Effect of Contact Conditions and (Surface) Stress on Surface Damage under Low Lambda Conditions

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1. Introduction

Rolling bearings are essential components in many industrial applications, including automotive, aerospace, and heavy machinery, where they operate under a wide range of load and lubrication conditions. Their performance and durability are significantly affected by contact stresses and surface interactions, which are directly dependent on lubrication quality. Under low lambda conditions, where the lubricant film is insufficient to fully separate contacting surfaces, asperity interactions become more pronounced, resulting in localized stress concentrations and increased surface damage.

In such conditions, surface damage in rolling bearings consists primarily of micro-pitting and wear [1], both of which reduce efficiency and accelerate failure, ultimately leading to maintenance issues and operational downtime. These damage mechanisms are strongly influenced by contact conditions, including surface roughness, lubricant viscosity, and operating speed, as well as the resulting stress distributions at the asperity level. Therefore, a detailed understanding of how contact conditions and stresses drive surface degradation is crucial for improving bearing reliability in low-lubrication environments.

This study investigates the effects of contact conditions and surface stresses on surface damage in rolling bearings under low lambda conditions using a combination of experimental and simulation approaches. By analyzing stress distributions and asperity level interactions, this research aims to identify the key factors that drive damage initiation and progression. The results will provide valuable insights into failure mechanisms and potential strategies to mitigate surface damage, ultimately enhancing bearing performance under challenging lubrication conditions.

2. Method

2.1 Experimental conditions

The effect of contact conditions and surface stress on surface damage under low lambda conditions was investigated through a series of rolling contact fatigue (RCF) tests using a thrust ball bearing test rig. Since asperity interactions, influenced by surface roughness and oil film thickness, play a critical role in contact conditions and stress distribution, key parameters such as lubricant viscosity, surface roughness, and rotational speed were adjusted to achieve target lambda values ranging from 0.05 to 0.90. To evaluate asperity-induced stress and its role in surface damage, test bearings were prepared with controlled raceway roughness between 0.02 and 0.06 µm and steel ball roughness up to 0.60 µm (RMS). In addition, surface damage was studied under different roughness conditions to gain a deeper understanding of stress concentration effects. Surface morphology observations were conducted to analyze the physical characteristics and fatigue structures of the damaged surfaces under selected test conditions.

2.2 Simulation conditions

To further investigate the contact conditions and surface stress on surface damage, a micro-EHL analysis was performed. This simulation approach provided a better understanding of the stress distribution and damage formation under low lambda conditions. In the micro-EHL analysis, surface roughness distributions – generated by ball roughness to replicate asperity interactions – were used as primary input parameters. These roughness profiles were incorporated into the simulation, which was conducted under the same conditions as the experimental tests, taking into account lubricant viscosity, rotational speed, load, slip ratio, and coefficient of friction. By directly comparing simulated and experimental results, this analysis clarified how variations in contact conditions and stress concentration affect surface damage mechanisms, providing a more comprehensive understanding of the factors that lead to bearing failure under poor lubrication conditions.

3. Result and Discussion

The influence of ball roughness and lubrication conditions on surface damage mechanisms under low lambda conditions has been well described in a previous study [2]. The results clearly show the trends for micro-pitting, wear, and no surface damage, demonstrating how ball roughness and lubrication conditions influence surface mechanisms. Figure 1 illustrates how variations in ball roughness, which influence contact conditions, affect surface damage mechanisms. Surface morphology analysis confirms that micro-pitting is the dominant damage mode at higher ball roughness ($Rq \geq 0.3$ µm). This can be attributed to increased asperity interactions, which generate localized stress concentrations and promote fatigue-induced crack initiation and propagation. In contrast, at lower ball roughness ($Rq = 0.1$ µm), wear is the dominant damage mechanism, characterized by material removal rather than crack initiation. Conversely, no significant cracks were observed at Rq = 0.1 μm, indicating that lower roughness promotes wear-type damage rather than fatigue micro-pitting. These experimental results suggest that asperity-induced stress concentrations drive micro-pitting at higher roughness levels, while lower roughness promotes wear-type damage due to direct metal-to-metal contact.

