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The influence of surface topography on the dynamic friction between acetylsalicyclic acid compacts and steel

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The influence of surface topography on the value of the dynamic friction coefficient, μ_d, for acetylsalicylic acid compacts sliding on steel has been studied using a model system. The value of $\bar{\mu}_d$, an average representative of a range of values of μ_d, measured during interfacial displacement, was found to be inversely related to the surface roughness of the steel. This indicates the existence of a friction mechanism involving adhesion, deformation and shear components and establishes a potential method for the amelioration of friction problems without recourse to lubricants.

1. Introduction
The basic adhesion theories of friction established by Bowden and Tabor [1] are generally successful at providing qualitative descriptions of frictional systems, but have been criticised by Rabinowicz [2] for their failure to consider the effect of surface topography. A discernible surface roughness effect has been reported with metals, such that for very smooth surfaces frictional resistance to sliding is very high due to excessive junction growth, resulting in a large contact area over which strong interfacial adhesion occurs. As the surface roughness is increased, friction decreases, until eventually rising again due to mechanical interlock at the contact interface [2]. The behaviour of steel surfaces during sliding is dependent upon their surface topography. For relatively rough surfaces, ($R_a > 3.2\,\mu$m), friction decreases during sliding, whilst for smooth surfaces, friction increases. This has been explained in terms of work hardening and wear processes [3]. One conventional "law" of friction dictates that friction is greater on rough surfaces than upon smooth, apart from a minority of cases where contact is such that roughness reduces the true area of interfacial contact [4].

It has been postulated [5] that dynamic friction (and thus the coefficient of dynamic friction) is not a simple material property and is affected by the environment and the sliding distance because of the changing contribution of the primary components of friction, namely: adhesion, deformation, and ploughing by hard asperities and wear particles.

An experimental model system for the determination of the coefficient of dynamic friction for organic powder compacts sliding on steel has been reported by James and Newton [6]. This system allows an examination of the influence of the surface topography of the steel.

2. Experimental details
2.1. Compaction materials
Acetylsalicylic acid (Monsanto crystalline) was sieved (Endecott (Test Sieves) Ltd) to provide 500 mg samples of size range +355 to 550 μm which were uniaxially compacted using a servohydraulic press to a maximum upper punch pressure of 101.86 kN cm^{-2} (80 kN force using 10 mm diameter plain faced punches) as described previously [6].

2.2. Preparation of model plates
Three flat plates, of BS 4649 type BO 1 tool steel case hardened to 62 Rc, were prepared for use in the experimental system in the following ways:

1. flat lapping on a "Kemet" plate revolving at

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320 rpm using a 14 μm diamond paste (Hyprez 14 FS 40);

2. as (1), followed by further lapping at 620 rpm;

3. as (2), followed by polishing with a 3 μm diamond paste (Hyprez 3 FS 47), using a felt bob rotating at approximately 2500 rpm.

Before use in each friction test, the plates were cleaned by successive immersions in ethanol, carbon tetrachloride and acetone within an ultrasonic bath. Between immersions, the plates were wiped with lens tissue.

2.3. Determination of surface topography

All quantitative surface analysis was based upon data from a Rank Taylor Hobson "Talysurf" 4 stylus profilimeter instrument (Rank Precision Industries Metrology Division, Leicester). A total of twelve profile traces were recorded from each steel plate – three lengthways (nominated the x-direction) and three widthways (the y-direction) – on each of the two sides of every plate. The analogue output from the Talysurf was fed into a PDP11 microcomputer (Digital Equipment Co., London) for analogue to digital conversion, analysis and storage. The signal was initially sampled at 5 μm intervals, i.e. a short wavelength cut-off was applied to the raw data. Further high-pass and low-pass filtering of the data was accomplished with a cubic spline filter.

A package of surface analysis programmes calculated various statistics of the peak height, valley depth, peak curvature and surface slope distributions. Autocovariance, autocorrelation, power spectrum, zero-crossing density and structure function data were also available.

2.4. Determination of the coefficient of dynamic friction

The coefficient of dynamic friction, μ_d, was measured directly under controlled conditions using a technique based upon linear displacement of a flat steel plate, as previously described by James and Newton [6]. A constant displacement rate of 0.2 mm sec^{-1} was used with initial normal loads of 250, 500 and 750 N, i.e. approximately 320, 640 and 955 kN cm^{-2}.

