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Effects of the Melting Processes, the Microstructures and so forth on the Behaviors of Sliding Wear in Several Carbon Steels*

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The purpose of this study is as follows: two groups of carbon steels were studied on effects of the melting processes, the metallographic structures, the seasons of summer and winter in Japan and the annealing in vacuum on the behavior of sliding wear at ambient temperature to 600°C, at which the oxidation tendencies of steels were taken into consideration. One group had been produced in air by a high frequency furnace, and the other had been remelted in a high frequency vacuum furnace after the production in air.

The relations between the results of wear test and the oxidation tendencies that were measured from increases in weight of the specimens heated at 700°C for 1 hour to oxidation were studied in the first place. Then, the effects of both seasons of summer and winter and the annealing in vacuum before the wear test on the behavior of sliding wear were studied at ambient temperature.

The results showed that the macroscopic oxidation tendency and the microscopic one must be considered in the study of the sliding wear, when the oxidation tendency obtained by heating at 700°C for 1 hour is called the macroscopic one and the oxidation tendencies of the broken surface at the welding contact points on the sliding area is called the microscopic one.

1. Introduction

In this report the following effects on the behaviors of sliding wear in carbon steels including mild steels were studied at ambient and high temperatures considering "oxidation tendencies of steels": the effects of production processes of steels, their microstructures, the annealing of the fixed specimens in vacuum before the wear test, and the seasons of summer and winter in Japan.

The author had indicated in the discussion⁽¹⁾ of the last report⁽²⁾ that the increases in weight of steels due to the oxidation — that are called macroscopic oxidation tendencies of steels — are comparatively more uniform for the carbon steels that had been produced from same materials and processes in author's Institute than other carbon steels on the market.

Therefore the carbon steels used in this report were produced with the same process as that in the other report⁽³⁾, but in two atmospheres, namely in vacuum and air. The first group of carbon steels is called a V-series and they were remelted in vacuum after the production in air and the second called a K-series were produced in air.

These two series were studied under the same experimental conditions on the behaviors of sliding wear without lubricants at ambient temperature to 600°C.

At the same time the author had found that there was a scattering of hardnesses on the surface of the fixed specimen of the low carbon steel⁽¹⁾ and the cause for it was the stressed layer due to surface grinding. Therefore in this report all fixed specimens were annealed at 650°C for 1 hour in vacuum before the wear test to eliminate the effect of the stressed layer on the behavior of sliding wear.

Moreover it was found that the behaviors of sliding wear in winter differ from those in summer in Japan, when the results of wear test with the specimens annealed in vacuum in this report were compared with the results for the specimens without the annealing that are described in the discussion⁽¹⁾ of the last report. Then the cause of this difference will be discussed considering the effect of the annealing in vacuum before the wear test on the behavior of sliding wear.

2. Experimental procedure

2.1 Experimental instrumentation

The wear tests are carried out with Dr. Ōkoshi's Rapid Wear Testing Machine⁽⁴⁾, in which

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a plane fixed specimen and a circular rotating specimen can be combined for testing under various experimental conditions at ambient temperature. In this study the heating equipment that consisted of a transformer and an autotransformer was attached to perform the wear test at high temperatures. Figure 1 shows those Rapid Wear Testing Machine and heating equipment that are already prepared for the sliding wear test at high temperatures.

Figure 2 shows schematically the wear testing method at high temperatures. The fixed specimen had a part of 6 mm in width, 3 mm in thickness and about 45 mm in length that will be heated. This specimen had been ground by machining and annealed in vacuum at 650°C for 1 hour after the grinding. The rotating specimen had a circular plate of 3 mm in thickness and about 30 mm in diameter and its cylindrical surface could be used to rub against the fixed specimen with the loads of P_0 .

In the beginning of the wear test the rotating

specimen is installed to the rotating shaft and its cylindrical surface is ground with a grinding stone attached to the wear testing machine to remove the eccentric rotation. The fixed specimen is installed rightly, so that this specimen can adjoin the rotating without a gap. Then the fixed specimen is connected to the heating equipment and heated to the test temperature with large currents and low voltages, by which both specimens are separated with a little gap. When the temperature rises to the test temperature, both specimens are contacted. At this time the test temperature drops a little, then the knob of the autotransformer is turned until the temperature reaches the test temperature again and after that the fixed specimen is kept at this temperature for about 30 seconds. Now the wear test starts with a switching on of the motor of the wear testing machine.

