Conclusions

The three dimensional shape effect of asperity on abrasive wear was analyzed with model experiments in the scanning electron microscope and the following results were obtained.

(1) Wear modes of shearing, cutting, and wedge forming were observed and each mode was related to attack angle and dihedral angle of asperity by wear mode diagram.

(2) Wear rate of aluminium or brass in cutting mode increases approximately linearly with attack angle in dry and lubricated condition.

(3) Wear rate of aluminium or brass becomes maximum at a certain dihedral angle in dry condition.

Acknowledgment

We would like to express our appreciation to Professor H. Abé, and thank Mr. M. Nakagawa for his experimental assistance.

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DISCUSSION

Jorn Larsen-Basse[1]

The authors present some interesting data and they should be encouraged to continue the work so that a more complete picture emerges. In particular, the results should be evaluated on the basis of the expected mechanics and measured coefficients of friction. The reasons for this suggestion follow.

It is intended here only to demonstrate that additional information can be extracted from the data and that this type of information should be used in planning additional experiments.

For a simple analysis we use, instead of the rake angle, the "angle of approach," λ, as the angle between the direction of tool travel and the normal to the tool face, see Fig. 11. This angle is given by

$$\cos\lambda = \sin\phi\,\sin\alpha/\sqrt{1-\cos^2\alpha\,\cos^2\phi})$$

Calculated values of λ for some selected values of α and ϕ are shown in Fig. 12 which also contains sketched-in regions for the various removal mechanisms for Al obtained from the authors' Figs. 4 and 5.

Cutting operates only when α is greater than 45 deg and λ is less than a similar value. This indicates that a change in mechanism occurs when the friction force is controlled fully by the shear flow stress. At this point lubrication would have no effect, as the data indicate.

As α increases toward 90 deg the range of λ-values which result in cutting increases. The range is further expanded by lubrication. Here, *the chip slides over the tool surface*; lower friction would ease this process and expand the cutting region at the expense of the wedge region. The expansion at the top of the λ-range, indicated by one data point, is more difficult to rationalize and that point should be confirmed.

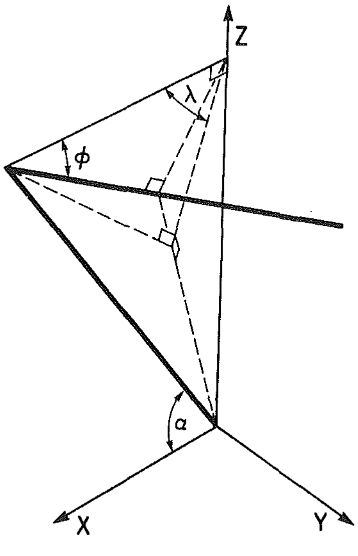

Fig. 11 Part of the cutting tool showing the angles of interest. X-axis is direction of travel.

The one data point for brass, obtained from Fig. 8, is shown as point X in Fig. 12. It lies in the range where interfacial friction is expected to have little or no effect on cutting mechanism; i.e., values for aluminum and brass and for dry and lubricated conditions should coincide.

The wear conditions of Fig. 7 for aluminum follow the ϕ = 52.5 deg contour in Fig. 12 as α increases from 45 to 90 deg. The λ-values decrease from 45 deg to around 35 deg and thus are close the upper border of the cutting region. Here, lubrication might promote the "ploughing/cleaving" (or "skating")

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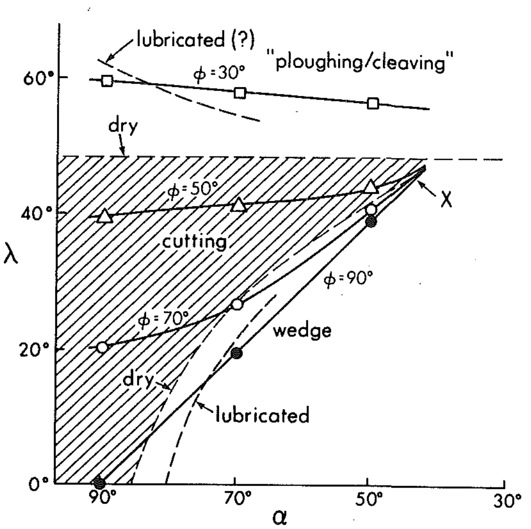

Fig. 12 Calculated λ-values and approximate regions for the removal mechanisms for aluminum workpiece

mechanism and thus give lower wear than for dry sliding, for the higher λ-values (lower α-values).

The corresponding conditions for brass in Fig. 8 follow the $\phi = 82.5$ deg contour of Fig. 12. It is near the other border of the cutting region, where lowered interfacial friction tends to replace the wedge mechanism with cutting. The results of the wear tests of Figs. 7 and 8 can then be explained very qualitatively. For comparison between the two materials the testing conditions should be similar.

D. H. Buckley[2]

The authors are to be complimented on their fundamental approach to the study of the abrasive wear process with the use of a single asperity model. One wonders, however, as to just how closely the author's model asperity resembles a real asperity rather than an abrasive grit.

