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Assessment of Lubricated Contacts—Mechanisms of Scuffing and Scoring

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SUMMARY

Scoring and scuffing are defined as two distinct but related forms of failure of hardened ferrous components lubricated by liquids. Experimental observations of these phenomena are described, and criteria for scoring and scuffing are discussed. The mechanisms proposed by various authors to explain these observations are enumerated.

The view presented here is that, under conditions yet to be defined, scoring is a gradual breakdown of the lubrication of interacting asperities, such lubrication being boundary or microelastohydrodynamic in nature, or a mixture of the two. The final scuffing stage represents a breakdown of the main elastohydrodynamic system, but this may be triggered by the deterioration in surface topography as a result of scoring.

An extension of a published theoretical treatment of elastohydrodynamic breakdown is proposed, and a critical experiment to assess the importance of edge effects in band contacts is suggested. The practical implications of the proposed mechanism are reviewed, and recommendations for further work are made. A possible thermal instability mechanism for the breakdown of boundary lubrication is outlined.

INTRODUCTION

This paper is one of a series dealing with an interdisciplinary assessment of lubricated contacts. The assessment focuses on various scientific elements of a lubricated contact generic to mechanical components such as bearings, gears and traction drive elements. In connection with the tribology aspects of mechanical components, two general needs seem to stand out. First, the development of more sophisticated design tools to predict performance. Second, an improved process for creating new tribology opportunities along with a more efficient means by which they can be carried into practice. To do this requires a growth in the scientific interdisciplinary knowledge base of lubricated contacts as well as continued use of the information generated from engineering experience.

There are many mechanical, chemical and metallurgical processes that collectively contribute to the tribology barrier problems of mechanical components. These barrier problems are reflected in the observation of various failure modes. As an example, the general failure modes associated with gears are shown schematically in figure 1 as a function of torque and pitch line velocity. These failure modes, represented by general engineering terms such as wear, fatigue and scuffing, are competitive processes and frequently interact with each other. For improvements in performance and efficiency there is a need to operate beyond current limits of speed, torque and temperature. In this regard, the interactive processes leading up to scuffing would seem to be of concern. Associated with scuffing is a preliminary process that can be defined as scoring. Both processes seem to have similar mechanical, chemical and metallurgical interactions that are also associated with the important process of run-in.

Neither scuffing or scoring have well-defined definitions. The former is involved more with local plastic deformation while the latter involves gross adhesive transfer. They both represent final stages in the breakdown of lubrication and are barriers to expanding the limits of lubrication for many types of mechanical components. The process leading to the threshold of failure is complicated. Consequently, current failure theories tend to be too narrow in scope, and the present understanding of the actual process is very limited. An assessment of these theories along with the observations of sliding failure investigations would seem to be appropriate in connection with expanding the scientific interdisciplinary knowledge base of lubricated contacts.

Academic Press Incorporated gave their permission to include material from a previously published review on scuffing (ref. 7).

SCORING AND SCUFFING OBSERVATIONS

Scoring and scuffing are two distinct but related barriers that may limit the performance of heavily loaded sliding counterformal contacts between hardened ferrous components lubricated by liquids. Perhaps the best explanation of the phenomena can be given by the observations of a scuffing test on a disk machine.

In such a test, the load is usually increased in steps at constant intervals of time. At first the loads and the temperatures of the disks are low and the surfaces are completely separated by a coherent elastohydrodynamic film. As the load is increased, more power is dissipated in friction, the temperature increases, and the film becomes thinner. Intermittent electrical contacts occur, and the highest asperity summits are flattened. The coefficient of friction often passes through a minimum value of 0.02 to 0.03.

Fine scratches in the direction of motion start to appear on the rubbing surfaces, often accompanied by the formation of transverse cracks, particularly on the slower surface. Material begins to transfer, mainly from the slower to the faster surface, and with some materials, a thin patchy layer of a transformed phase known to metallurgists as W1* (refs. 1 and 2) appears. The coefficient of friction may rise to 0.06-0.08. These phenomena are symptoms of scoring which is a gradual process, to which it may be difficult to attribute a definite starting point.