2.2 Experimental material

Every carbon steel that was used in this report as the fixed specimen had been produced by a high frequency melting furnace of 50 kg in capacity

Fig. 1 Wear testing machine (left) and the heating equipment (right)

Fig. 2 Schematic illustration of the wear testing method and the dimensions of the specimens

Table 1 Composition of the raw materials for the production of various carbon steels

Mark	Composition of raw materials kg					Chemical composition of each raw material without electrolytic iron
	Carbon steel with 0.10%C for machine construction	Electrolytic iron	Pig iron with high purity	Ferromanganese with low carbon content	Ferrosilicon	
K1	—	49.60	0.40	0.126	0.014	Carbon steel with 0.10%C; 0.10%C, 0.21%Si, 0.41%Mn, 0.011%P, 0.029%S.
K2	49.60	—	0.40	—	—	
K3	46.55	—	3.45	—	0.028	
K4	43.83	—	6.17	—	0.036	Pig iron: 3.41%C, 0.004%Si, 0.054%Mn, 0.008%P, 0.010%S, 0.01%Cu.
K5	40.80	—	9.20	—	0.056	
V1	49.90	—	0.10	0.085	0.007	Ferromanganese: 76.8%Mn, 0.96%C, 1.2%Si, 0.19%P, 0.01%S.
V2	47.40	—	2.60	0.100	0.020	
V3	44.00	—	6.00	0.114	0.022	Ferrosilicon: 76.41%Si, 0.09%C, 0.029%P, 0.003%S.
V4	41.00	—	9.00	0.130	0.030	
V5	38.20	—	11.80	0.140	0.040	The steels in V series were produced first in air with these compositions.

or a high frequency vacuum melting furnace of 100 kg in capacity in author's Institute. The ratios of the raw materials to make all carbon steels are shown in Table 1. The carbon steels of V-series in Table 2 were produced with remelting in vacuum after they had been firstly produced in air according to the ratio of combination in Table 1. They were remelted in a vacuum of 10^{-3} mmHg and then poured in to the ingot case in 10^{-4} mmHg. Those ingots were hot rolled to a bar of 20 mm in diameter and next to a plate of 5 mm in thickness.

The under section of Table 2 shows the chemical compositions of the steels of V-series that were made with above mentioned processes. The above section of Table 2 shows the chemical compositions of K-series, which were made in air with the ratio of combination in Table 1 aiming at nearly the same carbon contents as that of V-series respectively. The carbon contents of V1 was very low, so that only K1 was made from the electrolytic iron instead of the low carbon steel SIOC as the raw material. Each ingot of K-series was hot worked in the same way as one of V-series.

Every steel in V- and K-series after the hot working was heat-treated according to Table 2 and machined to the fixed specimens. The metallographic structures of all steels were studied and they showed the standard structure for carbon steels, consisting of ferrite only or ferrite and pearlite corresponding to their carbon contents in Table 2.

The rotating specimen was made of the same material as one in the last report⁽²⁾, namely the carbon steel with 0.64%C on the market. It was

Table 3 Conditions of wear test

Section	Experimental condition
Wear testing machine	Dr. Okoshi's Rapid Wear Testing Machine
Load and sliding distance	$P_0=2.1$ kg and $l_0=66.6$ m
Atmosphere and so on	In air and dry wear
Temperature of the fixed specimen	Ambient temperature, 200°C, 400°C and 600°C
Sliding speed for the wear test at ambient temperature	About 0.05, 0.1 to 1.1 (every about 0.1), 2, 3, and 3.6m/sec
Sliding speed for the wear test at high temperature	About 0.5, 1.2, 3, and 3.6m/sec

Table 2 Chemical composition, production method, heat-treatment, and Vickers hardness of the carbon steels used in the wear test

