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A Study on Valve Recession Caused by

Non-leaded Gasoline *

- Measurement by means of R. I. -

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The amount of wear debris from the exhaust valve seat in condensed water of exhaust gas was continuously measured by means of the R. I. method. At the same time, rotational and lateral motion of the valve were measured. Then the mechanism of the exhaust valve recession in using lead free gasoline as a fuel of the automobile engine was made clear as follows:

Cast iron flakes were removed from the valve seat and they adhered to the valve surface. And then, these deposits wore off the valve seat because of rotational and rolling motions of the valve. Especially, during about 20 minutes after the running conditions were changed, the valve motions became more violent and the wear also increased rapidly. Thus the overall abnormal wear of the valve seat was caused mainly by above mentioned transient phenomenon.

1. Introduction

When non-leaded gasoline is employed in automotive engines, the abrasion of exhaust valve seat made of cast iron becomes significant, and the gas sealing is apt to decrease. This phenomenon is called "valve recession", one of the serious problems related with the elimination of lead from gasoline. The mechanism, however, was not clarified sufficiently in past studies. Namely, the abrasion becomes more significant under certain operating conditions or in certain types of engines, and considerably long durations of gradual increase or decrease of abrasion are observed when gasoline is switched from leaded to non-leaded one or vice versa, but the reasons are not clear. On the other hand, Courtney(1), Giles(2) et al, have found new facts on the mechanism i.e., prominent objects or crater shaped flows occur on the contact surface of valve, being scraped off the contact surface of valve seat due to the rotation of valve when non-leaded gasoline is employed. This new abrasion mechanism gives a useful suggestion to the problems.

Authors have also been conducting continuous measurements of abrasion by means of radio isotope in order to solve the problem for a few years. Although it was not easy to trace the micro-constituent in gas by means of R. I., the measurements were facilitated because it was discovered that most of abraded powder was mixed into condensed water, hence the abrasion could be measured by measuring the radioactivity

of condensed water. It was found through the measurement of valve motion that the valve motion consists of not only rotation but also intense rolling motion which become direct causes of valve seat recession.

Authors intend to report on the mechanism of exhaust valve recession which has been clarified through these experiments.

2. Experimental apparatus & measuring methods

2.1. Measurement of abrasion by means of radio isotope

(1) Radiation of exhaust valve seat

Figure 1. Test exhaust valve seat
(1) outer ring (2) inner ring
A : protruding parts for screwing in inner ring

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To ensure the safety in experiments employing R.I. method that in valves exposure to radioactivities, it is vital to assemble the radiated valve seat into engine as quickly as possible with easy handling. Therefore, as shown in Figure 1, valve seat unit was divided into the outer ring (1) and the inner ring, then the outer ring made of brass was shrink-fitted to the cylinder head as shown in Figure 2.

Figure 2. Diagram of fitted test exhaust valve

(1) outer ring (2) inner ring

The inner ring is made of FC-23, weighing 11.5g, and fixed to the outer ring with screws. Thus it was provided with a protruding part to be screwed with a special tool, to avoid the direct touch by bare hands. Both rings were processed such that screwed surfaces could be tightly connected.

To radiate the inner ring, it was irradiated for 290 hours with JRR-No.2 atomic pile (thermal output 10 kw, heat neutron flux 3×10^{13} n/cm² sec) at Japan Atomic Power Research Institute. The specific activity immediately after the irradiation was about 4.5 mci/g., and that in the initial stage of use was about 2.7 mci/g.

(2) Abrased powder trap

Since the intensity of exhaust radioactivity must be extremely low for the sake of safety, it is difficult to measure it directly. Especially, in case of exhaust of internal combustion engine containing various conductive substances, it is furthermore difficult, hence it is necessary to condense the isotope i.e., abraded power. After conducting various experiments, it was found that a quantity of abraded power was contained in the condensed water content of exhaust after it had been cooled. Thus the apparatus was made accordingly as shown in Figure 3.

The exhaust gas was conveyed to the cooling tower, and the flow rate of cooling water was so adjusted that the exhaust temperature at the outlet port 10 of cooling tower would become 15°C - 20°C. The condensed water was then collected by a stainless steel funnel installed at the lower part of cooling tower and drained

outside through a felt filter.

Figure 3. Diagram of experimental apparatus.

