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Development of Wear Model concerning the Depth Behaviour

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Abstract: Wear model for predicting the behaviour of a depth is considered in this paper. It is deduced from the energy and volume based wear models such as the Archard equation and the workrate model. A new parameter of the equivalent depth (D_e = wear volume/worn area) is considered for the wear model of a depth prediction. A concenpt of a dissipated shear energy density is accommodated for in the suggested models. It is found that D_e can distinguish the worn area shape. A cubic of D_e (D_e^3) gives a better linear regression with the volume than that of the maximum depth, D_{max} (D_{max}^3) does. Both D_{max} and D_e are used for the presently suggested depth-based wear model. As a result, a wear depth profile can be simulated by a model using D_{max}. Wear resistance from the concern of an overall depth can be identified by the wear coefficient of the model using D_e.

Keywords: Wear model, wear depth, shear energy density, equivalent depth

Introduction

One of the important tasks for mechanical designers is to predict the life of a component and/or a structure. This is one of the failure analysis fields in solid mechanics such as fatigue, fracture mechanics, damage mechanics, contact mechanics and so on. In the tribological field as well, the wear prediction is also an important subject. The prediction is presented as a wear model. According to Meng and Ludema [1], more than 300 models have been presented in the *Wear* journal and at *Wear of Materials* conferences during 1957~1992. A wear model (sometimes called "wear equation") represents a relationship between the influencing variables of the wear and the wear amount. Even in the case of a sliding wear, 100 variables and constants were found to be used [1]. This enormous number of the models and the parameters is attributed to the complexity of the wear phenomena and the large scatter of the wear data usually found in the experiment.

Among the variables, contacting force and sliding distance are widely used since the multiplication of these yields an energy dissipation, which can be interpreted as a source of wear from a mechanical viewpoint. On the other hand, wear volume or weight loss is usually used as a wear amount. A linear relationship between the wear volume (or weight loss) and the multiplication of the contact force and slip distance has been generally proposed in the case of an adhesive and an abrasive wear [2] such that

$$V = K \cdot F \cdot S \tag{1}$$

where V is the wear volume, F and S are the contact force and the slip distance, respectively. The proportional constant K is termed as a wear coefficient that determines the degree of wear resistance.

Besides the wear volume and weight loss, the wear depth may be a more important parameter if a thickness reduction or a perforation is of a major concern for the structural integrity. Examples of it are the wear of a thin tube and a coating. So to speak, a shallow wear with a large worn area would be safer than a deep wear with a small worn area, when both have a similar wear volume. For this case, it is necessary to develop a wear model that deals with the wear depth rather than the volume or weght loss. However, a difficulty arises in this since the profile of the wear depth is usually random and the maximum of it is arbitrarily localized so that it is hard to be picked up. Therefore, it is useful to develop a parameter that can represent the wear depth properly and a model using it.

For the purpose of developing such a parameter and a model, Eq. (1) is re-investigated in this paper. The fundamental idea is to divide both sides of Eq. (1) by the worn area so that the relationship between a parameter like a wear depth (termed as an "*equivalent depth*" in this paper) and an dissipated energy density is produced. On the other hand, the profile of the wear depth is also considered by using the contact mechanics analysis. The relationship between the equivalent depth and the maximum wear depth is also discussed.

Short Review of the Volume-based Wear Models

The Archard equation

A typical example of the wear model using the volume (called a "volume-based model" *ad hoc*) like Eq. (1) is the Archard equation [3]. It is applicable basically in the case of an adhesive wear, which is written as

$$V = k \cdot \frac{F_n}{p_m} \cdot d \tag{2}$$

where V is the wear volume, k is the wear coefficient, F_n and d

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are the applied contact normal force and sliding distance, respectively. p_m is the hardness or flow pressure of the softer material between the two contacting bodies.

The wear coefficient, k, which is a dimensionless proportionality number, may be interpreted as the probability of producing a wear particle at any given asperity encounter [4]. When the shape of the asperity is assumed as a hemisphere, Eq. (2) can be re-written as

$$V = \frac{k}{3} \cdot \frac{F_n}{p_m} \cdot d. \tag{3}$$

Then, $k/3$ is equivalent to the dimensionless wear rate [2]. There are some discussions on the applicability of using k as a degree of a wear resistance. For instance, it can vary depending on the applied contact force, the sliding velocity, the temperature, the type of wear and other tribological conditions [4]. In short, the applicability of k can be validated if the wear mechanism is the same. Nevertheless, the Archard equation has been widely used since it has a simple form and an intrinsic interpretation of a wear.

