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The Wear of Steel in Lubricating Oil under Varying Load*

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In the present paper, the wear rates of a steel in lubricating oil are discussed under two step loads and two loads repeated block history.

The wear of steel is considered to be due to the surface fatigue under lubricated conditions except the severe condition accompanying the seizure. The results under two step loads show that the wear rate is a behavior quite analogous to those of fatigue, especially of fatigue crack propagation under two step stresses. The change of residual stress measured by X-ray diffraction and the change of surface hardness well explain the results. The wear rate under two loads repeated block history can be estimated quantitatively from the results and the considerations above mentioned. The noteworthy fact is that the wear rate is considerably lower under higher load applied periodically than under constant load.

1. Introduction

The lives of machine parts have come to be decided by the degeneration of their accuracy or efficiency due to wear rather than by their fractures with the progress of research on the strength of materials. Most machine parts are operated under lubricated condition, but the wear of metals in lubricating oil has not fully been made clear about its mechanism and the quantitative study of wear is very poor.

Previously, it was reported⁽¹⁾ that the wear of steel in the lubricating oil was considered to be due to the fatigue of contacting asperities under the repeated stresses except under severe condition accompanying the seizure. Bayer and others⁽²⁾ quantitatively treated the wear resistance of materials using Palmgren's equation for rolling bearings from the standpoint of fatigue. Kraghelsky⁽³⁾ also discussed the wear of material in relation to the fatigue life. However most investigations on wear have been carried out under constant load during runs. A report was made⁽⁴⁾ on the wear in which the load was varied during run, but the test was done by rubbing the metals against the abrasive stone and the mechanism of wear was considered due to

cutting. To predict the wear of machine parts in practical use, it is necessary to investigate the wear under service load. In usual fatigue, prediction of fatigue life under varying stress is an important problem. The study of wear under varying load has the same importance in this respect.

In the present paper, the wear tests of a carbon steel are carried out in lubricating oil under two step loads, where the testing condition is not so severe. Changes of the residual stress and the hardness of the worn surface due to the variation of load are measured. The behaviors of the wear being analogous with those of fatigue under varying load, the wear is discussed from the standpoint of surface fatigue. Further, the wear tests under two loads repeated block history are also carried out to make sure the above discussion. These results may contribute to the quantitative study of the lubricated wear under service loads.

2. Wear test

Wear tests are done by rubbing the annular surface of cylindrical tool against the surface of the plate test piece as is shown in Fig. 1. The test piece is fixed in a trough containing a machine oil with no additives. Shapes and dimensions of the cylindrical tool and the plate test piece are shown in Fig. 2. The cylindrical tool is made of quenched tool steel of 1.03%C. The test pieces are made of S35C steel whose chemical compositions are shown

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in Table 1. The test pieces are normalized for 1 hr. at 850°C prior to machining. Both the cylindrical tool and test piece are lap-finished using Al_2O_3 powders (#3 000) and oil. In order to measure the wear loss, ten Vicker's indentions are made on the rubbing surface of each test piece. The surface is again lapped slightly to remove the ridges around the indentions. Lastly the test pieces are annealed in vacuum at 650°C for 1 hr.

When the wear is measured by the weight loss of test pieces, the fixing and detaching of the test piece induce an unavoidable error⁽¹⁾. In the present study replicas of the worn surfaces are made without taking off the test piece from the testing machine and the diagonals of the Vicker's indentions of replica are measured. The details in practice are as follows. After the load is removed, the annular surface of the cylindrical tool is pulled up from the surface of test piece. Oil is taken out from the trough and the worn surface is degreased

and cleaned, then a replica of the worn surface is made by thin plates of celluloid. After the replica is removed from the surface, the trough is again filled with new oil, and the wear test is continued by giving the load quietly, the cylindrical tool being rotated prior to contact with the test piece. In Fig. 3, the square ABCD is the indentation on virgin surface and the square A'B'C'D' is the indentation after sliding the distance l . Reduction of diagonal Δd is obtained as a mean of AA', BB', CC' and DD'. Assuming that the surface is worn uniformly, the wear depth Δh is given by

$$\Delta h = \Delta d \tan \theta \quad \dots\dots\dots (1)$$

When an apparent contact area is signified by S_A , the wear volume W is shown as

$$W = S_A \Delta h = S_A \Delta d \tan \theta \quad \dots\dots\dots (2)$$

By substituting $S_A = 44 \text{ mm}^2$, $\theta = 15^\circ 57'$, the conversion equation between W and Δd is obtained as

$$W = 12.6 \Delta d \text{ mm}^3 \quad \dots\dots\dots (3)$$

The diagonals of ten indentions are measured by a microscope and Δd is obtained from the difference of arithmetical mean of diagonals at the worn surface from that of the virgin surface. Accuracy of the measurement is $0.6 \times 10^{-3} \text{ mm}^3$ in terms of the volume.

