Taiho Kogyo Tribology Research Foundation

Main report

Name: Prof. Matthew Brake

Theme: Investigating the destructive effect of the lubrication on elastic-plastic contact/collision of lubricated surfaces with application to spalling fatigue failure of rolling element bearings.

1. Progress and result of the research

Experimental Methods

Impact experiments were conducted in order to determine the relationship between lubrication properties and pertinent impact parameters. A 440C sphere, 1 inch in diameter, was fired against a 6061 aluminum sample with a thin film of lubrication on the target surface. The response of the system was measured for impact velocities ranging between 1.4 m/s and 5.4 m/s. The collision was recorded at a speed of 5297 frames per second with a high speed camera, and analyzed using the Digital Image Correlation Engine [1]. From the video data, the impact energy and amount of energy dissipated for each collision were calculated. Data on the permanent deformation was collected using a white light optical interferometry scanner. This device has repeatability values of 0.025 μm and resolution of 1 μm in the vertical direction, and 1 μm in the planar directions.

Preparations of the aluminum substrate were conducted in two phases. During the first stage of this project, the relationship between roughness, lubrication, and impact was explored. The aluminum samples were polished to 80, 240, 400, 600, and 1500 grits for different trials, which corresponded to R_a roughnesses of 6.3, 4.9, 3.4, 2.1 and 1.8 μm respectively. No significant relationship between roughness and permanent deformation of the substrate was found for both lubricated and unlubricated contact across the range of roughnesses studied. Thus, roughness was excluded as a parameter of investigation for the full study in order to keep the experimental plan within a feasible scope. Subsequently, the aluminum blocks were milled, resulting in consistent S_a roughnesses of 1.0-1.5 μm.

Four lubricants were used in these experiments: Renolit ST-80 lithium grease (chosen for its typical metal-on-metal usage as well as its load-bearing capacity, with viscosity 144.2 mm^2/s), Castrol GTX Ultraclean 5W-20 and 20W-50 engine oils (chosen because they both contain typical additives used in the motivating application, with viscosities of 52.97 and 155.5 mm^2/s respectively), and Mobil 1 Synthetic Grease (with a viscosity of 220 mm^2/s). These four lubricants all fit in the viscosity ranges cited for bearings in literature [2]. Each lubricant's thickness was varied from 0 (dry contact, which served as a control) to 0.575 mm (with intermediate thicknesses of 0.115 and 0.230 mm). Across all conditions, there were a total of approximately 1500 measured impacts.

Experimental Results

Figure 1 presents the coefficient of restitution (CoR) as a function of impact velocity. Shown are measured responses for the dry condition. The regression lines indicate a cubic relationship: after a steep initial decrease in the CoR, where the response of the material transitions from elastic to fully plastic indentation, the CoR slowly decreases for velocities above 2 m/s. The permanent plastic damage of the specimens is shown as a function of the impact velocity in Figure 1 as well. The permanent deformation is the depth of the impact crater, while the contact diameter is the diameter of the same impact crater.

A strong correlations exists ($r^2 = 0.91$ for a quadratic fit) between the permanent indentation depth and the contact radius (which is expected as the volume of a sphere segment is related to the cube of the radius). This correlation exists across both dry and lubricated conditions, and is shown in Figure 2.

As an example of the effect of lubrication, Figure 3 summarizes the response of the impacts against specimens coated with the 52.97 mm^2/s viscosity lubricant. In comparing the impact response of specimens coated with a 0.575 mm thick layer of lubricant, the COR, permanent deformation, and contact diameter (Figure 3) all appear to be lower than for the dry case (Figure 1). As the viscosity of the lubricant is increased (from 52.97 in Figure 3 to 155.5 mm^2/s in Figure 4), the COR, permanent deformation, and contact diameter all appear to increase again to a level slightly above the dry contact condition. In directly comparing the three different lubrication conditions, it is unclear if there is a statistically significant difference between them, thus necessitating a more in depth statistical analysis.

