Research Report

Oil Degradation in Second-Land Region of Gasoline Engine Pistons

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Abstract

The relationship between oil degradation and environmental conditions (temperature and gaseous components) was clarified by characterizing the oil and blow-by gas collected from the second land region of a piston by using a link mechanism during the actual operation of the engine. The oil extracted from the land region exhibited a lower total base number and higher total acid number than that in the crankcase. Also, more degradation products were found to form, and additive consumption was greater. This could be explained by combustion heat leading to higher temperatures in the land region than in the crankcase, and by the effect of the blow-by gases (hydrocarbons, NOx, and oxygen) which lead to oil degradation. The degree of oil degradation in the land region was found to be higher at lower rotational speeds combined with higher loads. NO_2 bubbling tests proved that the total base number of the oil falls as the its temperature and the NO_2 concentration increases. Reducing the amount of oil accelerated this tendency. Therefore, in addition to temperature and the blow-by gases, the amount of oil was also identified as being a major factor affecting the degradation of oil in the land region.

Keywords: Engine oil, Piston land, Link mechanism, Oil degradation, Temperature, Blow-by gas, Oil volume

1. Introduction

The operation of a gasoline engine causes its engine oil to degrade, which eventually reduces the oil's ability. Previous studies of oil degradation have generally examined the oil in the crankcase, with the oil-change interval being determined based on the properties of the oil in the crankcase. It is commonly thought, however, that the oil is subjected to different environmental conditions, such as temperature and gaseous components, in different parts of the engine. In particular, the oil around the piston lands is directly affected by combustion heat and blow-by gases. Therefore, the degree of oil degradation in these regions has always been assumed to be higher than in other regions.

To collect oil from the piston ring/cylinder bore region during the operation of an engine, a method using a link mechanism and holes in the piston land has been reported.[1-3] Previous studies of the characteristics of the oil in the piston ring/cylinder bore region have investigated the water content, the anion concentration,[2] the total base number, and the acidity of the condensed water[3] in the piston lands of a diesel engine. However, the relationship between the degeneration of additives, the characteristics of the oil, and the environmental conditions has not been clarified.

In the current work, we analyzed oil collected from the second land during the operation of a gasoline engine and were able to reveal a relationship between the oil characteristics and environmental conditions.

2. Experimental procedure

2. 1 Oil collection from piston second land

Oil from a piston's second land region was collected while the engine was operating. This was achieved by using a link mechanism attached to the piston, as shown in **Fig. 1**. Oil was collected from the thrust side and the anti-thrust side of the piston, through 1-mm holes in the collection sites. Suction was not used. The temperatures of the sampling tube positioned outside the engine and the oil collection vessel were maintained by a heater to prevent the condensation of gaseous components.

2. 2 Engine specifications and operating conditions

The specifications of the engine and the operating conditions are listed in **Table 1**. Oil was collected from the land region for five hours. After five hours, a sample of the oil in the crankcase was also collected for comparison with the oil from the land region. A commercial gasoline engine oil (10W-30, API grade: SG) was used. Prior to the start of each test, the oil in the engine was flushed and the oil filter was changed.

2. 3 Measuring the pressure at the second land

To clarify the influence of the drilled collecting holes on the land pressure, a pressure sensor was installed in the land, and the pressure measured both with and without the collecting holes. A silicon diffusion-type pressure sensor was used, as shown in **Fig. 2** and **Fig. 3**. The signal wire from the pressure sensor was led out of the engine through the link mechanism. The pressure inside the cylinder was measured by using a pressure gauge.

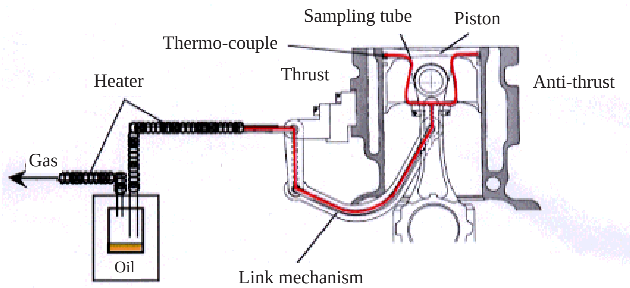

Fig. 1 Apparatus for collecting of piston second-land oil and blow-by gas.

