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Study on Wear Mechanism by Soot Contaminated in Engine Oil (First Report: Relation Between Characteristics of Used Oil and Wear)

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ABSTRACT

Increase of soot contaminated in engine oil caused by EGR system accelerates the diesel engine wear, especially in the valve train. Wear of metal is affected by many factors such as concentration and diameter of soot, oil film thickness, oil characteristics, etc. Effects of soot on metal wear were discussed from the point of view of soot concentration, and soot diameter and oil film thickness. Wear test was carried out by using four-ball wear tester. Consequently, it was made clear that wear increases proportionally to soot concentration, and relation between oil film thickness and soot diameter plays very important role in wear mechanism. Further, the surface of wear scar was observed by SEM to discuss effect of soot diameter on wear and existence of abrasive wear by soot and its occurrence conditions were suggested.

INTRODUCTION

Diesel engine has increased due to their fuel efficiency and lower running cost compared with gasoline engine, meanwhile, an environmental problem in the earth scale attract attention. Therefore, the regulation of exhaust gas emission for diesel passenger cars is becoming more severe in Japan day by day. The EGR system is believed to be the most effective and the simplest way to reduce NOx. However, adoption of EGR system for diesel engine is generally considered to cause some adverse effects such as increase of engine wear, especially valve train wear (1), because diesel soot intermixing into oil will increase and affect the lubricating system (2). It is expected to make clear the effects of wear by soot in engine oil, and to investigate the countermeasures.

Many researchers have suggested the relationship between soot and wear. Narita *et al.* (3) pointed out that there would be some correlation between wear mechanism of valve train and not only soot concentration but also oil film thickness or soot particle size, and soot existed in oil film of contact point wore metal direct. Also, Yosida *et al.* (4) pointed out the wear by the oil starvation, that soot makes a barrier to restrict oil supply into the contacts, as a result metal itself contacts and increase wear. Meanwhile, Cheng C. Kuo *et al.* (5) showed the groove on the M-11 crosshead which has groove widths close to the primary soot particle sizes and reported the relationship these width and primary soot particle size. Kagaya *et al.* (6) proposes crrosive wear mechanism which is caused by sulfuric acid attached to soot. In this way, it was researched that soot promotes the wear directly or indirectly.

It is thought that the abrasive wear is one of factors though the amount of wear by metal contact is large. From this point of view, it was tried to make clear the mechanism of an abrasive in this paper. Firstly, primary soot particle size was measured from photographs of soot. Secondly, The soot concentration of the used oil was made to change, and relationship between soot concentration and the wear scar diameter were examined. Thirdly, the relationship between primary soot particle size and oil film thickness was discussed, because oil film thickness at valve train is equivalent to it. Further, surface of the wear scar was observed in high magnification, and the mechanism of wear was suggested from the surface form. Also, primary soot particle diameter after the wear test of long duration was observed for investigating the effect of abrasive wear.

EXPERIMENTAL METHOD

MEASUREMENT OF SOOT PARTICLE DIAMETER – Soot in engine oil was observed by using transmission electron microscope (TEM). Observed sample was made in the following method. Small quantity of test oil was adhered to mesh, and only oil was completely removed by Hexane. Soot adhered on the surface of this mesh was observed with TEM. Magnification was at 50000 times so that the primary soot particle form could be observed. The distribution of primary soot particle diameters was obtained by photograph of 1000 primary soot particles by precise ruler, distinguished primary soot particle from aggregated it. As for the distribution of secondary soot particle, the particle that floated in Toluene was measured by laser Doppler particle analyzer.

OBSERVATION OF MEASUREMENT OF WEAR SCAR DIAMETER AND ITS SURFACE – The wear test was repeated three times for each condition and wear scar diameter was calculated from scars of 9 balls in due consideration of repeatability. Each scar was measured one direction and another direction right to first one. Therefore, the wear scar diameter is the mean value of 18 diameters. The deviation of mean diameter of each ball was less then 3%. Surface analysis of wear scar was carried out by hige-resolution scanning electron microscope (SEM). Magnification was at 50000 or 10000 times.

