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HOMMA Masao, ICHIMURA Hajime

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Wear Properties of Various Cast Irons Having Different Graphite Shapes*

Masao Homma and Hajime Ichimura**

*The Research Institute for Iron, Steel and Other Metals

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Synopsis

The wearing properties of various cast irons of flake, spheroidal, eutectic or other shaped graphite structures were investigated. As the opposite specimens, wormy flake graphite cast iron was also used. The test was carried out under a dry condition. By applying the least square method to the arrangement of experimental data some instructive features could be shown.

I. Introduction

In heretofore reported papers, the wearing phenomena were discussed from the total sum of wear amounts, the specific wear amounts at a certain wear distance, or the simple relation between wear amounts and distance.

The wear resistance characteristics in the sliding wear test of cast steels containing spheroidal graphite to various cast irons with flaky, spheroidal, eutectic forms of graphite have been reported by Abe(1). In the present study, though similar to it in conducting the test, a different analytical technique was used based on a new concept of “wear trend line”, which was deduced by applying the method of least square to the arrangement of observed data.

The reason for this was that the validity of the conventional methods of comparing the wear resistivities of different types of metal with one another from such concepts as “cumulative wear amounts”, “specific wear amounts” and “distance-wear characteristic curve” has long been doubted, and that the method of least square was viewed to arrive at more practical and reliable conclusions.

II. Methods of test and specimens

1. Equipment and testing

The test equipment used was a modified form of that which was planned by Fukao and is basically illustrated in Fig. 1, the modification being an addition of a device which makes it possible to weigh the lower specimen. The equipment was arranged to take up a number of specimens simultaneously.

* The 1086th report of the Research Institute for Iron, Steel and Other Metals.
** Riken Piston Ring Co., Kashiwazaki.
The lower specimens is shaped and dimensioned as shown in Fig. 2. A required number of specimens were set in the rotating shaft. The upper specimen of the size shown in Fig. 3 is inserted into the vertical slot provided in and through the specimen retainer, so that its lower end will rest on the lower specimen to hold a sliding contact, while the upper end provides a pivot point for the loading fixture of a ring form. By different pendent weights on this fixture, the loading on the upper specimen can be varied. The resting end of upper specimen was machined to the curvature of 30-mm radius to conform to the periphery of the lower specimen, and
the mating faces were both ground smooth to uniform fineness of 1.5 S finish by using emery cloth.

In prescribing the test conditions, the first problem was a proximate realization of the working conditions of piston rings of internal combustion engines, for the wears of piston rings were the ultimate object of the present study. Working conditions for the piston rings vary with types and operating conditions of engines. Taking, for instance, the frictional velocity, the average speed of piston rings in marine Diesel engines is between 4 and 6 m/sec, whereas in automotive Diesel engines it is of the order of 8 to 10 m/sec, and in motor-car and auto-bicycle gasoline engines it is from 12 to 15 m/sec. Instantaneous frictional speed, of course, varies greatly depending on the position of the ring during the stroke: In the present experiment a range of 1 to 5 meters per second was considered to be most appropriate on the basis of the fact that the wearing action is most pronounced near the top dead center, being effected by the pressure of explosion at that part of the cylinder. The second problem was of frictional pressure. This pressure too is variable as far as piston rings are concerned. The face pressure is usually from 1.5 to 2.5 kg/cm² at the most, but in actual service a back pressure acts on the ring during the explosion stroke. The back pressure can reach about 30 kg/cm² for the first ring, about 10 kg/cm² for the second, and about 3 kg/cm² for the third, thus changing the face pressure of the ring with the change of its groove position on the piston. Since pulley speeds of 4.86 and 3.05 m/sec and weighting of 50 kg/cm² had been used in the previous tests, these conditions were also adopted in the present case for convenience’s sake.

The test had to be of a dry non-lubricated metal-to-metal sliding wear.

In the present test, the measurement of the wear amounts, or the loss of metal, was effected by checking the mass reduction 8 times in succession at intervals of 20 kilometers, totaling 160 running kilometers for the sliding faces of the specimens. Before measuring each loss of mass, the specimens were washed clean with benzine, dried and put on a micro-balance for precision weighing.

2. Specimens

Six cast iron materials, whose chemical analyses and physical properties are shown in Table 1, were used for the upper specimens. For the lower specimens, the material shown similarly in Table 2 was used, which is a cast iron of wormy flake graphite.
Table 1. Chemical compositions and mechanical properties of the upper specimens.

