Wear Tests of Plastics by an Ultrasonic Vibration Method

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A special apparatus was constructed for tests of wear on plastics, the essential part of which is a metal rod vibrating at a high frequency (18.3 kc). Some experiments were carried out in the range from 140 to 560 g of the force of contact and from 25 to 75 μ of the amplitude of vibration. The amount of wear can be measured at any time of the duration of experiments. Polyethylene, Nylon-6 and Poly-vinyl-chloride were tested. Effects of force, amplitude, irradiation of γ-ray and other factors upon wear are investigated. Speculation on the mechanism of wear for the results is done with help of microscopic observation on rubbing surfaces.

1. Introduction

Plastics have been progressively used for a variety of industrial and technological purposes because of their unique properties. Among them, wear resistance is one of the most important properties, but it depends on many factors and its mechanism is very complex. Data on wear are now required under many different test conditions. This paper deals with the wear, analogous to the fretting corrosion of metal(1), between plastic and a rubbing rod. This method has been hardly used for plastics except for the preliminary experiment(2). To shorten time of test, we have constructed a special apparatus using the ultrasonic method. With this, effects of the force of contact, the amplitude of vibration, irradiation of γ-ray and other factors upon wear have been investigated. Some speculation on the mechanism of wear has been done with help of microscopic observation on rubbing surfaces.

2. Apparatus

Experimental apparatus used is schematically shown in Fig. 1, in which the rubbing rod, A, vibrates longitudinally at an ultrasonic frequency and rubs on the surface of a sample. This rod is made of a 13% Cr stainless steel of 2.5 mm in diameter and is connected to a metal horn, B, which is cemented to a magnetostriction vibrator. C. Resonance frequency of the system, A+B, is so chosen as to coincide with the resonance frequency of the vibrator, C (18.3 kc). All the vibration system, A+B+C, is fixed on the nodal circle of the horn to the wall of a cooling vessel, D. Thus, the large part of the vibration system is immersed in cooling water. This apparatus, though not capable of changing the frequency, can work at any amplitude in the range from 15 to 100 μ.

Sample S, as shown in the lower part of Fig.

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1, contacts with the rubbing rod under constant force with the aid of a pivot arm, E. Relation between this contact force $P$ and weight $W$ to be added to the arm is

$$P = 2.8 W$$

(1)

in this apparatus. Range of weights employed in this experiment is $W = 50 \sim 200$ g, therefore $P = 140 \sim 650$ g.

As wear progresses, slight rotation of the arm takes place and can be measured by a microscope as the displacement of a line marked on the end surface of the arm. The amount of wear is calculated by the following expression,

$$L = 1.392 \frac{P}{W}$$

(2)

where $L$ is the amount of wear in mm$^3$ and $I$ displacement of the marked line. Both this displacement and amplitude of the rubbing rod can be measured by two microscopes, respectively, at any time in duration of tests (see Fig. 2).

Cooling water of about 300 cc per min. was passed through a small hole drilled in the rubbing rod, otherwise the temperature would rise to a considerably high value. As it is impossible to take the temperature of the rubbing surface itself, the temperature inside the sample was instead measured by a copper-constantan thermocouple inserted just below this surface. Figs. 3 and 4 show the temperature versus the rubbing time for polyethylene and Nylon sample, respectively. When cooling was efficient, the temperature inside the sample was not so high, though it would locally reach nearly the melting point on the rubbing surface.

### 3. Materials

Samples used are listed in Table 1.

Samples, sheets of 2 mm thickness, were cut into the form as shown in Fig. 5 with a punching cutter and were polished with sand paper (#000). They were all heat-treated at 100°C for 2 hours to eliminate residual stress or to stabilize free radical induced by irradiation.

An attempt was made for Nylon to study the effect of water contents on wear; two kinds of samples were employed, one being left in atmosphere (about 4.6% water content) and the other stored

![Fig. 2 General view](image)

![Fig. 3 Rise of temperature in polyethylene samples (room temperature 22°C)](image)

![Fig. 4 Rise of temperature in nylon sample (room temperature 13°C)](image)

![Fig. 5 Form of test piece](image)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Maker</th>
<th>Density g/cc</th>
<th>Contents of plasticizer (D.O.P.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyethylene</td>
<td>Mitsui Chemical Co.</td>
<td>0.96</td>
<td>—</td>
</tr>
<tr>
<td>Nylon-6</td>
<td>Tōyo Rayon Co.</td>
<td>1.14</td>
<td>—</td>
</tr>
<tr>
<td>PVC</td>
<td>Tsutsunaka Celluloid Co.</td>
<td>0, 5, 10, 20</td>
<td>—</td>
</tr>
</tbody>
</table>
in a drier for 5 months. As measurements showed a little difference between the two, special care was not hereafter taken of water contents of Nylon.

