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DEVELOPMENT OF PROGNOSTIC TECHNIQUES FOR SURFACE DEFECT GROWTH IN RAILROAD BEARING ROLLING ELEMENTS

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ABSTRACT

Prevention of bearing failures which may lead to catastrophic derailment is a major safety concern for the railroad industry. Advances in bearing condition monitoring hold the promise of early detection of bearing defects, which will improve system reliability by permitting early replacement of failing components. However, to minimize disruption to operations while providing the maximum level of accident prevention that early detection affords, it will be necessary to understand the defect growth process and try to quantify the growth speed to permit economical, non-disruptive replacement of failing components rather than relying on immediate removal upon detection. The study presented here investigates the correlation between the rate of surface defect (i.e. spall) growth per mile of full-load operation and the size of the defects. The data used for this study was acquired from defective bearings that were run under various load and speed conditions utilizing specialized railroad bearing dynamic test rigs operated by the University Transportation Center for Railway Safety (UTCRS) at the University of Texas Rio Grande Valley (UTRGV). Periodic removal and disassembly of the railroad bearings was carried out for inspection and defect size measurement and documentation. Castings were made of spalls using low-melting, zero shrinkage Bismuth-based alloys so that a permanent record of the full spall geometry could be retained. Spalls were measured using optical techniques coupled with digital image analysis and also with a manual coordinate measuring instrument with the resulting field of points manipulated in MatLab™ and Solidworks™. The spall growth rate in area per mile of full-load operation was determined and, when plotted versus spall area, clear trends emerge. Initial spall size is randomly distributed as it depends on originating defect depth, size, and location on the rolling raceway. The growth of surface spalls is characterized by two growth regimes with an initial slower growth rate which then accelerates when spalls reach a critical size. Scatter is significant but upper and lower bounds for spall growth rates are proposed and the critical dimension for transition to rapid spall growth is estimated. The main result of this study is a preliminary model for spall growth which can be coupled to bearing condition monitoring tools to permit economical scheduling of bearing replacement after the initial detection of spalls.

INTRODUCTION AND BACKGROUND

Tapered-roller bearings are commonly used in freight railcar operation. These bearings are comprised of an outer ring (cup) and two inner rings (cones) with rollers as illustrated in Figure 1. In operation, a side frame is placed over the two bearings distributing the load of the railcar between the two. Due to the cups being fixed in place, the top hemisphere of the cup is always loaded. This area is known as the “loaded zone”. Unlike the cups, which are fixed, the cones are simultaneously rotating with the wheel and axle.

A common cause of railroad tapered-roller bearing failure is due to rolling contact fatigue (RCF) which may lead to spalling

[1]. According to Hertzian contact mechanics, the highest stresses exist near the surface. Maximum shear stress occurs just below (within 400 micrometers) the rolling surface due to contact loading [2]. Spalling usually occurs along the rolling surfaces of the bearing, typically known as the raceways. Spalls most commonly initiate at sites of subsurface inclusions [3]. When a spall initiates, metallic debris is introduced into the bearing's lubricant as well as the dynamic components. The pitting of the rolling surface and the addition of debris may result in misalignment of the rollers as they enter the loaded zone. This misalignment increases friction in the system resulting in higher operating temperatures and possibly accelerated breakdown of the lubricant [5]. Continued operation of the bearing will cause the spall to grow. The work presented here investigates the growth rate of spalls from outer rings (cups) that experienced spalling during field and/or laboratory service operation.

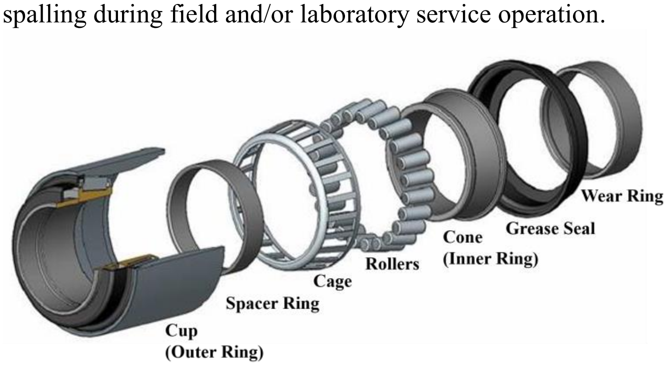

Figure 1. A detailed exploded view of a typical railroad tapered roller bearing assembly

EXPERIMENTAL SETUP AND INSTRUMENTATION

The experiments were performed utilizing two types of dynamic testers available at UTRGV's University Transportation Center for Railway Safety (UTCRS). Pictures of the four bearing and single bearing testers are provided in Figure 2 and Figure 3, respectively. Both tester types are equipped with hydraulic load cylinders to simulate various loading conditions of a bearing in field service. Bearings, which spalled in the laboratory, were generally being run on the four bearing testers, and many of the field-initiated spalls were also grown on both bearing testers. Much of the most recent data was obtained by running bearings on the single bearing tester.