The friction force is measured by the bending strain of cantilever attached to the holder at which the test piece is fixed, and its variation is recorded on the oscillographic paper. The lubricant is renewed after each run to prevent the change in the properties of the lubricant. The rubbing velocity is set at 0.15 m/sec through all the tests.

Fig. 1 Schematic view of the testing apparatus

Fig. 2 Shapes and dimensions of cylindrical tool and plate test piece

Table 1 Chemical composition (%) of S35C steel in the experiments

C	Si	Mn	P	S
0.34	0.24	0.67	0.011	0.008

Fig. 3 Dimensional change of the indentation due to wear

3. Wear curve under constant load and considerations

As was reported previously⁽¹⁾, when the wear tests of annealed steel were started from the contact of virgin surface, a transition point appeared in the wear curve when the test condition was not so severe as to cause a seizure. In the present paper, the transition point is also found on the wear curve as shown in Fig. 4.

At the initial stage of the running, when two surfaces are not yet intimate, high asperities are subjected to stresses greater than the flow stress. These asperities are easily broken into worn fragments through one or several times of adhesion or collision with asperities of the mating surface, and the wear is considerably large. This initial stage of wear is OA in Fig. 4. As the mating surfaces become intimate with each other, the contacts show elastic behaviors because of the increase in number of contacts and of work hardening, and the wear decreases significantly as is shown by AB. Fatigue failures of the surface asperities start from B, and the wear begins to increase again. Thereafter, the fatigue failure progresses steadily and the wear increases linearly, so the transition point appears at B. The stage after B may be regarded as a stage of stationary wear.

In the present wear tests, the frictional coefficients are almost invariably 0.05 under various magnitudes of loads, and so the loads may be used in place of repeated stresses of the contacting surface which are not yet known explicitly.

Figure 5 shows the relation between the load P and the sliding distance L to the transition point. The arrow means that no transition point is found at this sliding distance. This figure corresponds to a kind of $S-N$ curve of usual fatigue, and the experimental equation

$$P^{1.5}L = k, \quad (k=10^2) \quad (4)$$

Fig. 4 Wear curve under the constant load

is obtained.

Figure 6 shows the relation between the load P and the reciprocal of stationary wear rate w . The reciprocal of wear rate, $1/w$, is the sliding distance to produce a unit volume of wear loss, that is, the repetition number of stresses to produce a unit volume of wear loss. Accordingly, the figure is considered to correspond to the relation between the repeated stresses and the reciprocals of fatigue crack propagation rate in usual fatigue, and $w = mP^2$, ($m=4.2 \times 10^{-7}$).....(5) is obtained experimentally.

4. Wear test under two step loads in the stage of stationary wear and considerations

As is stated in the previous chapter, the region of stationary wear is considered to correspond to that of the crack propagation in usual fatigue. It is interesting to know whether the stationary wear shows the behaviors like those of fatigue crack propagation under varying stress when the contacting load is changed.

An example of wear curve in which the load is changed at a given sliding distance from the transition point is shown in Fig. 7. In Fig. 7,

Fig. 5 Relation between the load and the sliding distance to the transition point

Fig. 6 Relation between the load and the reciprocal of stationary wear rate

point B is the transition point and the testing load is changed at point C. The upper wear curve shows the result of high-low load change where the load is changed from the higher load $P_1=29.0$ kg to the lower load $P_2=24.0$ kg. The wear lies dormant from C and increases again from D. The lower one is the result of low-high load change where the load is changed from the lower load $P_1=24.0$ kg to the higher load $P_2=33.2$ kg. The wear increases in accordance with the higher load as soon as the load is changed. No remarkable change is observed in the coefficient of friction.

