Taiho Kogyo Tribology Research Foundation

Main report

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Theme: **Development, Application and Evaluation of a Novel Mixed and Boundary Friction Model**

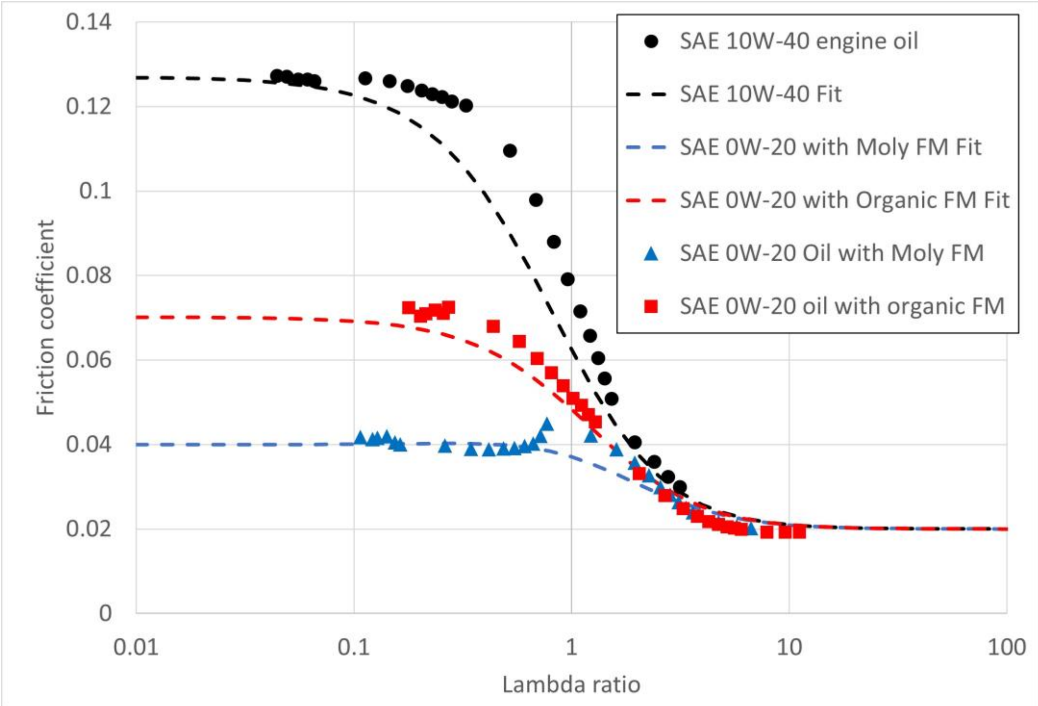
1. Progress and result of the research

Under a previous TTRF grant, a new approach for estimating mixed/boundary friction was developed [1] which was in better agreement with experimental data [2] than widely used models such as those based on the Greenwood Tripp contact model [3]. However, the initial approach was applicable to just lubricant base oils or lubricants that only contained anti-wear additives such as ZDTP.

A major goal of the current TTRF grant was to extend the model to also include the influence of friction modifiers in lubricants, which are widely used in passenger car engine lubricants.

The previous model found that the proportion of mixed/boundary friction in a contact, X, varied with the Lambda ratio, λ, according to $X = (1+\lambda^k)^{-a}$, with $k \approx 3/2$ and $a \approx 4/3$ [1]. It was realized that this equation could be modified to allow for friction modified lubricants by writing the equation as $X' = (c+\lambda^k)^{-a}$ where the constant c is greater than 1 for lubricants that contain friction modifiers. It is important to realize that the proportion of mixed/boundary friction is still given by X, but in effect the boundary friction coefficient, f_o, (the friction coefficient when λ=0) is altered for friction modified lubricants so as to become $f_o.X'/X$. The friction force predicted by the model is given by $(f_o.X'/X).X.W$, where W is the load on the contact. In the case of lubricant base oils, or lubricants that just contain anti-wear additives, X' = X, and so the mixed/boundary friction force is just $f_o.X.W$, whereas for lubricants that contain friction modifiers, the mixed/boundary friction force is given by $f_o.X'.W$. For both equations, once λ is greater than 4, X and X' are both close to zero, since the rough surfaces are almost completely separated by a fluid film, and once full separation occurs, friction due to mixed/boundary friction is essentially zero.

