LIGHT AND ELECTRON MICROSCOPIC STUDY OF SURFACES OF TEST-SPECIMENS TESTED IN WEAR APPARATUSES

By

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Several theories have been elaborated for the description and explanation of the wear of metals. Most of these theories deal with the case when no lubricant is present on the wearing surfaces.

Fewer theories deal with the wear in presence of lubricants. Such a theory is e.g. the one of *Kingsbury* and *Rowe* which applies for boundary lubrication conditions [1, 2, 3].

The common feature of these theories is that they try to find some relationship between the wear rate (the volume of material worn off during travelling the unit length of the wear path) and the physical characteristics of the contacting surfaces and the adsorption properties of the lubricant applied. In such relationships generally there are some variables which are quite difficult to determine. In the present work, a different approach was applied. The aim of this study is to give a phenomenological description of wear based on light and electron microscopic observation of the surfaces of test specimens worn under known conditions in model wear testing machines. This phenomenological description makes it possible to draw some conclusions concerning the mechanism of wear. Numerous types of wear testing machines have gained wide-spread application for the study of metal wear and, at the same time, for rating lubricants and their additives.

In this study, test specimens from the Shell 'four-ball' machine and from the Reichert wear tester were investigated. The four-ball machine is very widely used and the Reichert wear tester is also applied by a considerable number of testing laboratories.

The four-ball machine is suitable for rating lubricants, particularly those containing extreme pressure (EP) additives. By using the same lubricant and altering the material of the specimens the wear properties of different materials can also be studied. The basic principle of this machine is shown in Fig. 1. Three balls are pressed into a cup in such a manner that no displacement occurs. The cup is filled with lubricant. The fourth ball bears up against the mentioned three and rotates at 1440 rpm. The cup is pressed upwards by a load transmitted by a lever.

The contact of the balls is point-type at the beginning of the test. Later, a calotte-shaped contact area is formed as a consequence of wear. It follows from this arrangement that the generation of a hydrodynamic oil wedge can be neglected, thus the four-ball apparatus measures the lubricating effect based solely on the chemical characteristics of the lubricant.

One test lasts one minute and the applied load is constant. After each test, the balls are removed from the cup, the mean diameter of the wear track is measured and the wear area is calculated. After that, another test is carried out with another load and using new balls. The greater the load

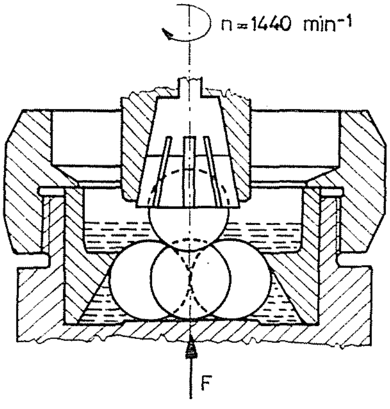

Fig. 1

which causes a sudden increase of the wear scar diameter, the better the tested lubricant (the more effective its EP additive). In case of an effective lubricant, the wear track remains comparatively small even at high loads and welding of the balls occurs at very high loads.

The surface of balls obtained in a series of tests as described above has been studied by light and electron microscopy. The balls which had a diameter of 12.7 mm and a hardness of 62 HRc were made of 105 Cr 2(W-1) steel contain-

Table 1

Data of specimens worn in the four-ball apparatus

Specimen No.	1	2	3	4	5
Load, kp	100	200	220	360	380
Mean diameter of the wear scar, mm	0,45	0,55	2.13	2.88	3.09
Area of the wear scar, mm^2	0.16	0.24	3.56	6.5	7.5

ing 1.05% carbon and 0.5% chromium. The lubricant applied in the measurements was a Hungarian-made commercial gear oil Hykomol K-90 which contains an EP-additive. Table 1 shows the data of the studied balls. The obtained results are also shown in a wear diagram (Fig. 2). It can be seen