The simulation results shown in Figures 2 and 3 further clarify this relationship by quantifying tangential stress variations under different conditions. These results provide an understanding of how surface roughness and asperity interactions affect stress distribution, which in turn affects surface damage mechanisms. Figure 2 shows that as the ball roughness (Rq) increases, the tangential stress also increases, particularly in cases where micro-pitting occurs. This finding is consistent with the experimental results and confirms that higher roughness leads to localized stress concentrations that accelerate fatigue damage [3, 4]. In contrast, no surface damage is observed at lower roughness where the tangential stress remains below the critical threshold required for crack initiation. Figure 3 shows the relationship between tangential stress and contact ratio. Higher contact ratios correlate with increased asperity interactions, resulting in higher stress levels that contribute to both micro-pitting and wear damage. Specifically, wear tends to occur at moderate stress levels and higher contact ratios, while micro-pitting dominates in high stress regions with low to moderate contact ratios. This distinction suggests that wear damage is strongly influenced by continuous asperity interactions, while micro-pitting is more stress driven. Overall, the simulation results support the experimental findings and highlight the important role of contact conditions and stress distribution in identifying the dominant surface damage mechanisms under low lambda conditions.

4. Conclusion

This study investigated the effect of contact conditions and surface stress on surface damage mechanisms under low lambda conditions through experimental and simulation analyses. The results showed that higher ball roughness increases asperity interactions and localized stress concentrations, leading to micro-pitting, while higher contact ratio promotes wear due to direct surface contact. Simulation results further confirmed that tangential stress and contact ratio are critical factors in damage progression. These results improve the understanding of the failure mechanism in rolling bearings and provide a basis for optimizing surface design and lubrication strategies to improve bearing life.

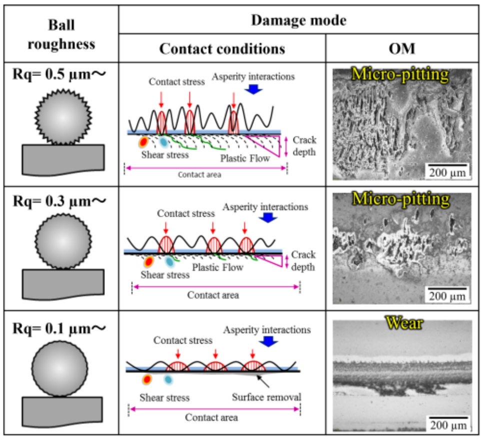

Figure 1 The effect of different ball roughness on surface damage

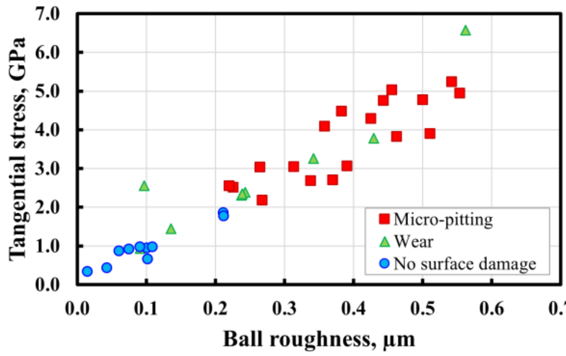

Figure 2 The relationship between tangential stress and ball roughness

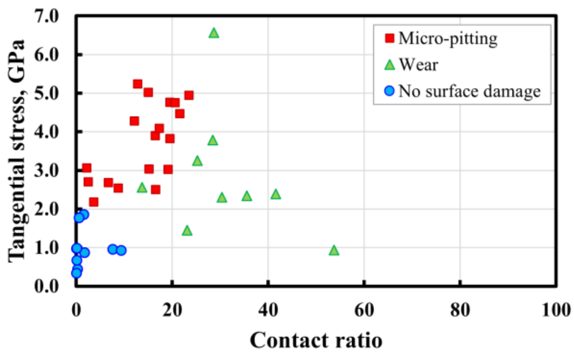

Figure 3 The relationship between tangential stress and contact ratio

References

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