- (1) pick-up to be used in the measurement of rotation and rolling motion of exhaust valve
- (2) exhaust valve seat
- (3) thermocouple employed in the measurement of exhaust temperature
- (4) cooling tower
- (5) filter to trap abraded powder
- (6) scintillation counter
- (7) outlet port for cooling water
- (8) inlet port for cooling water
- (9) thermocouple for measurement of cooling exhaust temperature
- (10) outlet port for cooling exhaust gas

Figure 4 shows a detailed diagram of the filter unit. The distance S between the filter and the scintillation counter was set constant as it had a direct relation to measured values. The distance to the filter was made as short as possible i.e., 12mm, and upper part of counter holder was made of vinyl chloride having high transmittivity against isotope. As for the filter holder located at the lower part of the filter case (h) a number of holes having 3ϕ were made on a disc with 70mm diameter in order to reduce the flow-out resistance of water, and to facilitate the smooth passing of γ ray. The surroundings of scintillation counter were cooled with water and kept constant at 15°C to prevent measuring errors caused by temperature variation.

Figure 4. Detailed diagram of abraded powder trapping filter unit

- (a) abraded powder trapping filter
- (b) scintillation counter
- (c) inlet port for condensed water
- (d) outlet port for condensed water
- (e) counter holder
- (f) inlet port for counter cooling water
- (g) filter holding unit
- (h) filter case

(3) Filter catching efficiency

Following experiments were carried out to confirm the catching efficiency of the filter i.e., to find out the rate of abraded powder of exhaust valve seat caught by the filter.

Total abraded powder was divided into three categories i.e., the quantity M_1 that goes out with exhaust after passing through the cooling tower, the quantity M_2 caught by the felt filter, and the quantity M_3 that goes through the filter together with the condensed water. Since the quantity that adheres to the exhaust pipe and the cooling tower is negligible, the overall abrasion quantity of exhaust valve seat can be considered equal to $M_1 + M_2 + M_3$. To measure the quantity M_1 of the above, 3 sheets of filters having 150 mm diameter were attached to (10) exhaust outlet port of cooling tower of Figure 3, as shown in Figure 5.

Figure 5. Abraded powder trapping filter

The intensity of radioactivity was measured thereby, and M_1 was obtained as follows.

$$\begin{aligned} \text{per hour: } Ag_1 &= N_0 V C \alpha \\ Ag_2 &= N_1 V C \alpha \\ N_0 V &= N_1 V + N_2 V \alpha \\ \alpha &= (Ag_1 - Ag_2) / Ag_1 \quad (1) \end{aligned}$$

where

N_0 : concentration of abraded powder at the position of (10). ($\mu\text{g/cc}$)

N_1, N_2 and N_3 : concentrations of abraded powder after passing through the first, second and third filters. ($\mu\text{g/cc}$)

Ag_1, Ag_2 : dosage rates (c.p.m.) of abraded powder remaining in each filter.

α : catching efficiency of filters (%), provided that the efficiency of each filter is the same.

V : exhaust flow rate (cc/hr.)

C : constant obtained by experiments (c.p.m./ μg)

Namely, α can be obtained by equation (1) through the measurements of Ag_1 and Ag_2 . Next, the abraded powder M_1 at the exhaust outlet port (10) can be written as follows.

$$M_1 = Ag_1 / C \alpha \quad (2)$$

Of the above, the constant C is obtained by the following method. Namely, with a known weight, artificial grain having the same radioactivity as that of the test exhaust valve seat is to be made, then it is divided and caught by each filter, and the readings of the measuring instrument at that time decide the constant C . For the above purpose, a test piece made of the same rod material as that of the test valve seat was irradiated together with the test valve seat and dissolved in aqua regia to produce 20 $\mu\text{g/cc}$ aqueous solution 25 cc, and ammonium chloride 10 % aqueous solution 5cc and ammonium 14 % aqueous solution 20cc were added were to produce a precipitate, which was then adsorbed onto a filter paper having 50mm diameter in such a manner that it made a uniform distribution. Further, the precipitate which had passed through the filter paper was dispersed by the dryer and the weight of the above sample was corrected accordingly. The valve, obtained by measuring the filter paper with the scintillation counter under the same conditions as those of actual measurements, was divided by the trapped precipitate weight. The valve thus obtained is the constant C .

Assuming the dosage rate of the filter (5) to be used in the experiments as Aw_1 , M_2 can be obtained as follows.

$$M_2 = Aw_1 / C \quad (3)$$

M_3 that goes through the filter (5) can be obtained from the following equation, by boiling and condensing 50 % of passed water quantity per hour, and measuring the dosage rate Aw_2 .

$$M_3 = 2 Aw_2 / C \quad (4)$$

The rate γ of abraded powder trapped by the measuring filters will be as follows by equations (2), (3) and (4).

$$\gamma = M_2 / (M_1 + M_2 + M_3) \quad (5)$$

The examples of $Ag_1, Aw_1, Aw_2, C, M_1, M_2, M_3$ and γ obtained by the above are shown in Table 1. It was found from the results that the difference of γ is small under different operating conditions and that about 80 % of total abraded powder can be caught and measured. Hence this method was employed.