Table 1 Engine specifications and operating conditions.

Engine type	4-Cylinder gasoline engine
Displacement	1600 cm^3
Engine speed	1000, 2000, 3000 rpm
Engine load	1/4, 2/4, 4/4
Oil temperature	90°C (Main gallery)
Water temperature	80 °C(Engine outlet)
Test duration	5 h

2. 4 Measurement of second land temperature

Oil degradation is greatly influenced by temperature. Therefore, the temperature in the second land region during the operation of the engine was measured at four points, adjacent to the oil collection holes (thrust side and anti-thrust side), and at the front and rear sides. The temperature was measured using K-type thermocouples. These thermocouples have strands that are 100 μm in diameter and contact points on the surface of the land region.

2. 5 Analysis of collected oil

Oil samples collected from the land region and the crankcase were analyzed by using infrared spectroscopy, and their neutralization number (total base number and total acid number) was measured. The neutralization number was measured as laid down in JIS K 2501. Given that only a small amount of oil could be collected from the land region, the minimum amount needed for measuring the neutralization number (the amount needed to change the concentration of a titration fluid) was determined.

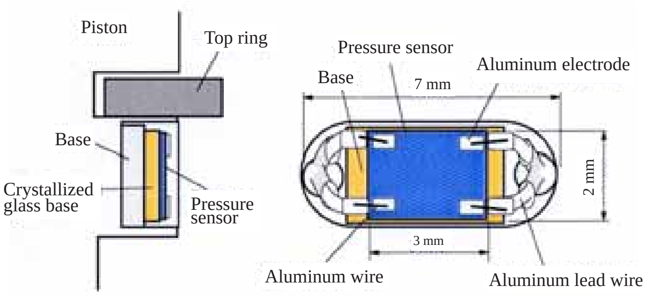

Fig. 2 Pressure sensor for pressure measurement at land region.

Fig. 3 State of attachment of pressure sensor to piston.

2. 6 Analysis of gaseous components

In addition to temperature, blow-by gases also have a degrading effect on oils.[4] Therefore, blow-by gas samples were collected from the land at the same time as the oil samples, and then analyzed to determine their hydrocarbon, NOx, and oxygen content. The hydrocarbon concentration was measured by introducing gas from the sampling tube directly into a gas chromatograph (GC). Because the flow rate of the gas in the sampling tube was so small, however, the NOx and oxygen concentrations were measured by first collecting the gas into a bag and then using an NOx meter and applying a GC technique.

2. 7 NO_2 bubbling test

An NO_2 bubbling test was performed to clarify the effects of temperature, NO_2 concentration and oil volume on the degradation of the oil. The test equipment consisted of a system for supplying NO_2 and air into the oil while stirring the sample. The test conditions are listed in **Table 2**.

3. Results and discussion

3. 1 Second land pressure

The pressure at the second land was found to increase at lower rotational speeds combined with higher loads. A maximum pressure of about 0.5 MPa was observed under 1000-rpm, 4/4 loading. This corresponds to 15 to 20 % of the maximum pressure inside the cylinder.

Figure 4 illustrates the pressure inside the cylinder and at the second land when the oil-sampling holes were both open and closed under the 1000-rpm, 4/4

Table 2 NO_2 bubbling test conditions.

Oil tempereture	90, 120, 150 °C
NO_2 concentration	0, 100, 500 ppm
Oil volume	5, 10, 20 ml
Test duration	2 h

loading. With the oil-sampling holes open, the pressure at the second land region was noted to be slightly lower than when the oil-sampling holes were closed, for a crank angle of 500 to 700° (that part of the stroke from expansion to exhaust), but no major change was observed. This result can be explained by the fact that the surface area of the oil sampling holes was very small in comparison to that of the second land region and the flow of the blow-by gases was resisted by the oil inside the sampling tube.

The above results indicate that the two 1-mm sampling holes on the thrust and anti-thrust sides of the second land had very little influence on the oil flow in the region. This indicates that the devised method of oil collection at the second land was satisfactory.

