Wear of Steel in the Lubricating Oil Containing Abrasive Particles

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The wear of steel is investigated under repeated rubbing in the lubricating oil containing hard solid particles. The rolling motion of particles between two surfaces gives plastic strains on the surfaces, and the surface is worn off due to fatigue failure under repeated plastic strains. By applying the knowledges on low cycle fatigue to the contact problems, the rate of stationary wear \( w \) is formulated.

The wear tests are carried out by rubbing the fixed test piece of carbon steel on the cylindrical surface of a rotating test piece of the same steel in machine oil containing SiC particles. The results are discussed in the formula. When the concentration \( C \) of SiC particles is large, the particles bear the whole load and \( w \) is in proportion to \( C^{1/2} \delta^2 H \) or \( C^{1/2} E^2 H^3 \), where \( \delta \), \( H \) and \( E \) denote the fracture strain, the hardness and the modulus of elasticity of materials respectively. When \( C \) is small, a part of the whole load is borne by metal-to-metal contacts and \( w \) caused by particles is found in proportion to \( C^{1/2} \delta^2 \) or \( C^{1/2} E^2 H^3 \).

1. Introduction

Wear of metals in the lubricating oil is considerably smaller than that without lubricants, and yet greatly increases when solid particles exist between pairs of sliding surfaces.

Most of the studies ever published on abrasive wear have been made on the case without lubricants or under the rubbing against virgin surface of abrasive paper as was investigated by Khurschov(1). Wear tests under lubricated conditions were made by Kosaka(2) by rubbing metals against abrasive stone, and the mechanism of wear was fairly cutting. Wears under repeated rubbing in the lubricating oil containing abrasive particles were also studied by the others(3) to (5). In these studies too, the cutting action of abrasive particles is considered to play a main role in wear mechanism.

In the previous study, the authors considered the wear of steel in lubricating oil as a phenomenon of surface fatigue when the rubbing conditions are not so severe(6). When two surfaces in contact slide each other, asperities of the surfaces come off to wear fragments by the fatigue failure due to repeated shearing which is caused either by adhesion or by collision. The relation of friction force or work done by friction of the surface to a reciprocal of wear rate showed quite good similarity to S-N diagram in usual fatigue.

For the wear due to abrasive particles, abrasive particles are embedded in the softer metal, and are considered to play the cutting action when the hardnesses of the mating metals are considerably different. However, when two metals have almost the same hardness, wear is considered to be caused by plastic fatigue due to the rolling motion of abrasive particles in the lubricating oil. In the present paper, wear tests of steel are carried out in the oil containing SiC particles, and the results obtained are discussed quantitatively.

2. Testing method and results

Wear tests were made by rubbing the fixed test piece of a steel against the cylindrical surface of a rotating test piece of the same steel in Machine oil containing SiC particles as abrasives whose average size was 20 microns in diameter. Testing apparatus is shown in Fig. 1 schematically. Chemical compositions and heat treatments of the test pieces are shown in Table 1. The shapes of the test pieces are illustrated in Fig. 2. The tests are carried out under the sliding speed \( v = 1.35 \text{ m/sec} \) and under the loads per unit projected area,
$p=1 \text{ kg/cm}^2$ and $2 \text{ kg/cm}^2$, by using oils of various concentrations $C$ in weight percentage of abrasives. Since a half of the rotating test piece is immersed in oil bath, abrasive particles in the oil are considered to be fully stirred through the test.

Wear curves are obtained by plotting the weight loss of test piece against the revolution numbers of the rotating test piece. The wear rate of both test pieces $w$ is calculated from the inclination of the straight portion of the wear curves. Let the diameter of the rotating test piece be $D$, the length in the sliding direction of apparent contacting area be $l$ and the width of the fixed test piece be $t$. The sliding distances of the fixed test piece and the rotating test piece become $\pi D$ and $l$ during one revolution of the rotating test piece. Since the areas of abrading surfaces of the fixed test piece and the rotating test piece are $tl$ and $\pi Dt$ respectively, the wear rates of both the test pieces are reduced from the weight loss $W$ during $N$ revolutions as Eq. (1),

$$w = \frac{W}{\pi D l N}$$

Fig. 3 shows examples of wear curve of the test made at $p=2 \text{ kg/cm}^2$, $C=1.0\%$.