Finally, there is a sudden increase of noise and vibration to levels that can be intolerable, and the coefficient of friction may show a further

*W1 is a very hard phase which appears white and featureless when etched. W2 is a layer of white material that may not be as hard, but is more frequently assoicated with scuffing of ferrous materials at least in disks and gears. These white phases are not very well defined metallurgically.

rise by a factor of 2-4. Parts of the surfaces become rough and heavily distorted. The original grinding marks and the score marks are completely obliterated, and there is often no indication of the direction of sliding. Another transformed phase, known as W2, is detected by metallurgical examination (refs. 1 and 2). This is a scuffing failure, which is a sudden process with a well-defined end point.

A sketch of the variation of friction force with time during such a test is shown in figure 2. The first indication that conditions are becoming severe is that the friction "overshoots" and then recovers at each load increase. Later, the friction force starts to increase towards the end of each load stage as the disk bulk temperature increases, and this is often a useful warning of an impending scuff. It seems appropriate to distinguish scuffing from scoring at about this stage.

The sequence of events just described is typical of disk machines operated at peripheral velocities of the order of 1-10 ms^{-1} and lubricated by straight mineral oils. Operation at higher speeds, or the presence of extreme pressure additives in the lubricant, may tend to obscure the "sudden death" nature of scuffing, and the mode of failure may tend rather to scoring.

The terms scoring and scuffing are often used indiscriminately, and comparisons between the results of different workers may be misleading unless the nature of the failure, and the experimental criteria used to define the failure point, are the same.

Some workers use as a failure criterion the continuous lack of a detectable electrical potential difference between the disks when they are placed in parallel with the lower resistance of a potential divider circuit with a maxiumum potential difference of the order of 10 mV. In the author's experience such a lack of potential difference may occur some time before the final scuff and at a lower load, particularly with a straight mineral oil.

Tests using more practical machinery such as gears, or cams and follower systems, are more difficult to conduct, since variation of the load during running may not be possible. Furthermore, the actual load may differ from that nominally applied, as a result of dynamic effects. Since conditions such as the slide/roll ratio may vary markedly during the operating cycle, initial failure is confined to a small fraction of the rubbing surfaces and may be difficult to detect. The force of friction is not easily accessible to measurement, and in gear tests the rig is usually shut down between load stages so that the rubbing surfaces may be visually inspected for damage. The failure criterion is usually based on the results of such a visual inspection. Comparison of the performance of different lubricants, for example, may be difficult if the appearance of the damaged parts is different. Even such an apparently trivial matter of whether the load is applied when the rig is at rest, or after it has been run up to test speed, may have significant effects, both on the visual appearance of the damaged parts and on the failure load.

The complex nature of the phenomena of scoring and scuffing, and the difficulties in the performance of the experiments and in the interpretation of the results, will be evident from the foregoing discussion. The mechanisms proposed by various authors to explain these observations will now be discussed.

BREAKDOWN OF BOUNDAY LUBRICATION

The Critical Total Contact Temperature Postulate

Historically, the most important of the mechanisms suggested by various authorities is that of Blok (ref. 3) where there is a limit to the temperature of contacting sliding surfaces above which lubrication breaks down. This proposal was advanced before the modern understanding of the importance of the elastohydrodynamic lubrication of concentrated contacts, and the proposer obviously had in mind the breakdown of boundary lubrication. In the extreme form of the postulate, the limiting temperature is characteristic of the four materials present: the two surfaces, the liquid lubricant and the gaseous environment; and is independent of running conditions such as loads and surface velocities. It was intended to apply only to lubricants such as straight mineral oils, without extreme pressure additives.

The total contact temperature is the sum of two components. The first is the bulk temperature, that is, the temperature of the parts at positions remote from the contact. In principle there is no difficulty in measuring or estimating it. The second component, the flash temperature, is the instantaneous rise in temperature of a surface as it passes through the heat source represented by the sliding contact. It is difficult to measure, as it is of very short duration and decays very rapidly with increasing depth below the surface. In most cases this additional component must be estimated, and Blok (refs. 4 and 5) developed methods by which such estimates may be made. They require a knowledge of the coefficient of friction, which may be difficult to measure in practical machinery.

Some support for this mechanism of failure may be obtained from experiments in boundary lubrication, in which the speeds of the parts are so low that hydrodynamic effects are negligible. In many systems there is a sudden increase in friction as the temperature is raised by external heating, but this seems to occur mainly with rather artificial lubricants, such as solutions of fatty acids in inert solvents, and with unrepresentative solids such as stainless steel. Studies with materials of more practical interest in general show no sudden breakdown, but a gradual increase of friction with temperature. At high sliding speeds such a gradual increase could in principle lead to thermal instability and a consequent breakdown of lubrication; a possible mechanism is outlined in the appendix.