Melting process	Mark	Name of steel	Chemical composition (%)					Hot working	Heat-treatment	Vickers hardness (10kg)
			C	Si	Mn	P	S			
In air	K1	Mild steel	0.014	<0.01	0.14	0.004	0.007	Hot-worked to the plate of 5 mm in thickness from the bar of 20 mm in diameter, that had been hot-worked from the ingot of 50kg.	Furnace cooling after heating at 900°C for 2hrs.	77
	K2	Mild steel	0.020	<0.01	0.12	0.014	0.030		Furnace cooling after heating at 900°C for 2hrs.	90
	K3	Carbon steel with 0.21%C	0.21	0.15	0.30	0.014	0.030		Furnace cooling after heating at 860°C for 2hrs.	113
	K4	Carbon steel with 0.38%C	0.38	0.18	0.30	0.012	0.027		Furnace cooling after heating at 830°C for 2hrs.	134
	K5	Carbon steel with 0.58%C	0.58	0.21	0.32	0.011	0.027		Furnace cooling after heating at 800°C for 2hrs.	164
In vacuum	V1	Mild steel	0.024	<0.01	0.19	0.013	0.030		Furnace cooling after heating at 900°C for 2hrs.	95
	V2	Carbon steel with 0.13%C	0.13	0.16	0.19	0.013	0.027		Furnace cooling after heating at 880°C for 2hrs.	106
	V3	Carbon steel with 0.35%C	0.35	0.21	0.21	0.013	0.027		Furnace cooling after heating at 840°C for 2hrs.	130
	V4	Carbon steel with 0.48%C	0.48	0.19	0.19	0.012	0.027		Furnace cooling after heating at 810°C for 2hrs.	141
	V5	Carbon steel with 0.64%C	0.64	0.21	0.21	0.012	0.024		Furnace cooling after heating at 780°C for 2hrs.	163

made to have a microstructure of pearlite by the following heat-treatment: furnace cooling after heating at 850°C for 5 hours.

All fixed and rotating specimens made of the above mentioned steels were paired and tested under the conditions in Table 3.

The hardnesses of the fixed specimens were measured after annealing in vacuum and polishing with emery papers and then buffer in the same manner as that for the observation of microstructures.

Furthermore the oxidation tendencies of the steels for the fixed specimens were studied. The test method is entirely same as that in another report⁽⁵⁾, namely the oxidation tendency was evaluated from the increase in weight per unit surface area of the specimen with 16 mm in diameter and 10 mm in height, that had been heated at 700°C for 1 hour. In this case several carbon steels on the market were additionally tested for the oxidation tendency to compare with that of the carbon steels in this report.

Finally the author discussed the effects of the annealing in vacuum before the wear test and the seasons of summer or winter on the behavior of

sliding wear. For this discussion the fixed specimens that had not been annealed in vacuum before the wear test were tested for the sliding wear under the same experimental conditions as in Table 3, and both results in summer and winter were compared with each other.

3. Experimental result

3.1 Result of the sliding wear tests at ambient temperature

Figure 3 shows the results of the wear tests at ambient temperature under the conditions in Table 3 with fixed specimens K1 to K5 annealed at 650°C in vacuum before the wear test. Figure 4 shows similarly the results of wear tests with V1 to V5 annealed at 650°C in vacuum before the wear test. All curves in Figs. 3 and 4 show the dependence on the sliding speeds that is well known in Japan. In other words the steels wore only a little at lower sliding speeds as a result of so-called "oxidation wear", the steels wore more with the increase of sliding speeds because of so-called mechanical broken wear", and the steels wore only a little again when the sliding speeds became higher. But it is found that they have a little

Fig. 3 Results of the sliding wear test at ambient temperature for the carbon steels in K-series

Fig. 4 Results of the sliding wear test at ambient temperature for the carbon steels in V-series

(a) K-series

(b) V-series

Fig. 5 Results of the sliding wear test at 200°C for the carbon steels in K- and V-series

difference, respectively, when all curves are compared with each other.

3.2 Result of wear test at high temperatures

Figures 5(a) and (b) to Figs. 7(a) and (b) show the results of the wear tests at 200°C, 400°C, and 600°C under the conditions in Table 3. Figures 8(a) and (b) show the results of the wear tests at various test temperatures with V1 or V5 as samples that were arranged from the above men-

Fig. 6 Results of the sliding wear test at 400°C for the carbon steels in K- and V-series

Fig. 7 Results of the sliding wear test at 600°C for the carbon steels in K- and V-series

Fig. 8 Results of the sliding wear test at ambient temperature to 600°C for the carbon steels V1 and V5

tioned results in Figs. 5 to 7.

There are clear differences between the curves for the low carbon steels and the high carbon steels in each series in Figs. 5(a) and (b) that show the results at 200°C.

The wear rate curves at 400°C became about irregular for each steel as in Figs. 6(a) and (b), but in regard to the K-series in Fig. 6(a) it seems that the peaks of wear rate moved to the positions of higher sliding speeds in order of K1 from K5, while the results of the V-series in Fig. 6(b) did not show the same behaviors as that of the K-series. The relation between the wear curves for each series at 600°C became very complex and irregular. Only K3, K4, and K5 in Fig. 7(a)

and V4 and V5 in Fig. 7(b) had nearly the same tendency in the wear rate curve. The wear rates at 600°C were generally greater than those at other test temperatures, namely at 200°C and 400°C, except in the range of lower sliding speeds.