The four bearing tester is capable of running four Class K or Class F bearings simultaneously. Testers include instrumentation for monitoring temperature and vibration of all bearings during operation, although that data is not used in this study. All bearings tested in this study were subjected to loads simulating a fully-loaded railcar which corresponds to a load of 153,000 N (34,400 lb) per bearing.

The four bearing tester permits the testing of multiple bearings in long duration experiments such as those performed for service life testing and qualification of bearing steel. The single bearing tester (SBT) is designed and built by the UTCRS research team for short duration testing where a railroad bearing can be subjected to operating conditions that more closely mimic field service conditions. As can be seen in Figure 3, the single bearing tester design suspends the railroad bearing at the end of a cantilever beam with an overhead load pressing down on the bearing through an adapter. This testing setup replicates the conditions experienced by freight rail bearings in field service operation.

Figure 2. Four bearing testers at UTRGV's UTCRS

Figure 3. Single bearing tester (SBT) at UTRGV's UTCRS

METHODOLOGY

Spalled bearings were obtained either from previously conducted laboratory service life tests where new bearings were run until they developed spalls, or from field service bearing removals that were found to have spalls on the outer ring (cup) raceways. A total of eight different bearings were run for extended periods of time in order to generate the data used for this study. Some of the experimental data used in this paper came from recent publications [3].

All data used in this study was collected from spalls on the outer bearing ring, also referred to as cup spalls. For bearings that spalled in the laboratory, once a defect was detected through vibration analysis of the acquired accelerometer data, the test was stopped and the bearing pressed off, disassembled, and cleaned for inspection. To permit detailed measurement of the spall while allowing continued testing of the bearing, a casting was made of the spall using a low-melting, zero-shrinkage bismuth alloy. Tacky tape was applied to the raceway to create a mold border around the defect and then molten alloy (80°C/176°F) was poured into the cavity to obtain a casting as pictured in Figure 4.

Figure 4. Bismuth casting procedure. Spalled surface with tacky tape (left); Bismuth alloy cast in place (right).

Once the casting was hardened and removed, the borders of the casting up to the spall impression were painted and the casting photographed. Images were then post-processed in MatLab™ to enhance the contrast. The enhanced image was imported into Image-Pro®Plus where measurements of area and other geometric parameters were performed. After castings were obtained, the bearings were remounted on the tester and run under load with periodic removal for measurement. Continued operation resulted in additional growth in the spall area and change in the spall aspect ratios and other parameters as depicted in Figure 5.

Figure 5. Spall growth in a bearing outer ring (cup) under continued operation (increasing mileage left to right).

In this initial evaluation, only mileage under full-load operation was thoroughly investigated. Some of these bearings were run for some period under loads simulating an empty railcar as part of other ongoing projects. The empty railcar operation mileage was briefly included in the analysis presented here.

RESULTS AND DISCUSSION

Spalls typically grow lengthwise on the bearing cup until they reach the rib of the bearing at which point the spall will grow along the raceway, as can be observed in Figure 5. Spall growth rates were calculated in terms of change in spall area per mile of loaded operation and are plotted in Figure 6. In general, there is no clear trend in the early stages of spall development as seen in Figure 7. This lack of trend is to be expected since spall formation is random both in location and in spall size.

