THEORETICAL PRINCIPLES AND TECHNIQUES FOR ENHANCING THE STRUCTURAL INTEGRITY OF BEARINGS

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Abstract: In mechanical engineering, shafts and bearings are considered the primary elements of power transmission mechanisms. Tribological processes such as friction, wear, and heat generation, which occur during their operation, directly affect the reliability and service life of the entire mechanism.

Key words: Gear wheels, operation, technical condition, wear, repair, capital,

durability, resource, write-offs, statistical, assessments, probability, indicators, reliability, probability, analytical calculation.

Аннотация: В машиностроении валы и подшипники рассматриваются как основные элементы механизмов передачи мощности. Трибологические процессы, такие как трение, износ и выделение тепла, возникающие в процессе их работы, напрямую влияют на надежность и срок службы всего механизма.

Ключевые слова: зубчатые колеса, эксплуатация, техническое состояние, износ, ремонт, капитальный ремонт, долговечность, ресурс, списание, статистическая оценка, вероятность, показатели, надежность, аналитический расчет

In recent years, both foreign and domestic researchers have conducted extensive studies on the physical, mechanical, and chemical processes occurring in tribological pairs, aiming to enhance their operational efficiency. The performance of bearings directly affects the service life and reliability of the entire mechanical system. During technological operation, bearings are subjected to external loads, heat, friction, wear, and other external influences.

At the same time, a thorough analysis of existing designs shows that the torque is often assumed to be a constant value applied to the bearing. In reality, due to the complex interaction between the inner ring and the shaft, the torque varies depending on the slip. Furthermore, in many studies, the motion between the shaft and the bearing is considered as rigidly connected, while elastic deformations are neglected, which can significantly affect the analysis results. Therefore, new quasi-dynamic models are being proposed that account for the interaction between the inner ring and the shaft and include the shaft's bending angle as an input parameter.

A number of studies have been conducted to investigate the performance of bearings under high-temperature and complex operating conditions. B. Caers and co-authors [14] tested deep-groove bearings made of martensitic and austenitic steels, ceramics, and hybrid materials using a specialized testing device (RHEOTESTER). This device was designed to simulate the operating conditions of the components. The results indicate that bearings made of martensitic steel perform unreliably at high temperatures (≥250 °C) and are susceptible to the detrimental effects of liquid metal embrittlement (LME). Austenitic steels, despite their corrosion resistance and stability at high temperatures, exhibit low load-carrying capacity due to the absence of hardening, making them unsuitable for use as bearings. Fully ceramic bearings demonstrated the longest service life, although their load-carrying capacity is limited. Overall, the performance of deep-groove bearings was found to be highly variable and unreliable under these conditions.

In industry, particularly in mechanical engineering, inorganic compounds are added to lubricants to reduce friction in existing bearings and improve their operational efficiency. In this study, the effect of an additive lubricant on the performance of a shaft–bearing pair under static load was experimentally investigated. The additive lubricant was obtained by incorporating 1 wt% molybdenum disulfide (MoS_2) into the base hydraulic oil, Shell Tellus 10. The experimental results demonstrated that the MoS_2-enriched lubricant formed a superior lubricating film under high load and temperature conditions, reducing the level of friction compared to the base oil. Consequently, the use of such a lubricant resulted in a significant decrease in wear and power losses.

Hydrodynamic bearings are widely used in high-speed rotating mechanisms [15]. Radial bearings carry loads in the radial direction and operate according to the hydrodynamic lubrication principle; they are among the most commonly employed bearing types in industry. They are particularly used in environments where vibration damping, noise reduction, and stable operation are required. Shaft–bearing systems play a critical role in minimizing power losses in mechanical systems.

The use of appropriate lubricants to reduce friction and wear in mechanical contacts plays a crucial role in minimizing power losses [16]. In rotating machinery, various industrial sectors incorporate additives into base mineral oils to extend maintenance intervals and reduce energy losses. Such additives consist of anti-wear agents, high-pressure-resistant compounds, and substances that prevent sediment formation. The proper selection of a lubricant directly affects the operational performance of a bearing. The primary cause of the greatest power losses on contact surfaces is the friction between moving components. The main function of a lubricant is to form a smooth separating layer between metal surfaces, preventing direct contact, and to dissipate the generated heat and wear particles.