The above mentioned results at high temperatures do not contradict that in another report⁽⁶⁾, in which a carbon steel with 0.89 %C was used as the fixed specimen and tested at 200°C to 800°C. Namely it is recognized from Figs. 8(a) and (b) that the peaks of wear rate moved to the position of high sliding speeds as the test temperature rose.

3.3 Results of hardness measurement and oxidation tendency test

Figure 9 shows the results of hardness measurement with the specimens that had been annealed in vacuum at 650°C and polished with a buffer by a Vickers hardness tester under loads of 10kg. Moreover the hardnesses of the specimens with low carbon contents and without annealing in vacuum are shown in this figure as a reference. It is found from Fig. 9 that the hardnesses of all carbon steels annealed in vacuum were nearly in proportion to the carbon contents and that the scatterings of their measurement values were smaller than those of the specimens without annealing in vacuum. That relation between the hardnesses and the carbon contents was the same as that in the other study⁽³⁾, in which one of the authors, TSUJI, and others studied on the mechanical properties of various carbon steels.

Figure 10 shows the results of the oxidation tendencies for the K- and V-series as well as the carbon steels on the market. In this figure the marks (S) and (V) mean the carbon steels with 0.27%C and 0.49%C in the last report⁽²⁾. It is found in Fig. 10 that the oxidation tendencies of the carbon steels in the K-series except K1 and K2 as well as those of the V-series except V1 were nearly the same, respectively. Moreover it is recognized again that the oxidation tendencies of steels are nearly the same when they are made of the same materials using the same procedure. For the carbon steels on the market their oxidation tendencies differed from each other depending on the carbon contents and the steel makers.

4. Consideration

In this consideration it is assumed that the mean free distance between the contact points over the frictional surface may be constant for the carbon steels used in this report when the final loads at the wear test are constant, although their hardnesses differ from each other. This assumption

Fig. 9 Vickers hardness of the fixed specimens after annealing in vacuum at 650°C for 1 hour

Fig. 10 Results of the oxidation tendency test for the carbon steels in K- and V series as well as the carbon steels on the market

originated from the study of N. Soda and T. Sasada⁽⁷⁾. Moreover it is assumed from the author's other report⁽⁸⁾ as follows. The phenomena of sliding wear occurs from the break of the above mentioned contact points, but in this case they are welded more strongly to each other again as they are oxidized less after the break. In other words the steel that is hardly oxidized may wear much while the steel that is easily oxidized may wear a little. Furthermore it is introduced in this consideration that the phenomenon of sliding wear at ambient temperature shows a microscopic behavior while that at high temperatures shows a macroscopic behavior as described in the other report⁽⁸⁾.

4.1 On the result of wear test at ambient temperature

When the oxidation tendencies of steels in the K- or V-series (Fig. 10) were compared with the results of the wear test (Figs. 3 and 4), respectively, it is found that the maximum values of wear rate for K1 and K2 with large oxidation tendencies are lower than those for K3, K4 and K5 with small oxidation tendencies. On the other hand the curves of wear rate for K1 and K2 became flat at the maximum, which was the same as the curve for the carbon steel with 0.49 %C that had been called V in the last report⁽²⁾.

All oxidation tendencies of the V-series were nearly the same and such steels as the V-series have the same maximum value of wear rate as shown in Fig. 4. But the maximum values of V1 and V2 were situated at a little higher gliding speeds than those of V3, V4 and V5. It means that the oxidation tendencies of the new clear surface created due to the break of contact points are greater or stronger for V1 and V2 than for V3, V4, and V5 although the macroscopic oxidation tendencies that were measured from the heating at 700°C for 1 hour were nearly the same. It is found from the results of hardness measurement that V1 and V2 are softer than V3, V4, and V5. Therefore it seems that the areas of true contact surface of the former group are greater than those of the latter. Namely the mean free distances of the contact points are shorter for the former than for the latter. Also the maximum values of wear rate for V1 and V2 would be situated at lower sliding speeds than that for V3, V4, and V5 according to the author's way of thinking⁽²⁾, because all oxidation tendencies of the V-series were nearly the same.