4. Experimental results and discussion

4.1 Polyethylene

To establish the relation between the amount of wear and the rubbing time, experiments were carried out under forces ranging from 140 to 420 g and amplitudes from 25 to 75 μ. Some of these results are shown in Figs. 6 and 7, the former giving one under a constant amplitude, 40 μ, and the latter under a constant force, 196 g.

At the stage of relatively small amplitude, wear, at first, increases rapidly and then does slowly; this tendency does not so much depend on forces (see Fig. 6). While, under large amplitude, wear increases rapidly and linearly with time up to a considerably long rubbing distance. (This is understandable if the rubbing distance would be taken in place of time, the abscissa of Fig. 7; distance being proportional to time × amplitude.)

The pressure of contact decreases as wear progresses. This might be thought to be the cause of the non-linear relation of wear vs. time in test of small amplitude. This interpretation, however, would be presumably incorrect, because it is not applicable for the result under large amplitude, in which, from microscopic observation of rubbing surfaces, the mechanism of wear can be supposed to be not so different from that in the case of small amplitude.

In order to seek another good reason, further experiment was performed. Slight lateral vibration was applied to the rubbing rod by resetting the horn. (Motion of the rod, under the microscope, could be observed as a very prolonged ellipse.) Experiments in such a case, even though done under small amplitude, showed that wear increases in linear relation to time for long period (see Fig. 8). In tests under small amplitude with slight lateral vibration or under large amplitude, wear dust is supposed to escape from the rubbing surface more easily than in tests under small amplitude. Then, it may be concluded that non-linear relation of wear vs. time in small

![Graph 1](image1)

Fig. 6 Wear vs. time under several forces and a constant amplitude, 40 μ (polyethylene)

![Graph 2](image2)

Fig. 7 Wear vs. time under several amplitudes and a constant force, 196 g (polyethylene)

![Graph 3](image3)

Fig. 8 Wear vs. time under amplitude, 40 μ and force, 196 g, showing the effect of lateral vibration

![Graph 4](image4)

Fig. 9 Relation between wear after 20 min and force of contact (polyethylene)
amplitude will presumably result from accumulation and lubrication of wear dust on the rubbing surface.

Fig. 9 shows the relation between the amount of wear after 20 min. and the force of contact. In fretting corrosion of metals, wear $L$ changes against force $F$ as

$$L \propto F^{0.7}$$

For plastic materials, however, experiments in more extensive range of forces would be necessary to prove such a relation. The amount of wear after a constant rubbing distance, 1.130 m, against amplitude are plotted for several contact forces in Fig. 10. In this case, wear increases in parabolic fashion with increasing amplitude and this character is independent of values of contact forces.

4-2 Irradiated polyethylene

Polyethylene is reinforced by irradiation of $\gamma$-ray, but is little known the effect of irradiation on the wear resistance. Then, some experiments were carried out. Two groups of samples were irradiated with $\gamma$-ray from $\text{Co}^{60}$, one group being sealed in ampoules, in vacuum of about $10^{-5}$ mm Hg and the other group in atmosphere.

Fig. 11 shows the result of wear test under amplitude, 40 $\mu$, and force, 196 g. Wear character can be highly improved by irradiation in vacuum, but not by irradiation in atmosphere. Though polyethylene is a so called crosslinking type plastic, it may be presumed that, near the surface of the sample exposed to oxygen, degradation by irradiation will take place more increasingly than crosslinking.

4-3 Nylon

Fig. 12 shows the results for Nylon-6 under an amplitude, 40 $\mu$, and forces, 140, 196, 280, 364,
420 and 560 g. In the interval measured, wear increases monotonously with time under both higher and lower forces, but under intermediate forces wear changes in somewhat complicated manner. Also, it is to be noticed that wear decreases with increase of force. To show this more explicitly, the wear after 20 min. was plotted against force (see Fig. 13).