The changes of topography of surfaces profiled by "Talysurf" in the direction perpendicular to sliding is shown in Fig. 4. Smooth virgin surfaces are roughened at the early period of rubbing, and later, approach a steady state. Greater roughness is seen at the central part of the width. Frictional heat at the central part is less dissipated from the surface than near the edges. Abrasive particles are also liable to escape from contacting surfaces near the edges. Accordingly, the rubbing conditions near the edges of test pieces are considered to become less severe, causing smaller roughness.

Fig. 5 shows the frequency distribution of surface roughness of a rotating test piece in the steady state. Average roughness $h_m$ is obtained from this distribution diagram by

$$h_m = \frac{\sum h_i f_i}{\sum f_i}$$

\[\text{Fig. 1 Schematic view of testing apparatus} \]

\[\text{Fig. 2 Test pieces (unit mm)} \]

\[\text{Fig. 3 Wear curves} \]
and plotted against \( C \) as shown in Fig. 6, where \( h_i \) is the roughness and \( j_i \) is its frequency.

Fig. 7 shows the micro-Vickers hardness values measured under load of 15g of surfaces tested with various \( C \).

Fig. 8 is the relation between the wear rate \( w \) and \( C \). In the figure, points show experimental results and curves are drawn using equations.

![Image of diagrams showing wear and roughness](image)

**Fig. 4** Changes of topography of surfaces tested at \( p = 2 \) kg/cm², \( C = 0.3\% \)

**Fig. 5** Distribution of surface roughness of rotating test piece tested under different concentrations of SiC particles

**Fig. 6** The relation between average roughness of abraded surfaces and concentration of SiC particles

- Fixed test piece
- Rotating test piece

**Fig. 7**
obtained later. In past studies, wear under continuous supply of new abrasives with no lubricants between mating surfaces was hardly affected by the quantity of abrasives, whilst wear in the lubricating oil containing abrasive particles was influenced by the concentration of abrasive particles.

3. Discussion

When wear test is started from the contact of virgin surfaces of two metals having similar hardness, abrasive particles in lubricants may be embedded in the surfaces, and the wear rate is considerably high due to the cutting action of these embedded particles at the early period. After further running, the wear rate decreases and settles down to a constant state. In the steady state, wear may be produced by a different mechanism from that at the early stage. In practice, hardly any cutting groove due to abrasive particle is found on the surfaces in the steady state.

As the test proceeds, cutting edges of abrasive particles become dull and metal surfaces are work-hardened so that particles are not to be embedded in the surfaces. Most particles roll between mating surfaces with no cutting action. The rolling motion of particles gives plastic strain on the surfaces, and the strain is repeated by the passages of particles. The surface is worn off due to fatigue failure after certain cycles of repeated plastic strain. In this case, plastic strain is considerably large, strain cycles necessary for failure is small, and the failure is considered due to so-called plastic fatigue or low cycle fatigue. In Fig. 9, microscopic photographs of tapered section near the surface in the direction perpendicular to friction are shown. Cracks are observed and suggest that the wear is due to fatigue. Wear in the lubricating oil with no solid particles is considered as a fatigue phenomenon after a large number of cycles of repeated friction force, and the coefficient of friction plays an important role, whereas, in the case of wear due to rolling motions of abrasive particles, only plastic strain may be taken into account.

Fig. 7 The relation between surface hardness of rotating test piece and concentration of SiC particles

Fig. 8 Test results and calculated curves of wear rate and concentration of SiC particles

Fig. 9 Photographs of tapered section of surface tested at $p=2$ kg/cm$^2$, C=0.3%
Let the number of abrasive particles existing on the unit contacting area be \( n \). When the particles roll on the surfaces without slip, the number of particles \( n' \) which pass over a point of the surface is given by

\[
n' = \sqrt{nL/2}
\]  

for sliding distance \( L \). If one wear fragment is produced after \( N \) cycles of plastic strain \( \varepsilon_p \), the number of wear fragments \( z \) for sliding distance \( L \) is given by

\[
z = \frac{n'}{N} = \frac{1}{2} \sqrt{\frac{nL}{\varepsilon_p}}
\]  