The relation between the length of dormant stage of wear l_d and the difference of load ΔP between the first higher load and the second lower load is shown in Fig. 8. The sliding distances from B to C under the first load, which is denoted by l_1 are 10 km and 0.54 km. In the present test range, the dormant stage of wear is prolonged with the difference of load independently of the magnitude of the second lower load P_2 . There is no

B is the transition point, C is the point of changing load, and D is the end of dormant stage in high-low load change
Fig. 7 Wear curves under two step loads and coefficient of friction

l_1 is the sliding distance from the transition point B to the point of changing load C in high-low load change
Fig. 8 Relation between the length of the dormant stage and the load difference

difference in the length of dormant stage between the cases of $l_1=0.54$ km and of $l_1=10$ km for the same difference of loads. However, when a higher load is applied for a short period of 0.27 km on the way to the stationary stage of wear under lower load, no dormant stage is found, though it is not shown in the figure. From this, it is concluded that some sliding distance under the higher load is needed for the dormancy of wear, but when the dormant stage appears the length of the dormant stage depends on the difference of the loads but hardly on the sliding distance under the first higher load. The experimental equation is obtained between l_d and ΔP as follows,

$$l_d = a \Delta P^{0.7}, (a=2.2) \dots\dots\dots (6)$$

The wear rates under the second load of high-low load change as well as of low-high load change are almost the same as the wear rates under the constant load which is equal to the second stage load.

These behaviors of wear are quite similar to those of the fatigue crack propagation under varying stress. Fatigue crack stops propagating for a while after the stress change of high-low two step stresses and then propagates again, whilst it propagates under the rate corresponding to the higher second stress soon after the stress change of low-high two step stresses. The dormant stage of crack propagation increases with the difference of two stresses⁽⁵⁾, and the crack rate after dormant stage is equal^{(5) (6)} to or slightly larger⁽⁷⁾ than the rate under the constant stress. The existence of dormant stage in the crack propagation is explained by the effect of compressive residual stress at the crack tip. From the similarity of behaviors of the wear under varying load to those of the fatigue crack propagation under varying stress, the stationary wear is supposed to progress by the surface fatigue.

To study further the wear behaviors under varying load, the changes of residual stress and hardness are measured. Residual stresses are obtained by the $\sin^2\psi$ method from the diffraction patterns of X-ray whose incidence angles are 0° ,

B is the transition point, C is the point of changing load, and D is the end of dormant stage in high-low load change
Fig. 9 Variation of residual stress under two step loads.

15°, 30° and 45°. X-ray used in the experiments is Cr-K α beam, and X-ray diffractions are photographed using the back reflection camera having a double pin hole of 1.0 mm diameter, the standard substance used being annealed Cr powder. Tube voltage is 30 kvp. Tube current is 15 mA.

Variations of the residual stresses of the worn surfaces with the sliding distance under two step loads are shown in Fig. 9. Stresses measured are the component in the direction of sliding. Points B, C and D show the transition point, the point of changing load and the end of dormant stage in wear curves respectively. All the residual stresses are compressive. At the initial stages, residual stresses increase to attain the maximum value, and afterwards decrease gradually to constant values. The decrease of residual stresses may be explained from the informations on fatigue that the residual stress is released as the fatigue damage proceeds. After the transition point the surface is worn steadily to leave a constant amount of the fatigue layer and the residual stress is kept constant.

For the high-low load change the residual stress is not reduced soon after the load change, but is gradually decreased to the value which is expected for the constant load test under the lower load. The result may be explained by the fact that when the material having residual stress is subjected to repeated stress, a certain number of repetitions of the stress is required for the reduction of residual stress⁽⁹⁾. Declining period of the residual stress is nearly equal to the dormant stage of wear. For the low-high load change the residual stress is increased to a nearly expected value under the constant high load test after short running of 0.54 km from the load change.

The hardness of the worn surface under varying load is shown in Fig. 10 against the sliding distance, together with the wear curve. Point B is

B is the transition point, C₁ is the point of low-high load change, C₂ is the point of high-low load change, and D is the end of dormant stage
Fig. 10 Wear curve and variation of hardness under two step loads

the transition point, C₁ is the point of low-high load change, and C₂ is the point of high-low load change. Hardness is measured by Vicker's hardness tester under the testing load of 25 g. The hardness of the virgin surface is 150. In the figure, the maximum hardness, the minimum hardness and the arithmetical mean hardness of five points are shown. Hardness rises at the initial stage and then reaches a constant value before the transition point appears. The hardness of worn surface is considered to depend on the residual stresses as well as the work hardening by repeated stresses. It is known to the authors⁽⁹⁾ that when a plate of annealed steel is subjected to tensile stress or compressive stress mechanically, the hardness is increased with compressive stress and is decreased with tensile stress. The same result is reported⁽¹⁰⁾.

For the low-high load change, C₁, the hardness increases readily to a certain constant value. This is due to the growth of workhardening and compressive residual stress. On the contrary, for the high-low load change, C₂, the hardness remains the value of the previous load for some sliding distance after changing the load and later gradually decreases to the constant value of the lower load. This may be explained by the facts that though the compressive residual stress decreases gradually after changing the load to the value of the second lower load, the work hardening remains in the state of the first higher load for a considerable sliding distance.