OIL FILM THICKNESS – It is necessary to consider oil film thickness in metal contact to clarify the wearing mechanism such as valve train which oil film is very thin. But it is very difficult to measure the oil film thickness of used oil containing soot experimentally, because huge amount of soot in engine oil prevents the light transmitting. Therefore, we calculated oil film thickness for the criterion from the equations shown in EHL (Elasto-hydorodynamic lubrication) obtained by Hamrock and Dowson (7), which is generally used. It is known that a film thickness of used oil does not follow this equation, but we assumed that the tendency would follow it. The equations are as followings;

$$\frac{h_{mean}}{R} = 2.69\left(\frac{U\eta_0}{ER}\right)^{0.67}(\alpha E)^{0.53}\left(\frac{W}{ER^2}\right)^{-0.067}\left(1-0.61e^{-0.73k}\right)$$

$$\frac{h_{min}}{R} = 3.63\left(\frac{U\eta_0}{ER}\right)^{0.68}(\alpha E)^{0.49}\left(\frac{W}{ER^2}\right)^{-0.073}\left(1-e^{-0.68k}\right)$$

$$\eta_0 = \nu\rho$$

h_{mean}	Mean oil film thickness	[m]
h_{min}	Minimum oil film thickness	[m]
η_0	Viscosity of the lubricant at atmospheric pressure	[Pa·s]
ν	Kinetic viscosity	[m^2/s]
ρ	Density	[kg/m^3]
R	Radius of curvature	[m]
U	Entraining surface velocity	[m/s]
E	Young's modulus	[Pa]
α	Pressure-viscosity coefficient	[Pa^{-1}]
W	Contact load	[N]
κ	Ellipticity parameter	[-]

It is understood from the equation that the lubricating oil film thickness is affected larger by the relative speed at contacting part and the viscosity, but smaller by load. Oil film thickness becomes thicker as the speed and the viscosity increases.

TEST CONDITION AND OBSERVATION OF SOOT

WEAR TEST CONDITION – Wear test was carried out by using Shell-Four-ball wear tester. This method is generally used for evaluation of wear. Further, according to the pre-examination, the results of Shell-Four-ball wear tester and of actual engine were agreed. Figure 1 illustrates it. It consists of fixed three balls in oil and rotated a ball. The test conditions are shown in Table 1 to reproduce the lubrication condition of valve train in diesel engine. The test ball for the examination used a steel ball.

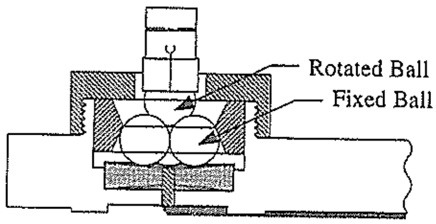


Figure 1. Shell-Four-ball wear tester

Table 1. Wear test conditions

Speed [rpm]	1500
Load [N]	294
Oil temp. [K]	363
Test duration [min]	15-120

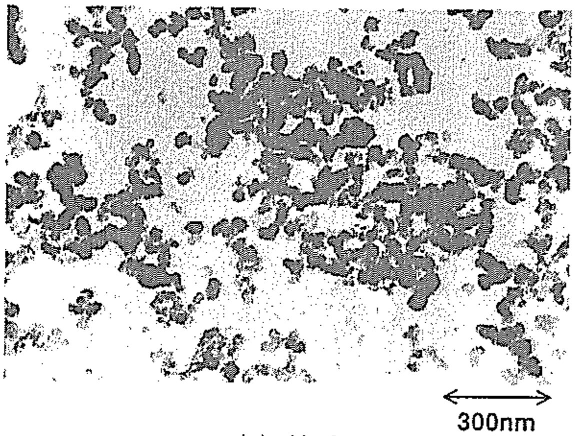
PROPERTIES OF TEST OILS – Operation conditions of engine and properties of test oils are shown in Table 2. Oils No.1-8 were prepared for discussing the effect of soot concentration on the wear, oils No.9 and 10 for investigating the relationship among the wear, primary soot particle size and oil film thickness. It is clear from Table 2 that viscosity increases with soot concentration under same engine oil. Oils No.1-5, 8, 9 and 10 were collected from the oil pan after various permanent engine tests. And Oils No.6 and 7 were prepared from Oil No.8.

