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Development of an interactive friction model for the prediction of lubricant breakdown behaviour during sliding wear

Y. Hu, L. Wang*, D.J. Politis, M.A. Masen

Department of Mechanical Engineering, Imperial College London, Exhibition Road, London SW7 2AZ, UK

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ABSTRACT

In this paper, a novel interactive friction-lubricant thickness model was developed to predict the evolution of coefficient of friction and the useful life of lubricant film. The developed model was calibrated by experimental results determined from pin-on-disc tests. For these experiments, a grease lubricant was applied on a Tungsten Carbide ball which slides against a disc made from AA6082 Aluminium alloy. In the pin-on-disc tests, the lubricant film thickness decreased with time during single path sliding leading to a rapid increase in the coefficient of friction. The breakdown of lubricant was divided into three stages, namely, the Stage I low and stable coefficient of friction region, Stage II region in which the coefficient of friction sees a rapid rise, and Stage III in which the coefficient of friction reaches a plateau with a value similar to that of dry sliding. In order to characterise the evolution of coefficient of friction throughout these stages, a novel interactive friction model was developed combining the effects of sliding distance, sliding speed, contact pressure and initial lubricant amount on the evolution of the coefficient of friction. This interactive friction model can be applied to situations involving lubricant breakdown in a dynamic environment such as the metal forming industry, where the use of traditional constant coefficient of friction values present limits in predictive accuracy.

1. Introduction

The study of lubrication breakdown in a lubricated contact has received some attention amongst metal forming researchers due to the growing demand for accurate FE simulation of boundary conditions. In most forming cases, a moderate quantity of lubricant applied between the workpiece and the tool can provide a separation barrier during the metal forming process [1,2]. This amount of lubricant typically involves the assumption of ideal full film lubrication conditions with low coefficient of friction and little wear due to moving objects. However, in many situations, it is not always possible to maintain ideal full film lubrication conditions and there may be considerable levels of non-hydrodynamic lubrication, e.g. boundary lubrication, that result in galling or wear on tooling and the product. This is especially essential for sheet metal forming processes, where the transportation of lubricant is uneven due to the non-uniform distribution of relative sliding distance, strain and contact pressure at the workpiece-tooling interfaces. Moreover, in many cases, lubricant is squeezed out towards regions with lower pressure and side leakage occurs, which will cause further loss of lubricant from the contact and lead to lubricant film breakdown. Therefore, an adequate quantity of lubricant applied prior to the forming operation does not guarantee that lubrication will be effective at all locations or at all stages of a forming operation [2,3].

In recent years, FE simulation has been widely used by metal forming engineers to analyse and optimise forming processes. The coefficient of friction, as one of the key inputs for an FE model, is normally assigned as a constant value [4–7]. However, in practice, lubricant film breakdown might dramatically increase the coefficient of friction, due to the direct contact between the workpiece and dies [8,9]. Classic models that do not take into account changes in the lubrication consistency, may cause inaccuracies in the FE simulation results. Therefore, understanding and modelling the lubricant breakdown behaviour, and the interaction with the evolution of the coefficient of friction and lubricant service life are of great practical importance.

Previously, the phenomenon of lubricant film breakdown has been studied in many fields, including mechanical transmissions [10–12], internal combustion engines [3,13], bearings [14–16] and metal processing [11,17–19]. The influencing factors of lubricant film breakdown have been identified and quantitatively studied. They can be classified into two groups: 1) the operation parameters, including geometry of the contact, sliding speed, load and lubricant amount; and 2) the interface characteristics, including lubricant properties, surface roughness, surface plastic deformation, boundary lubrication and squeezing/side leakage. Bowden and Tabor [3] reviewed the effects of

* Corresponding author.
E-mail address: liliang.wang@imperial.ac.uk (L. Wang).

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speed, lubricant viscosity and temperature on the lubricant breakdown phenomenon in various industrial applications. The sliding speed effects on the mechanism of breakdown were also studied by Begelinger and De Gee [20], in which friction-time diagrams as a function of sliding speed were presented and two important conclusions were drawn: 1) the breakdown time is viscosity dependent and 2) in the low speed region (velocity < 2 m/s), the load-carrying capacity of the lubricant film increases with increasing sliding speed. In Kingsbury's work [14], the effect of increasing lubricant quantity, as extending the running life time before lubricant film breakdown, was observed in ball bearing tests. This effect is also studied by Groche et al. [21,22] and similar conclusions were drawn in metal forming.

As a fundamental study of mechanisms of lubricant film breakdown with the effect from operation parameters, the present paper is concerned with the lubrication of bodies in normal point contact. The aim of this paper is to develop an interactive friction model to characterize the breakdown of the lubricant during sliding point contact and its interaction with the evolution of coefficient of friction. The parameters of lubricant film diminution and breakdown as a function of time and sliding distance due to lubricant transport, sliding speed, load, and the quantity of entrapped lubricant were studied experimentally at room temperature. Based on these results, the interactive relationship between the evolution of the coefficient of friction and the reduction of the lubricant film was modelled, enabling the coefficient of friction and lubricant breakdown to be predicted through a novel friction/film thickness interactive model.