3. 2 Amount of oil collected from second land

Figure 5 shows the amount of oil collected from the second land during operation under different conditions for five hours. The amount of oil collected tends to fall at lower rotational speeds combined with higher loads. Under a given load, the amount of oil supplied to the bore per unit time falls with a reduction in the rotational speed. For a given rotational speed, however, the amount of the blow-by gases increases with the load, as does the pressure at the second land, as mentioned above. Therefore, an increase in the load is thought to reduce the flow of oil from the third land to the second land. The changes in the amount of oil collected from the second land will thus correlate with the oil flow to that land, depending on the operating conditions.

3. 3 Neutralization number of collected oil

The methods used to measure the neutralization number (total base number and total acid number) of oils are laid down in JIS K 2501. The total base number (TBN) and the total acid number (TAN) are determined by using 0.1N HCl and KOH titration fluids, respectively. The size of the oil sample needed to measure the TBN and TAN are 1 ± 0.1 g for 5 to 20 mgKOH/g and 5 ± 0.5 g for 1 to 5 mgKOH/g. The TBN and TAN of the fresh oil used in our experiments were 6.5 mgKOH/g and 1.6 mgKOH/g, respectively. Therefore, the measurements required 1 g and 5 g of sample oil, respectively. As shown in **Fig. 5**, however, the amount of oil collected from the land was less than that needed to measure the neutralization number, except under 2000-rpm, 1/4 loading and 3000-rpm, 1/4 loading.

Figure 6 shows the changes in the measured TBN

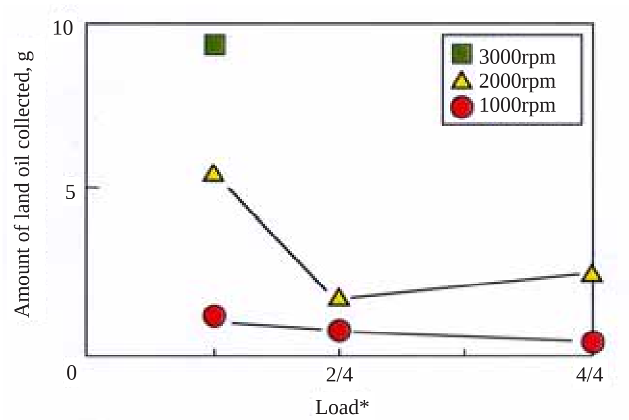

Fig. 5 Amount of oil collected from piston second-land.

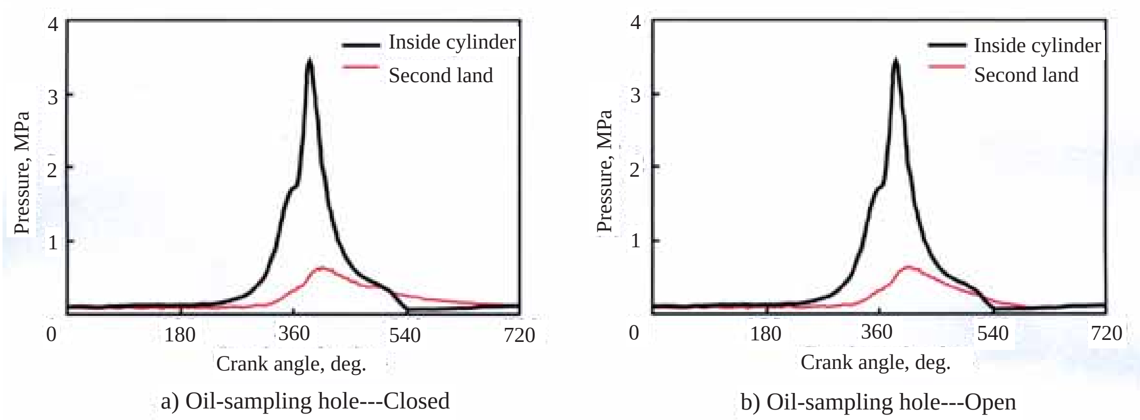

Fig. 4 Pressure at second land region and inside cylinder.