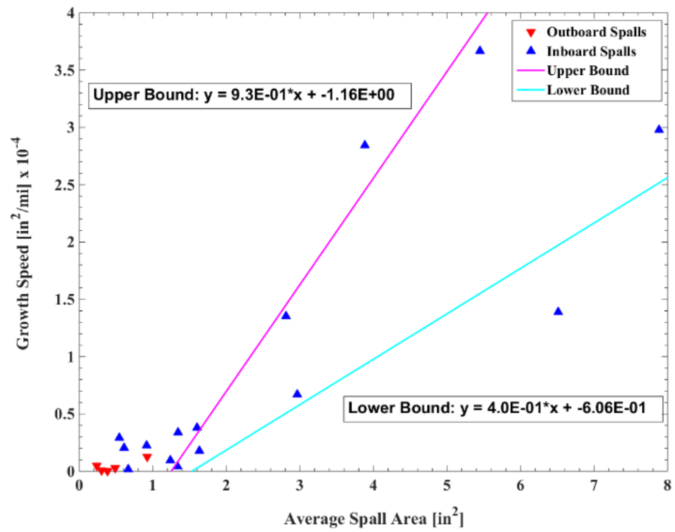

Figure 6. Growth speed correlation with spall area

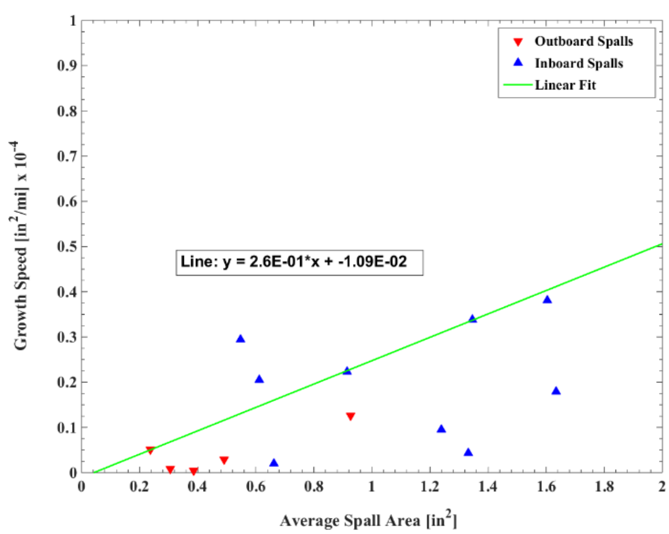

Figure 7. Growth speed of spalls less than 2 in^2 (13 cm^2)

Note that after spall areas exceed approximately 2 in^2 (13 cm^2), the rate of growth increases dramatically. The upper and lower bounds have slopes differing by a factor of 2.3. The presence of at least two modes of growth is not surprising as a change in mode is expected as the spall size approaches the diameter of the bearing rollers. When rollers can drop into the spall completely, they can be expected to induce a stress state and propagate damage differently than when they are kept above the floor of the spall by the shoulders of the defect, as illustrated in Figure 8. Once vibration excitation is triggered by any external source, it causes the rollers to vibrate, increasing the possibility for rollers to misalign upon entering the loaded zone of the bearing (top hemisphere). The latter results in enhanced frictional heating and roller deformation that generates significant amounts of heat and abrupt temperature fluctuations. Longitudinal spalls also initiate at the center of the roller (i.e. roller crown) and grow outward towards the ends of the tapered roller. The roller crown is the point of maximum stress when the roller misaligns during bearing operation [7].

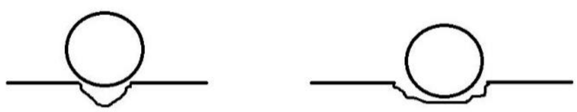

Figure 8. Probable basis of spall growth regimes

Inspecting spall growth data from both inboard and outboard bearing cup raceways, it does not seem that spall location is significantly affecting the growth rates, as demonstrated in Figure 7.

To this point, it has been assumed that only miles run under full-load produce significant spall growth. The final figure presented in this study has spall growth speeds plotted against total miles operated, including miles simulating an unloaded (i.e. empty) railcar or 17% of bearing rated capacity. Figure 9 shows that spalls larger than 2 in^2 now appear to fall along a single bound while those below 2 in^2 show no pattern in their response.

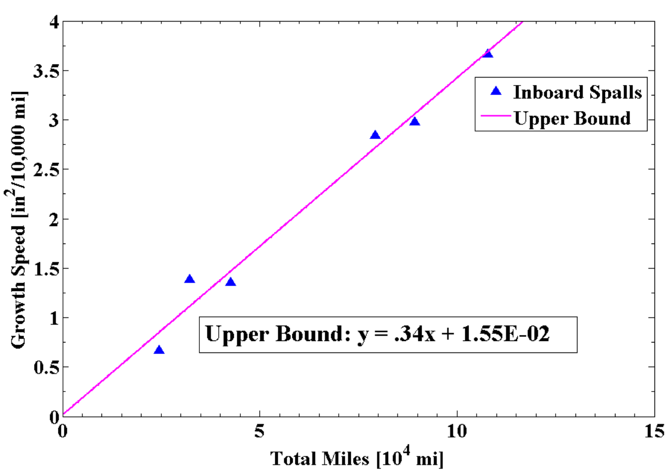

Figure 9. Spall growth rates versus total simulated miles of operation for spalls larger than 2 in^2 (13 cm^2)

The data presented in Figure 9 are potentially an extremely useful finding. Should the addition of more spall growth data continue to exhibit this behavior, then this correlation provides a sound basis for a worst-case model for spall growth. Spalls greater than 2 in^2 (13 cm^2) will grow according to a simple rule as a linear function of miles of operation, independent of the load status of the car. Below this threshold, growth does not appear to show any clear pattern of behavior, but spalls that small do not generally pose an immediate threat to bearing health.

CONCLUSIONS

With the available population of cup spalls, two tentative conclusions can be made. There appear to be two growth regimes with a sharp change in growth rates when spalls reach approximately 2 in^2 (13 cm^2) in area. Below this threshold, there is no clear trend in growth behavior based on area alone. However, the current data suggests that growth beyond this size is governed by a simple function of total miles of operation.

ACKNOWLEDGMENTS

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