2. Experimental set-up and test programme

Aluminium sheet is studied due to its industrial potential and also lubricated difficulty, which is easy to adhere and be worn [23]. For the production of the disc samples, AA6082 sheet at T6 condition with a thickness of 1 mm was utilised. The mechanical properties of the tested metal are: Young's modulus 72 GPa, Poisson's ratio 0.33, and Vickers hardness 100 HV. The test piece material was cut into squares with dimensions of 50 mm×50 mm. All samples were ground by silicon carbide emery paper to obtain uniform surface roughness. The arithmetic average surface roughness, Ra, was 0.50 (± 0.30) μm, which was measured through a 3D white light interferometry surface profilometer (Veeco Wyko NT9100). The ball material used as the counterpart in the friction tests was Tungsten Carbide WC-6% Co ball (Young's modulus 630 GPa, Poisson's ratio 0.23, Vickers hardness 1780 HV), 6 mm in diameter, due to its good abrasion resistance and low adhesion with aluminium as a potential coating material for aluminium forming [24]. To prevent contamination, both ball and disc were cleaned with acetone and dried in air before the application of lubricant. The lubricant used for the tests was a lubrication grease, OMEGA 35, made from polyethylene glycol, silicon dioxide and graphite. This lubricant features adequate performance in a high temperature environment application (up to 700 °C). The key physical parameters of OMEGA 35 are shown in Table 1.

Two lubricant application methods were used in the friction tests: 1) a precisely controlled quantity of lubricant was applied on the ball to simulate the non-hydrodynamic lubrication (insufficient lubricant) condition and 2) lubricant was evenly applied to the disc to simulate a full film lubrication condition. For condition 1), the lubricant was applied by a dedicated rig designed and manufactured by the authors' group with micro volume lubricant reservoirs of 0.16 μL 0.24 μL, and 0.4 μL, corresponding to an average mass of lubricant applied on the ball of 4 mg, 10 mg and 14 mg, respectively. For the full film lubrication condition, 100 mg of grease was applied on the disc's surface at a thickness of 500 ± 50 μm, which was measured by a plastic wet film comb (Elcometer 3238). The initial lubricated area was assumed to be the projected area of the ball.

Table 1
Lubricant data of OMEGA 35.

Kinematic viscosity (cSt)		Specific gravity (dimensionless)		Dropping point (°C)
40 °C	35	15 °C	1.33	260
100 °C	6			

The frictional behaviour was investigated on an Anton Paar pin-on-disc tribometer under a single direction sliding. The design, measurement and evaluation of tests were partly based on ASTM standards G99. Three sets of tests were designed, aimed at investigating the influence of lubricant transportation and film breakdown phenomenon. The variables are lubricant amount, sliding speed and load. Testing conditions are shown in Table 2 and each condition was repeated three times. The dry sliding test and the full lubricant test (tests no. 1 and 5) were designed for comparing with the steady state coefficients of friction in non-hydrodynamic lubrication. Loads of 0.5, 2 and 5 N were used which corresponded to the mean contact pressure, calculated using Hertz contact theory as, 0.25, 0.4 and 0.55 GPa, respectively. All friction tests were conducted in an ambient environment, at a temperature of 24 °C. The wear track created was analysed by a white light interferometry profilometer (WLI) and an optical microscope to investigate the wear tracks obtained under lubricated and dry conditions to identify the dominant friction mechanism. The coefficient of friction revolution for each test was smoothed. For each condition, different tests were combined and the averages (solid lines) and standard deviations (error bars) are given in Fig. 4.

3. Results and discussion

3.1. Lubrication, friction and wear mechanisms

In the case of insufficient lubrication, the coefficient of friction was low at the initial stage and followed by an abrupt increase of coefficient of friction indicating the breakdown of the lubricant film; finally, the coefficient of friction increases to a stable value similar to the dry contact situation. The results of experiment No. 3 are analysed in Figs. 1–3. The coefficient of friction evolution is shown in Fig. 1 and the wear track is shown in Fig. 2 with the surface topography shown in Fig. 3 after removing the wear debris and the residual lubricant. It is found that the evolution of friction can be divided into 3 stages according to the different coefficient of frictions.

In stage I, the coefficient of friction is low and stable, with an average value of approximately 0.1. No wear scar was observed in this stage (point 1) suggesting that the two surfaces were fully separated by the lubricant film. The friction in stage I may be primarily generated by the internal fluid shear stress of the lubricant at the interface [18]. During sliding, the thickness of the lubricant film gradually decreases due to lubricant transfer from the ball to the aluminium disc and lubrication mode changes from full film lubrication to mixed lubrication regime, which is defined as a transition state between full film lubrication and boundary lubrication and in which two lubrication mechanisms may be functioning [11]. In this mode, the coefficient of friction can be regarded as a constant [3,18].

In stage II, the coefficient of friction starts rising rapidly from about 0.1 and gradually slows down at a value of 0.65. In this regime, the coefficient of friction is highly variable and unstable because the friction stems from fracture phenomena at the surface [3]. At the beginning of stage II, the thickness of lubricant decreases to the height of the peaks on the aluminium surface. In that case, the normal force is supported by both the residual lubricant trapped in the contact and the surface asperities. A wear track develops on the surface, as shown in Fig. 3 point 2 and 3, initially the wear track is almost invisible and becomes wider and deeper with increasing sliding distance. The friction force of this mixed lubrication is supposed to consist of two components: the friction force generated from interacting asperities and the