Then, microscopic observation on the rubbing surface was done to inquire into this anomalous behavior of wear. Fig. 14 (c), shown for comparison with Nylon, is of polyethylene. This appearance did not so much change with changing amplitude or force. Meanwhile, the surface of Nylon, when rubbed under small force, 196 g, shows both ploughed and scored scars as seen in Fig. 14 (a). On the contrary, the ploughed scar disappears when rubbed under large force, 560 g, though unaccountable oblique strips instead come out (see Fig. 14 (b)).

The following speculation may be done from these observations:

1. Under small force, the rubbing surface will locally reach nearly the melting point and will be ploughed there by the rod due to strong affinity between Nylon and metal near that temperature.

2. Wear dust produced in such manner will easily escape from the boundary, because the mean temperature of the rubbing surface will not yet be sufficiently high to melt the dust.

3. This is supported from another fact that the white debris was produced, because, under small force, wear would take place inside Nylon by ploughing action and therefore the wear dust would mainly consist of Nylon particles.

4. Under large contact force, the mean temperature will rise to a considerably high value and wear dust will become good boundary lubricant. This will be the reason why wear resistance is rather larger than under small contact force.

5. Brown debris, supposed to consist of oxide particles of metal, appeared under large contact force. This suggests the wear takes place not only in Nylon but also in the rubbing rod.

Under the medium forces of contact, wear, at

(a) Nylon (force, 196 g)  (b) Nylon (force, 560 g)  (c) Polyethylene (force, 196 g)

Fig. 14 Micrograph (×450) of the rubbing surface (amplitude 40 μ)

Fig. 15 Wear vs. time under several amplitudes and a constant force, 196 g (nylon)

Fig. 16 Wear vs. time under amplitude 40μ and force 196 g, showing the effect of irradiation of γ-ray (nylon)
first, increases slowly and then rapidly as shown in Fig. 12. This will result from the fact that contact pressure decreases as wear progresses.

Curves in Fig. 15 show the relation between wear and time under a contact force, 196 g, and amplitudes, 40, 55 and 75 μ, respectively. Wear increased with increasing amplitude and thus anomalous character as shown in Fig. 13 did not take place when the amplitude was increased. The reason will be presumed as follows. Increasing amplitude, as well as increasing force of contact, will contribute to the rising of temperature. The former, however, will be more effective to make the wear dust escape from the contact surface than the latter.

4-4 Irradiated Nylon

Fig. 16 shows the result of wear test under an amplitude, 40 μ, and a force of contact, 196 g. Wear, even for samples irradiated in vacuum, increased with increasing dose, contrary to the expectation from the case shown in Fig. 11 of polyethylene. If, as mentioned above, wear of Nylon under such amplitude and force would be mainly due to ploughing action, this would increase with increasing degree of crosslinking. Thus, decrease of wear resistance by irradiation can be explainable to some extent from this mechanism of wear.

4-5 Poly-vinyl-chloride (PVC)

This plastic belongs to high-polymeric materials of degradation type for γ-ray and therefore reinforcement due to irradiation can not be expected. Meanwhile, as its mechanical property changes appreciably according to contents of plasticizer, measurements on this point were carried out, Di-ethyl phthalate being used for plasticizer. Low test condition was employed because of its small wear resistance, amplitude of 25 μ and force of 112 g. The result is that wear increases with increasing contents of plasticizer except for less contents than 5 % (see Fig. 17).

5. Conclusion

By the special apparatus constructed, careful measurements have been made of the wear of plastics rubbed by the metal rod as a function of amplitude, force, time and irradiation. The following results were obtained.

Fig. 17 Wear vs. time under amplitude 25 μ and force 112 g, showing the effect of plasticizer (PVC)

1) Of polyethylene, the form of wear-time (or distance) curve changed makedly with the amplitude of vibration, but little with the force of contact. Initial stage in which wear is proportional to time was prolonged with increasing amplitude. Of Nylon, the relation between wear and time varied in complicity with the force of contact.

2) The amount of wear of polyethylene varied with the force of contact. While, that of Nylon was rather smaller under increasing force than decreasing one, the opposite tendency to that of polyethylene.

3) The amount of wear of both polyethylene and Nylon increased parabolically with an increase in amplitude.

4) For polyethylene, irradiation of γ-ray in vacuum gave rise to marked improvement on the wear character, but that in air gave reverse effect. For Nylon, irradiation did not make the wear resistance better.

5) PVC had very inferior property for wear and no improvement has been expected by irradiation and/or addition of plasticizer.

References