<table>
<thead>
<tr>
<th>Mark</th>
<th>Materials</th>
<th>Chemical compositions (%)</th>
<th>Mechanical properties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>T.C G.C Si Mn P S Cr Ti</td>
<td>Tensile strength kg/mm²</td>
</tr>
<tr>
<td>C</td>
<td>Cupola iron</td>
<td>3.23 2.11 12.16 0.30 0.073 0.076 — —</td>
<td>—</td>
</tr>
<tr>
<td>W</td>
<td>Wormy flake graphite iron</td>
<td>2.80 2.26 1.81 0.35 0.17 0.047 — —</td>
<td>—</td>
</tr>
<tr>
<td>E</td>
<td>Eutectic graphite iron</td>
<td>3.16 2.60 2.25 0.46 0.092 0.009 0.119 0.168 — —</td>
<td>—</td>
</tr>
<tr>
<td>S</td>
<td>Semi-nodular graphite iron*</td>
<td>3.46 — 2.78 0.93 0.19 0.013 0.022 — —</td>
<td>—</td>
</tr>
<tr>
<td>N</td>
<td>Nodular graphite iron*</td>
<td>3.102 2.66 3.63 0.30 0.024 0.009 — — —</td>
<td>—</td>
</tr>
<tr>
<td>M</td>
<td>Black heart malleable iron</td>
<td>2.22 2.02 1.28 0.42 0.043 0.095 — — —</td>
<td>—</td>
</tr>
</tbody>
</table>

* Bull’s eye structure

Table 2. Chemical compositions and mechanical properties of the under specimen.

<table>
<thead>
<tr>
<th>mark</th>
<th>Materials</th>
<th>Chemical composition (%)</th>
<th>Mechanical properties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>T.C G.C Si Mn P S Cr Ti</td>
<td>Tensile strength kg/mm²</td>
</tr>
<tr>
<td>W</td>
<td>Wormy flake graphite iron</td>
<td>2.69 2.05 1.74 0.77 0.075 0.022 — — —</td>
<td>—</td>
</tr>
</tbody>
</table>

III. Logical bases for the treatment of experimental data

1. Conventional treatments for wear amounts and their shortcomings

For comparing the results of wear tests on different materials with one another, it has hitherto been customary to express the wear amounts as a function of the running distance, rotating speed of the test equipment, or time, and to visualize the wear characteristics by the so-called “distance-wear curve”. In another practice, specimens are subjected to wearing conditions for a given distance, and wear amount per unit distance is referred to “specific wear amount.” In some cases, however, a reliable conclusion cannot follow from the results obtained by these methods. For example, in Fig. 4 two wear curves cross each other at point “b”, and accordingly, on one side of this crossing point, specifically at point “a”, material B has worn more than A, while, on the other side, specifically at point “c”, the reverse is the case. Thus the comparison between the two materials A and B on the basis of “cumulative wear amounts” or “specific wear amounts” will lead to a conclusion which varies depending on the running distance.
Thus, the conventional methods have the following shortcomings:

1) Slightest variation of or variance among the test conditions and measurements can affect the conclusion to an amplified degree.

2) The amount of wear is not necessarily proportional to the running distance, and this fact misleads the conclusion according as the running distance is short or long.

3) The wear trend or the mode of wearing which characterizes each material cannot be seen distinctly.

2. Determination of the wear trend, its significance, and application of the method of least square

(i) Plotting of wear trend line

It is the common practice of testing of wear resistance to weigh successively the wear amount at regular intervals of running distance and to compute the specific wear amount and cumulative wear amount. This method, however, involves several complicated questions as pointed out above. Hence, in the present case, the observed results were adjusted by the following alternative method.

The amount of wear in running test was measured at regular intervals and was plotted as shown in Fig. 5. Owing to some layers with different wear resistance in the specimens, to instabilities which happen to exist in the material, or even to unavoidable changes in the condition of wearing, the plotted dots are usually liable to scatter. However, the overall view suggests a certain trend which rises or lowers toward the right, depending on the way in which dots are located. Even if the curve
Fig. 5. The relation between interval wear amounts and wear trend line.

is located by averaging these values mechanically or arithmetically, the located curve may be far from a best possible approximation to the yet invisible true trend line. However, the method of least square was applied to the present case as follows:

A straight line possibly close to all dots is deduced mathematically and drawn, the equation being \( y = ax + b \). Though an equation of the second degree may be used, problems normally encountered can be satisfactorily dealt with by the use of a linear equation. For the sake of convenience, the line obtained by the least square will hereafter be designated as "wear trend line", and its significance will now be mentioned.