Published experimental data [4] was used to estimate the value of c for lubricants containing different friction modifiers (MoDTC and glycerol monooleate (GMO)) and the modified equation was found to give a good fit to experimental friction data from Mini-Traction Machine experiments as shown in the Figure below. This work has been accepted for publication in Tribology Online [5] and a presentation is also planned to be delivered at the International Tribology Conference that is to be held in Fukuoka, Japan, in Sept 2023. In the figure below, the value of c for the molybdenum containing lubricant was estimated to be 2.38, whereas for the lubricant containing GMO (labelled as organic FM in figure) c was 1.56, and for the SAE 10W-40 engine oil, which did not contain a friction modifier, c = 1. In all cases, the value of f_o was assumed to be just over 0.12.



The importance of the work carried out is that relatively simple equations have been proposed that enable tribologists and engineers to quickly estimate the amount of mixed/boundary friction in a lubricated contact, provided the λ ratio is known. The proposed equation is a good fit to experimental data and can enable better estimates to be made for mixed/boundary friction forces and power losses. This is important as it is anticipated that mixed/boundary friction will become more important in future machines (since lubricant viscosities are decreasing, loads and temperatures are increasing, and machines, and the amount of lubricant in them, are getting smaller).

Software has been developed (which can potentially be made available to researchers that request it) for the important engine components that have significant amounts of mixed/boundary friction, namely the valve train and the piston rings. The valve train software has been implemented in Excel, whereas the more complex nature of piston ring lubrication required code to be written in Python. For both components, the software calculated the oil film thickness in the contact, for varying operating conditions, and allowing for different lubricant properties. The Lambda ratio, λ, was estimated by using the calculated oil film thickness values and assuming a surface roughness value. The equations developed under this grant were then used to estimate the friction forces (and power losses) due to mixed/boundary lubrication. It was previously found that the Greenwood and Tripp contact model [3], although still widely used within the tribology community in estimates of boundary/mixed friction, tended to underestimate the amount of mixed/boundary friction (a finding also noted by Leighton et al [6] in 2017).

Estimates for the financial and CO_2 impacts of mixed/boundary friction have also been made, initially for passenger cars. The results of this study were reported in a Plenary Presentation delivered at the LUBMAT 2023 international tribology conference held in Preston [7]. An extended version of this work will be prepared and submitted to the MDPI journal “Lubricants” as part of a special edition devoted to the LUBMAT 2023 conference.

It was estimated that mixed/boundary friction accounted for between 10-20% of fuel burnt in passenger car vehicles. If the distance driven in an average car is assumed to be 10,000 miles per year, the total fuel used is approximately 1000 litres. Under these conditions, it is estimated that between 100 and 200 litres of fuel, per car, per year, is used to overcome mixed and boundary friction. For the UK alone, where there are currently around 30 million passenger cars in use, the total financial cost of mixed/boundary friction in passenger cars, for the UK alone, per year, would be approximately $6 to 10 billion, and the CO_2 emissions associated with mixed/boundary lubrication (for UK passenger cars) would be in the range 10-20 million tonnes (since approximately 2.4 kg of CO_2 is released when 1 litre of gasoline is combusted.) In addition, around 0.7 kg of CO_2 is emitted during the extraction, manufacture and transportation of fuel.

Previously, Holmberg and Erdemir [8] have estimated the proportion of mixed/boundary friction in engines at around 10%, whereas the present work suggests a figure of 10-20%. There can be a significant difference in the amount of mixed/boundary friction depending on both engine design and the way in which vehicles are driven (with stop-start, city type driving, usually being more severe).

As part of this project, a broader look at the importance of mixed/boundary friction was also made. We have found that all costs related mixed/boundary friction accounted for approximately 6% of total world energy usage. Since lubricated friction has been estimated to account for 20% of total world energy usage, this suggests that a rough "rule of thumb" is that the costs of mixed/boundary friction are approximately one-third of the costs due to lubricated friction.

Holmberg and Erdemir [8] have previously estimated that mixed/boundary friction accounts for 3% of total world energy usage, but a more detailed look at their figure indicates this is only the percentage associated with the manufacture of replacement parts and does not include the costs of any machine downtime, nor those associated with transporting the replacement parts to where they are needed and fitting them. Therefore, our conclusion is that a figure of 6% is a more reasonable one to use, with 3% being "primary" costs (energy for manufacture) and another 3% being "operational" costs. These financial costs could also be converted into CO_2 emissions if required.

