EFFECTS OF PARTICULATE DEBRIS MORPHOLOGY ON THE ROLLING WEAR BEHAVIOR OF ALL-STEEL AND Si₃N₄-STEEL BEARING ELEMENT COUPLES

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ABSTRACT

Rolling contact fatigue experiments were performed on all-steel and hybrid Si₃N₄-M50 steel rolling bearing systems using particulate contaminated lubricants. The particulate contaminants used were glycothermally synthesized α-Al₂O₃ platelets or Arizona test dust. The effects of contaminant composition and morphology on rolling contact fatigue and wear behavior were explored. The effects of bearing element material properties on fatigue and wear behavior were also examined. Rolling wear behavior is related to bearing component material configuration and the type of particulate contaminant present in the lubricant. Component and particulate material properties such as hardness and elastic modulus are observed to affect rolling wear behavior. Wear mechanisms such as contact stress fatigue, indenting, cutting and plowing are observed.

INTRODUCTION

Improvements in rolling bearing design, material compositions, and lubricants have advanced bearing performance dramatically in the past 20 years [1-9]. The improved wear resistance and lifetime of hybrid bearings using Si₃N₄ rolling elements offer advantages in fuel economy and repair costs. Si₃N₄ rolling elements have a low thermal expansion coefficient, high strength and hardness, high thermal and chemical stability, and low density, providing less centrifugal force on the raceway than steel rolling elements at high rotational speeds. Ceramic rolling elements are also non-magnetic and, unlike all-steel bearings, will not weld when exposed to extreme rotational speed, friction, heat, or loss of lubricant during operation. The physical and chemical properties of the materials used as rolling elements will affect the wear behavior of the ball-lubricant-raceway system during rolling and sliding [10-11]. The size, size distribution, shape and material properties of particulate contaminants present in the lubricant system will also affect the wear behavior of a bearing system during rolling and sliding [12-16].

Contamination of the lubricant by particulate debris is one of the most common failure initiators in operating bearing systems [17-23]. In order to observe wear behavior under conditions actually experienced by bearing elements in service, particulate contaminants may be added to lubrication systems used in rolling contact fatigue (RCF) experiments. Two types of particulate contaminants were employed in this study, each simulating a different contamination scenario. The two types of particulate used were (1) Arizona test dust (ATD) and (2) glycothermally synthesized α-Al₂O₃ particulate. The ATD particulate was used to simulate the common wear scenario of environmental contamination of the lubricant system during engine operation in
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aggressive environments such as dirt and sand in a desert. The $\alpha$-Al$_2$O$_3$ particulate was used to simulate the common wear scenario in actual jet engine bearing systems of hard particulate contaminants in the lubrication system resulting from initial machining operations and subsequent wear of high strength engine component materials. The effects of particulate contaminant composition and morphology on rolling contact fatigue and wear behavior were observed.

EXPERIMENTAL METHOD

Rolling contact fatigue experiments

This study was performed using a modified rolling contact fatigue (RCF) test apparatus with a three-ball-on-rod configuration [24]. Bearing systems simulated were the M50-M50 all-steel system and the $\text{Si}_3\text{N}_4$ ball-M50 race hybrid bearing system. The balls are thrust-loaded against the rod by two cups held in place with three equally-spaced springs. The springs help maintain a constant load during the test, provided the wear track does not become wider than the initial Hertzian contact region. The rod samples used for all experiments were 9.5 mm diameter M50 VIM VAR steel. The ball samples were 12.7 mm diameter, AFBMA grade 5 and made from M50 VIM VAR steel or Toshiba TSN-03NH $\text{Si}_3\text{N}_4$. In order to represent jet engine conditions, a MIL-L-23699 jet engine lubricant was used. The rod sample was driven at 3600 rpm producing 2.389 stress cycles per revolution. All particulate-contaminated lubricant tests were run using a concentration of 1.0 g of powder to 4.0 l of oil. The same load was applied to all-steel and hybrid bearing tests, which results in a higher Hertzian contact stress in the hybrid bearing cases because of the higher elastic modulus of the $\text{Si}_3\text{N}_4$ balls [25-27]. The same load was applied to allow rotation of all-steel and hybrid tests between different RCF test stations for statistical accuracy. The RCF experiments were run under the experimental conditions listed in Table I. Select material properties are shown in Table II.