3. Results and discussion

The topographical analysis provided values for the surface parameters listed in Table I. The processing of the steel plates created the intuitively expected grading of surface topography, the most highly polished plate exhibiting the lowest value of RMS roughness, Table II.

All frictional tests resulted in contamination of the steel plates with acetylsalicylic acid (see Fig. 1) with the level of contamination reducing with

TABLE I Surface topography parameters

Parameter	Definition	Units
RMS_x	Root mean square roughness, x-direction	μm
RMS_y	Root mean square roughness, y-direction	μm
R_{ax}	Arithmetic mean roughness, x-direction	μm
R_{ay}	Arithmetic mean roughness, y-direction	μm
M_{0x}	Zero'th moment of power spectrum	μm^2
Pk_x	Mean peak height	μm
Vl_x	Mean valley depth	μm
Cv_x	Mean valley curvature	μm^{-1}
M_{2x}	Second moment of power spectrum	–
A_{sx}	Mean surface slope	deg
M_{4x}	Fourth moment of power spectrum	μm^{-2}
α_x	Nayak's bandwidth parameter	–
D_{px}	Mean peak density	mm^{-1}
γ^{-1}	Mean long-crestedness	–
M_{2e}	Second equivalent moment of power spectrum	–
M_{4e}	Fourth equivalent moment of power spectrum	μm^{-2}
D_s	Mean summit density	mm^{-2}

TABLE II Mean filtered roughness state for flat steel plates (a) 350 μm high-pass filtered

Final Surface preparation	Plate	RMS_x (μm)	RMS_y (μm)	R_{ax} (μm)	R_{ay} (μm)
14 μm polish 320 rpm	1	0.147	0.151	0.111	0.116
14 μm polish 620 rpm	2	0.022	0.015	0.015	0.011
3 μm polish	3	0.019	0.022	0.014	0.017

(b) 25 μm high-pass filtered

Final surface preparation	Plate	RMS_x (μm)	RMS_y (μm)	R_{ax} (μm)	R_{ay} (μm)
14 μm polish 320 rpm	1	0.129	0.116	0.099	0.088
14 μm polish 620 rpm	2	0.018	0.011	0.013	0.009
3 μm polish	3	0.004	0.009	0.003	0.007