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and TAN values when the size of the oil sample was smaller than the required amount. The TBN and TAN values are higher than those measured with the normal amount of oil. According to the standard, the admissible repeated deviation should be 1 mgKOH/g at 5 to 20 mgKOH/g and 0.1 mgKOH/g at 1 to 5 mgKOH/g for the TBN, and the average value × 0.12 for the TAN. For the TBN, the results are within the admissible range even when the size of the oil sample is only 0.1 g. However, there is the possibility that the TBN would be less than 5 mgKOH/g due to the degradation of the oil after the engine test, in which case for amounts less than 0.5 g the admissible range of 0.1 mgKOH/g would be exceeded. The admissible repeated deviation for the TAN of the sample oil is almost 0.2 mgKOH/g, and this is exceeded with sample sizes of less than 3 g. As the change ratio for TBN and TAN for each drop of titration fluid increases with a decrease in the size of the oil sample, it is supposed that the measurement error would be larger. Therefore, 0.01N HCl and KOH with a concentration of 1/10 of the standard value were used as the titration fluids, and the neutralization number of the oil sample was measured in the same way.

The increase in the measured neutralization number is found to become less as the size of the oil sample decreases, as superimposed in Fig. 6. In this case, the use of an oil sample of at least 0.2 g for measuring both the TBN and the TAN enables measurement with the admissible repeated deviation. When the size of the oil sample is 0.2 g, it is possible to measure the neutralization number of the collected oil in most cases. Therefore, the neutralization number of the collected oil was measured using 0.01 N HCl and KOH as the titration fluids.

The measured TBN and the TAN of the oil collected from the land and the crankcase are shown in **Fig. 7**. For the oil taken from the crankcase, the TBN and TAN change very little after operation for five hours under different conditions. The oil collected from the land, however, exhibited a

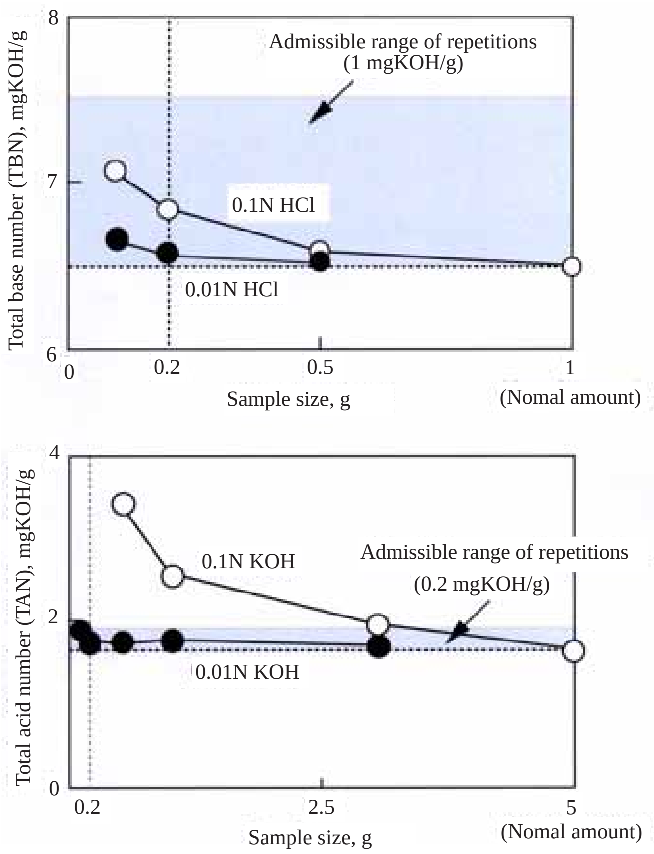


Fig. 6 Relationship between amount of sample oil and measured neutralization number values.

