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Interpretation of friction and wear properties of MoS_2 coated steel substrates

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Abstract

In a series of experiments, the friction coefficients and durability of steel substrates coated with thin films of molybdenum disulphide have been studied, for various values of the substrate roughness and the film thickness. The results are interpreted using a previously developed numerical contact model which simulates multiple asperity contact between rough surfaces. An additional mechanism involving failure by smoothing is suggested as a possible explanation of trends in previously obtained data for this tribological system.

Keywords: Friction; Molybdenum; Steel

1. Introduction

Thin films of molybdenum disulphide (MoS_2), which is a lamellar solid with weak interlayer bonding, can act as effective solid lubricants, giving rise to extremely low friction coefficients in inert environments. This makes the use of MoS_2 films attractive for space and vacuum applications where low friction is desirable. However, the use of these films is limited by their relatively poor durability and, in particular, the difficulty in predicting this property. If some method for understanding, and hence helping to predict, film durability were available, this would increase confidence in the use of MoS_2 films and could be used to help to optimise durability.

There have been many experimental studies of the friction and lifetime behaviour of MoS_2 films (see, for example, Refs. [1–5]), for a wide range of substrate types, operational environments and film preparation techniques. It is clear from such studies that the friction coefficient of MoS_2 films is dependent on a variety of parameters. These include load, contact stress, sliding speed, gaseous environment and deposition parameters. Another factor which is known to influence both friction and wear of sputter deposited films of MoS_2 is the surface roughness of the substrate to which the coating is applied. This paper reports on a theoretical and experimental investigation of the effects of this parameter.

The theoretical work is based on a numerical contact model described in Ref. [6], in which it is assumed that the frictional and lifetime properties of components coated with thin films are controlled by the details of the contact zones formed between asperities. Numerical simulation allows the total true contact area between surfaces to be determined, from which the frictional force is given by the product of this true contact area and the film's shear strength. The model for durability is then developed from the contact model, as outlined previously [7] and in Section (3.2.1.) below.

The model was used previously to interpret a limited number of tribological tests of MoS_2 films on various substrates [7]. A series of tests on a larger number of samples has now been carried out, which provides more reliable results. The details are given in Section (2). The measured friction coefficients and endurance lifetimes are then interpreted in Section (3) using the previous theoretical model, and some tentative sug-

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gestions are made regarding other possible failure mechanisms. The interpretation is discussed in Section (4).

2. Experimental details

Tests were conducted by sliding AFBMA grade 5 standard 52100 bearing steel balls on MoS_2 films deposited on EN31/52100 bearing steel thrust washer discs. The diameter of the balls was 7.14 mm and their nominal surface roughness R_a was 0.03 μm. The discs had inner and outer diameters of 6 and 19 mm respectively, had initially a nominal surface roughness R_a of 0.2 μm, and Vickers hardness in the range 800–850.

The test discs were polished using silicon carbide paper to three nominal surface finishes with R_a of 0.05 (three discs), 0.15 (three discs) and 0.30 μm (six discs). Surface parameters including the R_a, rms height and height correlation length (or equivalent parameter) were measured using a diamond stylus instrument 'talysurf'. The surface roughness of the balls was not measured and was assumed to be 0.03 μm in accord with the AFBMA standard. All discs and balls were cleaned by consecutive ultrasonic rinses in propan-2-ol (IPA) and Arklone-P.

All discs with R_a of 0.05 μm and 0.15 μm and three with $R_a = 0.3$ μm were coated with a 1.0 μm (nominal) film of molybdenum disulphide (MoS_2) by a r.f. magnetron sputtering process. The remaining three $R_a = 0.3$ μm discs were coated with a thicker film of 2.5 μm (nominal). The actual surface roughness values and MoS_2 film thickness values are shown in Table 1.

The r.f. magnetron sputtering technique is similar in principle to d.c. sputtering but the use of an r.f. field allows insulating materials to be sputtered directly onto the substrate. The introduction of magnetically assisted (magnetron) sputtering allows high deposition rates to be achieved. Prior to deposition, the substrate materials were cleaned by sputter etching for 15 min and the target was pre-sputtered for 30 min to clean and outgas the MoS_2 source. In all cases, the thickness of the MoS_2 was verified after testing using an X-ray photofluorescence technique.

Sliding friction tests were then conducted on a single-pin-on-disc tribometer operating in a unidirectional rotary motion. The apparatus is shown in Fig. (1). Tests were performed in an inert dry nitrogen environment. Two tests were performed per disc at track radii of 5 mm and 7 mm respectively. The sliding speed was 500 rpm and the applied load was 20 N (dead weight). Friction traces were recorded throughout the tests, and the film was judged to have failed when the friction coefficient exceeded 0.1. A total of 24 tests were conducted, six per selected surface roughness at each MoS_2 thickness. The mean endurance lifetimes of the films are shown in Table 1.

