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Applying Similitude Modeling Methods to Tribological Applications

Introduction

Tribology is a field encompassing topics such as friction, wear, and lubrication. Because tribological principles often act on a small scale, gathering accurate data can be difficult. The method of similitude is often used to scale down fluid dynamics problems by using dimensionless parameters. This project aimed to apply similitude modeling to instead scale up wear tests, which are often used in the field of tribology. To investigate the interaction between scaled-up surface forces and total wear amount, it was necessary to use a different force to represent the surface forces. The primary objectives of this study were to establish a method of scaling up tests to measure wear on a macroscopic level and to begin investigating the impact of varying parameters on wear amount.

Methods

Ten variables were identified that describe the process of wear: mass wear (Q), area of contact (A), sliding distance (l), normal pressure (σ), elastic modulus (E), adhesive strength (α), yield strength (S_y), surface roughness (R), average sliding velocity (v), and density (ρ). By applying the Buckingham Pi Theorem, seven dimensionless terms were determined which can be used to form an equation that describes wear at any scale:

$$\pi_1 = \frac{Q}{l^3\rho} \quad \pi_2 = \frac{A}{l^2} \quad \pi_3 = \frac{\sigma}{E} \quad \pi_4 = \frac{\alpha}{E} \quad \pi_5 = \frac{S_y}{E} \quad \pi_6 = \frac{R}{l} \quad \pi_7 = v\sqrt{\frac{\rho}{E}}$$

This project focused on the interaction between the first and fourth of these terms, specifically the effects of adhesive strength on mass wear. Adhesive strength is determined by the interaction of surface forces, such as van der Waals forces. Surface forces do not scale up automatically with the geometric scaling of the system like surface roughness or area of contact nor are they easily controllable like normal pressure or sliding distance. To overcome this problem, surfaces forces were instead represented on a larger scale by magnetic forces. Because it is soft enough to wear away in measurable amounts and can be easily observed, wax was used as the test material. Magnetic wax was created by mixing magnetite (Fe_3O_4) powder with melted paraffin wax. Test tubes were used as molds to create samples with spherical tips. An example of the samples used can be seen in Figure 1.

A macroscopically textured stainless-steel plate was used as the counterface against which the wax sample was rubbed for the wear test. Magnets of varying strength were used and placed directly under the plate. With four levels of magnetism investigated, including no magnet and three separate magnets, and three wear tests conducted for each one, there were a total of twelve tests run in a randomized order. Material properties, geometry, sliding distance, normal pressure, and sliding velocity were held constant, so the only parameter changed was the magnetic force representing the surface forces. An Rtec tribometer was used to hold the sample and apply a constant normal force of 1.5N between the sample and the counterface. The motion stage was programmed for 1000 cycles of a 38mm reciprocating line (for a total of 76m of sliding distance per test) with an average velocity of 17.1mm/s. This resembles the setup of a typical wear test commonly used in tribology.


Figure 1:Wax Sample

Wear was measured as the mass of material removed during the test. The mass of the sample was taken before the test. After the wear test, any wear debris remaining on the sample was cleaned off by gently rinsing the sample with distilled water and ethanol. The sample dried completely, and the final mass was measured. Wear was then defined as the difference between the initial and final mass measurements.

Results and Discussion


Figure 2: No Magnet Wear Debris Pattern


Figure 3: Small Magnet Wear Debris Pattern


Figure 4: Medium Magnet Wear Debris Pattern


Figure 5: Large Magnet Wear Debris Pattern

Wear debris patterns can be seen in Figures 2-5. The circle indicates the position of the magnet below the textured surface. This shows that the presence of surface forces at any level (Figures 3-5) causes a significant difference in how the wear debris of the wax builds up compared to when there is no magnetic force present (Figure 2). Without a magnetic force, the wax debris was well-distributed across the path of sliding with only a slight buildup present around the edges and at the turning points of the reciprocating path. When a magnet was used, the particles became magnetized and attracted to one another, so the wear debris built up almost exclusively at the ends of the path with very little debris accumulating across the length of the wear path. Some wear debris also collected on the sample during the tests. Figures 6 and 7 show a sample after the wear test with debris still attached and after being cleaned, respectively. Due to the wear that occurs during the test, the tip of the sample has flattened from its initial spherical shape.


Figure 6: Sample With Debris


Figure 7: Cleaned Sample After Test

The mass wear data for each of the 12 tests corresponding to the level of magnetism used is shown below in Figure 8. Although it was expected that the wear would be greater as the magnetic force increased, the evidence did not support this, and no obvious pattern emerged from the results. The average wear increased from no magnet up to the medium magnet but then dropped again when the large magnet was used. Figure 9 shows a comparison of the dimensionless terms $\pi_4=\alpha/E$ (surface forces) and $\pi_1=Q/(l^3\rho)$ (mass wear). The mean values of the three trials are shown with error bars indicating the standard error of the mean. Analysis was done using both the student-t test method and Tukey's method. This analysis showed no significant differences in the mass wear value means when comparing all four surface force values at a 95% confidence level.