The work conducted in this project has been communicated directly to Japanese researchers at the International Tribology Conference (Fukuoka, Japan, September 2023), where Dr Taylor presented the work described above, and in addition, delivered a plenary presentation on sustainable lubricants

We have also developed a programme of one day workshops to explain to other researchers how to calculate mixed/ boundary friction supported by unspent money from a previous TTRF grant. These workshops will be used to communicate details of the models that we have developed to predict mixed/boundary friction and to demonstrate the software that has been developed to analyse a range of contacts. We intend to make this software publicly available and we will further encourage more tribologists to make use of the results of this work funded by TTRF. The first workshop will be free to attend for PhD students (Europe wide) and the second workshop will be targeted at industrially based tribologists.

References:

1. R.I. Taylor & I. Sherrington, "A Simplified Approach to the Prediction of Mixed and Boundary Friction", Tribology International, 2022, Open Access. Available online at: https://www.sciencedirect.com/science/article/pii/S0301679X2200408X
2. J. Dawczyk, N. Morgan, J. Russo & H. Spikes, "Film Thickness and Friction of ZDDP Tribofilms", Tribology Letters, 67:34, 2019
3. J.A. Greenwood & J.H. Tripp, "The Contact of Two Nominally Flat Rough Surfaces", Proc. Instn. Mech. Engrs., **185**, pp 625-633, 1970
4. R.I. Taylor, "Tribology and Energy Efficiency: From Molecules to Lubricated Contacts to Complete Machines", Faraday Discussions, **156**, 2012

5. R.I. Taylor & I. Sherrington, "Prediction of Friction Coefficients in Mixed Lubrication Regime for Lubricants Containing Anti-Wear and Friction Modifier Additives", Tribology Online 2023 https://www.jstage.jst.go.jp/article/trol/18/4/18_185/_article
6. M. Leighton, N. Morris, R. Rahmani & H. Rahnejat, "Surface Specific Asperity Model for Prediction of Friction in Boundary and Mixed Regimes of Lubrication", Meccanica, 52:21-33, 2017
7. R.I. Taylor & I. Sherrington, "", LUBMAT 2023 conference, July 2023, Preston, UK (available at: https://clok.uclan.ac.uk/48018/)
8. K. Holmberg & A. Erdemir, "Global Energy Consumption Due to Friction in Passenger Cars", Tribology International, **47**, 221-234, 2012

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

(1) An application of the mixed/boundary friction approach to other important machine elements such as gearboxes and rolling element bearings would extend the current work to other important machine elements. Although estimates of the amount of mixed/boundary friction are available for passenger car engines, estimates of equivalent figures for heavy duty engines, gearboxes (both automotive and industrial) and rolling element bearings are not readily available, and are also expected to vary widely, depending on operating conditions, machine design, and lubricants used.
(2) Improved estimates of reliability and machine life on overall life cycle costs should be made. The work described here will allow estimates of both financial costs and CO_2 emissions to be made.
(3) At an analytical level, further work is needed to better understand how the value of c used in the equation for friction modified oils depends on the chemical and physical properties of the friction modifier additives.

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

Peer Reviewed Publications

(1) R.I. Taylor, "Rough Surface Contact Modelling – A Review", Lubricants, 2022, 10(5), 98; https://www.mdpi.com/2075-4442/10/5/98
(2) R.I. Taylor & I. Sherrington, "A Simplified Approach to the Prediction of Mixed and Boundary Friction", Tribology International, 2022, Open Access. Available online at: https://www.sciencedirect.com/science/article/pii/S0301679X2200408X
(3) R.I. Taylor & I. Sherrington, "Prediction of Friction Coefficients in Mixed Lubrication Regime for Lubricants Containing Anti-Wear and Friction Modifier Additives", Tribology Online 18(4) (2023) pp 185 – 192 https://doi.org/10.2474/trol.18.185
(4) R.I. Taylor & I. Sherrington, "", LUBMAT 2023 conference, July 2023, Preston, UK (available at: https://clok.uclan.ac.uk/48018/)
(5) A more detailed paper based on the LUBMAT conference preprint is planned to be submitted to MDPI Lubricants Journal Open Access. (Special Edition for papers from the LUBMAT 2023 conference)

Conference Presentations

(1) R.I. Taylor & I. Sherrington, "The Environmental and Economic Importance of Mixed and Boundary Lubrication", Invited Presentation, LUBMAT 2023 International Conference, Preston, July 2023
(2) R.I. Taylor & I. Sherrington, "The Use of S-Curves for Improved Prediction of Mixed and Boundary Friction", Presentation at International Tribology Conference, Fukuoka, Japan, September 2023