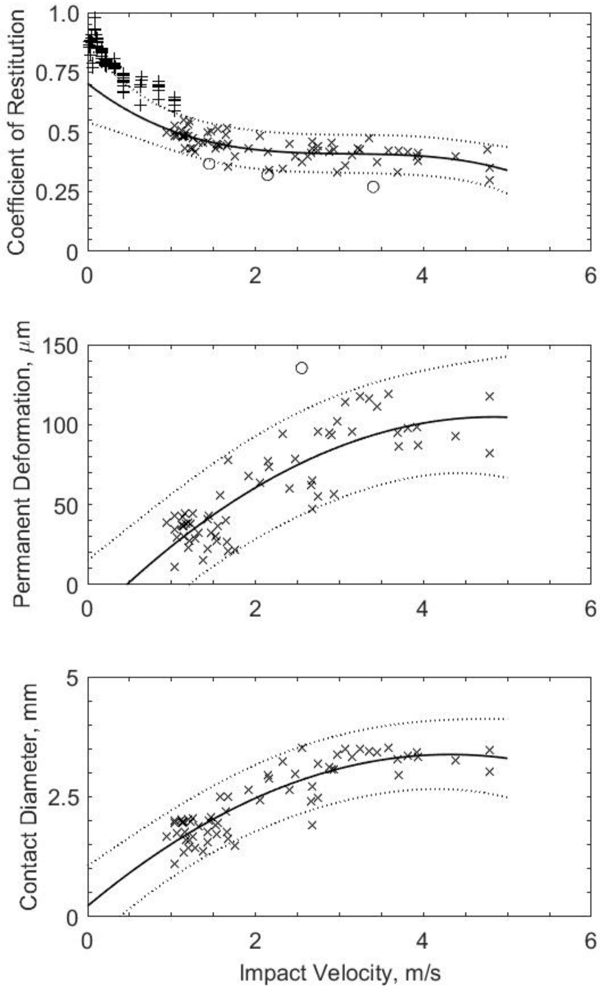

Figure 1: Measured response of impact against a dry surface as a function of impact velocity for (top) CoR, (middle) permanent deformation, and (bottom) diameter of impact crater. Solid black lines indicate the mean response, dashed lines indicate 95% confidence intervals. Experimental data from this study are indicated by 'x'. Outliers (excluded from the statistics) are indicated by 'o'. Data from a previous study [3] using the same materials is shown via a + symbol.

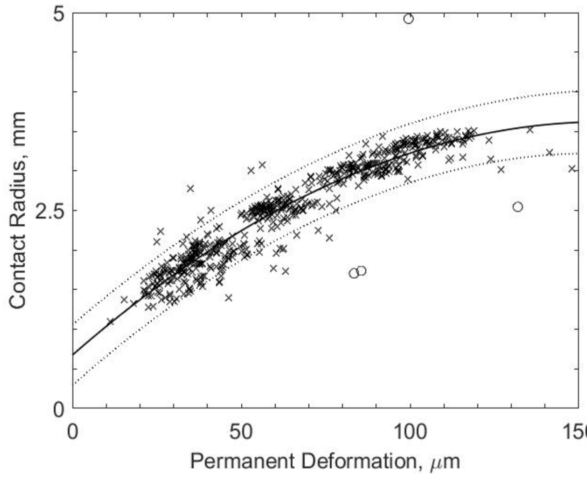

Figure 2: Measured contact radius as a function of permanent deformation for all impacts (dry, all lubricants, all lubricant thicknesses). Measured data is indicated with x's and o's, the latter of which are classified as outliers and are not used in the calculation of the mean and 95% confidence intervals. The mean response is indicated by a solid line, and the 95% confidence interval is indicated by a dashed line.