The evidence from scuffing tests is conflicting. Those workers finding evidence against the extreme form of the postulate of a constant critical total contact temperature seem to outnumber those reporting in its favor. For further details readers are referred to reviews by Blok (ref. 6) and by Dyson (ref. 7).

Some typical results of scuffing tests in a disk machine (refs. 8 and 9) are shown in figure 3. The tests were all undertaken with the same material, case-hardened EN 34 steel, with the same mineral oil in the same disk machine. A variety of peripheral velocities and surface finishes was used. Figure 3 shows the mean estimated total contact temperatures just before the end of each test, the tests being terminated either by scuffing or by reaching the load limit of the machine. Each temperature is the mean of at least two runs, usually at each of two defined initial surface finishes. There was no evidence that the level of surface finish influenced the total contact temperature just before scuffing. The 95 percent confidence limits of the mean of two results are estimated as ±40° C, with 24 degrees of freedom in the variance estimate.

It will be seen from figure 3 that there is not a single critical total contact temperature but many, and that the temperature is a complicated function of the mean rolling velocity, 1/2 $(u_1 + u_2)$, and of the sliding velocity, $|u_1 - u_2|$, where u_1 and u_2 are the peripheral velocities of the two disks.

The most plausible general conclusion is that the postulate gives a good engineering approximation over limited ranges of running conditions, but that it would be unwise to rely on it for an indication of the mechanism of failure.

Breakdown of Surface Films

Disks run in an inert atmosphere with an inert lubricant scuff at very low loads, but running in the presence of oxygen, either in the atmosphere or in the lubricant generates a visible protective film that can support heavy loads, even in a subsequent test under inert conditions (ref. 10). The failure load of disks run in an atmosphere containing oxygen may be increased by inclusion of extreme pressure additives in a straight mineral lubricating oil. Such additives are compounds usually containing one or more of the elements sulphur, chlorine and phosphorus, and the accepted explanation of their action is that they form non-metallic surface films that re-inforce the protection afforded by the oxide films usually present. This additional protection survives subsequent running with mineral oil alone at a load greater than the scuffing load found in a normal test with mineral oil alone present from the start.

The above observations indicate the importance of surface films, and it seems possible that the breakdown of these films may be the critical mechanism of scuffing failure.

This is certainly an over-simplification, since the importance of elastohydrodynamic effects in scuffing has been demonstrated in many experiments (ref. 7). It seems likely that the breakdown of surface films plays an important part in the breakdown of boundary lubrication, which it will be seen may precede and even precipitate the final scuffing failure by the breakdown of elastohydrodynamic lubrication.

Very little is known about the mechanism of surface film breakdown, and it remains a subject matter of further investigation.

Breakdown of Main Structure of Surface Topography

Hirst and Holland (ref. 11) found a very interesting relation between the failure of boundary lubrication and the topography of surfaces. They investigated a large number of surfaces covering a range of vertical and horizontal topographical characteristics. They divided the surfaces into two categories of 'safe' and 'unsafe.' As the contact temperature was increased by external heating, the safe surfaces showed a transition to high friction at high temperatures (~170° C), while the unsafe surfaces showed a transition to high friction at low temperatures (~55° C).

They found that both the vertical scale of the surface topography, measured by the standard deviation σ of the overall distribution of surface heights, and the horizontal scale, measured by the correlation length β^*, were important. They provided a contour map showing the division between safe and unsafe surfaces as a complicated function of the two variables σ and β^*.

They concluded from their results that failure occurred at the obliteration by plastic deformation of those features that they identified with the main structure of the topography. Deformation of the fine structure, of much shorter wavelength, that is superimposed on the main features, could be tolerated without severe wear.

These observations are very interesting, but they do not yet provide a mechanism of the breakdown of boundary lubrication that is complete enough to be applied to failure by scoring or scuffing. Again, further investigation would be rewarding.

Instability of Superficial Layers

Rozeanu (ref. 12) developed a stability criterion involving the gradient of the viscosity of the solid material in the superficial layers, and suggested that severe wear would occur if this viscosity gradient were such as to drive the criterion into the regime of instability. He also discussed the role of transient effects in provoking instability that may lead to scoring or scuffing (ref. 13).