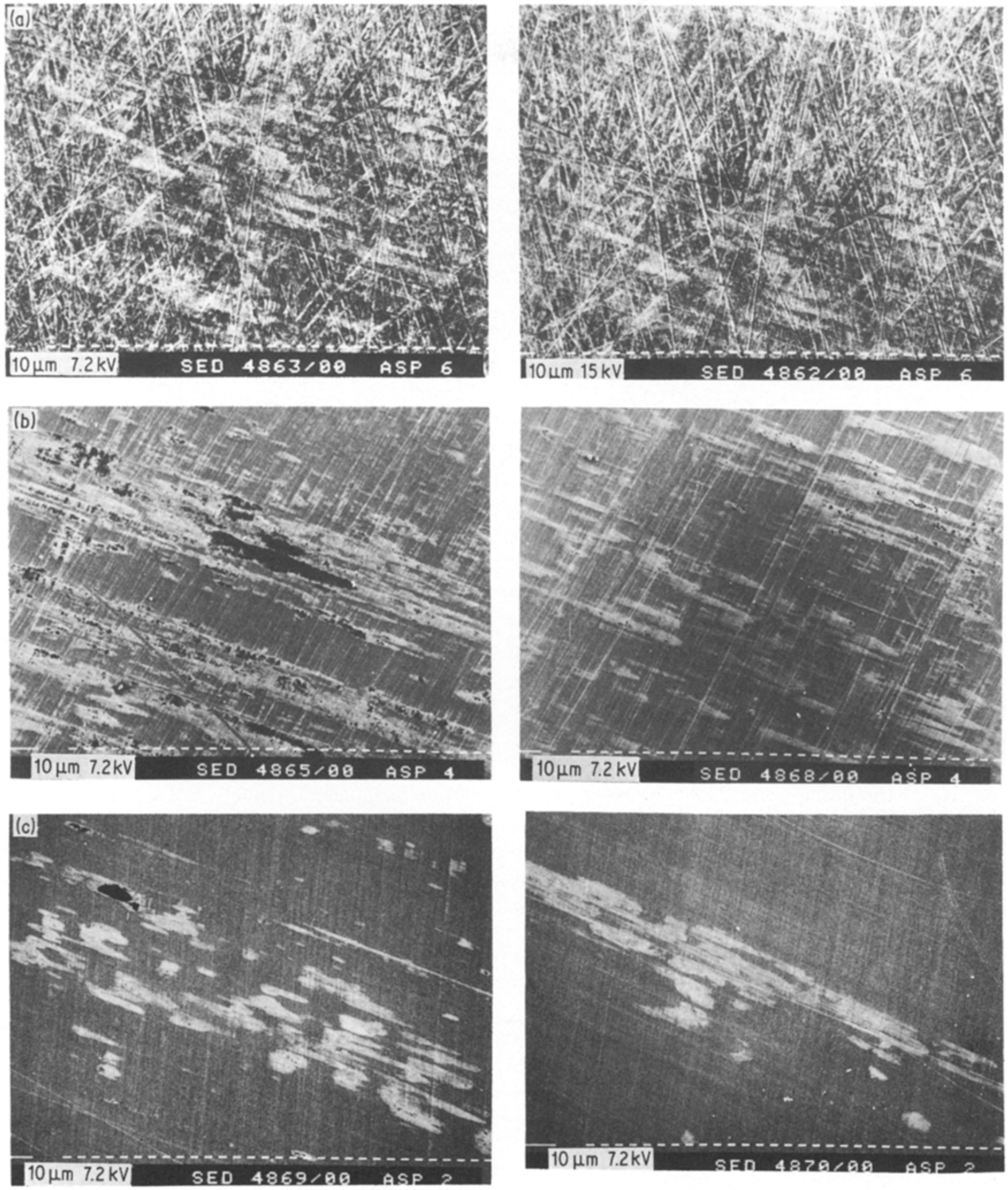


Figure 1 Scanning electron micrographs of acetylsalicylic acid on steel plates. (a) Steel plate 1. (b) Steel plate 2. (c) Steel plate 3.

decreasing RMS roughness. Typical results from friction tests using plate 1 are presented in Fig. 2 as the mean dynamic friction coefficient as a function of displacement during sliding (mean data from eight replicate tests). The value of μ_d is not constant, but varies throughout the test. This phenomenon creates difficulty when attempting to characterize the sliding system with a single value of μ_d. To simplify statistical analysis of the results, it is convenient to use a mean value of the dynamic friction coefficient, $\bar{\mu}_d$, representative of each test. Spearman rank correlation analysis established that there is no significant difference between the rank orders of results constructed

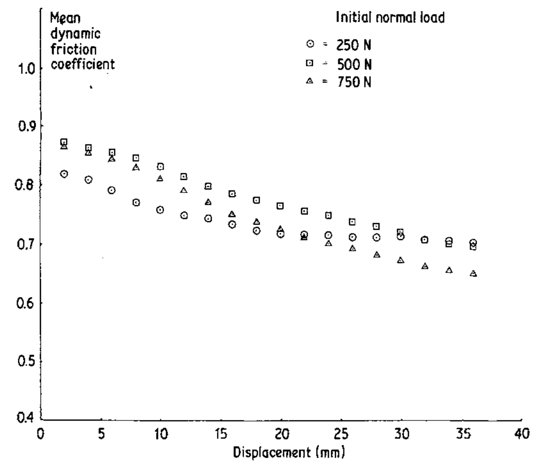


Figure 2 Mean dynamic friction coefficient as a function of displacement: acetylsalicylic acid sliding on plate 1 at 0.2 mm sec^{-1}.

using mean and individual values of the dynamic friction coefficient, i.e. μ_d and $\bar{\mu}_d$.

The correlation between $\bar{\mu}_d$ and the various surface topography characteristics of the steel plates is described by the data presented in Tables III and IV. An illustration of a typical correlation between $\bar{\mu}_d$ and a surface topography characteristic, RMSx, is shown in Fig. 3.