In Fig. 11, the relations of hardness and residual stress vs. contacting load is shown. Both the hardness and the residual stress are increased monotonously with the load. It is recognized in general that the harder the material, the greater the wear resistance of materials is. For the wear considered due to surface fatigue too, the wear resistance must increase with the hardness. It was made clear by

Fig. 11 Relation between residual stress, hardness and load

the authors that the compressive residual stress increases⁽¹¹⁾ the wear resistance of material under lubricated conditions. Therefore, when the wear test is carried under constant load, the residual stress and the hardness become constant values shown in Fig. 11, and the stationary wear rate is determined by the combinations of these two factors.

When the testing load is changed from the higher load to the lower load, the residual stress and the hardness show larger values for some sliding distance from the changing point than those under the constant lower load. At this sliding distance, the wear resistance of surface is improved than that under the constant lower load, so that the progress of fatigue damage in the worn surface is interrupted and no wear occurs. For the low-high load change, both the hardness and the residual stress increase to the value of the higher load rather immediately, thus the wear rate is shifted immediately to a larger wear rate of the higher load.

As mentioned previously, when the higher load is given for a short sliding distance of $l_1=0.27$ km on the way of to the stationary state of wear under the lower load, no dormant stage was found in the following run under the lower load. At the sliding distance of 0.27 km after changing the load from 28.0 kg to 33.2 kg, the residual stress is -5.3 kg/mm², the hardness is from 188 to 215 (average 201). These are almost the same values as those of the test under 28.0 kg constant load, and no influence of the higher load can be seen. Thus, a certain number of stress repetitions is needed to attain the proper values of the residual stress or the hardness corresponding to the higher load, and this may be the reason for no dormancy of wear mentioned above.

Fig. 12 Wear curves under the load change before the transition point

5. Experiments under two step loads before the transition point and considerations

The transition point of wear curve is known to correspond to the initiation of fatigue crack. Therefore, when the load is changed at some sliding distance before the transition point, the sliding distance to the transition point is considered to vary in the same way as is observed in usual fatigue life under varying stress. By applying the linear cumulative damage hypothesis in usual fatigue to the problem of wear under varying load,

$$l_1/L_1 + l_2/L_2 = 1 \quad (7)$$

is obtained. Here l_1 , l_2 are the sliding distances of the first load and the second load respectively, and L_1 , L_2 are the sliding distances to the transition point when tests are carried under the respective loads. The test conditions are $l_1/L_1=0.28, 0.50$ and 0.75 under the load difference $\Delta P=4$ kg and 2.2 kg respectively.

Examples of the wear curve under two step varying loads are shown in Fig. 12. The load is changed at point C, and a transition point appears at point B. The chained line shows a position of the transition point calculated by using the linear cumulative damage hypothesis. For the high-low load change, the transition point is considerably delayed from the calculated point, while for the low-high load change, the transition point appears close to the calculated point. Slopes of the stationary wear are almost the same as those of the broken lines which show the stationary wears under constant loads.

In Fig. 13, the relation between the cycle ratio of the first load l_1/L_1 and the fatigue damage $D=1-l_2/L_2$ is shown. The line $D=l_1/L_1$ expresses

Fig. 13 Relation between the fatigue damage and the cycle ratio, i.e., the sliding distance ratio of the first load

the linear cumulative damage hypothesis, that is, $\Sigma l/L=1$. Upper domain and lower domain divided by this line mean the cases of $\Sigma l/L < 1$, and $\Sigma l/L > 1$ respectively. From this, the sliding distance to the transition point is found longer than the calculated one for the high-low load change, and the larger the difference of two loads the longer this distance is. The sliding distance to the transition point is nearly equal to that estimated by the linear cumulative damage hypothesis for the low-high load change. The reason why $\Sigma l/L$ is greater than unity for the high-low load change is considered the fatigue damage restrained by the higher compressive residual stress due to the higher first load.

In usual fatigue under varying stress, different phenomena are known between the notched specimen and the smooth specimen. For the notched specimen, $\Sigma n_i/N_i$ is greater than unity under high-low stress change, whilst $\Sigma n_i/N_i$ is nearly equal to unity for low-high stress change, where n_i is the number of repetitions of stress σ_i and N_i is the number of repetitions to the failure. On the contrary, for the smooth specimen, $\Sigma n_i/N_i$ is smaller than unity for high-low stress change and $\Sigma n_i/N_i$ is greater than unity or equal to unity for low-high stress change. Thus, the sliding distance to the transition point in wear has the same meaning as the repetition number of stress for the fatigue failure of the notched specimen.