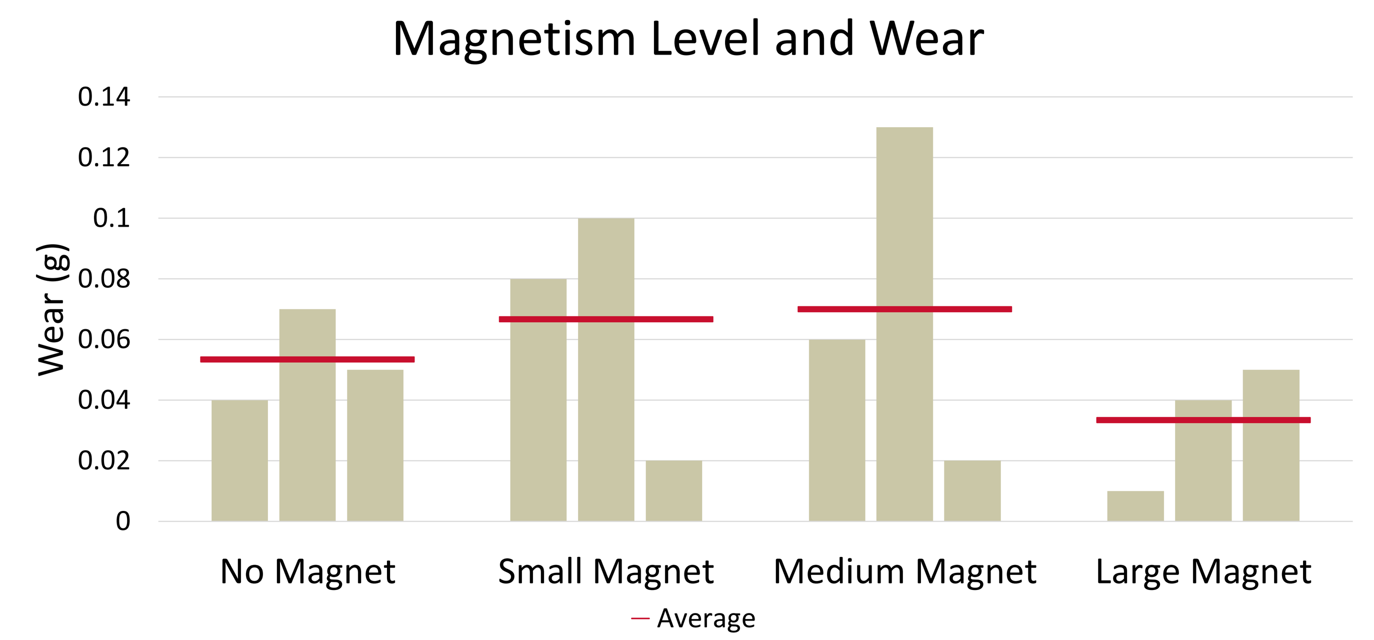

Figure 8: Magnetism Level and Corresponding Wear Data

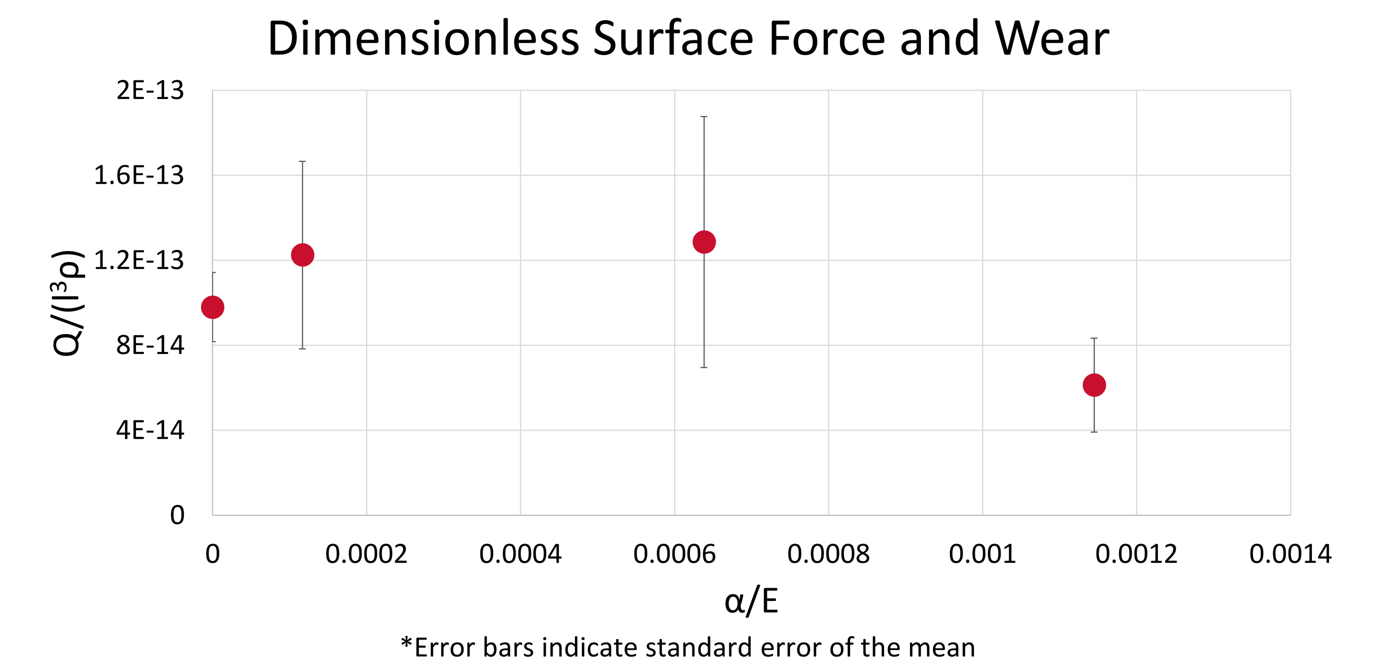

Figure 9: Dimensionless Surface Force and Wear Average Data

Conclusion

Qualitative observations showed that the presence of surface forces impacts the distribution of wear particles that accumulate during a wear test. The quantitative results, however, showed that, at the levels of magnetism tested, changing the dimensionless surface force value does not significantly impact the mean dimensionless wear value. A method of scaling up tests to measure wear on a macroscopic level was established, which provides a basis for future research to investigate how the other parameters discussed may impact wear amount. Establishing these relationships could then lead to the implementation of similitude modeling in various tribological applications.