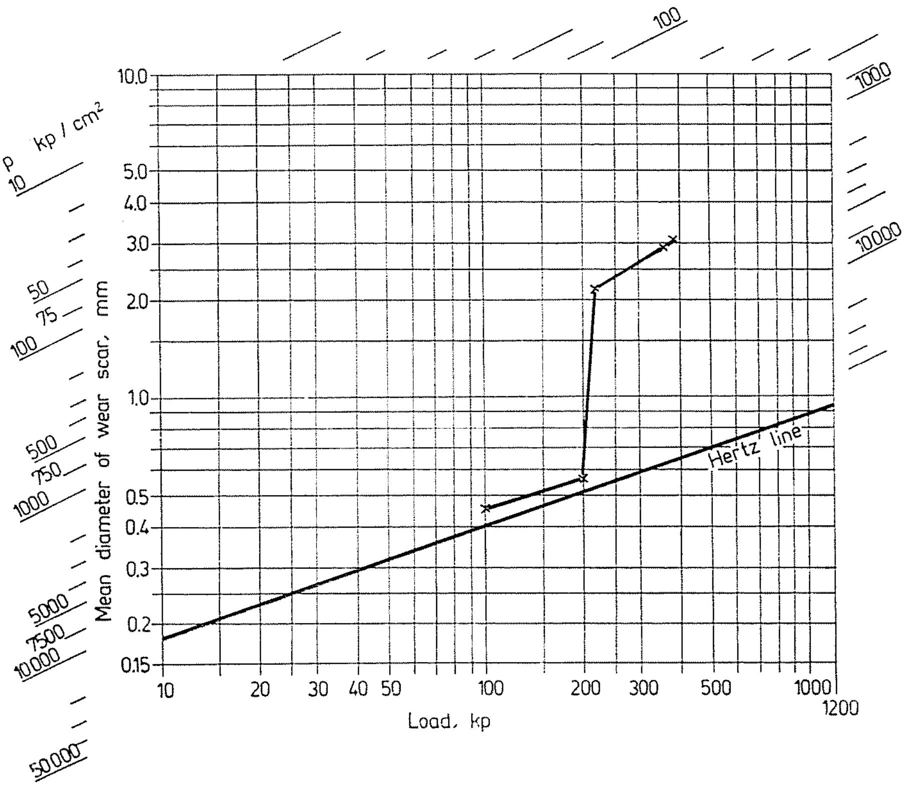

Fig. 2

in Fig. 2 that up to loads of 200 kp the size of the wear scar follows the so-called Hertzian line, then it increases suddenly and the mean specific pressure decreases. The Hertzian line connects the diameters of static deformations caused by the applied loads. This value is e.g. 0.18 mm at 10 kp and 0.60 mm at 300 kp load.

The wear diagram shows that up to 200 kp load the wear track is practically not bigger than the diameter of the static deformation. Significant wear starts to occur at loads greater than 200 kp and the appearing forms of wear can be followed very well by light and electron microscopy — as will be seen later.

The second series of the test specimen in this study originated from a Reichert wear testing machine, which is suitable for the study of the effect of lubricants and additives upon wear.

The principle of the Reichert machine is shown in Fig. 3. A stationary steel cylinder (this is the test specimen) is pressed to a revolving ring by a loading system. The test specimen has a length of 15 mm and a diameter of 10 mm.

The lower third of the rotating ring is submerged into the oil to be tested. The driving speed of the rotating ring is such that the ring always carries a sufficient amount of lubricant to the contact area. The type of contact between the ring and the test specimen is point-like at the beginning of the test. Later during the test, an elliptical wear track is formed on the test specimen. It follows from the loading conditions and the geometry of contact that at the

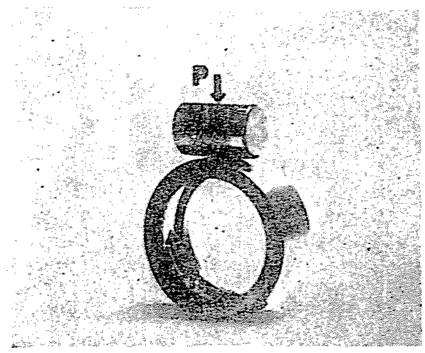

Fig. 3

beginning of the test, boundary lubrication conditions are dominating. Later, with the increase of the wear track, the role of hydrodynamic lubrication becomes significant. The lubricant is the more effective, the smaller the wear track after travelling along a given wear path. Usually the test is run until 100 m wear path has been travelled.

Four steel cylinders tested at different loads have been studied by light and electron microscopy. The cylinders had a hardness of 61 HRc. The tests were carried out with a base oil of the SAE-30 viscosity category.
The conditions of the tests were the following.

Table 2

Data of specimens worn in the Reichert apparatus

Specimen No.	I.	II.	III.	IV.
Load in the point of contact, kp	2	20	30	40
Area of elliptical wear scar, mm^2	0.45	10.3	16.2	27.9
Calculated specific load after formation of the wear scar, kp/cm^2	400	200	183	148

Speed of driving motor and rotating ring: 1500 rpm
Linear speed in the contact area: 1.65 m/sec
Wear path: 100 m

The results of the tests and the data of the studied specimens are given in Table 2.