RESULTS AND DISCUSSIONS

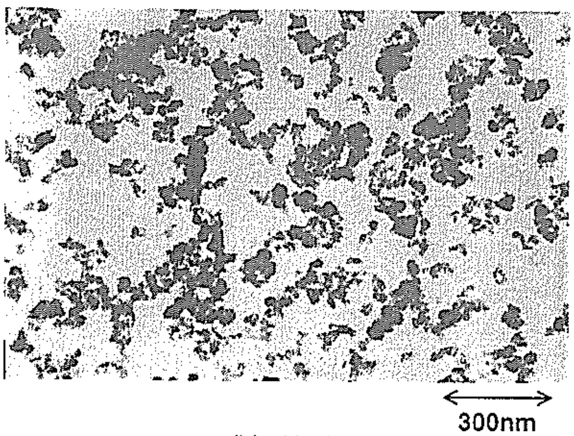
PHOTOGRAPH OF SOOT PARTICLES – Soot in 10 kinds of oil was observed by TEM, photographs of soot in No.9 and 10 are shown in Figure 2. It is clear from Figure 2 that primary soot particles are considerably in the diameter range of 20 to 40nm, and many particles aggregate and form secondary soot particles. Mean diameters of primary and secondary soot particles of No.1-5 are shown in Table 3.

Table 2. Properties of test oils

No.	1	2	3	4	5	6	7	8	9	10
Engine oil	10W-30 CD					10W Low dispersency			10W-30 CD	
Engine	4.9 *l*, DI, TC		5.2 *l*, DI, NA	21.2 *l*, DI, NA	19 *l*, DI, TC	3.3 *l*, IDI, NA			12 *l*, DI, TC	2.8 *l*, IDI, TC
Test cond.	EGR2B	Heavy duty				Full load / Full speed				
Test duration [h]	225	150	100	200	1012cycle	50			250	50
Kinetic viscosity 100°C [mm²/s]	12.6	13.1	29.5	27.2	11.8	5.04	13.0	43.5	16.7	71.4
Kinetic viscosity 40°C [mm²/s]	83.2	86.3	123.2	205.4	85.2	–	–	–	127	405
Soot concentration [wt%]	3.9	3.9	6.3	9.8	4.0	0.1	4.0	7.4	7.7	11.3



(a) No.9



(b) No.10

Figure 2. TEM photographs of soot particle

Table 3. Mean diameter of primary and secondary soot particle

	No.1	No.2	No.3	No.4	No.5
Primary soot [nm]	30.9	28.9	29.9	31.3	33.1
Secondary soot [nm]	140	160	150	160	150

As a result, the clear difference of each diameter and distribution of soot particle by the properties in test engines such as burning method wasn't observed.

CHANGE OF WEAR SCAR DIAMETER DUE TO TEST DURATION – The wear test under different duration were carried out to investigate the effect of test duration. Test oils were a new oil 10W-30 and used oils No.1-5 of which soot concentration were different. The test conditions were shown in the Table 2. Test duration was set up from 15 to 150 minutes. Relationship between the test duration and the wear scar diameter is shown in Figure 3.

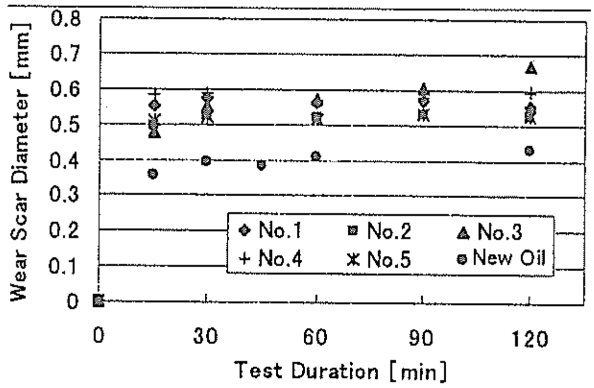


Figure 3. Test duration and Wear scar diameter

The wear scar diameters suddenly increased within 15 minutes after test started in all cases, and the increase rate of wear shows low and it was different in each oil. The wear mechanism can be classified into two stages from the appearance of its change. First stage appears until 15 minutes after test start, and it is caused by the metal contact because of a point contact and high contact pressure. It can be considered that this period is under the mixed lubrication condition. After it, the second stage appears. In this stage, the increase rate of wear scar diameter shows lower because a contact area becomes wider and contact pressure decreased as the result of the progress of wear. It can be considered that the oil film thickness increases direct or indirect wear by soot happens in this territory. Consequently, the amount of wear decreases in this period.