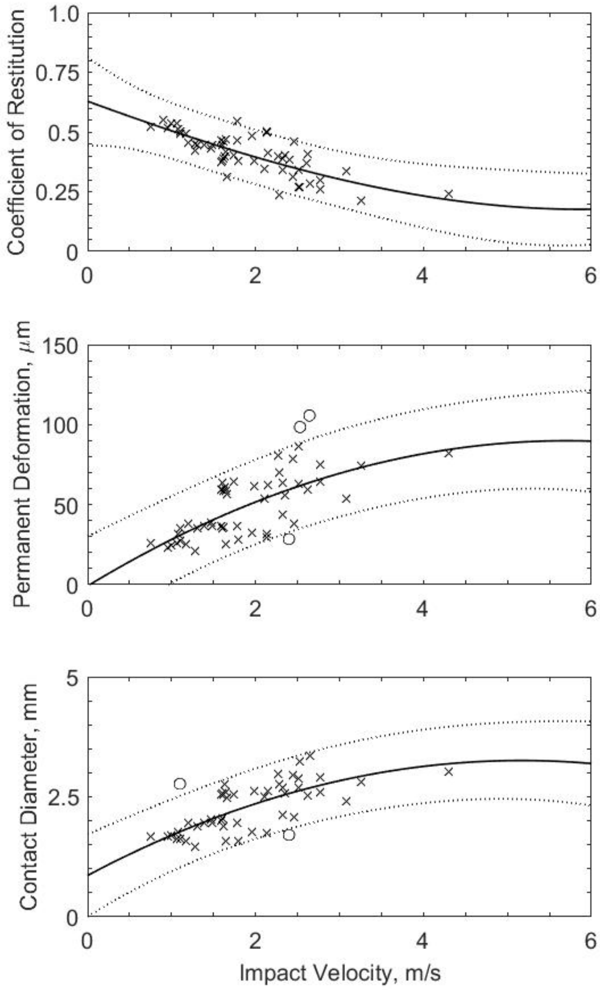

Figure 3: Response for impacts with a 0.575 mm thick layer of the 52.97 mm²/s viscosity lubricant. The legend is the same as Figure 1.

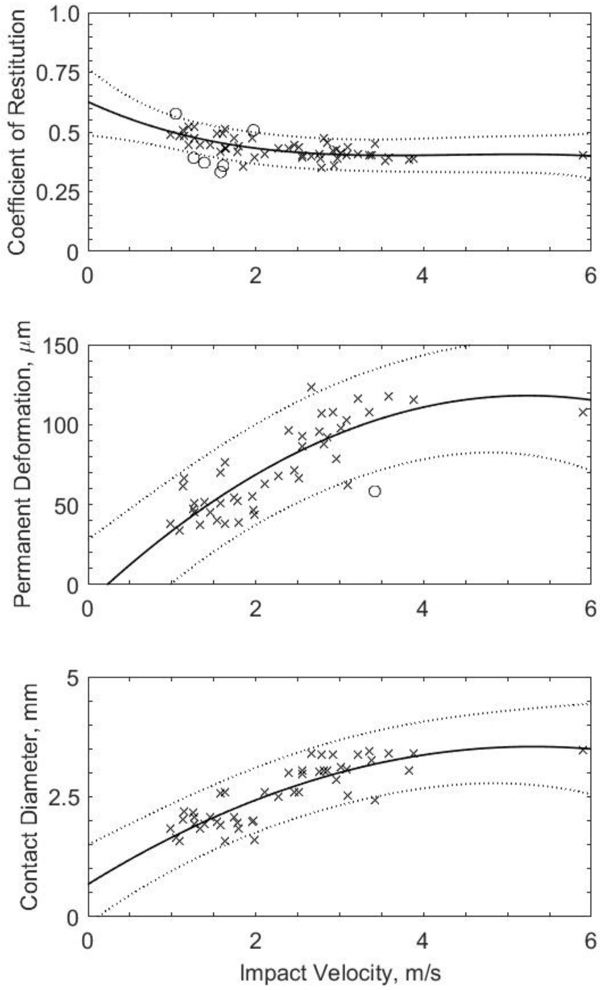

Figure 4: Response for impacts with a 0.575 mm thick layer of the 155.5 mm²/s viscosity lubricant. The legend is the same as Figure 1.