In the left-hand graph (1) in Fig. 6, the line A represents the equation wherein "a" is positive; B is the case where "a" is equal to zero; C is the case where "a" is negative. If "a" is positive, the line rises to the right but, if negative, falls down. When "a" is zero, the line is horizontal. A curve for cumulative amounts of wear, drawn on the basis of the wear trend line, will look like that shown in the right-hand graph (2) in Fig. 6. Line A will result in curve A', whereas line C will result in curve C'. Line B showing uniform rate of wear gives curve B'.

The larger the absolute value of "a" is, that is, the greater the angle of elevation is, the more remarkable will be the bend in the corresponding curve in the distance-wear graph (2). Stated differently, the absolute value of the magnitude

Fig. 6. The relation between wear trend line and cumulative wear amounts.
of "a" clearly suggests the manner with which the material progressively wears off with the running distance. The term "b" in the equation indicates the position on "y" axis from which the wear trend line starts or, stated specifically, the amount of initial wear in the test. Hence, the determination of the values of "a" and "b" for each material is the same thing as that of its wear characteristic.

Fig. 7 illustrates a case in which two wear trend lines A and B cross each other, indicating that the relation in specific wear amounts reverses between two materials at the point "m". In other words, before reaching the point "m", the rate of increase in wear is greater for material B than for A, but this relation reverses beyond the point "m".

![Image of wear trend line]

**Fig. 7.** An example of wear trend line.

It will be noted that the wear trend line depicts the way in which the specific wear amount changes with the distance, thus providing valuable information in not few cases in which a greater significance is attached to specific wear amounts than to cumulative wear amounts. This is another great advantage characterizing the technique based on the method of least square.

(ii) Indications of the degree of deviation of the experimental values

The deviations of experimental data are inevitable, and so the validities of wear trend line computed with observed values are different with different groups of metal. In the present case, the degree of deviation, or the degree of confidence was expressed as follows:

The sum of absolute values of difference between measured value and that corrected by the wear trend line at each running distance is divided by the number of measuring. This value R is taken to be the degree of deviation for each material.

The smaller value of R signifies a more stable wearing property of a material. Thus, the value of R is one of the indications of material characteristics.
IV. The results of experiment

1. Wear amount and wear trend line

The wear amount at a certain running distance and the wear trend line for various cast irons are shown in Figs. 8～13, the formulas of wear trend lines are shown in Tables 3 and 4, and the comparisons of the wear trend lines with one another are shown in Figs. 14 and 15. R in these figures is the mean value of the differences between measured values and those corrected by the wear trend line.

![Graph of wear trend line](image)

\[ y'_{m} = -0.067x + 39.8 \quad R = 3.4 \]

\[ y'_{u} = 0.022x + 8.9 \quad R = 3.3 \]

Fig. 8. The wear trend line of black heart malleable iron.

2. The comparisons of the total sum of wear amounts between measured and corrected values

These results are shown in Figs. 16～19. On the curves of the total sum of wear amounts calculated by measured values, curves are exchanged alternately, or contacted and are indistinct. But on the curves calculated by corrected values, mutual relations are distinct and the tendencies of such type as that of gradual increase, constant change, and gradual decrease are clarified.

The effects on the forms of wear curve, which are caused by abnormal measured values, and by the deviations due to different conditions of specimens in the initial stage, can be made as possible as small. Therefore, when the wearing properties
Fig. 9. The wear trend line of semi-nodular graphite iron.

Fig. 10. The wear trend line of wormy flake graphite iron.
Fig. 11. The wear trend line of cupola iron.

\[ y_L = -0.074x + 28.6 \quad R = 4.1 \]
\[ y_H = 0.018x + 4.5 \quad R = 1.6 \]

Fig. 12. The wear trend line of eutectic graphite cast iron.

\[ y_L = -0.069x + 31.4 \quad R = 4.4 \]
\[ y_L' = -0.044x + 36.6 \quad R = 4.8 \]

\[ y_H = 0.059x + 34.6 \quad R = 3.2 \]
\[ y_H = -0.0036x + 20.8 \quad R = 1.9 \]

Running distance km
Fig. 13. The wear trend line of nodular graphite cast iron.