A number of years ago Williamson[3] measured in detail the slopes of asperities and concluded that typical asperities are from 10 to 300 μ in high with slopes usually lying between 5 and 10 deg. They can occasionally be as steep as 25 deg according to Williamson. The authors asperity has a much steeper slope. Can such differences alter the observations?

The authors use for their abraded specimens aluminum and brass. Both of these materials are extremely softe relative to the very hard WC-alloy used for the model asperity. Their observations lead one to believe that the wear behavior was similar, as expressed in the wear modes described, namely shearing, cutting and wedge formation. Shouldn't however, the nature of the mechanical properties of the surface being abraded have an influence on the three modes of wear and the amount of each seen? For example, if one were abrading a hard steel surface rather than soft aluminum or brass the nature and amount of cutting and wedge formation might be altered appreciably. In fact if one abrades a brittle material, such as a ceramic, cutting and wedge formation might be completely eliminated. The authors comments would be appreciated.

J. Challen

The researchers have presented experimental results relating to hard three-dimensional indenters being traversed over soft surfaces. The work is of interest as the low (1.054N) normal force and varying geometries of the indenters probably reasonably well resemble asperity contacts between real surfaces or between grits and surfaces. As the title implies, the paper is concerned with abrasive wear and hence attack angles α less than 40 deg have not been examined but extension to cover low angles of α would be of interest in representing typical tribological surfaces. However the term "ploughing" has been annotated onto the low α (high 2ϕ) regions of the wear mode diagrams (Figs. 4 and 5). Although not specifically defining the term the authors deem the mechanism to be similar to that applying to sharper indenters (low 2ϕ) for which they use the terms, seemingly synonymously, "cleaving" and "shearing." Since there is only displacement of material but no net loss, the mechanism in question is undoubtedly akin to the steady state wave model as it applies to bluff indenters (high 2ϕ) which are close to being two-dimensional. The applicability of the wave model to waves emanating from the faces of a sharply pointed indenter (cleaving or shearing) has been treated by Torrance.[5]

The "cutting" mode was also found experimentally by Torrance for similar ranges of geometrical angles. He used higher loads of 7N and 50N and described the phenomenon graphically as "side wall stripping." For the two-dimensional configuration a theoretical cutting model was proposed in [8] which applied above critical values of attack angle and predicted wear rate increasing with attack angle and better lubrication as found in Figs. 7 and 8.

For not extremely high α values but for high 2ϕ values the "wedge" mode was found and this mode is again analogous to a model proposed in [8], namely the wear model where a non-steady state wave develops and is sheared off. As shown in Fig. 8 lubrication inhibits the formation of wedges and hence lowers the wear rate.

To summarize, this work by Kato et al. is of great interest to this discusser in that it is a further paper which appears to confirm the validity experimentally, using realistic, i.e., three-dimensional geometries and loads, of the three basic asperity interaction mechanisms put forward in [8]. It is to be hoped that further work is conducted and published which extends the range of α and 2ϕ values used and with friction forces and depths of penetrations being measured. Also of interest would be the stress-strain properties of the materials used as it has been shown in [9] that strain hardening would affect the location of the boundaries between the wear modes shown in Figs. 4 and 5.

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Authors' Closure

The authors wish to thank Prof. Jorn Larsen-Basse, Dr. D. H. Buckley, and Dr. J. Challen for their interest in our contribution and for their comments.

In answer to Prof. Jorn Larsen-Basse, the authors agree with his comment and believe the proposed angle of approach λ can be a good geometrical parameter to describe in abrasive wear mechanics, as is shown in Fig. 12.

The expected mechanics must at least involve parameters of α, φ, load, hardness, and the shear strength at the contact interface. This was successfully done previously for the abrasive wear with a spherical asperity and a wear mode diagram was proposed by K. Kato et al.[6]

A similar approach would be possible in the abrasive wear with a pyramidal asperity if the friction force could be related to the angle of approach λ.

In answer to Dr. D. H. Buckley, it is true that asperities on machined surfaces have slopes usually lying between $5 \sim 10$ deg. But we can sometimes expect larger values of slopes for hard abrasives on abrasive papers or grinding wheels especially when they form new cutting edges via brittle fracture.

On the other hand, we must consider another abrasive mechanism, namely plastic fatigue, if we expect correct results and ribbon-like micro-chips are still formed in general abrasive situations where slopes lye between $5 \sim 10$ deg.

If we change the abraded material from a soft one to a hard and brittle one, three modes of wear and the amount of each would be greatly changed. We can possibly expect more often the mode of brittle fracture or flaking.

The model abrasive asperity should be made of a harder material (such as diamond) than WC-alloy for this purpose, because our model asperity often yielded against steel.

In answer to Dr. J. Challen the authors think that the two dimensional wear model proposed by Dr. J. Challen et al. [8] is also available to give approximate explanation to the present results.

It was shown before that the two dimensional model was useful in explaining the abrasive wear caused by a spherical abrasive asperity and a wear mode diagram was proposed by Kato et al.[6]

If the theoretical friction force for the pyramidal abrasive asperity could be introduced, a similar wear mode diagram would be formed in the same way.

It is true that the strain hardening affects the wear mode. The differences of wear behavior between alumimum and brass shown in Figs. 7, 8, 9, and 10 would mainly come from the difference in strain hardening properties of these metals.

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