**Table I. Experimental Conditions**

<table>
<thead>
<tr>
<th>Ball</th>
<th>Rod</th>
<th>Lubricant Type</th>
<th>Lubricant Condition</th>
<th>Hertzian Stress*</th>
</tr>
</thead>
<tbody>
<tr>
<td>M50</td>
<td>M50</td>
<td>MIL-L-23699</td>
<td>Arizona Test Dust</td>
<td>5.19 GPa (753 ksi)</td>
</tr>
<tr>
<td>M50</td>
<td>M50</td>
<td>MIL-L-23699</td>
<td>$\alpha$-Al$_2$O$_3$</td>
<td>5.19 GPa (753 ksi)</td>
</tr>
<tr>
<td>$\text{Si}_3\text{N}_4$</td>
<td>M50</td>
<td>MIL-L-23699</td>
<td>Arizona Test Dust</td>
<td>5.97 GPa (866 ksi)</td>
</tr>
<tr>
<td>$\text{Si}_3\text{N}_4$</td>
<td>M50</td>
<td>MIL-L-23699</td>
<td>$\alpha$-Al$_2$O$_3$</td>
<td>5.97 GPa (866 ksi)</td>
</tr>
</tbody>
</table>

* Maximum Hertzian stress calculated for ball-on-flat using numerical techniques, see [25-27].

**Table II. Select Material Properties**

<table>
<thead>
<tr>
<th>Material</th>
<th>Vickers Hardness (kg/mm$^2$)</th>
<th>Elastic Modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M50</td>
<td>750</td>
<td>190</td>
</tr>
<tr>
<td>$\text{Si}_3\text{N}_4$</td>
<td>1500</td>
<td>310</td>
</tr>
<tr>
<td>ATD</td>
<td>1000</td>
<td>100</td>
</tr>
<tr>
<td>$\alpha$-Al$_2$O$_3$</td>
<td>2600</td>
<td>390</td>
</tr>
</tbody>
</table>
Particulate contaminants

The ‘fine’ grade of ATD used for these tests consists of particles >70 μm in diameter with a broad particle size distribution and random particle morphologies. ATD is composed of 60-70% SiO₂, 10-15% Al₂O₃, and the remainder being of various other oxides. The Al₂O₃ particles used in this study were glycothermally synthesized to produce a chemically pure and phase pure α-Al₂O₃ powder with a mean particle size of 1-3 μm, a narrow particle size distribution, and a highly controlled platelet morphology [28]. Particle size distributions of the two powders are shown in Figure 1. The ATD size distribution was specified by the vendor and was determined using a multisizer IIIE particle size analyzer. The α-Al₂O₃ distribution was determined using an electro-zone particle size analyzer. The particle size and morphological differences between the ATD and α-Al₂O₃ powders are apparent in the scanning electron micrographs shown in Figure 2(a) and (b), respectively.

Wear analysis

Scanning electron microscopy was used to observe wear features on ball and rod wear track surfaces. The M50 rod wear track surfaces were also examined using an atomic force microscope (AFM) to provide topographical images of the material surfaces as well as roughness values. The topographical image provides a three-dimensional picture of the wear surface, exposing wear characteristics and embedded debris. All tests were run to failure or stopped if the test time reached 700 h. The wear surfaces shown in this paper are from tests which ran near the average lifetime for that type of experiment. Shorter test times are indicative of increased wear in the system resulting in decreased lifetime of the test.