The data in Tables III and IV show that, irrespective of the initial normal load across an acetylsalicylic acid and steel interface sheared at 0.2 mm sec^{-1}, most of the surface topography characteristics measured in this study correlate with the frictional conditions to a significant degree at the

TABLE III(a) The correlation coefficients of linear regression analyses between the mean dynamic friction coefficients for acetylsalicylic acid sliding on steel at 0.2 mm sec^{-1} and the 350 μm high-pass filtered surface characteristics

Surface characteristic	Correlation coefficient for initial normal load of: 250 N	500 N	750 N
RMS_x	−0.7906	−0.8463	−0.8038
R_{ax}	−0.7939	−0.8294	−0.7987
M_{0x}	−0.7951	−0.7954	−0.7854
Pk_x	−0.7886	−0.8530	−0.8055
Vl_x	−0.7895	−0.8503	−0.8048
Cv_x	−0.7906	−0.8463	−0.8038
M_{2x}	−0.7949	−0.7909	−0.7835
A_{sx}	−0.7889	−0.8521	−0.8052
M_{4x}	−0.7947	−0.7875	−0.7819
α_x	0.5267	0.8480	0.6528
D_{px}	0.6477	0.8996	0.7436
γ^{-1}	0.3924*	0.0318†	0.2388†
M_{2e}	−0.7923	−0.7652	−0.7714
M_{4e}	−0.7915	−0.7602	−0.7689
D_s	0.2992†	0.0864†	0.1364†

*Not significant at the 5% confidence level, with 22 degrees of freedom.

†Not significant at the 10% confidence level, with 22 degrees of freedom.

5% confidence level. All the surface height distribution parameters, namely RMS_x, R_{ax}, Pk_x, Vl_x and M_{0x}, produce negative correlation coefficients of similar magnitude. Thus it is apparent that the shape of the surface height distribution, as represented by its mean and variance, is of importance in

TABLE III(b) The slopes of the regression lines from linear regression analyses between the mean dynamic friction coefficients for acetylsalicylic acid sliding on steel at 0.2 mm sec^{-1} and the 350 μm high-pass filtered surface characteristics

Surface characteristic	Slope of regression line at initial normal load of: 250 N	500 N	750 N
RMS_x	−1.805	−1.907	−1.955
R_{ax}	−2.402	−2.478	−2.575
M_{0x}	-1.722×10^{1}	-1.701×10^{1}	-1.812×10^{1}
Pk_x	−2.234	−2.386	−2.431
Vl_x	−2.023	−2.151	−2.197
Cv_x	-1.853×10^{1}	-1.959×10^{1}	-2.008×10^{1}
M_{2x}	-2.301×10^{2}	-2.261×10^{2}	-2.416×10^{2}
A_{sx}	-1.423×10^{-1}	-1.517×10^{-1}	-1.547×10^{-1}
M_{4x}	-1.921×10^{3}	-1.879×10^{3}	-2.013×10^{3}
α_x	1.700×10^{-2}	2.698×10^{-2}	2.241×10^{-2}
D_{px}	2.130×10^{-2}	2.917×10^{-2}	2.600×10^{-2}
γ^{-1}	6.020×10^{-2}	4.820×10^{-3}	3.900×10^{-2}
M_{2e}	-2.933×10^{2}	-2.797×10^{2}	-3.042×10^{2}
M_{4e}	-2.592×10^{3}	-2.457×10^{3}	-2.682×10^{3}
D_s	1.384×10^{-5}	-3.947×10^{-6}	6.726×10^{-6}

Note: The units of the slope are a function of the surface characteristics and can be derived by reference to Table I.

TABLE IV(a) The correlation coefficients of linear regression analyses between the mean dynamic friction coefficients for acetylsalicylic acid sliding on steel at 0.2 mm sec^{-1} and the 25 μm high-pass filtered surface characteristics

Surface characteristic	Correlation coefficient at initial normal load of:		
	250 N	500 N	750 N
RMS_x	−0.7850	−0.8623	−0.8072
R_{ax}	−0.7877	−0.8555	−0.8060
M_{ox}	−0.7877	−0.7396	−0.7582
Pk_x	−0.7894	−0.8505	−0.8049
Vl_x	−0.7878	−0.8552	−0.8059
Cv_x	−0.7898	−0.8493	−0.8046
M_{2x}	−0.7949	−0.7902	−0.7832
A_{sx}	−0.7887	−0.8526	−0.8054
M_{4x}	−0.7947	−0.7874	−0.7819
α_x	0.7927	0.8368	0.8011
D_{px}	0.5930	0.8803	0.7042
γ^{-1}	0.4430	0.0996†	0.2959†
M_{2e}	−0.7921	−0.7639	−0.7707
M_{4e}	−0.7915	−0.7601	−0.7688
D_s	0.3979*	0.0391†	0.2450†

*Not significant at the 5% confidence level, with 22 degrees of freedom.
†Not significant at the 10% confidence level, with 22 degrees of freedom.