6. The wear under two loads repeated block history

Studies are made on the wear behaviors under the load changes repeated from the beginning of contact of virgin surfaces. Tests are carried out under two loads repeated block history where the higher load is 33.2 kg and the lower load is 31.0 kg. One cycle of the load change l_0 is 5.4 km in the sliding distance. The ratio of the sliding distance l_1 under the higher load during one cycle to l_0 is signified by R , and $R=0.05, 0.1, 0.25$ and 0.5 are chosen for the experimental conditions. Since, from the results mentioned previously, wear lies dormant for a while after the high-low load change when the higher load is given for more than 0.54 km, the dormancy of wear is to be seen in every cycle of the load change for $R \geq 0.1$. And the dormant stage is known to be 3.7 km for the load difference of 2.2 kg.

In Fig. 14, load wave form and wear curve in the case of $R=0.25$ are shown as an example. Slopes of the broken lines show the stationary wear rates under

constant loads. The solid lines after B are drawn by using these broken lines and the dormant stage. For $R=0.25$, the period of the lower load is longer than the dormant stage, and small amounts of wear increments due to the lower load are observed at the last run of every load cycle, besides the wear due to the higher load. The chained line in this figure shows the averaged wear curve, and coincides well with the solid line drawn stepwise corresponding to the load wave form. The average wear rate under varying load is considerably lower than that under the constant lower load. After running of $l=38$ km, the load is kept at the lower load, and the wear rate is the same as that under the constant load after the dormant stage, independently of the load histories. In the running-in period, no change of the wear curve is observed due to the load change but the transition point B is found considerably later than the point calculated by the linear cumulative damage hypothesis.

As shown in Fig. 15, the stationary wear curves under varying load can be schematically drawn, and the average wear rates w_v are expressed as follows by using Eq. (5) and (6):

$$\text{For } l_2 > l_d$$

$$w_{va} = m[R(P_2 + \Delta P)^2 + (1-R)P_2^2 - \alpha P_2 \Delta P^{0.7}] \quad \dots\dots\dots (8)$$

Fig. 14 Load wave form and wear curve in the case of $R=0.25$

Fig. 15 Progress of stationary wear in the case of $l_2 > l_d$ and $l_2 \leq l_d$

and for $l_2 \leq l_d$

$$w_{vb} = mR(P_2 + \Delta P)^2 \dots \dots \dots (9)$$

Here, $R = l_1/l_0$, $\Delta P = P_1 - P_2$, and $\alpha = a/l_0$. The solid lines after B in Fig. 14 correspond to the solid lines in Fig. 15 (a) and the slope of the chained line in Fig. 14 conforms well with the average wear rate w_v of Eq. (8).

The relation between R and w_v/w_2 is shown in Fig. 16. w_2 is the wear rate when the lower load is given constant. Two solid lines of this figure are drawn using Eqs. (8) and (9). From this, it is concluded that the average wear rate is considerably lower under the higher load applied periodically and the average wear rate is decreased as R decreases. However, when the sliding distance under the higher load is 0.27 km, that is, R is 0.05, the wear rate shows almost the same value as that under the constant lower load and the value of R to minimize the wear rate must exist.

It is also found that, at $R \geq 0.1$, the sliding distance to the transition point becomes longer than that under the constant small load, whilst, the transition point appears close to the point under the constant small load at $R = 0.05$.

7. Conclusions

By using an annealed carbon steel for specimens, wear tests are carried out in oil under not so severe condition as accompanying the seizure. Following results are obtained.

Fig. 16 Relation between w_v/w_2 and the cycle ratio of the higher load

(1) In the wear curve under lubricated condition, the transition point appears, and it is the sliding distance to initiate the fatigue failure in the surface asperities.

(2) The sliding distance to the transition point has the same meaning as the repetition number of stress for fatigue failure of the notched specimen. When high-low load change is given before the transition point, the transition point appears later than the point calculated using the linear cumulative damage hypothesis in usual fatigue. For the low-high load change, the transition point appears near to the calculated point.

(3) The wear rate in the steady state shows an analogous behavior with that of the fatigue crack propagation. For the high-low load change, the wear lies dormant for some sliding distance from the changing point, and later begins to increase again. For the low-high load change, the wear rate increases corresponding to the higher load.

(4) The steady values of residual stress and surface hardness depend upon the testing load. The dormancy of wear and other wear behaviors by the load change are considered to be due to the combined effects of the residual stress, the hardness and the load.

(5) By giving the higher load periodically, the stationary wear rate is considerably lowered below that which is obtained when the load is given constantly.

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