Table 3. Wear trend lines of specimens, rotating velocity 4.86 m/sec.

<table>
<thead>
<tr>
<th>Materials of the upper specimen</th>
<th>The upper specimen</th>
<th>The under specimen</th>
</tr>
</thead>
<tbody>
<tr>
<td>mark</td>
<td>Wear trend line</td>
<td>Degree of deviation</td>
</tr>
<tr>
<td>Cupola iron</td>
<td>$y_H = 0.018X + 14.5$</td>
<td>R = 1.6</td>
</tr>
<tr>
<td>Wormy flake graphite iron</td>
<td>$y_H = 0.068X + 9.5$</td>
<td>R = 1.3</td>
</tr>
<tr>
<td>Eutectic graphite iron</td>
<td>$y_H = -0.003X + 20.8$</td>
<td>R = 1.9</td>
</tr>
<tr>
<td>Semi-nodular graphite iron</td>
<td>$y_H = 0.014X + 12.1$</td>
<td>R = 1.2</td>
</tr>
<tr>
<td>Nodular graphite iron</td>
<td>$y_H = 0.148X + 17.5$</td>
<td>R = 5.6</td>
</tr>
<tr>
<td>Black heart malleable iron</td>
<td>$y_H = -0.067X + 39.8$</td>
<td>R = 3.4</td>
</tr>
</tbody>
</table>

| mark                            | Wear trend line    | Degree of deviation|
| W' - C                          | $y'_{H} = -0.069X + 31.4$ | R = 4.4            |
| W' - W                          | $y'_{H} = -0.034X + 14.6$ | R = 2.6            |
| W' - E                          | $y'_{H} = -0.048X + 11.3$ | R = 1.6            |
| W' - S                          | $y'_{H} = -0.055X + 17.9$ | R = 1.5            |
| W' - N                          | $y'_{H} = -0.053X + 15.8$ | R = 1.8            |
| W' - M                          | $y'_{H} = 0.022X + 8.9$  | R = 3.3            |
Table 4. Wear trend lines of specimens, rotating velocity 3.05 m/sec.

<table>
<thead>
<tr>
<th>Materials of the upper specimen</th>
<th>The upper specimen</th>
<th>The under specimen</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mark</td>
<td>Wear trend line</td>
</tr>
<tr>
<td>Cupola iron</td>
<td>C</td>
<td>$y_L = -0.074X + 28.6$</td>
</tr>
<tr>
<td>Wormy flake graphite iron</td>
<td>W</td>
<td>$y_L = -0.052X + 27.4$</td>
</tr>
<tr>
<td>Eutectic graphite iron</td>
<td>E</td>
<td>$y_L = -0.059X + 34.6$</td>
</tr>
<tr>
<td>Semi-nodular graphite iron</td>
<td>S</td>
<td>$y_L = -0.043X + 22.0$</td>
</tr>
<tr>
<td>Nodular graphite iron</td>
<td>N</td>
<td>$y_L = -0.124X + 33.0$</td>
</tr>
<tr>
<td>Black heart malleable iron</td>
<td>M</td>
<td></td>
</tr>
</tbody>
</table>

![Graph of wear trend lines](image)

Fig. 14. The wear trend line of various cast iron rotating velocity 4.86 m/sec.

are discussed from the curves of total sum of wear amounts, it can be shown more clearly and accurately by the corrected curves.

V. Considerations

From the results of the present experiment the characteristic properties of wear of each cast iron could be approximately taken hold, but it was not so simple and easy that the order of wear resistibility of each cast iron could be determined rigorously. According to the classification shown in Fig. 9, the tendencies of
Fig. 15. The wear trend line of various cast iron rotating velocity 3.05 m/sec.

Fig. 16. The curve of measuring cumulative wear amounts of various cast iron rotating velocity 4.86 m/sec.
Fig. 17. The curve of correcting cumulative wear amounts of various cast iron rotating velocity 4.86 m/sec.

Fig. 18. The curve of measuring cumulative wear amounts of various cast iron, rotating velocity 3.05 m/sec.
wear are classified in the types of gradual increase, steep increase, constant change, steep decrease, and gradual decrease. In the following, the rotating velocity of 4.86 m/sec will be designated as “high velocity” and that of 3.05 m/sec “low velocity”.