The Workrate model

The Archard equation deals with the total wear volume and the total energy (or work) during the whole wearing process. Although a single path of a contact sliding can cause a detectable wear like a scratch test, a wear is usually detectable after some period wearing. Therefore, it may be hard to apply the Archard equation to the actual wearing process since it is necessary to implement a total sliding distance, which needs a considerable time. Instead, it will be useful if the equation is differenciated with respect to the time. A brilliant concept of this has been presented previously and the resultant equation is so-called the "workrate model" [5]. It is written as

$$\dot{V} = K\dot{W} = K\frac{d}{dt}\int PdS \tag{4}$$

where, $\dot{V}$ is the rate of the wear volume increase with respect to the time and $\dot{W}$ is the workrate. P is the contact normal force and S is the sliding distance. K is defined as a wear coefficient with the unit of Pa^{-1}.

The concept, "*rate*" in the workrate model is prominent since it can provide a life prediction from short-term experiments. If the actual workrate of the wearing components is known, the wear volume after a certain period of time can be estimated using the wear coefficient experimentally determined for that workrate. Then, the model can be used to compare the wear resistance by comparing the wear coefficients. However, it still includes the problem of a condition dependency as explained in the Archard equation. Again, it is necessary to define a certain range of a wear coefficient corresponding to the relevant wear mechanism. To compare simply the wear coefficients for determining a wear resistance can lead to an opposite result even at the same workrate if the mechanism is different. The wear mechanism is influenced by the contact force and the slip distance independently not by the multiplication of these, i.e. the work itself. The contact shape also affects it since the local contact traction and the slip distance can be altered depending on it although the same contact force is applied. Nevertheless, it has been used for the wear analysis of nuclear components due to its easiness of implementation to the experiments [6,7].

Investigation of the Wear Depth Parameter

Equivalent depth, D_e

If a wear depth is of primary concern rather than the volume, it will be helpful if a certain correlation between the volume and the depth can be defined. For the purpose of it, a simple geometry of the three dimensional shape of a wear volume such as a semi-ellipsoid, a hemisphere or a half torus have been supposed [8-9]. However, it is often found to be difficult to assume an appropriate simple geometry that could simulate the actual shape of a wear volume without an unacceptable error. A shape depends on the contact shape, the contact force, the slip regime such as a partial and a gross slip, and the slip distance.

On the other hand, the maximum wear depth (D_{max}) is considerably localized inside the worn area. Its location differs during each experiment even under the same wearing conditions. However, it is necessary to know the value of D_{max} since it is directly related with the perforation of the thin contacting bodies. Conclusively, it is necessary to develop a certain depth-like parameter that can be related with the maximum depth with a reliable and acceptable error bound. If developed, it has to be useful for the design of a wear resistance.

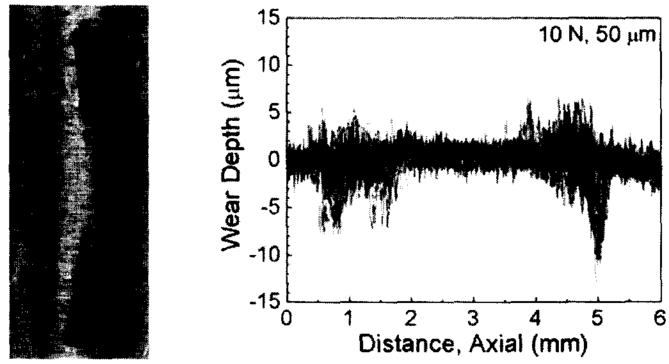
To this end, the wear volume is divided by the worn area. The result has a dimension of a length like a depth. It is termed as the "equivalent depth, D_e" presently. Therefore, D_e is a parameter comparable with the actual wear depth. In addition, it accommodates the geometrical feature of the wear scar such as the area and volume from the point of not only the magnitude but also the shape. If there exists a certain relationship between D_e and D_{max}, it can be used as a parameter to predict the life by incorporating the characteristics of the wear.