THE EFFECT OF SOOT CONCENTRATION ON WEAR – For examining the effect of soot concentration on wear, five kinds of oil with different soot concentration were prepared. Soot concentrations are shown in Table 2. The base oil of those oils were same. Oil No.8 was used oil after 50-hour engine test. No.6 was a used oil without soot which was obtained by removing soot as much as possible from oil No.8 with ultra high speed centrifugal separator. No.7 contained approx.50% soot of one of oil No.8. In addition, two oils of which soot concentration being medium of No.8 and No.7, and of No.7 and No.6 were prepared. The result is shown in Figure 4.

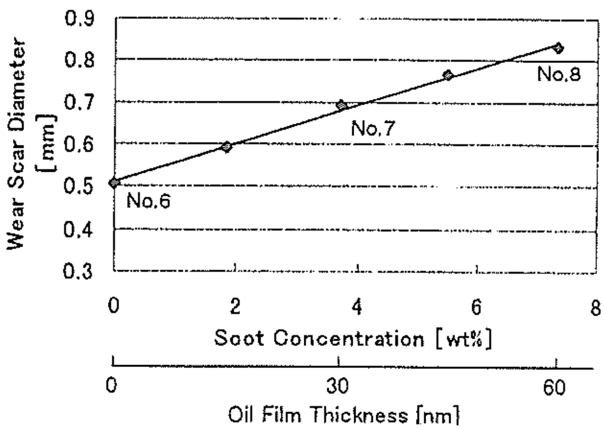


Figure 4. Relation between soot concentration / oil film thickness and wear scar diameter

Figure 4 shows that wear scar diameter increases proportionally with soot concentration. It is known that wear decreases with increase of oil film thickness. However, this result shows that wear increases with soot concentration though the oil film thickness increases which is the result of increase of viscosity. This result suggests that soot plays an important role in the wear. Figure 5 also shows the relationship between soot concentration and the wear scar diameter by used oils No.1-5 and fresh one 10W-30. As shown in Table 3, the mean diameters of primary and secondary soot particles were almost same. This result also indicates that wear increases proportionally to the soot concentration when new oil and soot particle diameter was same.

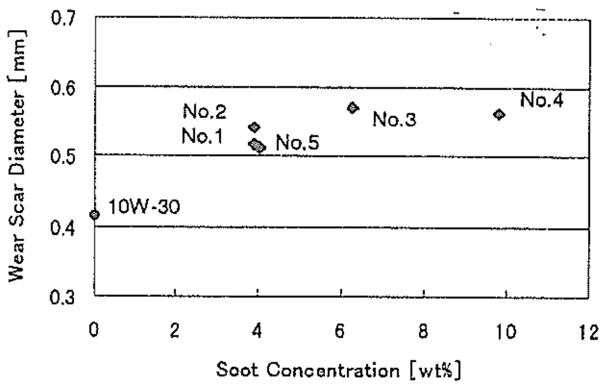


Figure 5. Soot concentration and Wear scar diameter

EFFECT OF PRIMARY SOOT DIAMETER AND OIL FILM THICKNESS ON WEAR – The wear test by oils No.9 and 10 were carried out on the condition shown in Table 1. Test duration was 60 minutes. The wear test result is shown in Figure 6. The wear scar diameter by No.9 becomes larger than one by No.10 though the soot concentration of No.9 is less than No.10 as shown in Table 2. This result suggests that the wear is affected not only soot concentration but some relation between primary soot diameter and oil film thickness. Figure 7 shows the particle size distributions of primary soot. The mean diameter and mean oil film thickness are shown in Table 4.