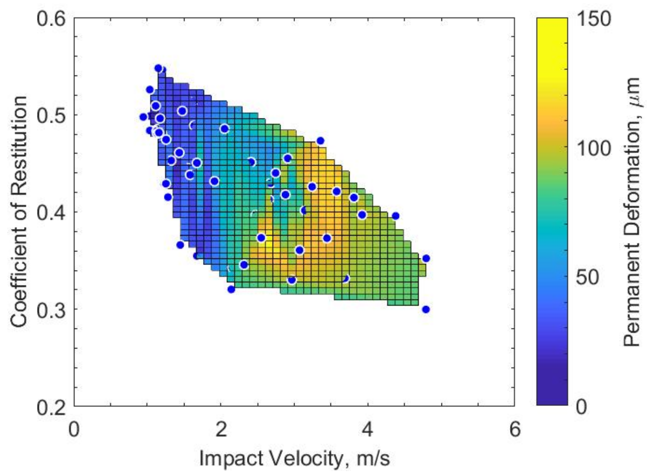

Figure 5: Permanent deformation as a function of impact velocity and CoR for the dry impacts. Blue dots are a subset of the measurements that are visible above the best fit response surface.

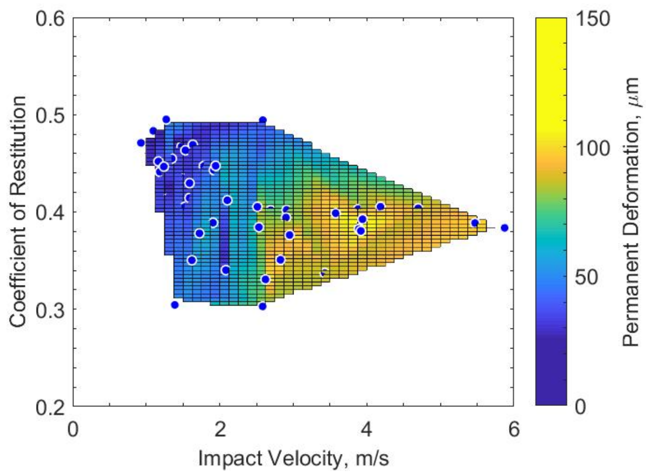

Figure 6: Permanent deformation as a function of impact velocity and CoR for a 0.23 mm thick layer of the 155.5 mm²/s viscosity lubricant. Blue dots are a subset of the measurements that are visible above the best fit response surface.

To better understand the contribution of the lubricant to the dynamics of elastic-plastic impact, first the permanent deformation is shown as a function of the impact velocity and CoR in Figure 5 for the dry condition. Here, the blue dots indicate data points above the response surface, with the remainder of the data points not being visible. Using a piecewise linear regression, the same curvilinear feature is observed where the maximum permanent deformation is not at the maximum impact velocity.

For the lubricated condition (shown for the viscosity of 155.5 mm^2/s), several trends emerge in comparing Figure 5 to Figures 6 and 7 (which have lubrication thicknesses of 0.230 and 0.575 mm respectively). First, low velocity impacts of lubricated surfaces have lower COR, which is perhaps due to more energy being dissipated by the lubrication. Second, at high velocities, less energy is dissipated by the lubricated surfaces, and this effect becomes more pronounced for thicker lubrications (compare Figure 6 to Figure 7, which has the thickest lubrication layer). Third, the maximum permanent deformation occurs at the highest velocities, in contrast to the previously observed trends from analyzing all of the data together.

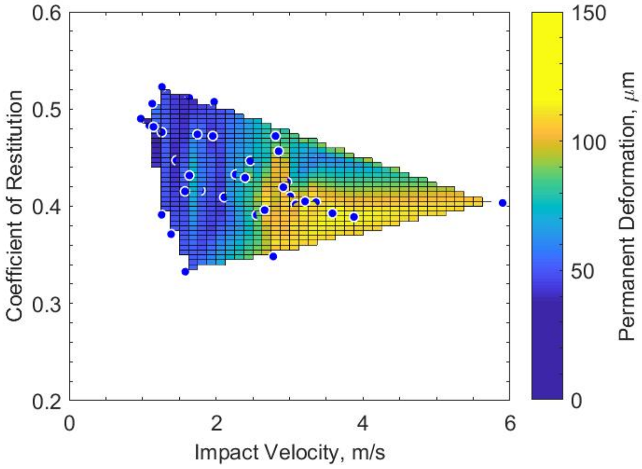

Figure 7: Permanent deformation as a function of impact velocity and CoR for a 0.575 mm thick layer of 155.5 mm^2/s viscosity lubricant. Blue dots are a subset of the measurements that are visible above the response surface.