Table 1
Description of samples and endurance lifetimes

Disc no.	R_a (μm)	MoS_2 thickness (μm)	Endurance (thousands) track	
			5 mm	7 mm
10	0.04±0.01	1.0±0.1	400	453
3	0.04±0.01	0.9±0.1	323	550
8	0.04±0.01	1.0±0.2	493	501
9	0.16±0.02	1.0±0.1	361	492
13	0.17±0.02	1.1±0.2	252	234
12	0.18±0.01	0.9±0.2	386	429
15	0.28±0.02	1.1±0.1	104	93
17	0.29±0.02	1.1±0.1	98	77
16	0.30±0.02	1.1±0.1	99	134
21	0.34±0.04	2.3±0.2	456	406
19	0.28±0.02	2.1±0.3	347	60[a]
20	0.32±0.02	2.2±0.4	355	504

[a]Test did not fail, an electrical problem tripped the system.

3. Interpretation

3.1. Friction coefficients

The numerical model described previously [6] involves the generation of random rough surfaces parametrised by two quantities: the rms roughness σ and the correlation length λ. For the gaussian statistics assumed in the model, the former is related to the more widely used centre line average roughness R_a, according to $R_a \approx 0.8\sigma$. The correlation length determines the distribution of peaks on the surface, but this is more usually characterised using the wavelength λ_q, defined by

$$\lambda_q = 2\pi \frac{\sigma}{\sigma_G} \quad (1)$$

where σ_G is the rms surface gradient. Since $\lambda = \sqrt{2}\sigma/\sigma_G$ [7], we therefore have

$$\lambda = \frac{\lambda_q}{\sqrt{2}\pi} \quad (2)$$

Talysurf measurements of the surface characteristics were performed on each sample. Average values of λ_q for the samples are given in Table 2. In order to simplify the analysis, a representative correlation length of 9 μm was chosen to characterize all the surfaces.

Calculations were then performed, generating 40 surfaces with the given statistical properties, and studying contact with a rigid flat under a load of 20 N. The material properties are given in Table 3. The nominal contact area between the surfaces was chosen to be a square of side length 0.5 mm. This length is uncertain,

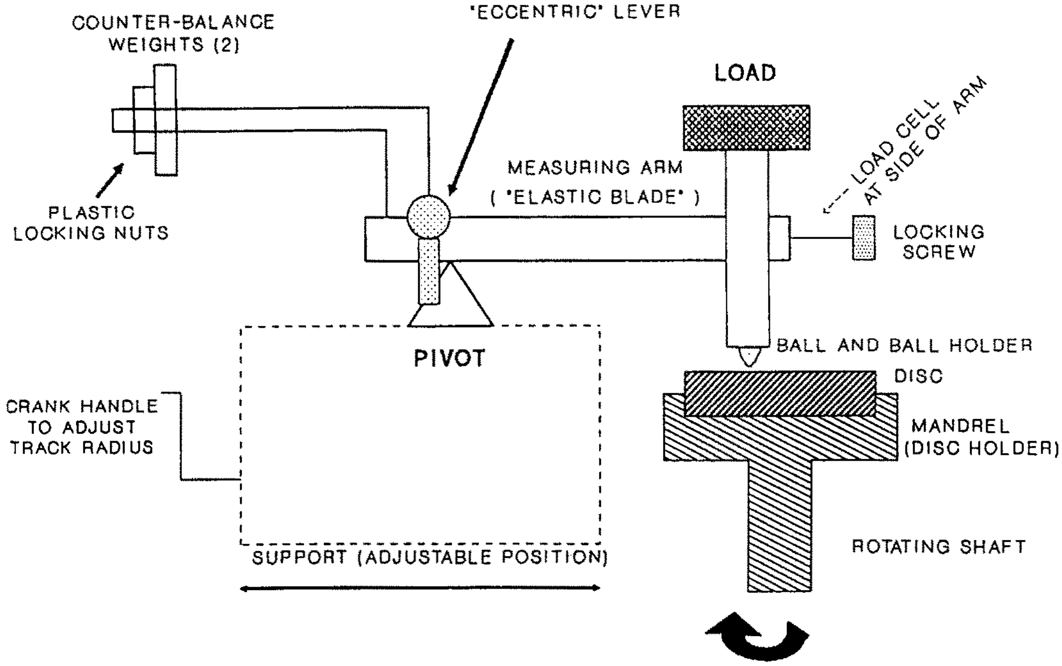

Fig. 1. Schematic diagram of tribometer.