Interrelation between D_{max} and D_e

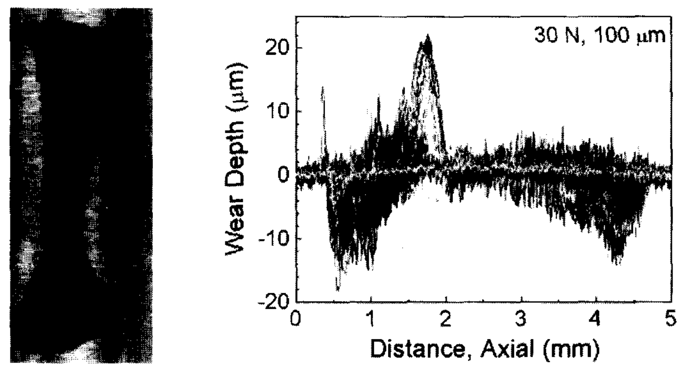
Experiment

A simple fretting wear experiment has been conducted to investigate the interrelation between D_{max} and D_e. The environment was an air at room temperature. As for the contacting specimens, a tube and a support were used. They were contacted with a predetermined contact force of 10 and 30 N. Reciprocating sliding was applied with a range of 50-100 μm. The dimension of the tube specimen was 9.5 mm in diameter, 0.6 mm in thickness and 50 mm in length. While, that of the support specimen was a plate spring made of a thin strip. Two types were used for the support specimen: type A had a concave contour in the transverse direction that surrounded the circumferential surface of the tube and a flat contour in the axial direction; type B had convex contours in both the axial and transverse directions. The thickness of the type A and B was 0.46 mm and 0.35 mm, respectively. The materials of both the tube and support were the same zirconium alloy.

Since to find the interrelation between D_{max} and D_e is the



(a) at 10 N-50 μm



(b) at 30 N-100 μm

Fig. 1. Typical wear scar view and depth profile in the case of the contact with type A spring (do not scale; aspect ratio is preserved).

very purpose of the experiment, the details of the material properties are not presented here. After 10^5 reciprocating cycles, wear scars on the tube specimen were measured thoroughly. The depth profile, the maximum depth and the volume were obtained. The worn area was measured by applying an image processing technique to the image data of the worn surface acquired using an optical measurting microscope.

Wear views and depth profiles

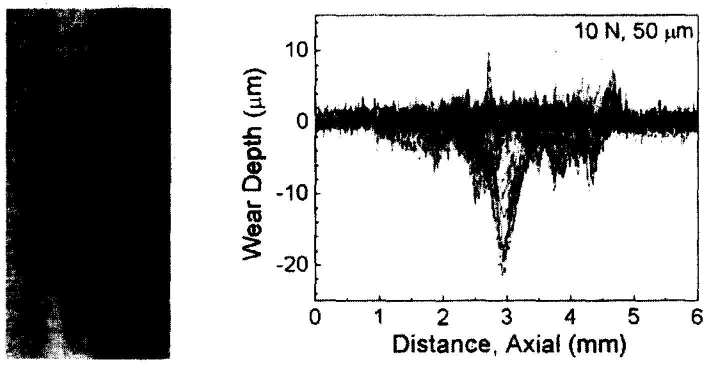
Figs. 1 and 2 give the typical wear views by the type A and type B spring, respectively, at the contact force of 10 N with the slip distance of 50 μm and 30 N with 100 μm. Firstly, as for the wear by type A spring, the wear scars appear near both contact edges at the condition of 10 N-50 μm. These separated scars expand inwards simultaneously and join, and becomes wider as the contact force and distance increase as shown in the case of 30 N-100 μm. In summary, the typical wear shape by type A spring is that it is wider at the edges and narrows inward to the center of the contact as shown in Fig. 1. It is found that the wear depth is greater in the wider wear region so that a W-shaped depth profile appears when type A spring is used.

While, a slender ellipse-like shape is found in the case of the contact with the type B spring regardless of the contact force and slip distance as given in Fig. 2. No separated wear was found even at 10 N-50 μm. However, the shape of the wear depth profile varies depending on the contact force. When the force is 10 N, the deepest wear occurs in the middle of the spring. So, the overall shape of the depth profile is U (or V). While it becomes a W-shape as the contact force increases to 30 N.