From the above mentioned consideration it can be also recognized that there are other oxidation tendencies besides the macroscopic oxidation tendencies obtained from heating, for example at 700

°C for 1 hour. That oxidation tendencies must be considered on the new clear surface created due to the break of contact points and can be called the microscopic oxidation tendency, that may depend on the microstructures of steels, namely ferrite, pearlite and so on.

4.2 On the results of the wear tests at ambient temperature and 200°C

In order to simplify and to make clear the following consideration the author tries here to introduce his way of thinking as in section 4.1, namely the macroscopic oxidation tendencies that were determined from the increase in weight of each specimen heated at 700°C for 1 hour as in Fig. 10, and the microscopic oxidation tendencies on the new clear surface created by the break of contact points.

Then the wear phenomena of mild steels of K1, K2, V1, and V2 with ferrite at ambient temperature and 200°C will be discussed with the above mentioned both oxidation tendencies. When Figs. 3 and 4, in which the results at ambient temperature were showed, are compared with each other, the maximum values of wear rate for K1 and 2 with large macroscopic oxidation tendencies are smaller than those for V1 and 2 with smaller macroscopic oxidation tendencies. This fact agrees with the conclusion in the other report⁽⁸⁾: the steels that are more oxidized wear only a little while the steels that are hardly oxidized wear more.

Next, when the results of the wear test at 200°C for K1 and 2 in Fig. 5 (a) are compared with those for V1 and 2 in Fig. 5(b), the maximum values for the former are greater than those for the latter against the above discussed results at ambient temperature. This contradiction will be explained as follows. Now it is calculated on the carbon steels of K1 and 2, and V1 and 2, what is the ratio of maximum value at 200°C to that at ambient temperature, respectively. The maximum values of both specimens K1 and 2 were about $54 \times 10^{-6} \text{ mm}^3/\text{kg}/\text{mm}$ at ambient temperature and about $31 \times 10^{-6} \text{ mm}^3/\text{kg}/\text{mm}$ at 200°C, namely the ratio of the latter to the former is 57.5%. On the other hand the maximum values of both specimens V1 and 2 were about $70 \times 10^{-6} \text{ mm}^3/\text{kg}/\text{mm}$ at ambient temperature and about $18 \times 10^{-6} \text{ mm}^3/\text{kg}/\text{mm}$ at 200°C, namely the ratio of the latter to the former is 25.7%. Also, the ratio of decrease of maximum values in the temperature range from ambient temperature to 200°C is larger for V1 and 2 than for K1 and 2. Furthermore the sliding speeds at which the wear rate at 200°C was maximum

are about 2 m/sec for V1 and 2 and about 1.1 m/sec for K1 and 2, as in Figs. 5(a) and (b), namely the maximum values were situated at higher sliding speeds for V1 and 2 than for K1 and 2. When the above mentioned behaviors are considered together with the macroscopic oxidation tendencies in Fig. 10, the behaviors of oxidation for K1 and 2 and V1 and 2 have to be assumed the same as the schematic behaviors of the carbon steels with 0.27 %C (the mark S) and 0.49 %C (the mark V) in the last report⁽²⁾. Figure 11 shows such schematic behaviors of oxidation for K1 and 2 and V1 and 2 as that in the last report.

The oxide film on stainless steels may be as strong as that of aluminum quoted in the last report⁽²⁾, and in this case the macroscopic oxidation tendencies of them are low because their surfaces can be covered with thick and thin oxide films to suppress the oxidation from progressing into the inside. In other words the microscopic oxidation tendencies of stainless steels have to be great or strong although their macroscopic oxidation tendencies are very low. Above mentioned way of thinking will generally apply to carbon steels, from which the schematic behavior in Fig. 11 can be also understood.

When the relationships between the rates of decrease of maximum values and their situations on the sliding speeds are considered on K1 and 2 and V1 and 2 again from the point of view in Fig. 11, the results in Fig. 5 may be interpreted as follows. When the fixed specimens K1 and 2 and V1 and 2 are heated to 200°C, the microscopic oxidation tendencies are accelerated, but the oxidation tendencies of the latter are so greater than that of the former, that the wear rates of the latter become smaller than that of the former. Moreover the sliding speeds must be higher to arrive at the maximum value of wear rate for V1 and 2 than for K1 and 2, if the mean free distances between the contact points at 200°C are not different from

Fig. 11 Schematic behaviors of the oxidation tendency of the carbon steels with low carbon contents, namely with ferrite

that at ambient temperature.