Under the plastic strain amplitude \( \varepsilon_p \), the cycle \( N \) to failure is given \( 9 \) by

\[
\varepsilon_p N^{1/2} = \delta
\]  

where \( \delta \) is a material constant and corresponds to the fracture strain. Eq. (4) becomes as follows by using Eq. (5),

\[
z = \frac{\varepsilon_p \sqrt{nL}}{2\delta^{1/2}}
\]  

When an abrasive particle is depressed on the surface, assuming the particle is spherical in shape of diameter \( d_0 \), the average plastic strain \( \varepsilon_p \) in the indentation of diameter \( d \) is given \( 10 \) by

\[
\varepsilon_p = m \frac{d}{d_0}
\]  

where \( m \) is a material constant. Therefore, \( z \) is expressed as

\[
z = \frac{m^2}{2} \frac{d^{\alpha} \sqrt{nL}}{\delta^{1/2}}
\]  

Weight of the wear fragments \( AW \) is

\[
AW = zDV\gamma
\]  

where \( D \) is a volume of one wear fragment and \( \gamma \) is the specific gravity of the material. By substituting Eq. (8) into (9), \( AW \) is reduced to

\[
AW = \frac{m^2}{2} \frac{d^{\alpha} \sqrt{nL}}{\delta^{1/2}}
\]  

The average diameter of wear fragments is said to be nearly equal to the roughness of the abraded surface \( 11 \), and Fig. 9 shows that asperities are broken near their roots. Hence, the volume of wear fragment is considered to be in proportion to the third power of average roughness \( \delta_0 \), and

\[
AV = \delta_0 \gamma
\]  

is obtained. Eq. (10) becomes

\[
AW = \frac{m^2}{2} \frac{d^{\alpha} \sqrt{nL}}{\delta^{1/2}}
\]  

Since the number of portions to produce \( AW \) is considered to be in proportion to the number of particles \( n \) on the unit contacting area, the total wear \( W \) per unit contacting area is expressed by

\[
W = \frac{k'nAW}{2} = \frac{m^2k'}{2} \frac{d^{\alpha} n^{\gamma} \delta_0}{\delta^{3/2}} L
\]  

The diameter \( d \) of the indentation is given by the hardness \( H \) and the load on one particle by

\[
\frac{P}{n} = \frac{\pi d^4 H}{4}
\]  

Substitution of \( d \) in Eq. (14) into Eq. (13) leads to Eq. (15) by representing the various constants as a constant \( K \).

\[
W = \frac{K h_0 \gamma L}{\delta^3 H d_0^4} p^{\gamma/4} - \frac{\gamma}{4}
\]  

The wear rate \( w \) is expressed as follows,

\[
w = \frac{W}{L} = \frac{K h_0 \gamma L}{\delta^3 H d_0^4} p^{\gamma/4}
\]  

As \( n \) is considered to be in proportion to the concentration \( C \) of particles, by putting \( n = nC \), Eq. (16) becomes

\[
w = \frac{K h_0 \gamma L}{\delta^3 H d_0^4} C^{\gamma/4}
\]  

Eq. (17) is available for the condition when \( C \) is large enough to bear the whole load on particles. When \( C \) decreases, load on one particle increases, particles penetrate deeply in the surface, and the metal surfaces come into contact with each other. A fraction of load is borne by metal-to-metal contacts, and there exist two kinds of wear, that is, the wear due to abrasive particles and the wear due to metal-to-metal contacts. However, the latter may be so small as to be negligible comparing to the former. When \( n \) is smaller than \( n_0 \), which is the number of particles at the critical state giving the metal-to-metal contact, the load \( p' \) borne by particles is expressed as

\[
p' = \frac{\pi d^4 H n_0}{4}
\]  

Schematic views of contacts are shown in Fig. 10, where (a) illustrates a case of \( n > n_0 \), and
(b) illustrates a case of \( n \leq n_e \). In the figure, \( d_0 \) is the diameter of particle, \( h \) is the depth of indentation of particle, and \( h_a \) is the average roughness of surface. When \( d_0 - 2h \) becomes \( 2h_m \), metal-to-metal contacts take place. At \( n \leq n_e \), the diameter of indentation is invariably given from Fig. 10(b) by

\[
d^2 = 4 \left( \frac{d_0}{2} \right)^2 - h_a^2 \tag{19}
\]