RESULTS AND DISCUSSION

Due to the cyclical compression and release of Hertzian contact stresses on the ball and raceway material surfaces as a ball rolls along a raceway in a bearing configuration, the primary wear mechanism which results is contact stress fatigue. Contact stress fatigue in the Si₃N₄ occurs in three stages [29]. Stage I is microcrack formation at the grain boundaries which leads to surface roughening and occasional grain removal. Stage II is Hertzian-type cone crack initiation. Stage III is the propagation and coalescence of Hertzian cone cracks which leads to macroscopic material removal from the surface. As Hertzian contact damage occurs on the rolling element surfaces, wear particles are removed from the material surfaces and deposited into the lubricant. Particulate contaminants may also be introduced into the lubricant from the production and operational environment. Secondary wear mechanisms of indenting, cutting, plowing and embedding result from the three-body wear induced by the particulate contaminants in the lubrication system. Three-body wear occurs when a particle which is larger than the elastohydrodynamic lubrication (EHL) layer passes between the rolling element surfaces, contacting both the ball and raceway surfaces. An indentation results if the particle is large enough and hard enough to produce inelastic deformation. These indentations may produce subsurface lateral cracking and subsequently lead to spallation of the ductile M50 surface. The three-body contact results in mode I stresses on the surface of the brittle Si₃N₄ and may subsequently cause Hertzian cone cracking. Failure modes in both M50 steel and Si₃N₄ result in
Figure 1: Particle size distribution comparison of ATD and \( \alpha\)-Al\(_2\)O\(_3\) powders.

Figure 2: SEM photomicrographs of particulate contaminants, (a) ATD, (b) \( \alpha\)-Al\(_2\)O\(_3\).
the removal of a macroscopic portion of material from the surface. The mechanisms of crack initiation and propagation are, however, very different [13, 29-30].

**Wear mechanisms on ball wear track surfaces**

Figures 3(a) and (b) are SEM photomicrographs of wear surfaces on ball samples run under ATD particulate contaminated lubricants. Figure 3(a) shows the wear surface of an M50 ball which was run with an M50 rod. Figure 3(b) shows the wear surface of a Si₃N₄ ball which was run with an M50 rod. Comparison of the topographical differences between Figures 3(a) and (b) indicates that more wear occurred on the M50 ball surface than on the Si₃N₄ ball surface when using ATD particulate. Larger damage sites, such as the one at the bottom right of Figure 3(a), occurred more frequently on M50 ball surfaces than on the Si₃N₄ surfaces. Wear mechanisms such as indenting, cutting, and plowing are suspected from the appearance of the M50 ball wear surface in Figure 3(a). Cutting and plowing damage is evident in the alignment of the scars on the wear surface, which follow the direction of rolling. Large, sharp indenters may cause subsurface lateral cracks which develop into spalls on M50 surfaces. Figure 3(b) shows that very little wear occurred on the Si₃N₄ surface when using an ATD contaminated lubricant. A few small damage sites were observed, indicating that minor surface fracture damage was occurring. The damage on the Si₃N₄ surface was much less severe than that observed on the M50 surface. The cutting and plowing damage is not present on the Si₃N₄ wear surfaces. The reason less damage was inflicted on the Si₃N₄ surface than the M50 steel surface is because of the greater hardness of the Si₃N₄ relative to the ATD particulate. This limited wear by the ATD particles on the Si₃N₄ balls did not appreciably decrease the fatigue life of Si₃N₄-M50 hybrid experiments, compared with runs using as-received lubricants [12-13].

Figures 4(a) and (b) are SEM photomicrographs of wear surfaces on ball samples run under lubricants contaminated with glycothermally synthesized α-Al₂O₃ particulate. Figure 4(a) shows the wear surface of an M50 ball run with an M50 rod. Figure 4(b) shows the wear surface of a Si₃N₄ ball run with an M50 rod. It is apparent from the difference in number of damage sites shown in Figures 4(a) and (b) that the M50 ball surface was indented more by the Al₂O₃ particles than the Si₃N₄ surface. Figure 4(a) exposes the wear mechanism of indenting in its most obvious state. The large hexagonal α-Al₂O₃ platelets produced distinct hexagonal indentations in the M50 steel wear surface, as well as non-symmetrical indentations with smaller particles on end. The large indentations may cause subsurface damage which can eventually result in spallation of material from the M50 surface. The lack of cutting and plowing damage on the M50 surface by the Al₂O₃ particles shown in Figure 4(a) compared to the ATD run shown in Figure 3(a) is probably due to the smaller particle size and size distribution of the Al₂O₃ particulate. The extremely large particles in the ATD powders may get wedged in front of the rolling element and be unable to pass between the ball and race. This wedge action may result in the particle cutting or plowing through the rolling element material as it is ground into smaller particles. The large particle size of the ATD powder is likely the reason more damage is generated in the all-steel system by the ATD particles than by the Al₂O₃ particles. The lower elastic modulus of steel results in a larger EHL layer thickness in the all-steel case, as opposed to the hybrid case. Using Al₂O₃ particulate with a larger particle size should induce more wear in the all-steel system. Comparison of Figure 4(b) with Figure 3(b) indicates that larger damage sites are produced on the Si₃N₄ surface by the Al₂O₃ particles, than by the softer ATD particles. ATD particles are
Figure 3: SEM photomicrographs of ball wear tracks generated using lubricants contaminated with ATD, (a) wear track on an M50 ball run with an M50 rod, 5.19 GPa, 440 h, (b) wear track on a Si$_3$N$_4$ ball run with an M50 rod, 5.97 GPa, 580 h.