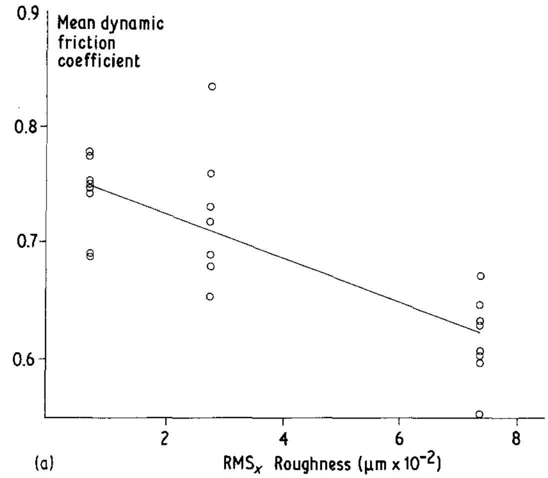
determining the frictional conditions as quantified by the value of $\bar{\mu}_d$. The negative values of the correlation coefficients indicate that, with the steel surfaces studied, increasing the variation of the surface about the mean *x-y* plane reduces the mean dynamic friction coefficient, i.e. the greater the surface "roughness", the lower the dynamic friction. This is depicted by the negative slopes of the regression lines shown in Fig. 3.

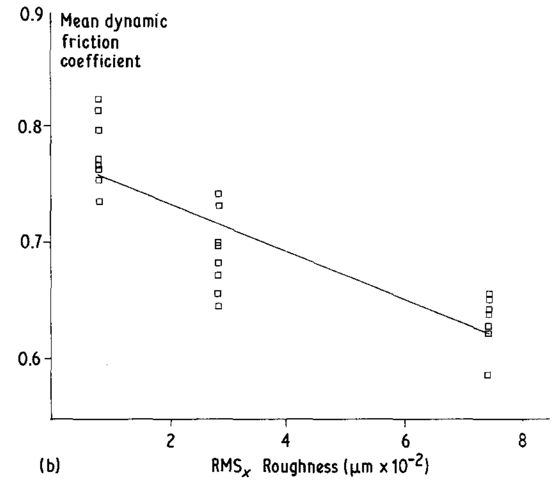
The slopes of the regression lines in Tables III and IV show a large range in magnitude, indicating that a change in the various surface characteristics results in a correspondingly variable degree of change in $\bar{\mu}_d$. This is partly due to the differing magnitude of the surface characteristics and in particular the fact that several of them are variances, and hence squared terms. A large slope implies that a relatively small alteration of the relevant surface characteristic produces a large change in the dynamic frictional conditions. To utilize these data, it is necessary to consider the ease with which any given feature of the total surface topography can be altered. For example, a small change in the variation of the peak curvature (as measured by M_{4x}) will result in a relatively large change in the value of μ_d. However, changing the peak curvature in a controlled manner is extremely difficult. A change in the RMS surface roughness has a less dramatic effect on dynamic friction, but is relatively simple to achieve.

The steel surface asperity shape, as defined by the slope characteristics A_{sx} and M_{2x}, and the curvature characteristics Cv_x and M_{4x}, has an effect on the dynamic friction between acetylsalicylic acid and steel similar to that of the asperity height, RMS_x. As the asperity slope and curvature increase, less dynamic friction is generated between the steel and the acetylsalicylic acid. Again, both the mean and the variance of the slope and curvature distributions affect the interfacial conditions.

