Taiho Kogyo Tribology Research Foundation

Main report

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Theme: Modelling the influence of friction modifiers and anti-wear films on friction in the mixed/boundary lubrication regime

1. Progress and result of the research

A literature review of rough surface contact models was carried out which has since been published in mid-2022 in the MDPI Lubricants journal [1] (the paper can be accessed at: https://www.mdpi.com/2075-4442/10/5/98). During the review it became apparent that the original plan, to extend the Greenwood-Williamson models to allow for surface layers (to simulate tribo-films) would not work as intended, since such models essentially contain a dimensionless group ($\eta\beta\sigma$) where η is the density of asperities per unit area, β is the radius of curvature of the asperities, and σ is the combined RMS roughness of the surfaces. It has been pointed by numerous researchers in the scientific literature that these parameters are not independent and ($\eta\beta\sigma$) is essentially constant, with a value typically in the range 0.03-0.05. The main effect of the combined RMS roughness, σ, is then on the lambda ratio, λ, defined as the dimensionless parameter h/σ where h is the oil film thickness separating the surfaces. Therefore, it is the surface roughness of the tribo-layer that is important in determining the "shape" of the mixed/boundary friction curve when plotted against λ, not the thickness of the tribo-layer. In addition, models that extend the Greenwood-Williamson analysis to allow for surface layers and/or tribo-films have already been published, so it was felt that there would be little benefit in developing an additional model of this type.

Recent experimental friction data (from a Mini-Traction Machine) became available in 2019 [2] (from Imperial College) in which the proportion of mixed/boundary lubrication, X, was explicitly reported as a function of λ. Importantly, both lubricants without additives (base oils) and lubricants which contained ZDDP tribo-films were all found to fit on the same common curve, provided the RMS roughness of the tribo-film was used in the analysis of the friction data. To check this concept of a "universal" curve, additional published MTM friction data from the scientific literature was analyzed in the same way, and this additional oil data was found to lie on the same curve as that proposed by Imperial College. When the proportion of mixed/boundary friction, X, was plotted against λ, the common curve took the form of a "reverse S-curve". If the data was plotted against $1/\lambda$, the common curve took the form of an "S-curve". In hindsight, this should not have been a surprise, since the contact of rough surfaces is essentially a growth process, since the proportion of mixed/boundary friction, X, grows with $1/\lambda$ (from X = 0% at large values of λ, when the rough surfaces are completely separated, and there is no metal-to-metal contact, to 100% when $\lambda = 0$ and there is no lubricant film separating the surfaces) and growth processes are known to lead to parameters that vary according to an "S-curve".

A standard equation for reverse S-curves was used, and when modified to take account of the fact the tribological data is usually plotted against the logarithm of λ, it was found that a relatively simple equation, $X = (1 + \lambda^k)^{-a}$ provided a good fit to the experimental equation (where the best-fit values were found to be approximately $k \approx 3/2$ and $a \approx 4/3$). This very straightforward equation can be used by engineers and tribologists to quickly estimate the amount of mixed/boundary friction of a lubricated contact. The mixed/boundary friction force would then simply be given by $f_o.X.W$, where f_o is the friction coefficient when λ=0, X is given by the equation above, and W is the total load acting on the contact. The lambda ratio, λ, clearly needs calculating to estimate X, but there are well known methods for estimating the oil film thickness in a lubricated contact, and the RMS roughness can be measured experimentally using a profilometer. The value of f_o is typically in the range 0.1 to 0.15 but will depend on the materials used and the operating conditions – load, speed, temperature, and is usually measured experimentally.

One potential criticism of the first stage of this work could be that the curve fit on which the equation was based was from a single tribometer (the Mini Traction Machine, from PCS Instruments) operating over a limited range of speeds/loads/temperatures, with relatively smooth surfaces. Consequently, additional experimental data was sought to check the validity of the proposed mixed/boundary friction equation. The simple proposed equation was found to be in reasonable agreement with data from these other tribometers.