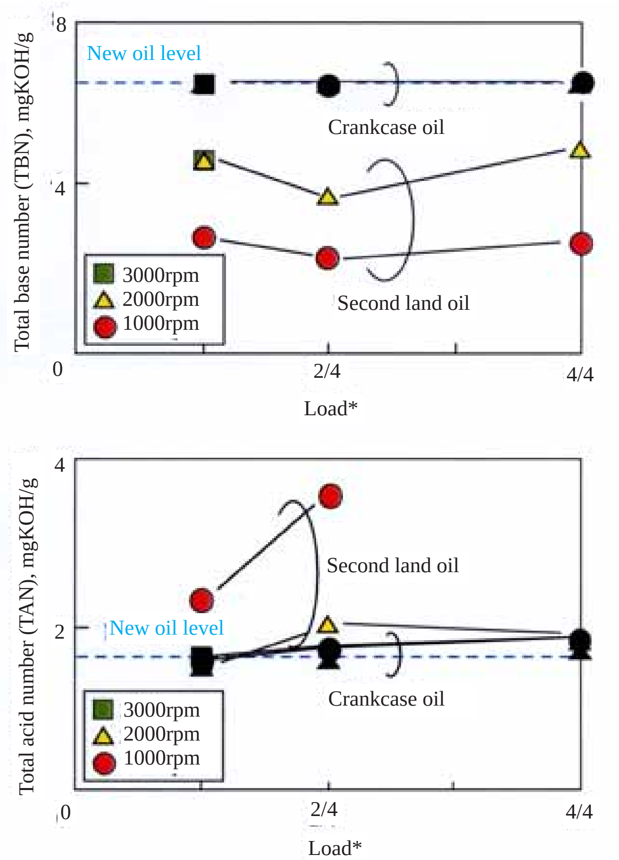


Fig. 7 Neutralization number of collected oils.

notable drop in the TBN value and an increase in the TAN value. The amount of these changes was found to be much greater when the engine was operating at lower rotational speeds combined with higher loads.

3. 4 Composition of collected oil

The difference spectra derived from the infrared (IR) spectra of the oil collected from the lands and the crankcase under 1000-rpm, 4/4 loading and that of the oil taken from the crankcase before testing, are shown in **Fig. 8**. In the figure, the areas above and below the dotted line indicate an increase in the amount of degradation products and a decrease in the amount of oil components (corresponding to additive consumption), respectively.

For the oil taken from the crankcase, no difference was observed in the compositions of the samples taken before and after the testing. The same results were obtained under different operating conditions. For the oil collected from the land, however, the formation of degradation products, such as carboxyl, nitrate and sulfate, was observed. Also, the amount of ZnDTP, an additive which aims to prevent wear and oxidation, and that of a metal-type detergent (carbonate), at around 1500 cm^{-1}, were found to have fallen. A reduction in the amount of viscosity index improver was also observed, at 1730 cm^{-1}. The formation of degradation products and the consumption of additives was more notable at lower rotational speeds combined with higher loads. This coincides with the results obtained by measuring the neutralization number.

These results indicate that the composition of the oil in the crankcase barely changes, but that of the oil collected from the land changes significantly. Consequently, it can be supposed that the environmental conditions experienced by the oil in the two locations differs considerably.

3. 5 Second land temperature

The degree by which the oil degrades in the land region was found to be greater than that of the oil in the crankcase region. One of the reasons for this is thought to be the influence of the heat of the combustion chamber. The mean temperature, as determined by taking measurements at four points, on the thrust and anti-thrust sides and at the front and rear of the second land, is shown in **Fig. 9**. At high rotational speeds combined with high loads, the temperature of the land rises to a high level. The temperature at the second land is 25 °C and 70 °C

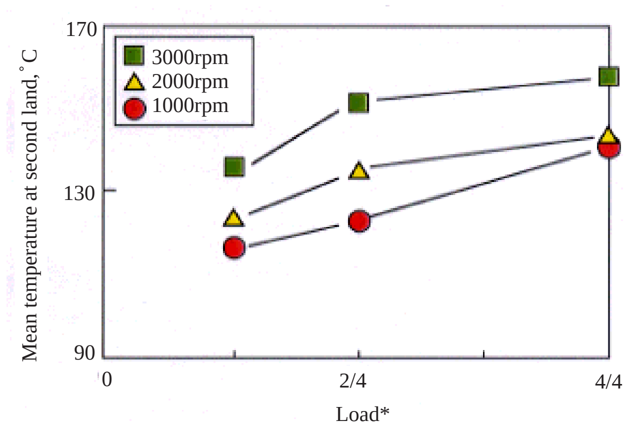
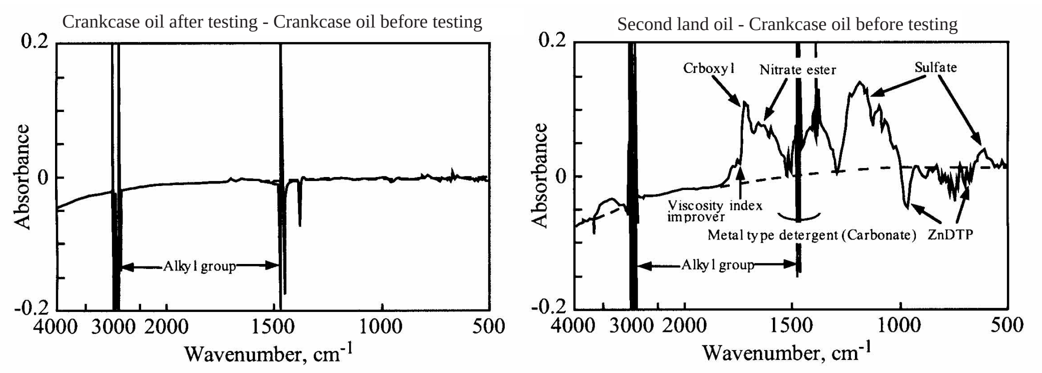