Microscopic study of the worn specimens and discussion of the observations

The microscopic observations were carried out with a Neofot type (Carl Zeiss, Jena) microscope in reflected light.

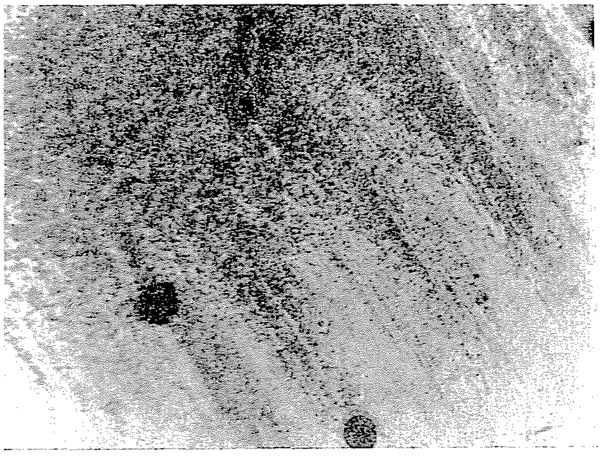

Fig. 4

The magnification of the pictures published here is uniformly 320×.

The pictures taken from the surface of balls worn in the four-ball apparatus are discussed first.

Ball 1. (load: 100 kp)

Very slight wear can be observed, light scratches can be seen in the direction of movement (Fig. 4). The dark spots in Fig. 4 are additional contaminations on the surface and have nothing to do with the tests.

Ball 2. (Load: 200 kp)

Very slight wear, its character being the same as that observed in the case of Ball 1. (Fig. 5) Fig. 5 shows the edge of the wear track.

Ball 3. (Load: 220 kp)

Severe wear suddenly starts (cf. wear diagram, Fig. 2). This is clearly shown by the condition of the surface which differs very much from that observed at 200 kp load. Near the outlet end of the wear track, deep grooves are present (Fig. 6). Fig. 7 shows the inlet of the track. The inlet edge is sharp, the proportion of flattened areas is significant. The latter finding points to plastic deformation.

Ball 4. (Load: 360 kp)

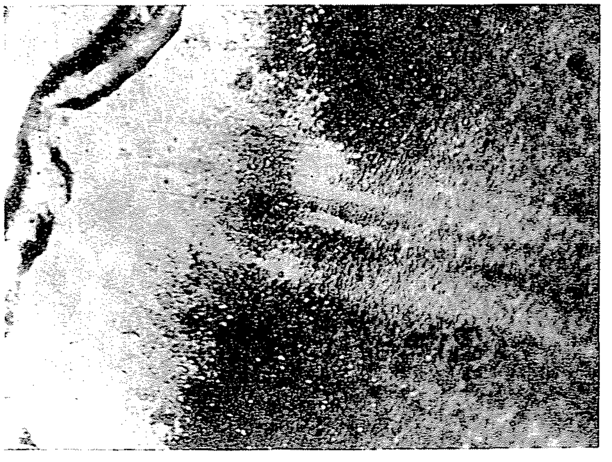

Fig. 5

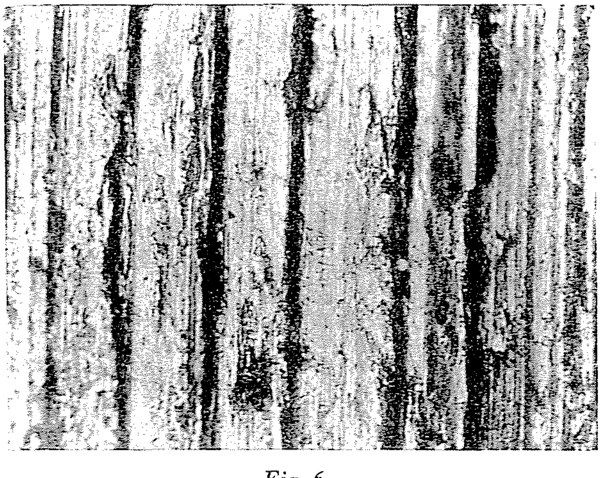

Fig. 6

Very severe wear, in the middle area of the track, deep and well defined grooves can be seen (Fig. 8). The inlet edge is sharp in this case too, and the formation of grooves begins immediately at the edge. At the outlet edge, plastic flow having occurred, protruding material could be observed.