In recent years, the use of laser technologies in mechanical engineering and tribology has been recognized as one of the most promising methods for strengthening the working surfaces of machine components. Laser beams allow precise control over the microgeometric structure, hardness, and metallurgical changes in the surface layer of metals. As a result of this process, the coefficient of friction of bearings decreases, their wear resistance increases, and their service life is significantly extended.

Under the influence of laser irradiation, a high-temperature zone is formed in the surface layer for a very short period. The rapid cooling of this zone leads to the formation of a fine-grained martensitic structure. Such a layer provides high hardness, smoothness, and resistance to thermal deformation on the working surface of the bearing. Studies have shown that laser-treated surfaces enhance the stability of the lubricating film, improve hydrodynamic friction, and reduce energy losses due to friction.

In their research, S. Pradhan and colleagues extensively analyzed the role of Laser Surface Texturing (LST) technology in improving tribological properties. According to their findings [17], micro-patterned textures created by laser stabilize the hydrodynamic pressure between the surface and the lubricant, thereby enhancing the operational efficiency of bearings. They emphasized that the LST method significantly improves the surface functionality of metals, reduces friction, and extends service life.

In studies conducted by S. Li and others, micro-grooves and circular dimples were fabricated on GCr15 bearing steel using laser treatment [18]. The results indicated that the geometry of the surface texture had a significant impact on tribological performance. When optimal parameters were selected, the coefficient of friction decreased by 25–40%, and wear resistance improved.

In the scientific work developed by P. J. Blau, four primary functions of surface texturing were identified:

1. Controlling the lubricant flow and film thickness
2. Serving as a channel for lubricant supply to the surface
3. Capturing particles generated during the friction process
4. Reducing bearing pressure by improving load distribution

All of these factors arise as a result of laser surface texturing and contribute to enhancing the tribological performance of the surface. In a 2023 study by S. Pradhan and colleagues, a comprehensive analysis was presented regarding the application of laser surface texturing across various fields. The authors emphasized that controlling the microstructure of a surface using a laser beam plays a crucial role in reducing energy losses during friction and improving the lubricant retention characteristics of metals.

Overall, laser technologies serve as an effective means for reinforcing contact zones on bearing working surfaces, improving microgeometry, enhancing the stability of lubricant films, and increasing operational efficiency. Properly selected laser parameters allow precise control over the tribological state of metals. For this reason, laser-based surface modification is currently being extensively studied in tribology as a resource-efficient, environmentally safe, and high-tech approach.

Analysis of Materials Used in Bearings

The reliability and long-term operational efficiency of technological machinery in the mechanical engineering industry are directly dependent on the quality and precision of their key components, such as shafts and bearings, as well as the tribological properties of the materials used. These elements are constantly subjected to mechanical loads, friction, thermal effects, and variations in lubrication conditions. Therefore, the correct selection of materials for shafts and bearings is crucial for extending their service life and improving energy efficiency.

Modern machines are designed to operate at high speeds, large torques, and variable loads. This necessitates the use of materials with superior mechanical, physical, and tribological properties compared to conventional carbon steels [19]. In particular, high strength, wear resistance, surface smoothness, and corrosion resistance are considered primary criteria in contemporary tribology. Consequently, a detailed analysis of the composition of metals and alloys intended for shafts and bearings, as well as their processing technologies, is essential.

When selecting materials for shaft components, the main criteria include strength, fatigue resistance, surface hardness, and machinability. The most commonly used shaft materials are steels such as 45, 40X, 40CrNiMo, 42CrMo4, and 38X2MYuA [20]. These are medium- to high-carbon alloy steels, with a primary advantage being their high potential for mechanical property enhancement through heat treatment.

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