Figure 4: SEM photomicrographs of ball wear tracks generated using lubricants contaminated with Al$_2$O$_3$, (a) wear track on an M50 ball run with an M50 rod, 5.19 GPa, 600 h, (b) wear track on a Si$_3$N$_4$ ball run with an M50 rod, 5.97 GPa, 115 h.
likely comminuted by the hard Si$_3$N$_4$ surface. The Al$_2$O$_3$ particles cause noticeable damage on the Si$_3$N$_4$ surface, as shown in Figure 4(b). This increased damage results in dramatic reductions in the fatigue life of hybrid bearing experiments using Al$_2$O$_3$ particulate contaminants [12-13].

**Wear mechanisms on rod wear track surfaces**

Figures 5(a) and (b) are SEM photomicrographs of wear surfaces on rod samples run under ATD particulate contaminated lubricants. Figure 5(a) shows the wear surface of an M50 rod which was run with M50 balls. Figure 5(b) shows the wear surface of an M50 rod which was run with Si$_3$N$_4$ balls. The tests were run at the same load, which results in a greater Hertzian contact stress in the hybrid case due to the greater elastic modulus of Si$_3$N$_4$ balls relative to M50 balls. It is apparent from the comparison of Figures 5(a) and (b) that more damage is produced on the M50 rod surface by rolling contact with Si$_3$N$_4$ balls than with M50 balls. The increased Hertzian contact stress produced by the greater elastic modulus of Si$_3$N$_4$ relative to M50 steel results in a decreased EHL layer thickness in the hybrid bearing system, when compared to the all-steel system. Using a lubricant contaminated with ATD results in increased wear of the M50 steel rod in the hybrid bearing system when compared to the all-steel system, under the same applied load, due to the greater hardness of Si$_3$N$_4$ relative to M50 and the reduced EHL layer thickness. The reduced EHL layer thickness allows an increased number of contaminant particles to become involved in three-body wear in the hybrid bearing system.

Figures 6(a) and (b) are SEM photomicrographs of wear surfaces on rod samples run under lubricants contaminated with glycothermally synthesized α-Al$_2$O$_3$ particulate. Figure 6(a) shows the wear surface of an M50 rod run with M50 balls. Figure 6(b) shows the wear surface of an M50 rod run with Si$_3$N$_4$ balls. Distinct hexagonal indents can be seen on the wear surfaces shown in Figures 6(a) and (b) similar to those seen on the ball sample in Figure 4(a). Smaller indents are present for the Al$_2$O$_3$ test results shown in Figure 6(a) than in the ATD test results shown in Figure 5(a) due to the smaller particle size of the Al$_2$O$_3$ particulate relative to the ATD particulate. The indentation damage produced by the Si$_3$N$_4$ balls on the M50 rod shown in Figure 6(b) is more excessive than that caused by the M50 balls shown in Figure 6(a). These results indicate that the number and depth of the indents are increased when Si$_3$N$_4$ balls are run against an M50 rod than when M50 balls are run against an M50 rod under the same applied load. This increased damage with Si$_3$N$_4$ balls is a result of the increased Hertzian contact stress in the hybrid bearing case relative to the all-steel case and the greater hardness of Si$_3$N$_4$ relative to M50, as previously shown in Figure 5.