N r.p.m.	2000	5000
Ag1 (c.p.m.)	19880	90528
Aw1 (c.p.m.)	99524	386944
2Aw2 (c.p.m.)	5001	27490
M1 (μg)	63.18	287.69
M2 (μg)	309.96	1205.10
M3 (μg)	15.58	85.61
C (c.p.m./μg)	321.09	321.09
γ (%)	80	76

Table 1.

(4) Measurements of radioactivity damping rate

The radioactivity of irradiated exhaust valve damps as time goes by. For instance, the half valve period of Fe^{59} is 45.1 days. Therefore, it was necessary to prepare a sample having a known weight, and to measure the dosage rate every day. The aforementioned precipitate sample was thus set prior to the commencement of experiments at the same position as that of catching filter (5), and the dosage measured to find the dosage rate per unit weight.

2-2 Measurements of rotation and rolling motions of exhaust valve.

Electric capacity method was employed in measurements of exhaust valve rotation and rolling motions. First, to measure the rolling motions, a capacity pick-up was installed above the valve guide, as shown in Figure 6. A detailed diagram is shown in Figure 7.

Figure 6. Installed position of capacity pick-up

Figure 7. Detailed diagram of pick-up

(1) lead wire (2) bakelite to insulate pick-up (3) O-ring (4) electrodes A and B (5) pick-up holder

Two electrodes were so situated that they faced one another. The insulation between two electrodes and that of pick-up holder were made by bakelite 2, and they were fixed by some adhesives. A shielding wire having an outer diameter 2mm was used for the lead-wire 1, and it was connected to the cylinder head to prevent noise and a failure caused by the vibration of lead wire. The diameter clearance between the valve rod and electrodes was set at 0.2mm because the clearance between the valve rod and the guide was 0.1mm.

The measurements of rotation of exhaust valve were done as follows. A cutting was made on a part of the valve rod shown in Figure 8 with 2mm depth, 4mm length and 3mm breadth. As this part faced electrodes, a significant change occurred in the capacity. This phenomenon was observed by an oscilloscope, and at the same time, outputs from 2 pick-ups were put through the smoothing circuit and recorded

Figure 8. Exhaust valve for measurement of valve rotation.

by a pen-type recorder. The cut position was so adjusted that it might agree with the pick-up position when the valve was open. An ordinary valve without a cutting was employed in the measurement of rolling motion of the valve rod, and measured by the oscilloscope.

2-3 Test engine

A test gasoline engine made by Mitsubishi Motors Corp., having a mono-cylinder 4 cycle, bore x stroke = 73φ x 76 mm (318 cc), and O.H.C. valve mechanism was employed in the tests. This engine was installed at Atomic Power Research Laboratory of Musashi Institute of Technology. The power was absorbed by an eddy-current electric dynamometer, and the temperature of cooling water was set at 80°C constant at the outlet port. A thermocouple made of alumel-chromel having an outer diameter 0.3mm was used to measure the exhaust temperature, and a hot junction was fixed at the position where the gas temperature at the center of exhaust pipe located 15cm behind the exhaust valve could be measured.

Experiments were also conducted to vary the exhaust temperatures by adjusting the ignition advance. Both leaded and non-lead gasoline were used in the experiments, and the properties are shown in Table 2.

	specific research gravity	octan number	Pb(C ₂ H ₅) ₄
non-lead	0.75	91	0.00
lead	0.74	91	0.8

Table 2.

3. Results of measurements

3-1 Measured results on wear rate

Figure 9 shows typical examples of measured results obtained by one-hour operation made under a constant engine speed and a constant load. The upper line shows the exhaust temperature and the lower line shows the dosage i.e., the quantity of abraded powder trapped by the filter. The value of worn quantity of valve seat should be multiplied by 1.25 as the trapped rate is about 80 % of total wear. It is found from the graph that a great amount of initial wear is ob-

Figure 9. Typical measured result of amount of valve seat wear

Figure 10. Effect of load on steady wear (relation between load and wear rate)

served in the first 20 minutes after the engine has been started, but the wear tends to decrease as time goes by, then becoming a steady wear inherent to the operating conditions.