Rozeanu's experimental results are very striking and it does not seem possible to explain them on the basis of commonly accepted ideas. His interpretation is unconventional and does not seem to have found widespread acceptance, but his ideas would repay further study.

Thermal Instability

Thermal instability has been proposed as a mechanism of scoring and scuffing by many authors, but detailed quantitative work that can be applied to failure of these types has been lacking. A possible thermal instability mechanism for the breakdown of boundary lubrication, depending on a coefficient of friction increasing with increasing contact temperature, is outlined in the appendix.

BREAKDOWN OF ELASTOHYDRODYNAMIC LUBRICATION

Conventional Approach

The importance of elastohydrodynamic lubrication in scoring and scuffing is well documented (ref. 7) and it is an obvious move to estimate the minimum thickness of the elastohydrodynamic film just before scuffing and to compare it with the surface roughness. These values are indeed found to be of the same order, but there is no close correlation. Film thicknesses estimated for conventional smooth-surface theory showed no correlation with surface roughness over a range of more than 3/1 in roughness, while the results ranged from failure at an estimated film thickness of 0.5 μm to no failure at 0.065 μm, both for an initial surface roughness of 0.4 μm R_a (refs. 8 and 9).

Effect of Surface Roughness

The foregoing estimates of minimum film thickness were obtained from conventional smooth-surface theory, but this is obviously inapplicable when the film thickness is of the same order as the surface roughness. The roughness will also change the geometry of the contact, since asperity interactions will occur outside the band of contact calculated from Hertzian mechanics.

A treatment of the scuffing failure of circumferentially ground disks in which the effect of surface topography is taken into account both in the hydrodynamic and in the contact mechanics, has been proposed (ref. 14). In conditions approaching scuffing, a large part of the load must be carried by asperity interaction. The fundamental assumption was that interacting asperities, under relative sliding, could be protected from severe damage by the presence of a lubricant of very high viscosity, produced by the high pressures generated by the main elastohydrodynamic system. As the load and disk bulk temperatures increase, the surfaces approach one another and continue to maintain the effectiveness of the main elastohydrodynamic system. But the limit to this process is reached when all the applied load is carried by asperity interactions. No further approach is possible and the geometry is that of the static contact. Any further increase in temperature renders the main elastohydrodynamic system ineffective, and the resulting severe surface damage is interpreted as a scuff.

The method of calculation of the above process was refined by Rossides and Snidle (ref. 15) who also provided more experimental evidence. Some of their results are shown in Figure 4 as a comparison between the predicted theoretical critical disk bulk temperature and the mean experimental temperature of the two disks just before scuffing. The failure load is assumed to be known, but no disposable constants have been used to fit the data. This is a calculation from first principles, using the model outlined in the foregoing. The results are encouraging in view of the many approximations and uncertainties of the theory.

A Possible Extension

The method just described is restricted to directional surfaces with surface texture (lay) in the direction of motion, such as circumferentially ground disks. An extension to general surfaces should be possible by the use of the method of Patir and Cheng (ref. 16) who model a surface as an array of rectangular tiles of varying thickness affixed to a smooth substrate. The rate of flow of lubricant, under a pressure gradient, through a rectangular channel formed by two such surfaces is calculated, and the pressure gradient is then deduced from the usual hydrodynamic condition of continuity of flow.

In their published work, Patir and Cheng select the thicknesses of the tiles as random numbers with stipulated variance and correlation, but the thicknesses could equally well be selected to match any required real surface, provided that a map of the heights of such a surface were available. The contact mechanics of the system could then be placed on a basis more consistent with the hydrodynamics than in previous treatments in which the weakest link is probably the extrapolation of the asperity pressure-compliance relation to very severe degrees of interpenetration. For this purpose, the relation between force and penetration of a rigid rectangular punch into an elastic half-space would be used.

Another way in which the treatment of references 14 and 15 should be extended is to take account of a possible correlation between the height distributions of the two surfaces. Evidence is now being found that in some circumstances the heights of the two surfaces along traverses transverse to the direction of motion may show strong negative correlation, the peaks of one surface fitting into the valleys of the other, and vice versa (refs. 17 to 19). In the present treatment the heights are assumed to be uncorrelated, and if significant correlation is found to be present its effect should be taken into account.