Fig. 9 Mean temperature at piston second-land region.



a) Crankcase oil

b) Second land oil

Operating condition: 1,000rpm-4/4 load

Fig. 8 Composition of collected oil (IR differential spectra).

higher than that in the crankcase under 1000-rpm, 1/4 loading and 3000-rpm, 4/4 loading, respectively. This result is thought to be caused mainly by the fact that the rotational speed is closely correlated to the number of combustion cycles (combustion heat) in unit time and the speed of sliding between the ring and the bore (friction heat), and the applied load is closely correlated with the amount of heat generated by combustion. Therefore, we can infer that one of the reasons for the higher degree of degradation of the oil at the land region is exposure to higher temperatures.

3. 6 Gaseous components

In addition to temperature, blow-by gases also influence the degradation of oil. Accordingly, the concentrations of hydrocarbons, NOx and oxygen in the blow-by gas collected from the land were measured. The hydrocarbon and NOx concentrations are shown in **Fig. 10**. The concentration of the hydrocarbons tends to increase at higher rotational speeds combined with higher loads, with this concentration being 15 to 55 times higher than that in the exhaust gas. The concentration of NOx, on the other hand, is higher under 2/4 loading than under 1/4 loading, and then falls under 4/4 loading. This phenomenon can be explained by the fact that the air-fuel ratio under 4/4 loading reaches the state of rich combustion. The concentration of oxygen under 3000-rpm, 1/4 loading is 18%, which is much higher than the 0.63 % measured in the exhaust gas.

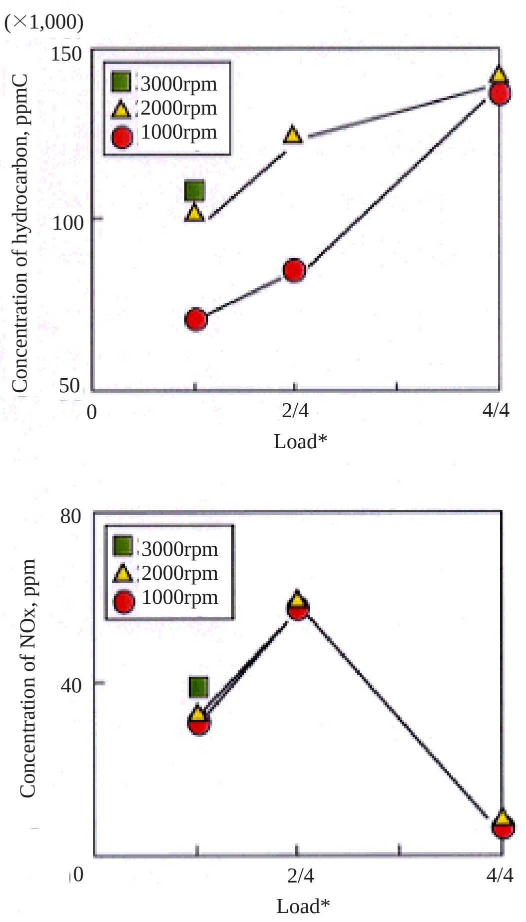


Fig. 10 Composition of blow-by gas.