Broadly speaking, the experimental data suggested that X was approximately 30-50% when λ=1. The proposed equation gives a value of X ≈ 40% when λ=1. A comparison was carried out for other asperity friction models in common use today. Somewhat surprisingly, the Greenwood-Tripp model [3], which is still widely used today, predicts a value for X of only around 13% for λ=1, suggesting that this model significantly underestimates the amount of mixed/boundary lubrication in a contact. This conclusion agrees with recent published work by Leighton et al [4] which also found the Greenwood-Tripp model underestimated the amount of mixed/boundary friction, when compared with experimental measurements.

The above work has been reported in detail in an international peer reviewed journal as an Open Access research paper in Tribology International [5]. (A widely distributed tribology journal that has an impact factor of 5.62).

The derived equation does not, at present, apply to lubricants containing friction modifier additives. This is because such additives are thought to only form relatively thin films on surface asperities, so are not likely to significantly change the λ ratio. Instead, friction is reduced by the low shear molecularly thin films sliding over each other. Towards the end of the project, it was realized that a slight adaptation of the new equation could be used for friction modified oils. By changing the equation from $(1 + \lambda^k)^{-a}$ to $(c + \lambda^k)^{-a}$ where c is greater than 1 for friction modified oils (and c = 1 for base oils and oils containing anti-wear additives only), there is the potential to fit the friction versus λ curves of friction modified oils. Work is ongoing to check if data published in the scientific literature can be fitted in this way.

The importance of the work carried out to date is that a relatively simple equation has been proposed that enables 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 should 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).

Unfortunately, no significant progress was made in modelling the growth of tribo-films and their dynamics. A review of relevant recent papers on this topic was carried out, and it was concluded that most research work was focused on predicting the thickness of the developed tribo-films, whereas as described above, the parameter most relevant for predicting mixed/boundary friction is the roughness of the developed tribo-films.

References:

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

(1) It has been reported experimentally, by Imperial College, that the surface roughness of ZDDP tribo-films is significantly different from that of the underlying substrate (in the case of the Mini-Traction Machine, the original RMS roughness of each surface was only 4 nm, whilst the RMS roughness of the thick tribo-film was around 40 nm). ***Predicting the roughness of tribo-films as they grow is a problem that remains to be solved***

(2) The present work needs extending to include the effect of friction modifier additives. Friction modifiers generally form molecularly thin films, which will not significantly affect the λ ratio, but can change the shape of the friction curve. The shear stress of the friction modifier film needs including in any equation that is used to predict mixed/boundary friction. ***Further work is needed to extend the simple mixed/boundary equation to allow for lubricants that contain friction modifiers*** (however, it should be noted that such additives are only used in around 15-20% of lubricants sold worldwide)

(3) Prediction of f_o (the maximum friction coefficient at low speed). Even with the simple equation proposed, a value of f_o still needs to be included to calculate friction losses. A typical value would be 0.1 to 0.15, but it is known this value depends on operating conditions and materials used. For a particular materials combination, if f_o is known for one set of operating conditions, it would be very useful if f_o could be predicted at another set of operating conditions. ***Further work is needed to develop an equation that predicts f_o as a function of operating conditions.***

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

(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) Invited presentation at the online Swiss Tribology 2022 meeting (28th June 2022). Presentation titled "A Simplified Approach to Mixed/Boundary Friction Using S-Curves"

(4) Invited presentation at UK Net Zero tribology meeting organized by the Institution of Mechanical Engineers, 30th June 2022. Presentation titled "The Economic and Environmental Costs of Mixed/Boundary Lubrication"

(5) R.I. Taylor & I. Sherrington, "Prediction of Friction Coefficients in the Mixed Lubrication Regime for Lubricants Containing Anti-Wear and Friction Modifier Additives. Submitted to Tribology On-line. (November 2022)

We will continue to disseminate results of this research funded by TTRF in open literature and will encourage the application of the method developed by publishing examples of its application and by introducing the method to our own graduate students.