A POSSIBLE SYNTHESIS

The International Research Group of the OECD has identified two successive stages in the failure of simple rigs such as four-ball and pin-on-disk machines (refs. 20 to 24). Their results are sketched in figure 5(a). At sufficiently low sliding speeds, a breakdown in hydrodynamic lubrication occurs first as the load is gradually increased. This breakdown is manifested in a large increase in friction and a modest increase in wear rate. The load can still be carried by boundary lubrication, but this in turn breaks down as the load is further increased, this second breakdown being detected primarily by a large increase in wear rate; the increase in friction is small.

The OECD work is limited to systems with point contact and with one surface stationary, and there is an urgent need to extend it to cover conditions more nearly approaching those of practical interest. In such machines hydrodynamic effects may be expected to be more important, and the line of hydrodynamic failure would be higher. The line of boundary lubrication failure, on the other hand, may be little affected.

Figure 5(b) shows a possible result of such changes. At sufficiently high sliding speeds, boundary lubrication would fail while hydrodynamic conditions were still favorable, and it would be noticed only when the hydrodynamic conditions had deteriorated to such an extent that appreciable asperity interaction occurred. It seems possible that this could be associated with the mechanism of scoring.

To accomodate this picture in the model of scuffing failure proposed in the section on "Effect of Surface Roughness," it is necessary to assume that not all the interacting asperities are protected from damage by the presence of a lubricant of very high viscosity produced as a result of the pressurization by the main elastohydrodynamic system. Interactions occuring outside the main pressure field would not be so protected, and would rely on boundary or on microelastohydrodynamic lubrication, or on a mixture of the two. This would explain the gradual scoring stage - the production of the metallurgically transformed W1 phase during this stage indicates that at least a partial breakdown of lubrication is occuring.

The final scuff would still be caused ultimately by a breakdown of elastohydrodynamic lubrication, but this breakdown may be triggered by the deterioration in the topography of the surfaces during the preceding scoring stage.

EXPERIMENTAL APPROACH

In band contact between parallel-sided disks, scuffing usually starts at one edge and works inwards, and the importance of edge effects is uncertain and difficult to investigate directly. Edge contact may be avoided by the use of crowned disks, but the grinding conditions are different from those of parallel-sided disks and the surface topography is probably also different. There seem to be unexplained differences in the behavior of disk machines with band and elliptical contacts.

A rig in which this aspect could be investigated is sketched in figure 6. It is essentially a crossed cylinders machine with a variable skew angle θ. At $\theta = 90$ deg there would be circular contact, and increasing θ would give first a complete and then a truncated ellipse of contact. Finally, with $\theta = 180$ deg, there would be parallel band contact. Each cylinder would be a parallel-sided disk, and would be driven independently. Each drive shaft would incorporate a torque meter, a thrust bearing to take end thrust and a load cell to measure it. Temperatures would be monitored by embedded and trailing thermocouples, and electrical contact resistance would also be measured.

To detect the transverse cracks often found during the scoring stage, particularly on the slower surface, a crack detector would be used. The crack detector described by Phillips and Chapman (ref. 25) consists of a commercial tape recorder head riding on the oil film adhering to a disk surface. This arrangement enables fatigue cracks to be detected, but it is not known whether it would be sensitive enough to detect cracks produced by scoring.

Since scoring precedes and may trigger scuffing, it seems worthwhile to concentrate attention on this stage of failure. Metallurgical examination to detect the presence of the transformed phases W1 and W2 before scuffing may be required, and the ability to monitor surface topography without removing the disks from the machine would be very useful. Some experiments should be run in which the slower disk is made radioactive by thin layer activation. A scintillation counter placed near the surface of the faster disk, but remote from the slower disk, would monitor the transfer of material from the slower to the faster disk. A large increase in this quantity would signify entry into the scoring stage, and may very well be the first indication of distress. In any experimental investigation of scoring and scuffing, a parallel investigation of boundary lubrication with the same materials, surfaces and lubricant is recommended. It could probably be done by fitting a very low speed drive such that hydrodynamic effects are negligible. The coefficient of friction would be measured as a function of disk bulk temperature, firstly on natural cooling immediately after the end of the main run at test speed, and secondly on reheating by an external heater, preferably up to the highest total contact temperature observed in the main run. The load would be the highest reached in the main run.