Table 2
Average rms wavelength and correlation length of surface topography for each set of conditions

Film thickness (μm)	R_a (μm)	Mean λ_q (μm)	λ (μm)
1.0	0.04	32	7.2
1.0	0.17	46	10.4
1.1	0.29	40	9.0
2.2	0.31	49	11.0

Table 3
Material properties of 52100 steel substrates coated with MoS_2 film

Young's modulus	200 GPa
Poisson's ratio	0.3
Yield stress	1.5 GPa
Film shear strength	18 MPa
Specific wear rate	2.9×10^{-18} m^2 N^{-1}

but calculations performed with half the above contact area yielded no significant differences in friction coefficient.

Fig. (2) shows the predicted friction coefficients and endurance lifetimes for 1 μm thick MoS_2 coatings, for a range of roughnesses. The measured friction coefficients are in good agreement with the calculations, both in the order of magnitude and the dependence on roughness, which is small. The friction coefficients can only realistically be measured within an accuracy of 0.005. The measured friction coefficient for a film thickness of 2.2 μm and $R_a=0.31$ μm was about 0.017 but is not shown in the figure. This value is to be compared with the calculation at the relevant roughness in Fig. (2) for 1 μm coatings, since the model predicts no dependence of friction coefficient on film thickness. Again, agreement is good.

In some tests, the friction coefficient exhibited a pronounced 'bump' in its evolution, occurring very early on in the life of the sample. This is illustrated for the 1 μm thick coatings with R_a of 0.05 μm in Fig. (3). The mechanism for this effect is not clear, but several may be suggested. One possibility is that it is due to the reorientation of the MoS_2 crystal planes under rubbing. The low friction shown by MoS_2 arises from the lamellar crystal structure, but initially the lamellae will not all be parallel to the coating surface. Deformation is more difficult, and leads to greater friction, when rubbing occurs on planes not parallel to the lamellae. However, although the reorientation would reduce the friction with time, it is not clear how an initial increase in friction might come about. This might be due to the smoothing of the pin surface to a level similar to the disk surface. Alternatively, there might be metal-to-metal contact around the start of the hump, with the film re-forming from reservoirs in the valleys to reduce the friction again later. Another mechanism might involve the formation of blisters which are redeposited as loose film, which wears more quickly than the adhered film. The hump would be due to the initial blister formation.

3.2. Durability

Fig. (2) also shows calculated and measured coating lifetimes. In this section we consider these in more

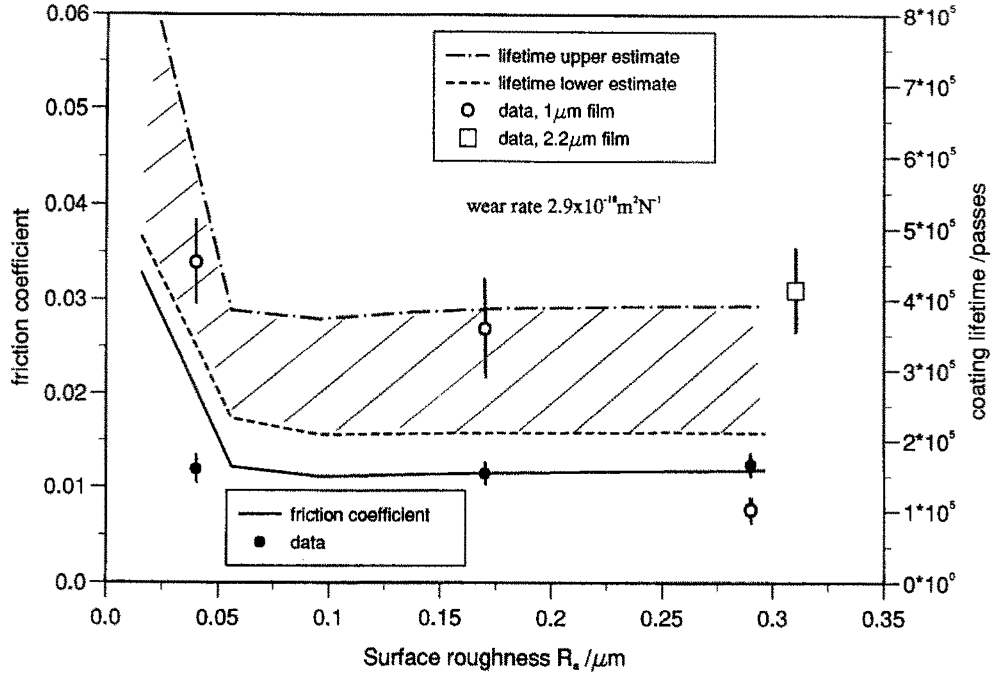

Fig. 2. Comparison of measured and calculated friction coefficients and lifetimes for a 1 μm MoS_2 film on a steel substrate of various roughnesses. The lifetime for a 2.2 μm film at one roughness is also shown.