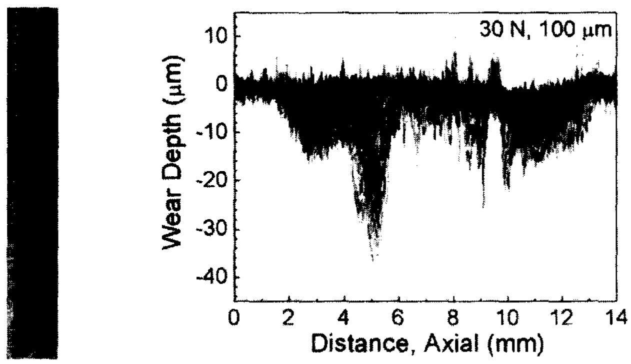
Results

Fig. 3 shows the relationship between the wear volume and the worn area plotted from the present experiment data. Different increasing behaviour is found depending on the volume shape (i.e., W- and U-shape). Wear data by type A shows a narrow scatter band regardless of the contact force. While, the increasing behaviour of type B is different depending on the contact force. When the contact force is 30 N, it is almost similar to the behaviour of type A. However, it increases faster when the contact force is 10 N. The U-shaped wear volume occurred in the case of the type B spring at 10 N. W-shaped wear appeared in the other cases (type A at 10 and 30 N, type B at 30 N). Therefore, the U-shaped wear shows a larger wear volume than the W-shaped wear if the worn area is the same. It also implies that the U-shaped wear reveals a deeper wear in average when the worn area is the same. D_e is lower in the case of the W-shaped wear.

The relationship between the depth parameter (D_{max} and D_e) and the wear volume is investigated. Since the depth parameter has a dimension of the length, the power of three (cubic) is comparable with the dimension of the volume. Fig. 4 gives the result. If D_{max} is used for the parameter, most of the data shows a linear manner to the wear volume except for one, which is considerably far from the linearity. That is the data of type B at



(a) at 10 N-50 μm



(b) at 30 N-100 μm

Fig. 2. Typical wear scar view and depth profile in the case of the contact with type B spring (do not scale; aspect ratio is preserved).

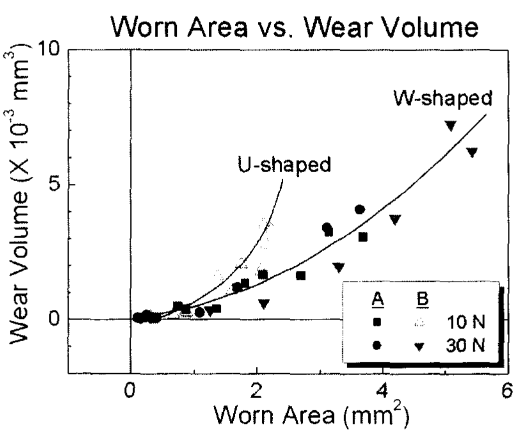


Fig. 3. Relationship between wear volume and worn area.

30 N. A long but very localized deep wear scar was found in that specimen. In addition to that, it cannot provide a distinctive difference between D_{max} and the volume especially for the data of type B at 10 N: data of almost the same D_{max} reveals different volumes.

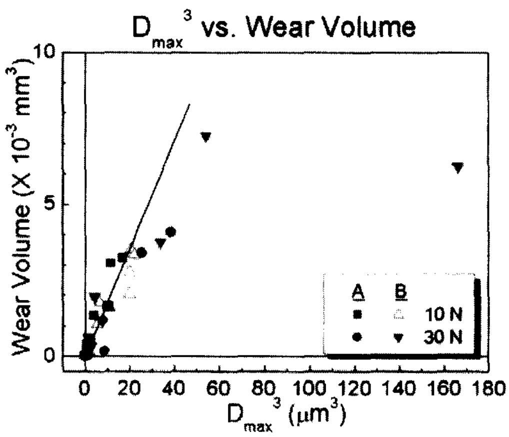
Instead, when the data is re-arranged with respect to D_e, a better distinction is found. Even the largely deviated data at 30 N of type B mentioned above can be included in the linear relationship. The difference of the wear volume shape is also shown. Again, the U-shaped wear (type B at 10 N) can be regarded to have a smaller worn area when the volume is the same since D_e is larger at the same wear volume. The reason for the lower D_e at the same wear volume in the case of the W-shaped wear is attributed to the wider distribution of the contact stresses that makes the worn area become larger.