It is found in Fig. 3, that the wear curves were nearly smooth at the maximum of wear rate for K1 and 2. It means that the dependence of wear rate on the sliding speeds, namely the dependence of the behavior of the microscopic oxidation tendency on time, is hardly recognized in the zone of such flat curve. In other words the progress of the microscopic oxidation of K1 and 2 may be slow, which can be also known from Fig. 11. The progress of the microscopic oxidation in V1 and 2 is quick, then their curves at the maximum of wear rate become sharper than those of K1 and 2.

When the difference between the maximum values of K1 and 2 and V1 and 2 is considered in connection with their oxidation tendencies, the relation between their oxidations and wear rates can not always be said to be so simple as the above mentioned. Moreover this holds true for the relation between the humidity in atmosphere and the wear rate, which may be described later.

4.3 On the result of the wear test at high temperatures

It is found in Fig. 6(a) and Fig. 7(a), respectively, that the peaks of the wear rate are situated at higher sliding speeds in the order of K1, K2, K3, K4, and K5 at each test temperature. It seems that each microscopic oxidation tendency approaches the macroscopic one with a rise of the test temperatures. The microscopic oxidation tendency may be larger or stronger in the steel with ferrite at high temperatures as well as at ambient temperature than in the steel with pearlite as described in section 4.1. Therefore the peaks of wear rate at high temperatures in carbon steels move farther to the position of higher sliding speeds as those steels have lower carbon contents.

4.4 Effects of the seasons in Japan and the annealing in vacuum before the wear test on the wear phenomena at ambient temperature

When the results of wear test in winter in Japan (Figs. 3 and 4) were generally compared with those in summer⁽¹⁾ for all carbon steels in this report, it was found that there are nearly similar behaviors between the results in both seasons for each series of K and V. But when the curve of wear rate in winter 1969/70 is exactly compared with that in summer 1969 for each carbon steel, a little difference is noted. In order to see whether this difference is due to the effect of annealing in vacuum before the wear test or to that of the seasons, the following experiments were performed, because the fixed specimen without annealing in vacuum had been used in the wear test in summer

Table 4 Weather conditions at noon of the days in Tokyo, on which the wear tests in Figs. 13 and 5 to 7 were carried out (from the weather data by the Tokyo Meteorological Observatory)

Season	Wear test		Weather conditions at noon in Tokyo		
	Test temp. and kind of specimen	Date	Vapor pressure mb	Relative humidity %	Atmospheric temperature °C
Summer	Ambient temp. and K1	July, 26, 1969	27.6	60	31.3
	Ambient temp. and V1	July, 28, 1969	29.5	72	32.1
	Ambient temp. and K5 and V5	August, 4, 1969	30.9	70	30.6
	Ambient temp. and K1 and V1	August, 5, 1969	29.7	80	27.7
	Ambient temp. and K5 and V5	August, 7, 1969	29.3	61	32.1
Winter	Ambient temp. and K1, V1 K5, and V5	December, 22, 1969	4.7	35	11.3
	Ambient temp. and K1, V1 K5, and V5	February, 10, 1970	1.7	18	5.9
	200°C to 600°C and K1 to K5	Mean value of 6 days from December 1 to 6, 1969	5.7	39	12.4
	200°C to 600°C and V1 to V5	Mean value of 8 days from November 14 to 28, 1969	7.6	45	15.0

Fig. 12 Effect of the both seasons, summer and winter in Japan, and annealing in vacuum before the wear test on the behavior of sliding wear of the fixed specimen V5 at ambient temperature

Fig. 13 Effect of both seasons, summer and winter in Japan, on the behavior of sliding wear at low sliding speeds and at ambient temperature

1969 while the results in this report were obtained from the wear test in winter 1969/70, whereby the fixed specimens had been annealed before the wear test.

The fixed specimens K1, K5, V1, and V5 were chosen out of all specimens. Those specimens were not annealed before the wear test and were tested in the same season as ones in this report, namely in winter. The above mentioned results, the results in Fig. 3 or 4, and the other results⁽¹⁾ with the specimens not annealed in summer are summarized, and Fig. 12 shows the results of V5 as a sample of those results. The other specimens K1, K5, and V1 showed also nearly the same behaviors as in Fig. 12.