The usual technique of increasing the load in a stepwise manner at intervals during the run has many disadvantages. Much information on the behavior of the system at lower loads is lost, and the sudden load changes themselves may have deleterious effects on running conditions. For example, electrical contact frequently increases immediately after a stepwise load increase, and then decreases again.

Hydraulic or pneumatic application of load would permit a preprogrammed increase of load with time, e.g. an exponential increase could be imposed. It would be necessary to make several different runs with disks prepared to the same specification. The runs would have to be terminated after different periods of running, i.e. with different final loads. The disks could then be analyzed by metallurgical and other physical techniques, and the topography of their surfaces established. The starting load and the rate of load increase with time should be included among the experimental variables.

CONCLUSIONS

From this assessment of some of the experimental and theoretical work on scoring and scuffing of lubricated contacts the following conclusions are drawn:

1. Scoring and scuffing are very complex phenomena and a multidisciplinary approach is required to establish more reliable failure criteria as well as to systematically expand the operating conditions limited by the scuffing and scoring failure mode.

2. It seems possible that under certain conditions, scoring is the result of the gradual breakdown of the boundary lubrication of interacting asperities, while scuffing is the subsequent sudden breakdown of the main elastohydrodynamic system. This second breakdown may be triggered by the deterioration in surface topography caused by scoring.

3. Suggested approaches that could be followed include the Hirst and Hollander characterization of surfaces liable to a breakdown of boundary lubrication, and the OECD work on regimes and modes of failure.

4. Some published work on the failure of elastohydrodynamic lubrication, in which the effects of surface topography both on the hydrodynamics and on the contact mechanics are taken into account, should be extended by the use of the Patir and Cheng's method of dealing with rough surfaces. It may be necessary to take account of correlation between the height distributions of the two surfaces.

5. The role of edge effects in the scuffing of band contacts is obscure. An experimental method is proposed to investigate these effects.

6. It is recommended that future work concentrate more on the scoring stage of failure.

7. Investigation of boundary lubrication with the same materials, surfaces and lubricant should run in parallel with experiments on scoring and scuffing.

8. The breakdown of boundary lubrication may be controlled by a thermal instability mechanism on an asperity scale. A simple solution is outlined.

APPENDIX - THERMAL INSTABILITY IN BOUNDARY LUBRICATION

Consider an asperity contact between two surfaces, in the form of a circle of radius a as shown in figure 7. If the rate of heat generation per unit area of contact, $\bar{q}$, is uniform and if the Peclet number, defined later, is low enough, the maximum equilibrium temperature rise $\delta\theta_{max}$ occurs at the center of the circle:

$$\delta\theta_{max} = \frac{1}{2}\frac{\bar{q}a}{\lambda}$$

where λ is the thermal conductivity (refs. 4 and 5). It may be shown that the mean temperature rise over the contact area is

$$\delta\bar{\theta} = \frac{4}{3\pi}\frac{\bar{q}a}{\lambda} = 0.4244\frac{\bar{q}a}{\lambda}$$

This relation is not very sensitive to the distribution of the rate of heat generation, e.g., for a semi-elliptic distribution,

$$\delta\bar{\theta} = \frac{9\pi}{64}\frac{\bar{q}a}{\lambda} = 0.4418\frac{\bar{q}a}{\lambda}$$

Now $\bar{q} = \bar{\mu}\,\bar{p}\,u_s$

where

$\bar{\mu}$ is the mean coefficient of friction
$\bar{p}$ is the mean pressure over the contact area

and

u_s is the sliding velocity

The mean temperature over the contact may then be written:

$$\bar{\theta}_c = \theta_0 + \theta_1\bar{\mu} \tag{A1}$$

where

$$\theta_1 = \frac{0.42\,\bar{p}\,u_s\,a}{\lambda}$$

If there is a linear relation between the mean coefficient of friction and mean temperature,

$$\bar{\mu} = \mu_0 + \mu_1\bar{\theta}_c \tag{A2}$$

Equations (A1) and (A2) give a solution

$$\bar{\theta}_c = \frac{\theta_0 + \theta_1 \mu_0}{1 - \mu_1 \theta_1}, \quad \bar{\mu} = \frac{\mu_0 + \mu_1 \theta_0}{1 - \mu_1 \theta_1}$$