Figures 10 and 11 show the wear rates under steady abrasion conditions in relation to the effects of loads and engine speeds. Effects of load increase gradually at the first stage in accordance with an increase of load, but a sudden increase is observed after the load has exceeded 1/2; and the effects under high engine speed also show similar tendency, with a sudden increase under high speed. It is thus found that the wear rate becomes abnormally high under load and high engine speed. It is also found that the wear rate with lead gasoline is substantially lower than that of non-lead gasoline.

Figure 11. Effect of engine speed on steady wear (relation between engine speed and wear rate).

Figure 12 shows the measured results obtained when the load is set constant at 1/2 load, and the engine speed is gradually increased every 30 minutes from 2000 r.p.m., to 3000 r.p.m. and 4000 r.p.m. It is found that some significant increase of initial wear rate appears each time the engine speed is changed. A thin solid line in the figure shows the measured results obtained under half load and 4000 r.p.m. It must be noted that the wear rate after 70 minutes have passed becomes greater where the engine speed is changed, even though the two measured results show almost equal wear rates in initial operation stage; and that the initial wear appears at every change of engine speed affecting conditions of the vehicle have great effect upon the total wear.

Figure 12. Effect while engine speed is varied once in every 30 minute.

Figure 13. Effect while load is changed in every 30 minutes.

Figure 14 shows the measured results obtained when the engine speed is kept constant at 4000 r.p.m., but load is varied; and the ignition timing is so adjusted that exhaust temperature remains constant. Sudden increase of wear rate is observed each time the load is changed, and as a result, the wear rate after 60 minutes have passed is very high. That is to say, it is found that the effects of load are attributed directly to load itself, not to the exhaust temperature.

Further Figure 15 shows the results obtained in a case where the engine speed and load were set constant at 4000 r.p.m. and half respectively, and where the ignition timing was adjusted and exhaust temperature was varied. From the results it was not recognized either that the exhaust temperature is a major factor of valve seat wear. Namely, even if the temperature was changed, the wear rate showed a similar value to that under 4000 r.p.m. and half load.

It can be concluded from those measured results that the overall wear rate is greatly affected by initial wear resulting from the changes of engine speed and load, rather than the exhaust temperature. Therefore, in order to find out causes for sudden increase of wear rate that occurs when the engine speed or load is changed, measurements of exhaust valve rotation speed were carried out.

3-2 Results of measurements of exhaust valve rotation speed

Figure 16 shows the changes of electrodes. Because of the structures of the electrodes, the capacities of both electrodes change symmetrically to one another, hence the rotation speed can be measured in terms of cycle number of one of electrodes.

Figure 17 shows the valve rotation speed against the engine speed, and it is

Figure 14. Effect of load in constant exhaust gas temperature.

Figure 15. Effect of exhaust gas temperature in constant engine speed and load

found from the figure that the valve starts rotating after the engine speed exceeds 3000 r.p.m. in this engine, and the rotation increases suddenly under high engine speed. On the other hand, no effect was observed upon the valve rotation when the load was varied.

An interesting discovery made from Figure 18 is that some phenomenon was recorded in which the valve rotation speed suddenly increased temporarily immediately after the engine speed had been increased. It seems that this phenomenon has some relation to the increase of initial wear. It was also found from Figure 19-(a) that the valve does not rotate constantly under low speed operation, but it changes its direction once in a while.

Figure 16. Typical recorded of exhaust valve rotation speed.

Figure 17. Exhaust valve rotation speed.

3-3 Measured results of valve stem rolling motion

Figure 20 shows the changes of two electrodes capacities. If the valve stem is positioned at the center of the guide, both lines will be symmetrical; but one of the lines may show higher values or it may be reversed as compared with the other, because the valve stem is not actually positioned at the center of guide, and due to the lack of linearity against the gap. As for the entire motions, a large and slow rolling was observed when the valve was open, and intense rolling was observed after it had been seated. The period of intense vibration accords with the inherent vibration (about 400 Hz in this engine) of valve system rolling motion.

Figure 21 shows the effects of engine speed under the stable condition, and it is found clearly that a large vibration occurs when it is seated under high rotation.

Figure 22 shows results when the load is varied. The left side of the figure shows that the higher the load, the more intense becomes the rolling motion immediately after the load is changed. The right side, under stable condition, shows that the vibration resulting from seated condition has no relation with the load.

Figure 23 shows the comparison between the effect (A) caused by the changes of operating conditions and the effect of rolling (B) upon the wear. It is clear from the figure that the rolling motion of valve increases immediately after the changes and the sudden increase of wear resulting from the former.

Figure 18. Temporally increase of exhaust valve rotation speed.

Figure 19-(a). Low valve rotation speed at low engine speed.

Figure 19-(b) Valve direction change under low engine speed operation.