From Fig. 12 it is clear that the forms of three curves differ from each other. Particularly, they differ in the zone of low sliding speeds. Considering the effect of annealing in vacuum before the wear test on the behavior of wear rate in winter it is recognized in Fig. 12 that the maximum value of wear rate is greater for the fixed specimens with annealing in vacuum than for ones without annealing, but the peaks of wear rate for both specimens are situated at nearly the same sliding speeds. It was found moreover that there were very large scatterings in the measured values of wear rate in the zone of very low sliding speeds, particularly in summer. Therefore all results of the wear test at low sliding speeds in winter and summer, that were obtained

with the fixed specimens K1, K5, V1, and V5 without annealing in vacuum, are gathered in Fig. 13. Table 4 shows the temperatures and humidities at noon of the experimental days, on which the wear tests in Fig. 13 were performed, furthermore the temperatures and humidities of the other days, on which the wear tests at high temperature were performed, are shown in this table as reference.

It is clear from Fig. 13 that the scatterings in wear rate are greater in summer than in winter. One of the causes for this may be high humidity in summer as shown in Table 4.

The behavior of the macroscopic oxidation tendency of each carbon steel in summer is nearly the same as that in winter although the absolute values of the macroscopic oxidation tendencies differ from each other in both seasons as described in the other report⁽⁵⁾. According to this study the macroscopic oxidation tendency in summer is larger than that in winter.

When the results in Fig. 13 are discussed considering the above mentioned behaviors of the macroscopic oxidation tendencies in both seasons and the behaviors of wear rate in Fig. 12, the following contradiction is found. The maximum value of wear rate in summer would be smaller than in winter if the macroscopic oxidation tendency is larger in summer than in winter. Only at very low sliding speeds the wear rate is smaller in summer than in winter, but the maximum value is larger in summer than in winter. This contradiction will be made clear with a further study on the effect of humidity upon the wear.

It can be considered on the effect of annealing in vacuum before the wear test on the behaviors of wear as follows. The stressed layer due to the surface grinding was removed with this annealing, in other words the surface of the specimen became so soft that the maximum value of wear rate increased, but the oxidation tendency of the specimen was not changed by this heat-treatment, also a movement of the peak of wear rate to the direction of the horizontal axis did not occur.

5. Conclusions

In this study various carbon steels with 0.014 to 0.64 %C that had been produced from the same materials in air or were remelted in vacuum in author's Institute were tested on the sliding wear without lubricants at ambient temperature to 600°C; and the effects of the melting processes, the microstructures, both seasons of summer and winter in Japan, and annealing in vacuum before the wear test upon the behavior of sliding wear

were studied and the following results were obtained.

(1) A carbon steel with large macroscopic oxidation tendency, that was measured under heating at 700°C for 1 hour, had a lower maximum value of wear rate than one with small macroscopic oxidation tendency.

(2) When carbon steels had various carbon contents but nearly the same macroscopic oxidation tendency, their maximum values of wear rate were about the same. But the position of the peak of wear rate in relation to the sliding speeds was situated at a little higher sliding speed for the steels with low carbon contents, namely with ferrite, than for the steels with high carbon contents, namely with pearlite. This means that the behaviors of oxidation on the broken surface of contact points (this is called the microscopic oxidation tendency) differ from each other for carbon steels although they have nearly the same macroscopic oxidation tendencies.

(3) From the results of mild steels K1, K2 V1, and V2 with ferrite it was found that the steel with small macroscopic oxidation tendency may have large microscopic oxidation tendency, when the surface of steel can be covered with an oxide film to prevent further oxidation to the inside. The above mentioned way of thinking may be also obtained from the following results: When the test temperature rises from ambient temperature to 200°C the maximum value of wear rate drops more for the steels V1 and 2 than for K1 and 2. On this occasion the former have smaller macroscopic oxidation tendency than the latter.

(4) For the steels in K-series the peak of wear rate moved to the direction of higher sliding speeds with a rise of test temperatures. It seems that the microscopic oxidation tendency drew near to the macroscopic one as the test temperature rose.

(5) The effects of the seasons on the behaviors of sliding wear are as follows. The wear rate at low sliding speeds was smaller in summer than in winter while the maximum value of wear rate was greater in summer than in winter. This may be an effect of the vapor pressure in air, namely humidity, on the oxidation tendency, and the mechanism of this effect will be studied in a next experiment.

(6) When the fixed specimen had been annealed in vacuum before the wear test, the maximum value of wear rate became greater than when it had not been annealed. But the sliding speeds, at which the maximum value of wear rate appeared, were unchanged, because only the stress

in the machined surface was removed with the annealing and the oxidation tendency was not affected by the annealing.