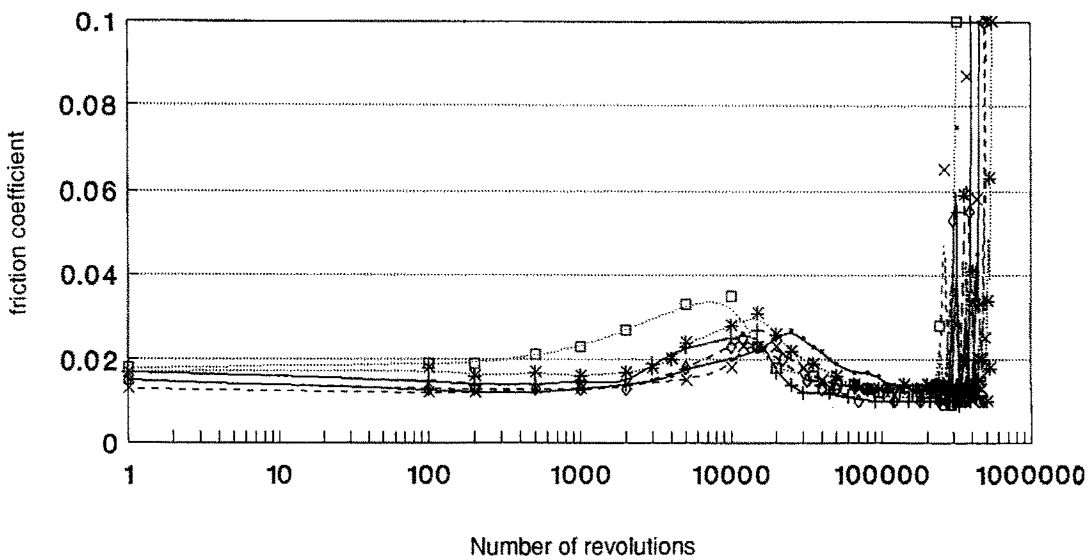

Fig. 3. Evolution of friction coefficient with number of revolutions, for six tests using 1 μm MoS_2 films of nominal roughness 0.05 μm, showing the 'bump' early in the coating lifetime.

detail, describing two possible mechanisms for film failure.

3.2.1. *Failure by asperity breakthrough*

A model of film failure by asperity breakthrough has previously been described [7]. The model assumes that contact between surfaces occurs at the asperities, and that film wear takes place under these areas of contact, with film failure occurring when the film is totally worn away under one of the contact areas. The numerical contact model is used to calculate the details of all of the contact areas, in particular their sizes, locations and shapes. Each contact area is assumed to obey the macroscopically observed Archard wear law [8], in which the volume of material lost in a sliding wear process is proportional to the applied load and the relative distance of sliding. So, for the ith contact area supporting load W_i the volume of material lost on sliding a small distance δX may be written

$$\delta V_i \propto W_i \delta X \quad (3)$$

The total material lost on sliding a relative distance X_i is then given by

$$V_i = A_i \delta z_i = \int_0^{X_i} \frac{dV_i}{dx}\,dx = kW_iX_i \quad (4)$$

where A_i is the area of contact, and δz_i is the depth of material lost at the contact. At each pass of the slider across an asperity more material is lost according to Eq. (4), with film failure occurring when the film is totally worn away at any one asperity contact. The model assumes that the depth of material to be lost is equal to the film thickness (this assumption differs slightly from that used in Ref. [7], where it was assumed that the depth of material to be lost was equal to the film thickness less the indentation under each asperity contact). The above theory [7] then gives the number of passes, at the ith contact area, at which this failure will occur as

$$n_i = t\left(\frac{1}{\varepsilon WL}\right)\left(\frac{A_i}{W_iX_i}\right)\sum_i^N W_iX_i \quad (5)$$

where t is the film thickness, W is the total load between the surfaces, L is the length of the slider, N is the total number of contact areas and ε is the specific wear rate (the volume of material lost per unit applied load per unit distance of sliding) used in the Archard wear law. Film failure occurs at the asperity with the smallest value of n_i. Since the model is statistical, predictions for the average and standard deviation of lifetimes are obtained.