1. Cupola cast iron

At high velocity it is of gradual increase type, whereas at low velocity it is of gradual decrease type. The specific wear amounts are large at low velocity in the initial period, but after the running distance of 140~160 km, it becomes large at high velocity, although the degree of deviation of measured values is small. The wears of opposite specimen are the type of gradual decrease, but it was less at high velocity. The wear amounts of cupola cast iron are small following semi-nodular cast iron, but the increases of wear amounts of the opposite iron are conspicuous.

2. Wormy flake graphite cast iron

At high velocity it is of gradual increase type and at low velocity, it is of gradual decrease type. In the initial period the specific wear amounts are large at low velocity, and after this period, the reverse is the case, exchanging the wear trend line at 140~160 km distance. At both velocities the degrees of deviation
are small and it shows stable wearing properties. The opposite iron shows gradual
decrease type at high velocity and gradual increase type at low velocity and does
not wear largely.

Compared with other materials, the total sum of wear amounts of this iron is
small, following semi-nodular iron. But the wear trend line is of steep increase
type and the specific wear amounts after 160 km running are more than those of
cupola iron and eutectic graphite iron, although in the initial period this is least. At
low velocity the total sum of wear amounts is nearly similar to those of cupola irons
and spheroidal graphite irons, but both irons have the different wear trend lines and
are not reliable by a large degree of deviation. Generally speaking, wormy flake
graphite irons, being similar to cupola irons, are less wearing, following semi-
nodular irons.

3. Eutectic graphite cast iron

At high velocity it is of constant change type, whereas at low velocity it is of
gradual decrease type. In the case of the opposite specimen, the former is of
gradual decrease type and the latter is of gradual increase type. The wear
amounts of the upper and the lower specimen are large at low velocity and show
a large degree of deviation. Generally speaking, this iron is less wearing than black
heart malleable iron and nodular graphite iron, and more wearing than semi-
nodular iron, wormy flake graphite iron and cupola iron. But the wear amounts of
the opposite specimen are least among all other materials. It seems from these
facts that in the combinations of wear between flake and eutectic graphite iron,
the wear amounts of each iron are different, by such conditions of combination as
either rotar or stater.

4. Semi-nodular cast iron

At high velocity it is especially of gradual increase type, whereas at low velocity
it is of gradual decrease type, and in the case of the opposite specimen it is of gradual
decrease type at both velocities. Each of the upper and the lower specimen, being
less wearing at high velocity, is stable to wear, and of all other specimens each shows
a least degree of deviation, and is least wearing at high and low velocity, although
the wear amount of the opposite specimen is comparatively large.

The micro-structure of semi-nodular graphite iron, being obtained in the
case of imperfect nodularizing of graphite, is the mixed-structure of nodular and
wormy flake graphite, and it is better wear-resisting, comparing with nodular or
wormy flake graphite iron. The better wear resistibility of this iron will be under-
stood from the structural characteristics, but not from the hardness, because this
structure showed about $H_{RB}101$, while the hardnsses of nodular and cupola cast
iron were $H_{RB}100$ and $H_{RB}98$, respectively, these difference being very small.

5. Nodular graphite cast iron

At high velocity it is of steep increase type, having more wear amount, and
the wear of the opposite specimen is of gradual decrease type, having less wear amount. The wear properties of nodular graphite cast iron are extremely changeable with the transition of velocity, it showed a large degree of deviation, and is least reliable of all other materials.

6. Black heart malleable cast iron

At low velocity the wear amount was about 500 mg after 5 minutes of running and the continuation of experiment was impossible.

At high velocity it is of gradual decrease type, although all other materials are of gradual increase type, and the wear of the opposite specimen is of gradual increase type, although all other materials are of gradual decrease type.

The total sum of wear amounts until 160 km of running distance is largest among all other materials, although the wears of the opposite specimen are comparatively small. This special wear phenomenon may be caused by the lowest hardness of H_{R67} among all other materials, and by the ferrite matrix.

Conclusions

It is not sufficient to treat the wearing phenomena only by the total sum of wear amounts, the specific wear amounts for a certain running distance, or by the simple relation between wearing amount and distance. In the present experiment, the wear phenomena were analyzed by the wear trend line drawn by the least square method, and it was shown that semi-nodular graphite irons were most wear-resistive and reliable, followed by wormy flake graphite irons and cupola irons, and that the wears of nodular graphite iron and black heart malleable iron were remarkably large, and not reliable in the proceeding of wear.