The relationship between D_{max} and D_e is provided in Fig. 5. The upper bound of D_{max} with respect to D_e is estimated and drawn artificially. For the data of type A, an approximate linear relationship is found between D_{max} and D_e. However, the scatter band becomes larger as D_e increases in the case of the wear by type B. From type B at 10 N (U-shaped wear), it seems that the maximum depth is saturated although D_e increases further. This was also shown in the wear volume in Fig. 4. This implies that the contact force of 10 N would be a proper design value for the contacting force of type B to restrain a wear failure. From the above-mentioned features, it is concluded that D_e can be used as a parameter for a wear model.

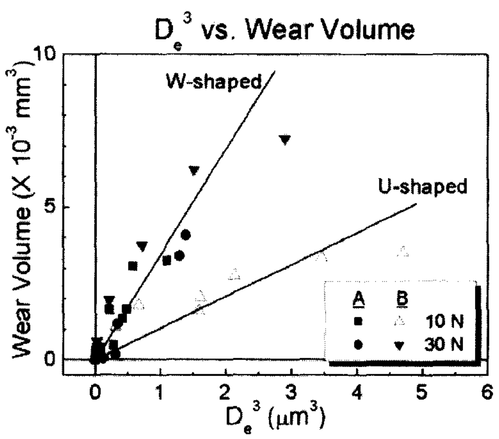
The Depth-based Wear Models

A wear model for the depth profile

As shown in the W- and U-shaped wear (Figs. 1 and 2), the wear depth profile varies depending on the contact shape, configuration and slip distance and regime. It is useful to predict the depth profile to identify the location of the



(a) Relationship between D_{max}^3 and wear volume



(b) Relationship between D_e^3 and wear volume

Fig. 4. Comparison of the parameter D_{max} and D_e in the correlation with wear volume.

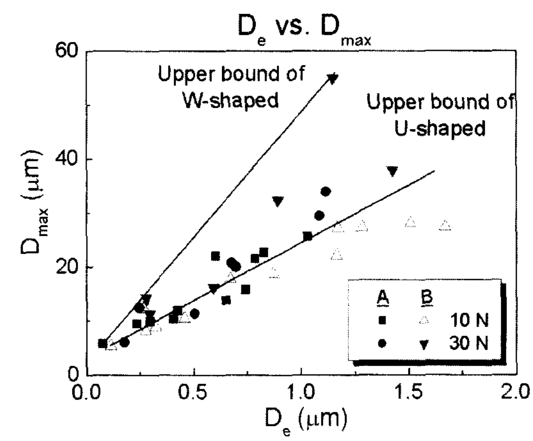


Fig. 5. Relationship between D_{max} and D_e.

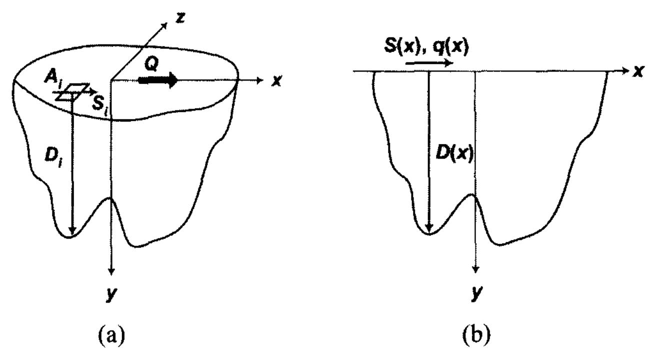


Fig. 6 Illustration of the wear volume: (a) three dimensional shape and (b) two dimensional shape.

maximum depth and its relative severity compared with the depths inside the worn area. In this section, it will be shown that the contact mechanics can be used to evaluate the depth profile.

It is logical if the contact force, F, in Eq. (1) is replaced with the contact shearing force, Q, to follow the physical definition of the energy dissipation (or work). Then, Eq. (1) is to be written as

$$V = K \cdot Q \cdot S \tag{5}$$

The volumetric shape of a wear can be illustrated as shown in Fig. 6(a). When an infinitesimal area within the contact region is chosen (A_i), the wear depth at that location is designated as D_i. Then, the total wear volume is to be written as the sum of the multiplication of A_i and D_i such that

$$V = \sum_i V_i = \sum_i A_i \cdot D_i . \tag{6}$$

If the slip distance S at the i-th location within the worn area is designated as S_i, Eq. (2) is re-written as

$$V_i = A_i \cdot D_i = K \cdot Q_i \cdot S_i = K \cdot Q \cdot S_i \tag{7}$$

then, the wear depth at that location is derived to be

$$D_i = K \cdot \frac{Q}{A_i} \cdot S_i = K \cdot q_i \cdot S_i \tag{8}$$

where q_i is the shear traction (stress) at the i-th location.