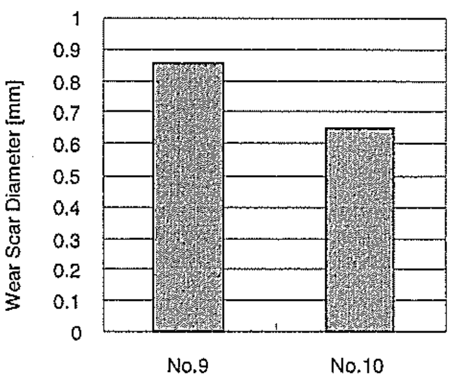


Figure 6. Wear Scar Diameter

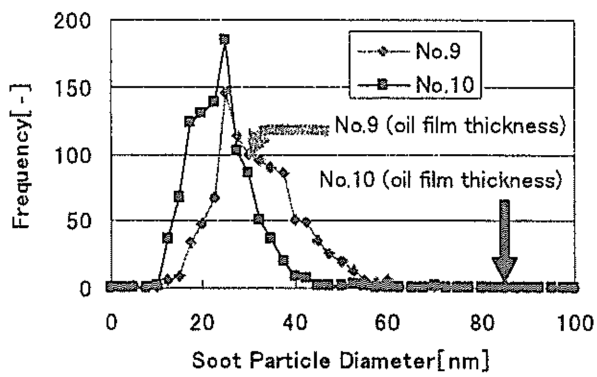


Figure 7. Particle diameter distribution of primary soot

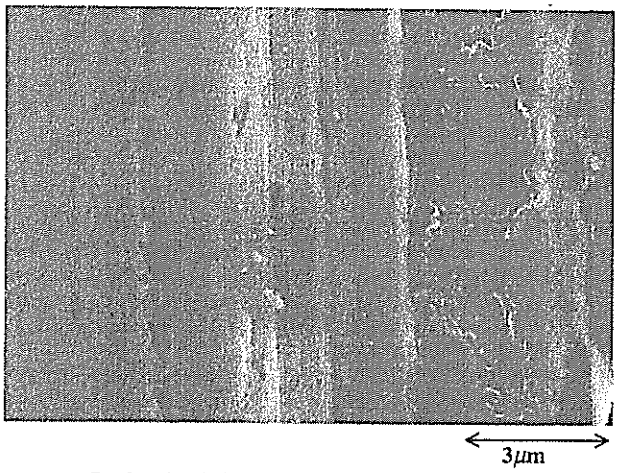
Table 4. Mean diameter of primary soot particle and mean oil film Thickness

	No.9	No.10
Mean diameter of primary Soot [nm]	33.1	24.2
Mean oil film thickness [nm]	30	84

In case of No.9, primary soot particle diameter is very close to oil film thickness. The other hand, one of No.10 is much smaller than oil film thickness. It is easily thinkable that there are many particles equivalent to oil film thickness or larger particles in No.9 compared with No.10. It is suggested that the existence of soot particles of which diameter is equivalent to oil film thickness, contributes the acceleration of wear, and not only the concentration of soot but the relation between primary soot diameter and oil film thickness are very important to discuss the wear by soot.

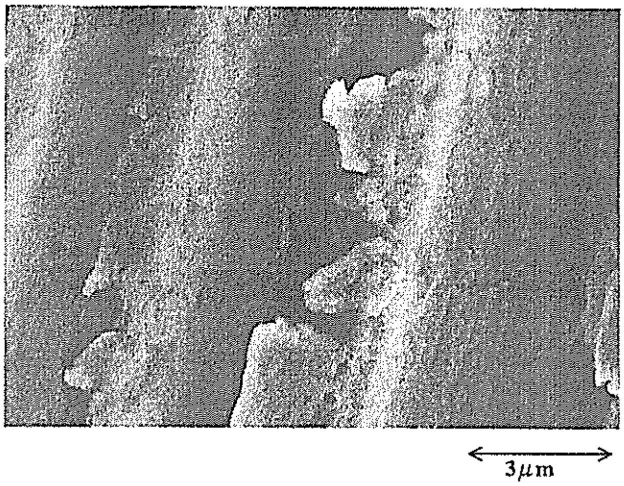
OBSERVATION OF THE WEAR SCAR – The wear scar by fresh oil (10w-30 CD) is shown in Figure 8, oils No.9 is in Figure 9 and oil No.10 is in Figure 10 with various test durations. In case of fresh oil Figure 8, the rough grooves scooped by metal contact are observed. On the other hand, when the soot particles are contained like Figure 9 and Figure 10, many smoother grooves are formed. Furthermore, the fine streaks of which width are equivalent to soot particle diameter, are observed on the wear scar in 60 minutes by oil No.9 Figure 9 (b), but not by oil No.10 Figure 10 (a). This result means that the narrow and fine streaks are formed in case that the particle diameter of primary soot is relativity larger than the oil film thickness, It can be assumed that these fine streaks were scraped directly by primary soot particles and suggests the existence of the abrasive wear which the primary soot particles scrape the metal directly. And it also suggests that the abrasive wear is one of main factors on wear under that condition.