From the experimental results, the average roughness \( h_a \) and the micro-Vickers hardness \( H_v \) of abraded surfaces are regarded as constant in spite of slight changes of these values with \( C \), then \( p' \) is expressed as \( p' = \beta n \). At the critical state, as \( p = \beta n \),

\[
p' = n \frac{p}{n_e} = \frac{C}{C_0} p \tag{20}
\]

is obtained, where \( C_e \) represents the percentage concentration of solid particles at the critical state.

From Eq. (14),

\[
p = \pi \frac{d^2 H_m}{4} = \pi \frac{d^2 H_C}{4} \tag{21}
\]

is given, and so

\[
p = \frac{\alpha \pi}{C_e} \left( \frac{d_0}{2} \right)^2 - h_a^2 \frac{H}{4} \tag{22}
\]

is obtained by using Eq. (19).

At \( C \leq C_o \), the wear rate is expressed by substituting \( p' \) in Eq. (20) into \( p \) in Eq. (17) and by using Eq. (22) as follows,

\[
w' = K_a \frac{C^2}{C_e} \frac{h_a \gamma}{H^2 d_0^2} \left( \frac{d_0}{2} \right)^2 - h_a^2 \frac{C_0^2}{C} \tag{23}
\]

The wear rate \( w' \) is found to be independent of load \( p \).

The dependencies of the wear rates upon the concentration \( C \) are shown schematically in Fig. 11. The wear rate is in proportion to \( C^{1/2} \) and \( p \) when \( C \) is larger than \( C_o \), while it is in proportion to \( C^{3/2} \) independently of \( p \) when \( C \) is smaller than \( C_o \). The critical concentration \( C_p \) is varied by load.

Eq. (17) shows that the wear rate is inversely proportional to \( \delta H \) at \( C > C_o \), and Eq. (23) shows that the wear rate is inversely proportional to \( \delta^2 \) at \( C \leq C_o \). In other words, the harder or the more ductile the materials are, the higher wear resistance the materials have. Since the plastic fatigue strength is dominated by \( H/E^{(3)} \) where \( E \) denotes the elastic modulus of material, \( \delta \) is considered in proportion to \( H/E \), and Eqs. (17) and (23) become

\[
w = K_a \frac{C^2}{C_e} \frac{H_a \gamma}{H^2 d_0^2} \frac{p}{C_0^{1/2}} \tag{24}
\]

and

\[
w' = K_a \frac{C^2}{C_e} \frac{H_a \gamma}{H^2 d_0^2} \left( \frac{d_0}{2} \right)^2 - h_a^2 \frac{C_0^{3/2}}{C} \tag{25}
\]

respectively. Accordingly, when \( C \) is larger than \( C_o \) wear resistance is in proportion to \( H^2 E \), and when \( C \) is smaller than \( C_o \) it is in proportion to \( H^2 E^2 \). Oberle(44) called \( H/E \) or \( H^2 E^2 \) as Modell factor and regarded these as a criterion of wear resistance. The relations above obtained are analogous to these Modell criteria.

From Fig. 6 and Fig. 7, \( h_a = 2.5 \) microns \( H_v = 450 \) are taken. By using \( E = 2.1 \times 10^4 \) kg/mm², \( \gamma = 7.85 \) g/cm³, and \( d_0 = 20 \) microns, the curve for large \( C \) in Fig. 8 is expressed by

\[
w = 3.04 \frac{Eh_a \gamma}{H_v d_0^2} \frac{p}{C_0^{1/2}} \tag{26}
\]

where \( K_a = 3.04 \) is used in Eq. (24). As is predicted in Fig. 11, the experimental values of \( w \) are lower than the curve calculated by using Eq. (26) when \( C \) is small. In this region of \( C \), Eq. (25) should be applied.

