-disk tribometer.

Fig. 9. Experimental tests of solid lubricants for contact strength [28]

On this basis, an orthogonal experiment with four factors and three levels was designed to investigate the effects of different components of solid lubricants on tribological characteristics. Solid lubricants with nanoparticles can improve the antifriction ability: the friction coefficient is higher than that of micron graphite, and the friction coefficient of nano-sized molybdenum disulfide is reduced compared with that of micron-sized molybdenum disulfide. According to the experimental results, the optimal formula of composite solid lubricants was graphite nanotubes: molybdenum disulfide: polyamide: carbon.

The improvement of tribological properties by applying different textured surfaces has been reported by many researchers. In these studies, most of the surfaces used were textured by lasers. However, this texturing method has several problems, including thermal effects, accumulation formation, possible pit shapes, and lower efficiency than mechanical methods. Traditional mechanical texturing methods also have some problems. In the study [29], an alternative method was developed using vibrocutting using a diamond indenter that vibrates in the depth direction with an amplitude of tens of microns. The asperities formed around all the pits during texturing can be removed by additionally performing conventional microcutting. Dry sliding tests were performed using steel balls on surfaces textured by both the proposed and conventional cutting methods for comparison. A series of sliding test results were analyzed using the coefficient of friction and observations of worn surfaces. As a result, the textured surface obtained with a relatively high areal density (40%) where the inclusions were completely removed showed the lowest coefficient of friction and wear. Thus, the proposed texturing method can be recommended for creating surface textures for better tribological properties.

Conclusions

1. Wear and contact fatigue are the main factors of guideway degradation, which largely depend on the friction between the contact surfaces. Optimization of roughness and tribological parameters can improve their durability.

2. Optimization of lubricating structures (using molybdenum disulfide, hexagonal boron nitride, etc.) allows to significantly reduce the coefficient of friction and improve antifriction properties, especially during running-in and normal wear.

3. The dynamic characteristics of the guideways play a key role in the accuracy and stability of the operation. The stiffness of the contact pair decreases with the increase of the friction path, and the temperature and wear affect the contact deformation.

4. Wear prediction methods based on the Archard and Hertz theories allow for optimizing load distribution between balls and raceways, which helps to increase the accuracy of friction and wear prediction.

5. New materials, such as cubic boron nitride, as well as hydrostatic guides, provide high rigidity, damping, and motion accuracy, but require further research for implementation in practical applications.

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Диха О.В., Дитинюк В.О., Ковтун О.С., Фасоля В.О., Гетьман М.В. Підвищення зносостійкості напрямних: трибологічний аналіз, текстура поверхні та мастильні матеріали

У статті розглянуто основні режими руйнування напрямних, зокрема знос і контактну втому, які залежать від тертя між контактними поверхнями. Досліджено вплив трибологічних параметрів, зокрема шорсткості поверхонь і мастильних структур, на експлуатаційні характеристики лінійних напрямних. Особливу увагу приділено динамічній поведінці напрямних, яка визначає точність та стабільність роботи механічних систем. Для прогнозування зносу використано математичні моделі на основі теорії Арчарда та Герца, що дозволяють оцінювати розподіл навантаження та контактні деформації. Окремо досліджено вплив мастильних матеріалів, зокрема дисульфіду молібдену та гексагонального нітриду бору, на зменшення коефіцієнта тертя та покращення антифрикційних властивостей. Розглянуто перспективи використання новітніх матеріалів, таких як кубічний нітрид бору, для підвищення стійкості напрямних до зносу. Запропоновано методи оптимізації навантаження між елементами кочення, що сприяє підвищенню довговічності напрямних. Одержані результати можуть бути використані для вдосконалення конструкцій механічних систем та зниження експлуатаційних витрат.

Ключьові слова: знос, тертя, контактна втома, жорсткість, мастильні структури, динаміка напрямних, оптимізація навантаження