The rough groove that may be formed by metal contact is observed on the wear scar by oil No.9 in 15 minutes Figure 9 (a). But after 60 minutes Figure 9 (b), the rough groove disappears and the fine streak of which width is equivalent to soot particle diameter is found. Furthermore, as test duration progressed Figure 9 (c), it was confirmed that the fine streaks became deeper and clearer. It shows that metal contact is dominant at the beginning of test. It is thought that the abrasive wear occurs in this period but the metal contact deletes grooves by the abrasive. In case by oil No.10, the abrasive wear which wasn't observed in 60 minutes Figure 10 (a) was observed partly in 120 minutes Figure 10 (b). Subsequently, the abrasive wear increases and dominates with test time. The abrasive wear was observed in all cases at the second stage regardless of the soot concentration.

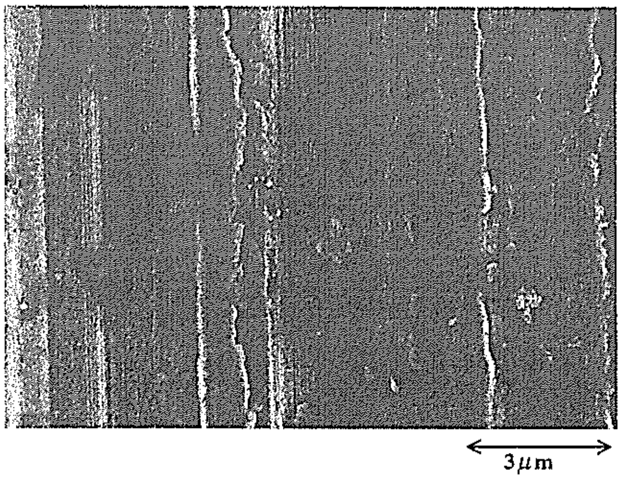


By fresh oil (10W-30 CD) (60 minutes)

Figure 8. SEM photographs of wear scar

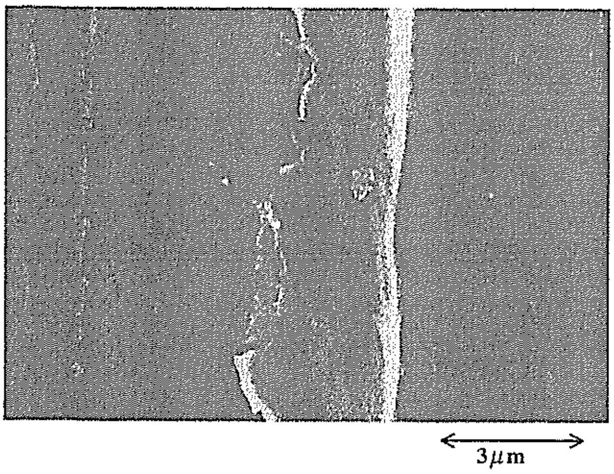


(a) By used oil No.10 (60 minutes)

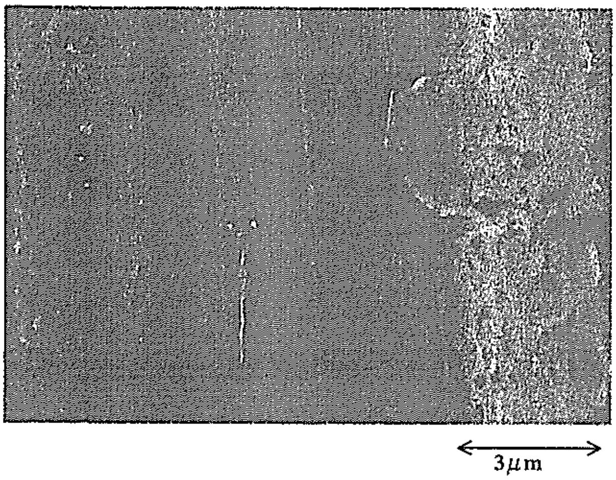


(b) By used oil No.10 (120 minutes)