When the above geometry is deduced into a two dimensional one, it can be illustrated as shown in Fig. 6(b). Now, the depth profile along the sliding direction (presently, x), $D(x)$ is written as

$$D(x) = K_a \cdot q(x) \cdot S(x) \tag{9}$$

where $q(x)$ is a shear traction on the contact, and the term, $q(x)\cdot S(x)$ becomes a dissipated shear energy density from the contact surface. Here, K_a is a wear coefficient that has the unit of Pa^{-1}. The "*density*" is used, in particular, since it has the dimension of the product of a force and a stress.

To evaluate $q(x)$ and $S(x)$, the contact mechanics is used. The details of the theory can be referred to in [10]. The numerical method [11] to obtain $q(x)$ may be used when the contact normal traction ($p(x)$) is sophisticated and a partial slip regime prevails. The method has been found very useful to evaluate $q(x)$ as long as $p(x)$ is known. On the other hand, a neat solution for $p(x)$ has been developed for any complex shape of the contact and configuration [12]. Resultantly, the

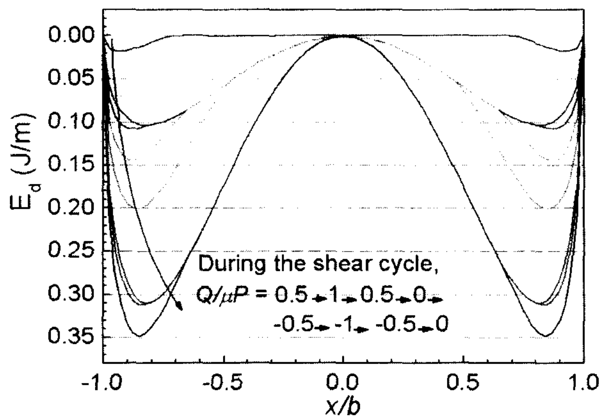


Fig. 7. Behaviour of the friction energy density during a shear cycle in the case of a partial slip.

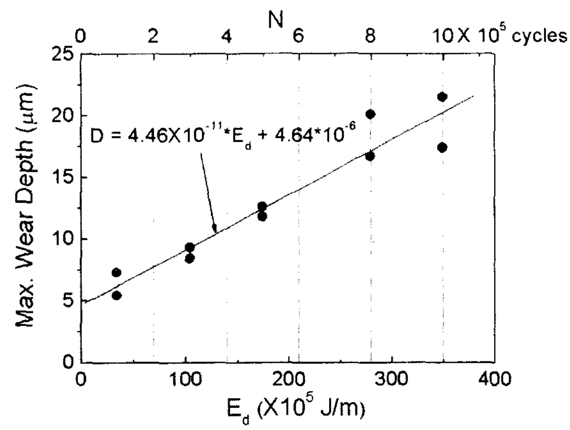


Fig. 8. Curve fit for describing the linearity between the wear depth and the friction energy density as the shear cycle increases.

contact shear traction can be obtained in any case of a two-dimensional contact problem when the methods in both references [11,12] are used.

The wear coefficient may be used to determine the wear resistance against the depth increase at a certain location within the worn area. For instance, the increase rate of the maximum wear depth with respect to the wearing cycle is determined by comparing the measured and the evaluated results. For this, a differentiation of Eq. (9) with respect to the cycle number, N, can be derived such as

$$\left.\frac{dD(x)}{dN}\right|_{atD_{max}} = K_a \cdot \left.\frac{d\{q(x)\cdot S(x)\}}{dN}\right|_{atD_{max}} . \qquad (10)$$

Fig. 7 shows an example of the depth profiles evaluated in the case of a partial slip and the contact shape of type A. The dissipated shear energy density is deginated as E_d. It reveals an increasing behaviour of the dissipated shear enegy density during a reciprocating shear cycle between $Q/\mu P = 0.5$ and 1.0 where Q and P are a shear and a normal contact force, respectively, and μ is a static friction coefficient (presently, 0.3). It is shown that the overall shape of the profile is a W as shown in Fig. 1. When the location of the maximum energy density (i.e., the maximum wear depth) is focused on, the dissipated energy density during a shear cycle is evaluated as 0.35 J/m.