TABLE IV(b) The slopes of the regression lines from linear regression analyses between the mean dynamic friction coefficients for acetylsalicylic acid sliding on steel at 0.2 mm sec^{-1} and the 25 μm high-pass filtered surface characteristics

Surface characteristic	Slope of regression line at initial normal load of:		
	250 N	500 N	750 N
RMS_x	−1.870	−2.028	−2.048
R_{ax}	−2.481	−2.661	−2.705
M_{ox}	−2.031	−1.882	−2.082
Pk_x	−2.262	−2.406	−2.457
Vl_x	−2.068	−2.216	−2.254
Cv_x	-1.861×10^{1}	-1.976×10^{1}	-2.020×10^{1}
M_{2x}	-2.328×10^{2}	-2.285×10^{2}	-2.443×10^{2}
A_{sx}	-1.428×10^{-1}	-1.524×10^{-1}	-1.553×10^{-1}
M_{4x}	-1.922×10^{3}	-1.880×10^{3}	-2.015×10^{3}
α_x	1.240	1.292	1.335
D_{px}	6.200×10^{-2}	9.090×10^{-2}	7.850×10^{-2}
γ^{-1}	6.380×10^{-2}	1.416×10^{-2}	4.540×10^{-2}
M_{2e}	-3.003×10^{2}	-2.859×10^{2}	-3.112×10^{2}
M_{4e}	-2.597×10^{3}	-2.462×10^{3}	-2.687×10^{3}
D_s	1.700×10^{-5}	2.000×10^{-6}	1.100×10^{-5}





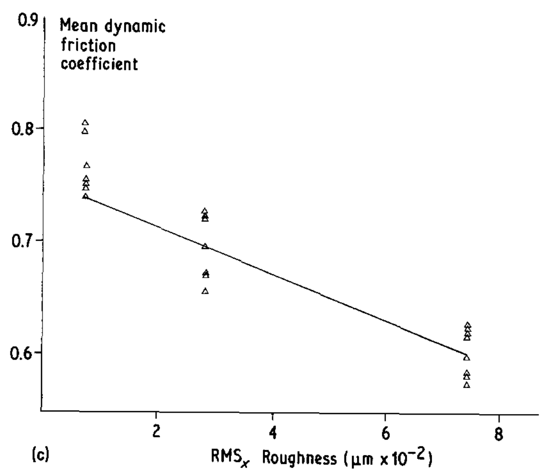


Figure 3 Mean dynamic friction coefficient as a function of RMS surface roughness for acetylsalicylic acid sliding on steel at 0.2 mm sec^{-1}. (a) Initial normal load 250 N, 25 μm high-pass filtered RMS$_x$ data. (b) Initial normal load 500 N. 25 μm high-pass filtered RMS$_x$ data. (c) Initial normal load 750 N. 25 μm high-pass filtered RMS$_x$ data.

The spatial properties of the steel surface are equally as important as the asperity shape and size. Both the peak density in the direction of sliding, D_{px}, and the power spectrum bandwidth parameter, α_x, correlated significantly with the mean dynamic coefficient. The correlation coefficients and regression line slopes are positive, indicating that increasing the density of surface peaks or the range of wavelengths forming the topography results in increased dynamic friction. The effect of an increased range of wavelengths within the surface topography (i.e. an increased bandwidth), namely to increase the value of μ_d, may be due to the inclusion of physically significant wavelengths or the progressively larger proportion of such wavelengths present in the total surface structure. It is possible that high frequency, low wavelength features reduce the dynamic friction between acetylsalicylic acid and steel. Evidently, fine diamond polishing is detrimental to interfacial sliding since despite the fact that the total power spectrum bandwidth of the steel surface is increased, there is a concomitant reduction in the proportion of features responsible for limiting the magnitude of the dynamic friction coefficient.

The long-crestedness, γ^{-1}, taken to quantify the extent of directional anisotropy of a surface, correlates significantly with the mean dynamic friction coefficient at only the 10% level of confidence when the initial normal load is 250 N. Under higher normal load conditions, the level of correlation is reduced greatly. This suggests that dynamic friction between acteylsalicylic acid and steel is a surface phenomenon primarily dependent upon the interfacial topography in the direction of sliding alone.