Figure 20. Typical record of valve rolling motion

Figure 21. Effect of engine speed at steady state (full load)

Figure 22. Exhaust valve rolling motion.
(influence of load)

3-4 Changes occurring on exhaust valve surface

Figure 24 shows an enlarged figure of surface of the exhaust valve, and Figure 24-(a) shows a valve surface when it is operated with leaded gasoline, showing no change on the surface. (b) shows a valve surface after eight hours of operation with non-leaded gasoline and a cast iron seat, and some deposit of cast iron can be observed on the valve surface. This phenomenon is also demonstrated in the radioactivity measurements of the valve. It can be easily understood that the deposit causes a deterioration of airtightness, and it scrapes out the seat of the counterpart. (c) shows the comparison between the valve operated with non-leaded gasoline, and the condition of the valve after 18 hours passed after the operation is switched from non-leaded gasoline to leaded gasoline. It is seen from the figure that the projected part is gradually smashed down, and disappears. This phenomenon corresponds with the trends of initial wear rates shown in Figure 25.

The deposit is thus considered the main factor of initial wear. Figure 24-(d) shows the results on a valve seat made of stellite when it is operated with non-leaded gasoline. The characteristic point is that the surface of the exhaust valve is scraped out reversely thus showing no protrusion. From Figure 25, it is also found that the deposit disappears in 25 hours after the

Figure 23-(a) Effect of changes of engine operating condition on valve seat wear

Ph. 1 4000 r.p.m.
full load

Ph. 2 4000 r.p.m.
full load

Ph. 3 5000 r.p.m.
full load

Ph. 4 5000 r.p.m.
full load

Ph. 5 4000 r.p.m.
full load

Figure 23-(b) Effect of variation of engine operating condition upon the exhaust valve rolling

Figure 24-(a) A valve surface after operation with leaded gasoline.

Figure 24-(b) A valve surface after operation with non-leaded gasoline and cast iron seat

Figure 24-(c) Switched from non-leaded gasoline to leaded gasoline

Figure 24-(d) A valve surface after operation with non-leaded gasoline and stellite valve seat

Initial wear occurs at time of engine speed change from 2000 to 5000 rpm while employing leaded gasoline

Figure 25 Variation of initial wear after switched from non-leaded gasoline to leaded gasoline

switching has been made, and the initial wear become negligible, indicating that the initial wear is small under operation with leaded gasoline.

3-5 After switching from non-leaded gasoline to leaded gasoline

Figure 26 shows the trends of wear rate during 32 hours of operation; (a) shows the wear under steady operation, and the absolute values are found to be small. (b) shows the values in which the wear under fluctuated operation is incorporated into them, and they are found to be large. It is also found that both of the above will not reach the wear values inherent to leaded gasoline operation.

3-6 Indicator diagrams of non-leaded gasoline and leaded gasoline operations

Figure 27 shows the indicator diagrams of non-leaded gasoline and leaded gasoline operations. It has been confirmed from the above that the pressure fluctuation remains the same regardless of lead content in gasoline.

4. Conclusion

The mechanism of exhaust valve recession caused by non-leaded gasoline can be considered as follows.

The cast iron of valve seat material deposits on the surface of the exhaust valve which in turn scrapes off the valve seat of the counterpart due to the rotation or rolling motion of the valve. This phenomenon becomes especially intense immediately after the operating conditions are changed.

In relation to the above, the following characteristics were confirmed through experiments.

(1) About 80% of overall abraded powder of valve seat is included in the exhaust condensed water. R.I. method (radioisotope method) was thus employed, by utilizing the above point.

(2) Wear suddenly increases under high engine speed and high load.

(3) The rotation of valve is greatly affected by the engine speed, especially after the acceleration it makes a temporary increase. On the other hand, the effect of load is negligible.

(4) The rolling motion of valve stem also increases under high engine speed. It increases immediately after the engine speed or load is increased.

(5) These valve motions are closely related to wear.

(6) The effect of exhaust temperature is not significant.

(7) It takes about 25 hours for the deposit to disappear and the wear inherent to leaded gasoline operation to be restored, when gasoline is switched from leaded one to non-leaded one, then back to leaded one again. This has important significance in practical use.

(8) In case of stellite valve seat, the surface of the exhaust valve is scraped off and no deposit occurs.

Figure 26-(a) Reduction process during 32 hours. (steady wear)

Figure 26-(b) Total wear reducing process during 32 hours

Figure 27. Indicator diagrams

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References

1. D. Godfrey and R. I. Courtney., paper 710356, (1971)
2. William Giles., SAE Transactions, Vol. 80, (1971) P.1475, paper 710368.