Discussion

To test the effects of lubrication and thickness rigorously, a three-way ANOVA test is performed for the CoR, permanent deformation, and indentation diameter separately as functions of the lubrication thickness, viscosity, impact velocity, and interactions between those three variables. In all cases, the impact velocity has a p value less than 0.0001, as expected. For the CoR, viscosity has a significant p value of 0.0003, and the interaction between viscosity and velocity has a p value less than 0.0001 as well. This indicates that both impact velocity and lubrication viscosity significantly influence the CoR, but not the lubrication thickness (for the thicknesses studied).

In testing the permanent deformation, a different trend is observed. Again, the impact velocity has a p value less than 0.0001, but the viscosity no longer has a significant p value (0.2042). Instead, the thickness has a significant p value of 0.0003, and all interactions are found to be significant too. By contrast, the indentation diameter is significantly dependent on impact velocity (p value less than 0.0001), lubrication thickness (0.0001), and, to a lesser extent, viscosity (0.0058). As well, the interactions between the impact velocity and both the lubrication thickness (0.0008) and viscosity (0.0001) are significant. Thus, from this three-way ANOVA test, there is a statistically significant difference in the measured responses of the CoR, permanent deformation, and indentation diameter as functions of the impact velocity and lubrication properties.

The ramification of these findings is that the lubrication has a significant and curvilinear effect on the damage of a substrate due to impact. Low viscosity lubricants are shown to increase the energy dissipation of a lubricated impact but decrease the permanent damage of the substrate. By contrast, high viscosity lubricants decrease the energy dissipation of a lubricated impact but increase the permanent damage. One potential explanation for this is the shear behavior of the different lubricants. With high velocity impacts, due to the high strain rates, it may be the case that plug flow occurs where only the lubrication directly under the impactor is displaced/compressed; whereas for low viscosity lubrications, the fluid flows more easily, allowing significantly more dissipation by the lubrication away from directly under the impactor. It can be inferred from these results that WECs could be ameliorated through the use of lower viscosity lubricants. Further work, though, is necessary to confirm this.

2. Subjects remain to be solved in future/Subjects required further investigation

The present research focused on experimentally assessing the effect of lubrications on impact properties. The next stage of this research will focus on the theoretical modeling of elastic-plastic hydrodynamic lubrication (EPHL). In particular, computational modeling will be used to explain the observed contradictory behavior: that for higher viscosity lubrications, less energy is dissipated by the impacts, but there exists larger permanent deformations. With this new body of experimental evidence, ongoing theoretical work can be validated and new formulations for the interaction between the lubrication and substrate can be proposed.

3. Plan and past presentation or publication of your research results

Preliminary work for this project was presented at the 2019 STLE Annual Meeting [4]. The completed research will be presented at the 2020 STLE Annual Meeting in May, 2020. Additionally, a journal article is planned for a special issue on Tribology in the open source journal *Frontiers in Mechanical Engineering*.

References

[1] P. L. Reu, D. P. Rohe, L. D. Jacobs, "Comparison of DIC and LDV for Practical Vibration and Modal Measurements," *Mechanical Systems and Signal Processing*, **86**, pp. 2-16, 2017.

[2] N. G. Popinceanu, "A Study of Rolling Bearing Fatigue Life with Mineral Oil Lubrication," *Wear*, **22**, pp. 21-37, 1972.

[3] M. R. W. Brake, P. L. Reu, and D. S. Aragon, "A Comprehensive Set of Impact Data for Common Aerospace Metals," *ASME Journal of Computational and Nonlinear Dynamics*, **12**, pp. 061011-1-23, 2017.

[4] S. E. Ahadzie, H. Ghaednia, and M. R. W. Brake, "When Does Roughness Affect Elastic-Plastic Contact?" *2019 STLE Annual Meeting*, Nashville, TN, May, 2019.