In our model, we assume that the wear rate of sputtered MoS_2 film is uniform, that is, that the wear rate does not change with film thickness. There is some evidence to suggest that film wear rate, in some circumstances, may not in fact be uniform. Such cases could ultimately be accommodated by our model, but the modifications required were considered beyond the scope of the present study. Fig. (2) compares the observed coating lifetimes, for the 1 μm films, with the lifetimes calculated according to the above asperity breakthrough model. The predictions are given as upper and lower estimates, which are one standard deviation above and below the mean lifetime, for 40 surface realisations. The specific wear rate ε is an input to the calculation, and this can be varied to alter the order of magnitude of the calculations. The value used here, however, shown in Table 3, is typical of the materials concerned [7]. The measurements are in good agreement with the calculations, except for the roughest sample.

Earlier measurements of the durability of 1 μm MoS_2 films on steel substrates [3] yielded somewhat different results. In the low roughness region, $R_a < 0.2$ μm, the lifetimes were rather less than the predictions based on a very similar durability model, and less than the measurements reported here. For higher roughnesses, the data are more consistent. The two datasets are shown in Fig. (6). Although the earlier data were based on a limited number of measurements, and interpretation must be cautious, a possible reason for the reduced durability of the smoother samples in the earlier experiments is proposed in the next section.

For the roughest substrate, we can examine the effect of film thickness on endurance. For an increase in thickness from 1 to 2.2 μm, the lifetime rose from 103 ± 18 to 414 ± 60 thousands of passes. The calculated mean lifetime is 580×10^3 passes for the thick coating which again overestimates the measured value.

The position is therefore that the asperity breakthrough model can account for the film lifetimes at low roughness values for the present set of measurements, although the behaviour for $R_a \approx 0.3$ μm is less well accounted for. However, earlier results are inconsistent with both the new data and the model predictions for low roughnesses.

3.2.2. Roughness evolution

An alternative mechanism of film failure may operate in particular circumstances. The asperity breakthrough failure model used in the above analysis assumes that the initial asperity wear rate, which depends on roughness, is constant throughout the whole lifetime of the coating. However, for a film of thickness much larger than the initial roughness, this is not realistic. For these circumstances, a considerable depth of coating has to be removed before the highest asperity of the substrate can emerge: it is unrealistic to expect that the surface roughness will remain the same during this process, and so the asperity wear rate will change with time.

We suggest here a simple model which describes the evolution of roughness during wear, but first, let us examine the implications of a change in roughness with time. During the wear of a surface by a smoother slider, the roughness decreases, and according to Ref. [7], the asperity wear rate falls. This means that the asperity breakthrough lifetime assuming a constant roughness throughout will underestimate the true breakthrough time. Also, the friction coefficient increases, which introduces a second possible failure mechanism which will be referred to as failure-by-smoothing. As the roughness decreases, the friction coefficient rises, due to the increased real contact area [7], and at a particular roughness the friction coefficient will exceed the chosen failure threshold. The coating will then fail, not because of asperity breakthrough, but because it had become too smooth and exhibited high friction. This failure mechanism can in principle operate for all initial roughnesses, but in the case of rougher films (relative to film thickness), asperity breakthrough occurs before the surface is sufficiently smoothed. The coating will fail by whichever mechanism operates first.

First, let us consider the evolution of roughness using the following simple model. We assume that the rough surface slides against a perfectly flat slider. The total volume worn after sliding distance X is again given by Archard's law:

$$\Delta V = W\varepsilon X \tag{6}$$

where W is the total load and ε is the specific wear rate. If there are N contacts with mean area $\bar{A}_i$ and mean load $\bar{W}_i$, then the mean depth worn at each asperity after sliding distance X is

$$\Delta z = N\bar{W}_i \varepsilon X / N\bar{A}_i \tag{7}$$

X is equal to Ln where L is the length of the slider and n the number of passes, so

$$\frac{d\Delta z}{dn} = L\bar{p}\varepsilon \tag{8}$$

where $\bar{p}$ is the mean pressure on the asperities. The roughness will decrease as the asperities are worn away. If the centre line average roughness is R_a then we might write, approximately,

$$\frac{dR_a}{dn} = -\frac{1}{2}\frac{d\Delta z}{dn} \tag{9}$$

The factor of 1/2 represents the removal of material only at the peaks of the surface topography, but is only intended to be approximate. The mean asperity pressure $\bar{p}$ can be found from the numerical simulations and is shown against R_a in Fig. (4). A similar plot was given in Fig. (3) of Ref. [7]. The numerical results can be represented remarkably well by a tanh function:

$$\bar{p} = \sigma_y \tanh(R_a/d_a) \tag{10}$$

where σ_y is the yield stress and d_a a fitting constant. Together with Eqs. (8) and (9) this leads to a smoothing equation:

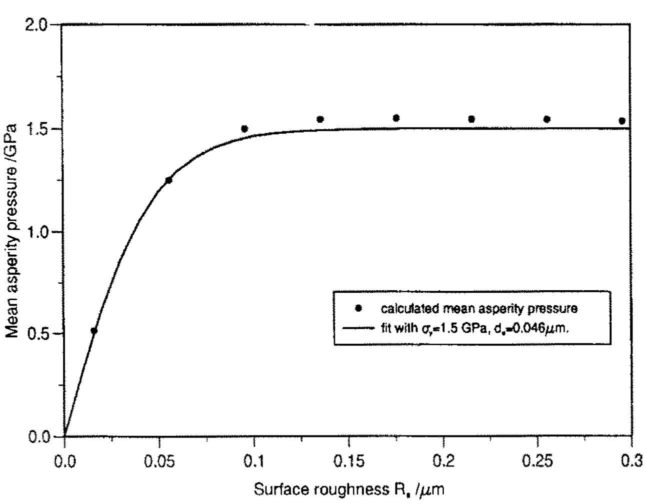

Fig. 4. Roughness dependence of the mean pressure on each asperity, fitted to the function $p = \tanh(R_a/da)$.

$$\frac{dR_a}{dn} = -\frac{1}{2}L\varepsilon\sigma_y \tanh(R_a/d_a) \tag{11}$$

Integrating this equation gives the evolution of roughness, which can be inverted to give n_f, the number of cycles required to reduce the roughness from R_{ai} to R_{af}:

$$n_f = \frac{2d_a}{\varepsilon L\sigma_y}\ln\left(\frac{\sinh(R_{ai}/d_a)}{\sinh(R_{af}/d_a)}\right) \tag{12}$$

This is an increasing function of initial roughness. The result can be interpreted as simply a model of the smoothing of the surfaces with increasing number of passes, or one can go further and use it as the basis of a failure-by-smoothing mechanism.

3.2.3. *Failure by smoothing*

Writing the friction coefficient as

$$\mu = \frac{sN\bar{A}_i}{N\bar{W}_i} \tag{13}$$

where s is the shear strength of the coating, leads to

$$R_{af} = d_a \tanh^{-1}\left(\frac{s}{\mu_f\sigma_y}\right) \tag{14}$$

where μ_f is the threshold friction coefficient for failure, and so

$$n_f = \frac{2d_a}{\varepsilon L\sigma_y}\ln\left\{\left[\left(\frac{\sigma_y\mu_f}{s}\right)^2 - 1\right]^{1/2}\sinh(R_{ai}/d_a)\right\} \tag{15}$$

This is the predicted endurance lifetime. For parameters we follow Ref. [7] and choose $\sigma_y = 1.5$ GPa, $\varepsilon = 2.9\times10^{-18}$ m^2 N^{-1}, $s = 18$ MPa, $L = 0.5$ mm, $\mu_f = 0.1$, and from Fig. (4), d_a is estimated to be 0.046 μm for the samples used in this study.

An example calculation showing the evolution of roughness and friction coefficient with wear is shown in Fig. (5). The rise in μ towards the end of life is fairly rapid but smooth. Many tests, however, failed when the friction coefficient increased catastrophically through the threshold value. This behaviour is more characteristic of asperity breakthrough, and is a feature which may serve to distinguish the two mechanisms in practice. A second characteristic feature of the failure-by-smoothing mechanism is that the failed coatings are not worn away to expose underlying substrate.

A set of predictions for film lifetime according to the smoothing model, using values of d_a, ε and L given earlier, is shown as a solid curve in Fig. (6), and compared with the new data, shown as open circles. For low initial values of R_a, failure by smoothing is favoured since the predicted lifetimes are lower than those produced by asperity breakthrough, shown in Fig. (2). However, as noted earlier, the data reported here are in better agreement with the breakthrough model