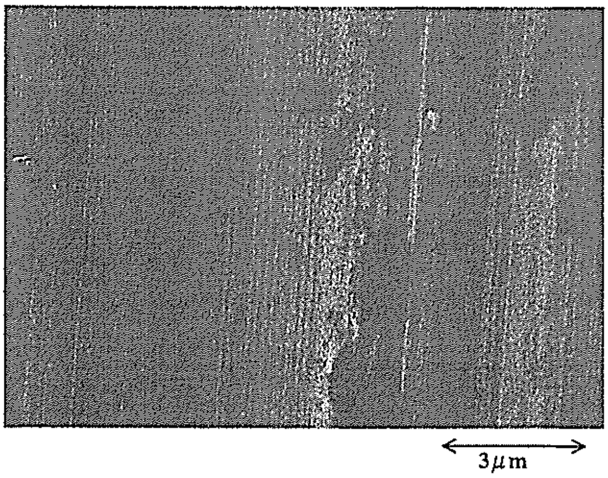
Figure 10. SEM photographs of wear scar



(a) By used oil No.9 (15 minutes)



(b) By used oil No.9 (60 minutes)



(c) By used oil No.9 (120 minutes)

Figure 9. SEM photographs of wear scar

THE CHANGE OF PRIMARY SOOT DIAMETER BY WEAR TEST – It can be considered that the shape and diameter of primary soot particles changes when they behave as abrasive media. Therefore, the wear test for 10 hours was carried out by oil No.9 which formed fine streaks on wear scar and particle diameter of primary soot before and after the test was measured. Figure 9 shows the particle diameter distributions of primary soot before and after 10-hour test. However, the mean diameters and distributions scarcely changed. It suggests that the primary soot particle is hard and scrapes the metal surface directly.

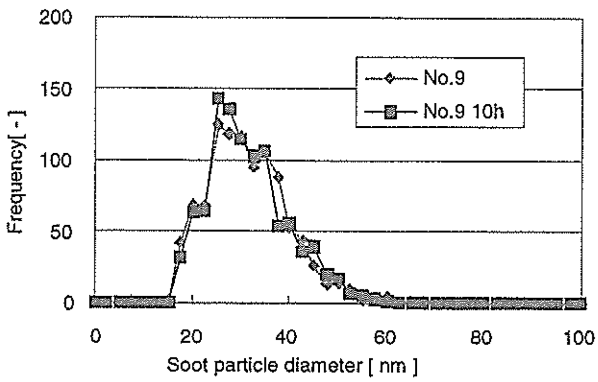


Figure 10. Distributions of Soot particle diameter before and after 10 hour test

CONCLUSION

Soot particle in the engine oil was observed by TEM, and the wear scar by SEM. It is found that particle diameter of primary soot is about 30nm, but these diameter wasn't very changed by the influence of burning method. Wear increases proportionally to the soot concentration when the characters of soot and fresh oil are same. Wear rate is rather small when oil film thickness is larger than particle diameter of primary soot, and accelerated when soot particle diameter is equivalent to oil film thickness. In the latter case, the fine streaks are formed in the wear scar. It can be considered that those fine streaks are scraped by primary soot particles directly, and the abrasive wear is one of main factors on wear. We compared the wear scar diameter by new oil and used oil without soot for investigating the influence of degradation of oil except soot. Therefore, the wear scar by used oil without soot grew a very little lager then by new oil. It is suggest that the effect of the deterioration of oil on the corrosive wear is little.

It is well known that the diameter of aggregated soot is also other main factor on wear which causes the oil starvation. However, in this paper, it is paid attention to the effect of only the primary soot diameter and oil film thickness on wear, though we believe that the aggregated soot give some influences on wear. Further, it is difficult to assume the oil film thickness of non-Newtonian fluid like oil contaminated soot, also the film thickness of used oil under the condition of very high shear and pressure like the valve train is difficult from one calculated by measured viscosity as Newtonian fluid. We trying to measure oil film thickness of used oil experimentally and viscosity in the actual lubrication. Those will be reported the following papers.

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