When \( C_o = 0.05 \% \) is assumed for the tests of \( p = 2 \) kg/cm², \( \alpha \) is obtained from Eq. (22). Since \( K_o^{1/2} = 3.04 \), Eq. (25) is calculated as

\[
w' = 2.88 \times 10^{-4} \frac{Eh_a \gamma}{H_v d_0^2} \left( \frac{d_0}{2} \right)^2 - h_a^2 \frac{C_0^{3/2}}{C} \tag{27}
\]

Curves in Fig. 8 show the relations between the wear rate and the concentration of particles in oil calculated by Eqs. (26) and (27) for \( p = 1 \) kg/cm² and \( p = 2 \) kg/cm², and are found to agree significantly with the experimental results.

At \( C \leq C_o \), \( d = 19.4 \) microns is obtained from Eq. (19) for \( h_a = 2.5 \) microns, and \( n_e \) under \( p = 2 \) kg/cm² is calculated from Eq. (21) as follows,

\[
n_e = \frac{4p}{\pi d^2 H_v} = 15 \tag{28}
\]

Total weight of SiC particles existing between mating surfaces is calculated as follows,

\[
Q = n_e \frac{4}{3} \pi \left( \frac{d_0}{2} \right)^2 \gamma' = 19.6 \times 10^{-4} \text{ mg} \tag{29}
\]

where specific gravity of SiC particles \( \gamma' \) is 3.12. The weight of machine oil of specific gravity \( \gamma'' = 0.92 \) existing in the space between two mating
surfaces is given as follows,
\[ Q' = 1 \times h_n \times \gamma' = 0.230 \, \text{mg} \] .......................... (30)
by assuming that grooves whose cross sections are shown in Fig.10 are parallel to each other in the direction of friction.

From these equations
\[ C_s = \frac{Q}{Q'} \times 100 = 0.085\% \] .......................... (31)
is obtained.

The value of \( C_s = 0.05\% \) used previously is not so far from 0.085%.

Coefficients of Eqs. (24) and (25) are determined from average values of experimental results for both the test pieces. Strictly speaking, the wear rate of the rotating test piece is always larger than that of the fixed test piece. The difference may arise from the rubbing conditions of both the test pieces. In macroscopic scale, the rubbing surface of the fixed test piece always contacts the mating surface, and the surface temperature due to frictional heat is kept constant. Meanwhile on the rotating test piece, the contact of surfaces is intermittent during one revolution, and the surface temperature is cyclically varied. Therefore, it is considered that the surface of the rotating test piece is subjected to repeated thermal strain at the rate of one cycle per revolution, and the effect of thermal fatigue is added to plastic fatigue to cause greater wear in the rotating test piece than in the fixed test piece. To make this effect clear, wear tests are carried out using test piece as shown in Fig.12. When the fixed test piece as shown in Fig.12 is used, the surface of the rotating test piece is subjected to repeated thermal strain at the rate of 2 cycles per revolution.

The ratio of the wear rate of the rotating test piece to that of the fixed test piece is plotted against \( C \) as shown in Fig.13. It is obvious that the ratio tends to rise as pressure and number of thermal strain cycles per revolution increase.

4. Conclusion

The wear of mating metals having similar hardness is investigated in lubricating oil containing abrasive particles. The rolling motion of particles between two surfaces gives plastic strains on the surfaces, and the surface is worn off due to fatigue failure under repeated plastic strains. By applying the knowledge on low cycle fatigue to the contact problems, the rate of stationary wear is formulated. According to this, the harder or the more ductile the materials are, the lower the wear rate is. The wear resistance is in proportion to \( H^2/E^2 \) at large concentrations \( C \) of abrasive particles in oil, and is in proportion to \( H^2/E^2 \) at small concentration of abrasive particles.

The variations of the wear rate with the concentration of abrasive particles and with the load are also known, and when \( C \) is larger than \( C_o \) the wear rate is in proportion to \( C^{1/2} \) while it is in proportion to \( C^{1/\gamma} \) independently of \( \gamma \) when \( C \) is smaller than \( C_o \). The critical concentration \( C_o \) is varied by load.

The experimental results obtained on steel test pieces in machine oil containing SiC particles are applied to the above considerations. Further, the difference of the wear rate between the fixed test piece and the rotating test piece is considered due to the repetition of thermal strain.
References

(1) M.M. Khruschev: *Proc. Conf. on Lubrication and Wear*, (1957), p. 655, IME.