**Atomic force microscopy**

Figure 7(a) shows an AFM image of an M50 rod wear track tested with Si$_3$N$_4$ balls and a lubricant contaminated with ATD particulate. The original finishing marks remain present after almost 600 hours of testing. Figure 7(b) shows an AFM image of an M50 rod wear track tested with Si$_3$N$_4$ balls and a lubricant contaminated with Al$_2$O$_3$ particles. The arrows mark two white vertical protrusions which are Al$_2$O$_3$ particles embedded in the M50 rod. The original finishing marks have been removed by abrasive wear in 40 hours, indicating more wear is induced in the hybrid bearing RCF system by Al$_2$O$_3$ particulate than by ATD, due to the greater hardness of Al$_2$O$_3$ particles.
Figure 5: SEM photomicrographs of rod wear tracks generated using lubricants contaminated with ATD, (a) wear track on an M50 rod run with M50 balls, 5.19 GPa, 440 h, (b) wear track on an M50 rod run with Si$_3$N$_4$ balls, 5.97 GPa, 580 h.

Figure 6: SEM photomicrographs of rod wear tracks generated using lubricants contaminated with Al$_2$O$_3$, (a) wear track on an M50 rod run with M50 balls, 5.19 GPa, 380 h, (b) wear track on an M50 rod run with Si$_3$N$_4$ balls, 5.97 GPa, 575 h. Arrows indicate hexagonal indentations.
Figure 7: Atomic force micrographs of wear track surfaces on M50 rods run with Si₃N₄ balls, 5.97 GPa, (a) ATD in oil, 580 h, (b) Al₂O₃ in oil, 40 h. Arrows indicate embedded Al₂O₃ particles.
CONCLUSIONS

The morphology, e.g. size and shape, and material properties, such as hardness and modulus, of particulate debris present in the lubricant have a pronounced effect on the wear behavior under rolling contact conditions, such as occurs in bearing elements. The material properties and configuration of the rolling elements will affect the wear behavior of a bearing system as well. If the particulate debris present in the lubricant has a diameter larger than the thickness of the EHL layer, three-body wear will result. The type of three-body wear which results is dependent on the properties and morphology of both the particulate contaminants and the bearing elements. Figure 8 is a schematic diagram of the wear process in the Si3N4-M50 steel hybrid bearing system with particulate debris present in the lubricant. It is adapted from the schematic developed by Chen et al. under contact loading conditions [13, 29]. If the particulate debris is large and soft, such as ATD, it may be comminuted between the rolling elements, producing cutting and plowing damage on a ductile bearing surface. If the debris is small and hard, it may cause cutting and plowing damage on a ductile bearing surface, such as M50 steel. Small and hard particulate may cause surface fracture damage in a brittle surface, such as Si3N4. Large debris passing through the bearing-race gap may cause subsurface lateral cracking in a ductile surface, which can lead to spallation. Large debris passing through the bearing race gap may cause Hertzian cone cracking resulting from a coalescing of cracks resulting from mode I stresses in a brittle material. If the ball material has hardness and elastic modulus values greater than the raceway material, as Si3N4 balls are to an M50 steel raceway, then more damage to the raceway material will be generated during three-body wear with particulate debris present in the lubricant. The complex system of particulate debris morphology and material properties, bearing element configuration and material properties, and system performance parameters such as Hertzian contact stress and rolling speed, will determine the resultant wear behavior of the bearing system. The present study suggests that a controlled particle size with narrow size distribution will help distinguish wear mechanisms due to particulate contamination. A range of particle sizes should be employed in future work to study various wear mechanisms.

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REFERENCES

Direction of Contact Stress Fatigue Loading

Si₃N₄ Ball

M50 Race

Direction of Rolling

Hard-Particulate Debris in Lubrication System

Small Debris
Three Body Wear

Cutting and Plowing Wear

Large Debris
Indentation

Hertzian Cone Cracking and Spallation

Extra-Large Debris
Grinding of Particles

Cutting and Plowing Wear

Figure 8: Schematic diagram of the wear process in the Si₃N₄-M50 steel hybrid bearing system with particulate debris present in the lubricant.