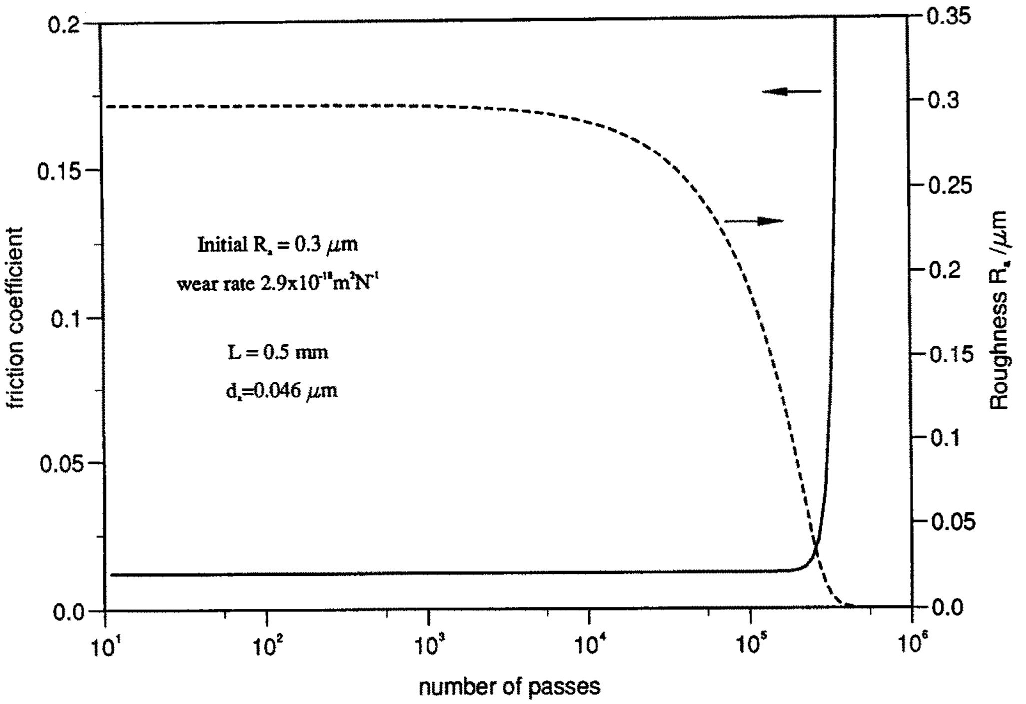

Fig. 5. Evolution of roughness and friction coefficient according to smoothing model, assuming there is no lower limit to roughness.

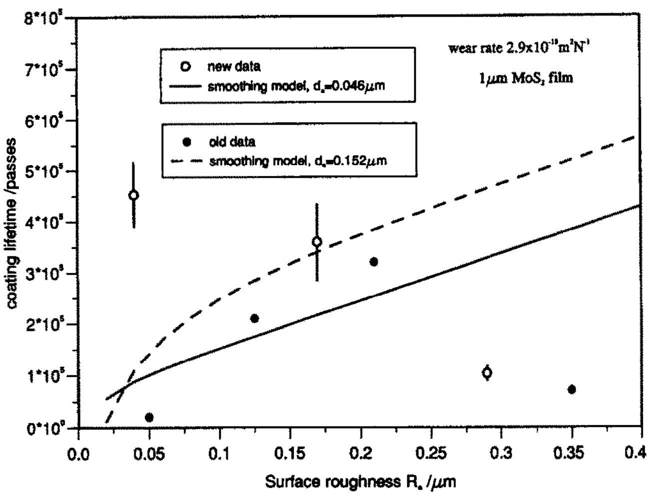

Fig. 6. Comparison between measured coating lifetimes and values predicted by smoothing model, for latest data, and data from Ref. [1].

than with the smoothing model. The older data [3], however, shown as solid circles, are better described by the failure-by-smoothing model. We shall comment on the reliability of the older data in the next section.

A possible reason for the apparent failure of the smoothing model is the assumption of a smooth slider. In Fig. (5), the roughness tends to zero at large times, but more realistically, it would be expected to fall no lower than the roughness of the slider. From Fig. (5), the required roughness at failure (i.e. when μ is equal to 0.1) is about 0.005 μm, well below the roughness of the slider in the tests, which is estimated to be about 0.03 μm. Therefore the smoothing model would not lead to failure for these tests, and so no tendency for the lifetime to rise with roughness is seen in the data.

The difference between the test specimens used in Ref. [3] and those used here would appear to be the surface correlation length λ: here a value of 9 μm is used, based on surface characterisation, whereas in Ref. [7] a value of 20 μm was used based on the observed friction coefficients. This results in a different value of the fitting parameter d_a (see Fig. (3), Ref. [7]) equal to 0.152 μm. The smoothness at failure for these calculations is 0.018 μm which is more likely to be attainable, though this is by no means assured. Lifetimes according to failure-by-smoothing are shown as a dashed curve in Fig. (6) for $d_a = 0.152$ μm, for comparison with the data from Ref. [3], shown as solid circles. The shape of the durability measurements is well represented, though the predictions are a slight overestimate.