As mentioned above, high concentrations of hydrocarbons, NOx and oxygen, all of which contribute to the degradation of oil, were detected in the blow-by gas collected from the land. This suggests that the degradation of oil in the land region is also influenced by the high temperatures and blow-by gases.

Given the results obtained for the temperature and gaseous components, the degree of degradation at the land region has been believed to be higher at higher rotational speeds. But, in fact, the degree of degradation was found to be higher at lower rotational speeds. This is thought to be caused by the difference in the amount of oil in the land region. That is, because the amount of oil collected from the land region decreases at lower rotational speeds, the amount of oil actually lubricating the land is also small, as shown in Fig. 5. Therefore, the degradation is much greater at lower rotational speeds.

3. 7 Influence of NO_2, temperature and amount of oil on oil degradation

The influence of the oil temperature, NO_2 concentration, and amount of the oil on oil degradation was investigated by an NO_2 bubbling test. For NO_2 concentrations of 0 ppm and 100 ppm, the TBN barely changed, even though the oil temperature was increased to 150 °C, as shown in **Fig. 11**. When the NO_2 concentration was increased to 500 ppm, however, the TBN was found to decrease with increased oil temperature. As the amount of oil decreases, the influence of the oil temperature on the oil degradation becomes clear. These results show that the degradation of the oil is accelerated by increases in the NO_2 concentration and temperature and a reduction in the amount of oil.

The reduction in the amount of oil causes an increase in the ratio of the area in contact with the gaseous components. Besides, the oil flow around the land is thought to infer how long the oil will stay around the land. Given these factors, the amount of oil in the land region is thought affect the degree of oil degradation.

4. Conclusions

Oil samples collected from the second land of an engine's piston during operation of the engine were characterized, and the relationship between the oil degradation and environmental conditions was clarified. The following conclusions can be drawn from the results of this study.

(1) In this study, the characteristics of the oil in the crankcase barely changed, while the following changes were observed in the samples collected from the land:

・Reduction in the total base number and an increase in the total acid number

・Formation of degradation products and the consumption of additives

(2) The temperature at the land was 25 to 70 °C higher than that in the crankcase, and the concentrations of hydrocarbons and oxygen at the land were high. These factors are assumed to accelerate the degradation of the oil around the land.

(3) The degree of degradation of the oil around the land was closely related to the amount of oil in the land region.

From the above results, we can see that the oil used for lubrication between the piston rings and the cylinder bores is subjected to extremely severe conditions and degrades more quickly than that in the crankcase. Consequently, it is necessary for the industry to consider the oil characteristics and environmental conditions in the sliding zone when developing materials and surface treatments used for piston rings and cylinder bores.

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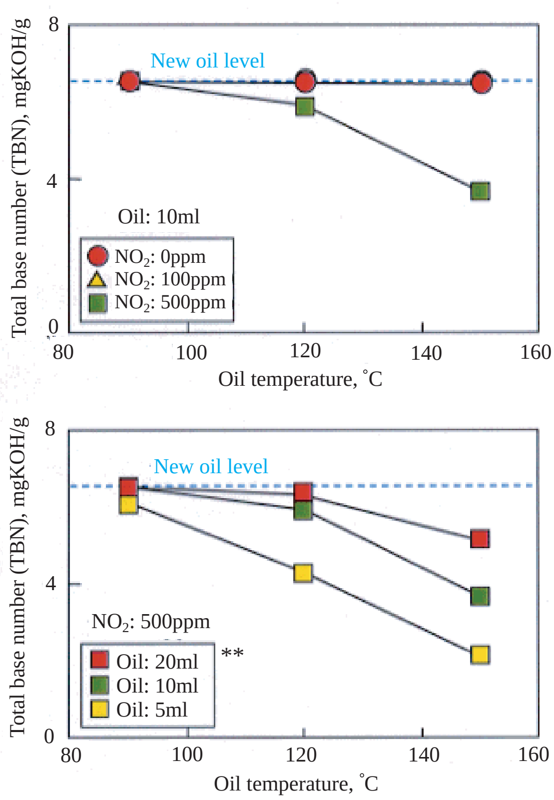

Fig. 11 Influence of NO_2, temperature and amount of oil on TBN.

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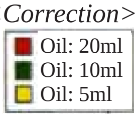

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