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- (4) Okoshi, A., et al., *Report of the Physical and Chemical Institute* (in Japanese), Vol. 31, No. 2 (1955-3), p. 103.
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- (7) Soda, N. and Sasada, T., *Report of the Aeronautical Institution, Tokyo University* (in Japanese), Vol. 4 (1964), p. 50.
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Discussion

F. HAYAMA (Waseda University):

(1) It may be right that the maximum values of wear curves are controlled by the magnitude of the oxidation tendency, but there may be two cases: the maximum values of wear curves are controlled or not by this oxidation tendency. The first case can be the wear under mild conditions. On the other hand under large pressures, namely large maximum value of wear rate, such factors as the adhesion, the mechanism of surface-break etc. may have great effects on the behaviors of sliding wear and it can be neglected whether the oxidation tendencies are large or small. The questioner wants the author's opinion on the above mentioned stand point.

(2) On the effect of vapor pressures on wear the author said that the wear rate at low sliding speeds was smaller in summer with high humidity than in winter while the maximum values of wear rate behaved conversely, namely it was greater in summer than in winter.

According to the questioner's study^(*) the wears of pair of pure iron or a pair of 70-30-brass became small at humidity above 60% and dropped under the same conditions to a fourth at humidity of 100% at low sliding speeds, namely in the oxidation wear zone. On the other hand the maximum value of the wear of 60-40-brass was greater at high humidity than at low humidity. In this case the questioner concluded from the observations of wear surface etc. as follows. The oxidized wear particles are very fine and gather with a suitable moisture (or humidity). Hereby their adhesion abilities to the wear surface increase and this wear surface is covered with a film of the oxidized wear particles, also it can cause easily an oxidation

wear and reduce wear amount. Although the maximum value of wear rate appears slightly in dry atmosphere it can disappear in some cases in wet atmosphere. On the other hand the large wear particles caused by the wear with a bright worn surface can easily flow with a suitable moisture, and they can hardly adhere to the worn surface, accordingly the substantial amount wear increases with high humidity. Then the questioner asks how the wear surface behaves in author's study, and wants to know the author's opinion about the above mentioned reasoning.

Author's closure

(1) The author has not studied the effect of the load on the sliding wear until now. Therefore it is stated here that the effect of the load or contact pressure on the sliding wear in the other study^(*) can be explained with the author's way of thinking. Append.-Fig. 1 shows the wear curves for a pair of a quenched high speed steel No. 2^(*), which were tested with the same Rapid Wear Testing Machine as the author's under various final loads at ambient temperature. Append.-Fig. 2 shows the same results as those in Append.-Fig. 1 but those curves were so drawn, that each contact pressure became the same in the region of sliding speeds from 0.28 to 1.5 m/sec. The real area at the contact surface between two specimens may increase with an increase of the load or contact pressure, so that the mean free distance between the small contact points can become shorter. Therefore when the oxidation tendencies of the tested steels are the same, but the load or

(*) Hayama, F., *Jour. Japan Inst. Metals* (in Japanese), Vol. 33, No. 8 (1969), p. 934.

(*) Okoshi, A., et al., *Report of the Physical and Chemical Institute* (in Japanese), Vol. 31, No. 2 (1955-3), p. 103.

(*) The mark of this steel is now SKH2 according to the JIS.

Append.-Fig. 1 Results of the wear test on the quenched high speed steel No. 2

contact pressures in the wear test are different, the position of the peak of wear rate may slide to the direction of low sliding speeds with a rise of contact pressure, but these maximum values may be about the same as shown in Append.-Fig. 2.

At first in the author's studies the term abrasion had been used to give the mean of severe wear at high temperatures and to distinguish from the mild wear at ambient temperature. It can be said that to raise the test temperature in the wear test is one of the severe conditions. For instance the wear rate becomes very high at 600°C because of an increase of the weldability between both specimens and the softening, but the maximum value of wear rate appears at high sliding speeds because the oxidation tendency becomes strong with a rise of the test temperature. But a little

Append.-Fig. 2 Curves of wear rate at constant contact pressures

change in the oxidation tendency and its effect on the behaviors of sliding wear may be counteracted with other factors under the severe conditions. The author will publish in the near future the fact that a steel with more ferrite has a great effect of the oxidation tendency on the behaviors of wear rate at high temperatures while a steel with pearlite has a small effect. In other words the degree of the effect of the oxidation tendency on sliding wear may be changeable depending on such factors at the test temperature and the micro-structure.

(2) The author did not study the wear surfaces and the wear particles that were obtained in this wear tests. Therefore to his regret the author can not answer to the questioner.