Instability occurs if $\mu_1 \theta_1$ tends to unity. Thus all asperity contacts with a radius greater than a critical value

$$a_c = \frac{\lambda}{0.42 \, \bar{p} \, u_s \, \mu_1}$$

will show instability. The effective Peclet number at the critical radius is

$$(Pe)_c = \frac{u_s \, a_c}{2\psi} = \frac{\rho c}{0.84 \, \bar{p} \, \mu_1}$$

where

ψ $\lambda/\rho c$ is the thermal diffusivity
ρ is the density

and

c the specific heat of the material

The mean pressure p will be taken equal to the hardness H. The results of Hirst and Stafford (ref. 26) in boundary lubrication suggest a value of μ_1 of approximately 10^{-2} K^{-1} for worn stainless steel surfaces. If the same value is adapted for hardened steel, with

$$\rho = 7.8 \times 10^3 \text{ kg m}^{-3}$$

$$c = 540 \text{ J kg}^{-1} \text{ K}^{-1}$$

$$H = 7 \text{ GPa}$$

then

$$(Pe)_c = 0.072.$$

i.e., low enough for the low Peclet number flash temperature theory to be used. For a thermal conductivity λ of 45 W m^{-1} K^{-1}, and other numerical values as before, the critical asperity radius is

$$a_c = 1.56 \, u_s$$

where a_c is in μm and u_s is in m/s.

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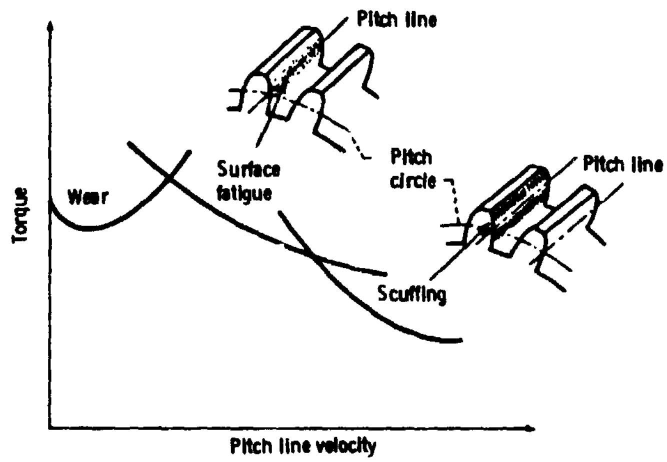

Figure 1. - General tribology failure modes in gears.

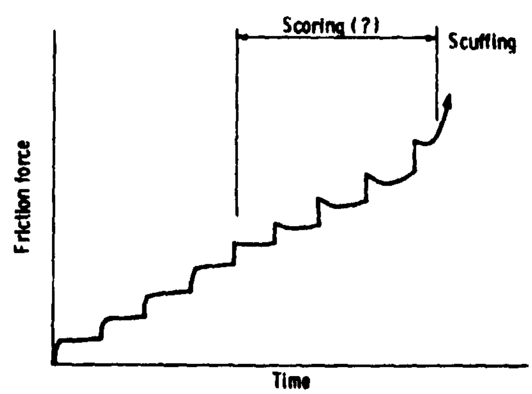

Figure 2. - Sketch of variation of friction force with time during a scuffing test on a disk machine.

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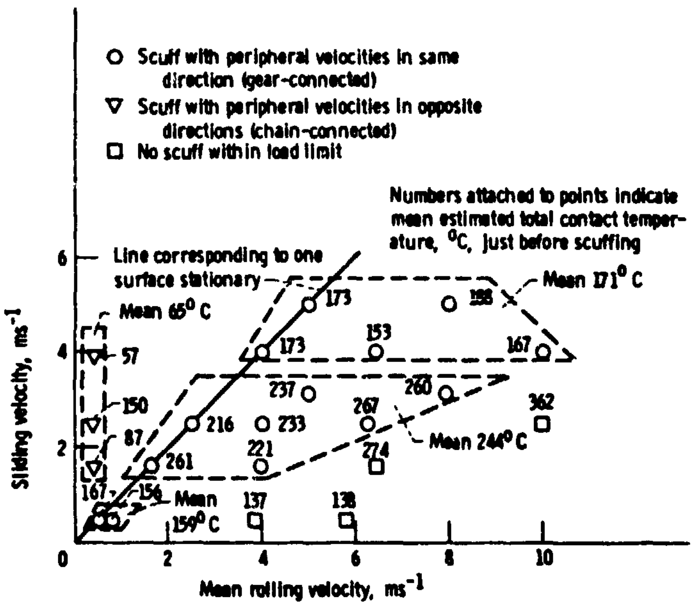


Figure 3. - Effect of rolling and sliding velocities on total contact temperatures at scuffing.