Although the second and fourth equivalent power spectrum moments, M2e and M4e, exhibit a strong negative correlation with the mean dynamic friction coefficient, in every case the correlation coefficient provided by the x-direction data, i.e. M_{2x} and M_{4x}, are significant at higher probability levels. In accordance with this, the three-dimensional surface summit density, D_s, fails to provide a significant correlation coefficient in contrast to the two-dimensional equivalent, D_{px}.

The general pattern of correlation between the surface topography of the steel and the dynamic friction coefficient discussed above is the same for both 350 and 25 μm high-pass filtered surface data.

The general pattern of correlation between the detailed surface topography and the dynamic friction coefficient remains constant, irrespective of the normal load and filtering of the data. This implies that one fundamental mechanism is responsible for the dynamic friction between acetylsalicylic acid and steel. The results show that the magnitude of the dynamic friction coefficient is primarily dependent upon the surface topography of the steel. The load normal to the contact interface exerts some influence, and the steel surface is contaminated by acetylsalicylic acid under all sliding conditions. This, together with the damage sustained by the compacts, indicates the involvement of a wear phenomenon deformation interaction. Adhesion between steel and acetylsalicylic acid occurs to an extent determined by the steel surface topography, and the interfacial loading and shear conditions. This suggests that a ploughing component of the dynamic friction exists and that large asperities remain clear of the adhered acetylsalicylic acid. Clearly there is an interrelationship between adhesion and friction. Whilst an increase in asperity height slope and curvature reduces the dynamic friction, the adhesive contamination increases, but not sufficiently to prevent deformation and ploughing of the powder compact.

The dynamic friction between acetylsalicylic acid and steel is obviously generated by a combination of adhesive, shear and ploughing components. With highly polished smooth steel surfaces the frictional resistance to sliding is generated by interfacial adhesion. Upon application of a tangential force, shear occurs at the contact interface and the shear strength of the acetylsalicylic acid–steel junctions and the true area of bonding determine the magnitude of the friction coefficient. The area of bonded junctions will be influenced by both the normal and tangential forces which determine the extent (if any) of junction growth. As sliding proceeds, some resistance is also produced by the steel asperities deforming and ploughing through the compact surface. Adhesive wear progressively damages the sliding face of the compact, leaving debris on the steel surface. As the debris accumulates during multiple sliding, increasingly less adhesion occurs between the acetylsalicylic acid compact and the steel surface, and in effect the compact slides across a boundary lubricant layer. The shear strength of junctions between the acetylsalicylic acid debris and the compact itself is less than that of junctions with the steel surface. Consequently, the dynamic friction coefficient is reduced.

With unpolished steel surfaces, adhesion at the contact interface is strengthened by an increased depth of asperity interaction. The higher sharper asperities penetrate any contaminant surface films and increase the amount of mechanical interlock. When sliding is induced by tangential stress, shear occurs, not at the interface between acetylsalicylic acid and steel, but within the powder compact itself. The adhesion at the contact interface results in a shear strength greater than that of the powder compact which has an inhomogeneous distribution of strength. The compact surface undergoes excessive deformation and work hardening during compaction and is stronger and denser than the material within the bulk of the compact; consequently, the probability of failure below the surface is increased. Once failure occurs, sliding results in continued deformation and ploughing of the progressively weaker acetylsalicylic acid presented to the steel counterface. The adhesion and mechanical interactions continue, but the hard steel asperities plough through the compact with increasing ease and shear of the acetylsalicylic acid produces less frictional retardation than disruption of the adhesive junctions.

An alternative partial explanation of the effect of an increased asperity height may be that the mean surface separation is increased due to the elasticity of the larger steel asperities. The total contact area and extent of adhesion is reduced, thereby limiting the dynamic friction. However, the amount of damage to the powder compacts caused by asperity interactions suggests that this phenomenon is not particularly effective.

In practical terms, the results show that when sliding acetylsalicylic acid compacts across steel, the intuitive and widely practised approach to limiting friction of polishing the steel, to produce a smooth surface finish which is pleasing to the eye, is not the best approach to reducing the value of the dynamic friction coefficient. In fact, an unpolished, ground and flat lapped steel surface creates less frictional retardation to sliding, but unfortunately also damages the compact surface. The balance between the dynamic friction coefficient and the level of compact damage must be examined to identify the optimum compromise. Careful attention to the preparation of the steel will produce a surface topography with satisfactorily low friction properties without excessive wear of the compact.

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