A more sophisticated model of roughness evolution could be devised, but would probably show features similar to those of the above simple treatment. In general, we would expect the durability to be independent of the thickness of the coating and to depend on the roughness of the slider. This is not seen in experimental studies with MoS_2 films, but measurements of the lifetimes of soft metal coatings on steel show a number of features of the smoothing model, including a wear rate which falls as the coating becomes thinner, a friction coefficient which increases smoothly with time during the wear test, and a failure lifetime which is insensitive to the initial film thickness [9,10]. However, the model may not be appropriate for soft films, since ploughing may dominate the wear.

The model is probably not a suitable description of the failure of the coatings in this study, since the predictions due to the failure-by-asperity breakthrough mechanism describe the data well. Also, analysis of failed samples revealed that most of the MoS_2 had been worn away. Furthermore, the endurance does seem to depend on the film thickness in the expected manner according to failure-by-breakthrough. Nevertheless, the alternative failure mechanism exists and could in principle operate in some circumstances.

4. Discussion and conclusions

In an earlier study [3], the friction coefficients and endurance lifetimes of MoS_2 coatings on 52100 steel substrates were measured and compared with the predictions of a model which simulates the contact and wear of numerically generated surfaces [6,7]. A second set of measurements has now been made, for a different geometry and load, involving repeated tests to estimate the accuracy of the results. The measurements varied within an acceptable range from test to test. The mean friction coefficients and lifetimes are consistent with the results of the first study, except for the samples with 0.05 μm R_a nominal roughness, which in the previous study had higher friction coefficients and lower lifetimes. Since the statistical usefulness of the previous dataset was limited, however, this discrepancy may be of doubtful significance.

These results can be explained using a numerical contact model. Random surfaces characterised by a rms roughness, σ, and a correlation length, λ, are generated and loaded against a rigid flat to produce elastoplastic asperity deformation. Using an ensemble of surfaces together with appropriate material parameters, the friction coefficient and asperity wear rate can be calculated, together with the variability between samples [7].

Talysurf measurements of the surface topography suggest a value of λ in the range 7.2–11 μm for the various choices of film thickness and substrate roughness, which is less than the value of 20 μm used in Ref. [7] in order to explain the measured friction coefficient. Reducing λ gives rise to a reduced friction coefficient at low R_a, an effect which was demonstrated in Fig. (8) of Ref. [7]. This is consistent with the reduced friction coefficient at low roughness observed here.

The change in the observed coating lifetime may also be due to the lower value of λ. It has been suggested here that there are at least two possible coating failure mechanisms, or more precisely two ways in which the friction coefficient can exceed a chosen failure threshold. The first, which was described in detail in Ref. [7], occurs when the coating is removed entirely from at least one asperity, such that the substrate comes into contact with the slider and increases the friction. The second new mechanism relies on the fact that as the coating wears against a smoother slider, it becomes less rough, and the friction coefficient increases since it is roughness dependent. The coating fails by whichever process is completed first. The failure-by-smoothing mechanism should apply in principle for films which have a high ratio of thickness to roughness, such that the emergence of asperities due to wear is delayed. The failure-by-asperity breakthrough mechanism should operate for smaller values of this ratio.

However, the smoothing mechanism will not apply if the coating roughness cannot be reduced to the value at which the friction coefficient reaches threshold. The lower limit for the evolving coating roughness is the roughness of the slider, assuming the slider does not wear. For this reason, the failure roughness is inaccessible for surfaces with λ equal to 9 μm, and so the coating always fails by the asperity breakthrough mechanism. For $\lambda = 20$ μm, however, the dependence of the mean asperity pressure on roughness is different, and it may be possible for the failure-by-smoothing mechanism to operate. This may explain why the coating lifetimes measured previously [3] were seen to rise initially with surface roughness, as shown in Fig. (6). However, caution must be exercised, since the data referred to was very limited and may be misleading. Proof that failure-by-smoothing occurred is not available: clear evidence would be the presence of a continuous film of MoS_2 in the wear track after the sample has failed, but this is not supported in these tests.

The study of the tribological properties of MoS_2 coated steel substrates reported here, together with their interpretation, has confirmed the value of numerical modelling of surface contact and film performance. It has been suggested that the correlation length, characterising the distance between peaks on the surfaces, affects both the friction coefficient and endurance lifetime of the coating. It has previously been demonstrated that the surface roughness affects these quantities. With the understanding gained, it may be possible to choose surface textures to optimise the performance of tribological coatings.

Acknowledgements

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