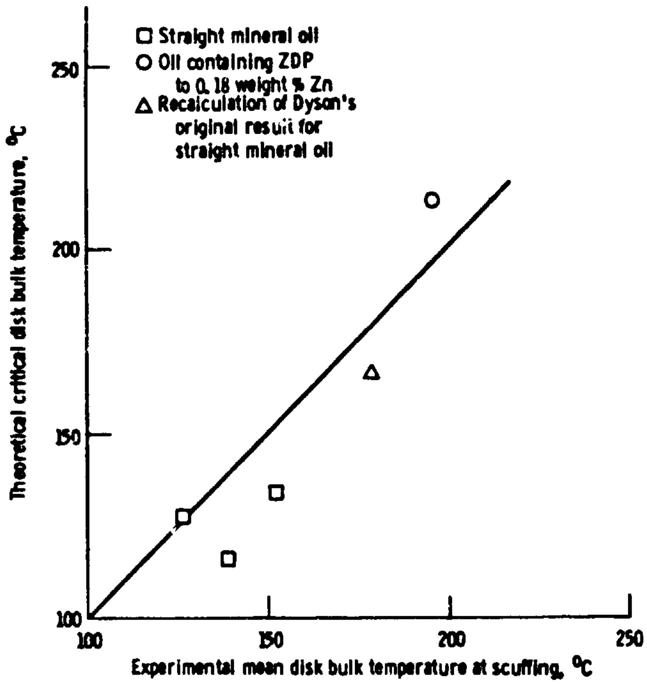
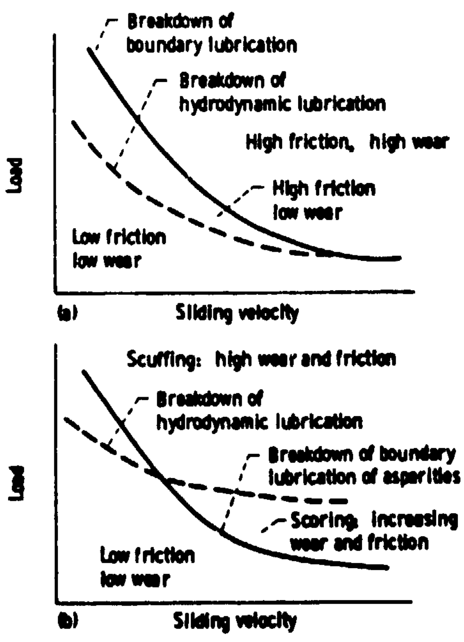


Figure 4. - Comparison of experimental scuffing conditions with theory.



(a) OECD results from pin-on-disk machine under pure sliding conditions.

(b) Suggested extension to disk machines and lubricated contacts with combined rolling and sliding.

Figure 5. - Regimes of operations.

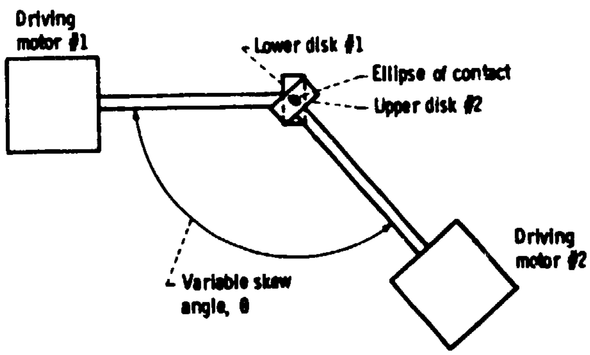


Figure 6. - Proposed experimental scuffing rig.

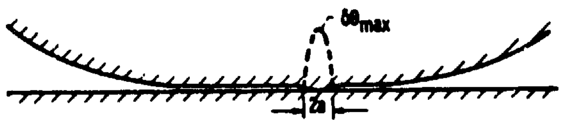


Figure 7. - Asperity contact for simple thermal instability model.