While, Fig. 8 shows the behaviour of the maximum wear depth observed as the number of cycles is increased up to 10^6 in the experiment. It is found that the maximum depth increased in a linear manner. Therefore, Eq. (10) is validated since it also provides a linear relationship between the depth increase rate and the energy density rate. When the data of the observed maximum depth is deduced by a linear curve fit, the following formula is derived.

$$D_{max} = 4.46\times10^{-11}E_d + 4.64\times10^{-6}, \qquad (11)$$

which implies that the maximum depth increases by 1.561×10^{-2} nm per a shear cycle.

What needs to be discussed with regards to the linear curve fit in Fig. 8 is that the data up to 10^5 cycles has not been included in the fitting. This period is regarded as a running-in that occurrs at the early stage of a wearing. The wear mechanism during the running-in period is usually different from the remaining major periods of a wear damage. So, it can be said that the linear regression in Fig. 8 without accommodating the data up to 10^5 cycles is reasonable to obtain a wear coefficient value that represents the wear behaviour.

A wear model using the equivalent depth

Besides the above mentioned wear model for the depth profile, Eq. (1) can be deduced in a different way using the equivalent depth. So to speak, when both sides of Eq. (1) are divided by the overall worn area, A, it becomes

$$\frac{V}{A} = D_e = K_e \cdot \frac{Q}{A} \cdot A = K_e \cdot \tau \cdot S \qquad (12)$$

where τ is an overall shear stress on the contact surface. There may be debate about the overall worn area used for evaluating the shear stress in Eq. (12). It is physically correct if an actual contact area is used rather than it. The size of the contact area is different from the overall worn area if a partial slip condition prevails or a three body abrasion [13] occurs on the contact. That is, a portion of the whole contact area is worn out where the slip occurs in the case of the partial slip condition. A small clearance region outside the actual contact is worn out due to the agglomerated wear debris in that region in the case of the three body abrasion. Therefore, the worn area in the case of the partial slip is smaller than the actual contact area, while that of the three body abrasion is larger than it.

However, it is difficult to accurately determine the actual contact area. If a percussion contact, which often occurs in a fretting wear, is accommodated for in the wear mechanism, it may well be more difficult. On the other hand, it is certain that a wear cannot occur unless an actual contact occurs. So, it is regarded here that the overall worn area can be assumed as a contact area without causing a considerable error.

Similar to Eq. (10), Eq, (12) can also be differentiated with respect to the cycle N so that the rate of the equivalent depth is derived as

$$\frac{dD_e}{dN} = K_e \cdot \frac{d(\tau \cdot S)}{dN} = K_e \cdot \tau \cdot \frac{dS}{dN} \quad (13)$$

Again, the wear coefficient, K_e has the unit of Pa^{-1}. A higher K_e value implies that the wear depth increases faster under the same condition of the shear energy density dissipation. Oppositely, a better wear resistance is expected if K_e is lower. The linear relationship between D_{max} and D_e in Fig. 5 can give a linear relationship between K_a and K_e as well. The validity of Eq. (13) can also be addressed due to the linearity between D_{max} and D_e. In the present experiemental result shown in Fig. 5, the difference between D_{max} and D_e is found to be in the order of 10.

Conclusions

A wear model for predicting a depth behaviour is considered in this research. It is useful for thin structures when a thickness reduction or a perforation due to a wear is of primary concern. The equivalent depth (D_e = wear volume/worn area) and the maximum depth (D_{max}) are investigated. The depth-based wear models are considered with D_{max} and D_e. By consulting the contact mechanics and the experimental results, the following are concluded.

1) The presently considered parameter, D_e reveals a better data regression capability than D_{max}. Therefore, it is soundly suggested that D_e can be used as a parameter for a wear model of a depth prediction.

2) The profile of the wear depth is simulated well by the suggested wear model using D_{max}. The wear resistance from the concern of the maximum depth can be identified by the wear coefficient (K_a) of that model.

3) Another wear model which was suggested by using D_e can predict the behaviour of the overall wear depth. The wear coefficient of that model (K_e) can be interpreted as a generalized resistance against a wear depth increase.

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