Ball 5. (Load: 380 kp)

Very severe wear. In the middle part of the track, broadening and merging of the grooves can be observed (Fig. 9). The inlet edge is well defined, but not as sharp as at 360 kp load, signs of melting could be seen. At the outlet edge, heavy plastic flow could be observed, similarly to the case of 360 kp load.

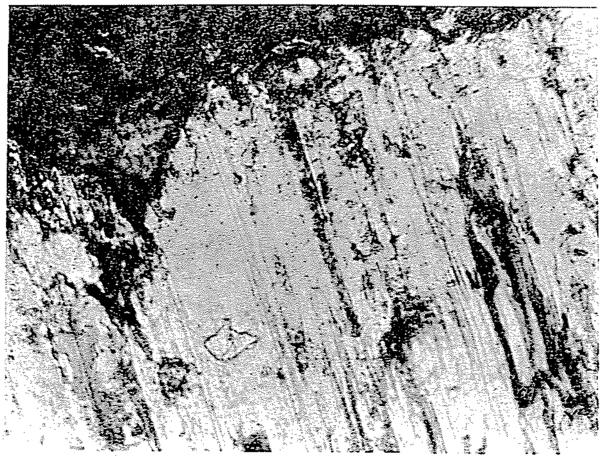

Fig. 7

Fig. 8

The microscopic pictures clearly show the changes in the condition of the worn surfaces as the load increases. The sudden change observed between 200 and 220 kp which is also indicated in the wear diagram, causes an abrupt deterioration in the condition of the surface too.

The difference between the inlet and outlet edge of the track wear can also be very well observed. At the inlet edge, the rotating ball shears off the material while at the outlet edge, the material carried away from the track — which flows partly owing to the action of friction heat, and partly owing to pressure — is accumulated. Based on the microscopic observations, the wear process can be described as follows: at small loads, the surface damage is represented by the formation of very slight, fine scratches.

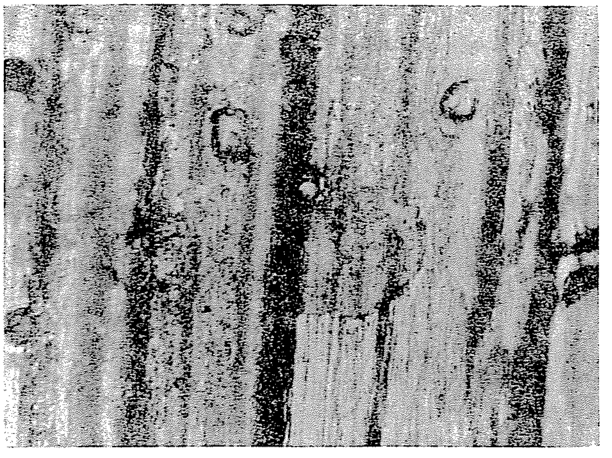

Fig. 9

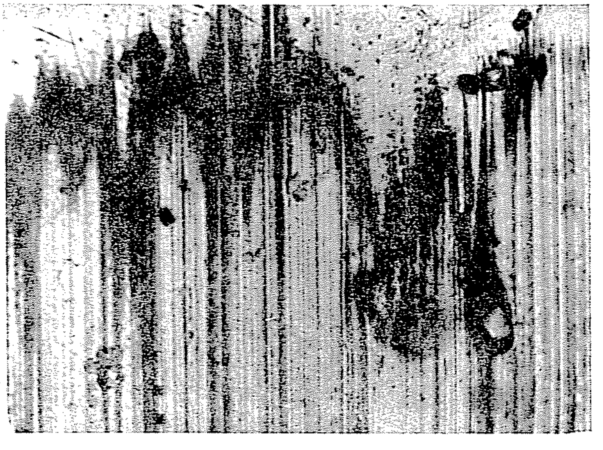

Fig. 10

The character of wear changes little when the load is increased within a certain range, the only change is that the wear becomes more uniform.

Increasing the load beyond a critical value, severe damage of the surface suddenly starts. This is accompanied by plastic flow and microwelding. The rupture of the microwelds results in tearing out parts of the material from the worn surface.

On further increase of load, the torn-out parts groove the surface, and under the effect of even higher load, the extent of plastic flow increases, the grooves broaden and merge, while the size of the carried-away material particles increases.

Fig. 11

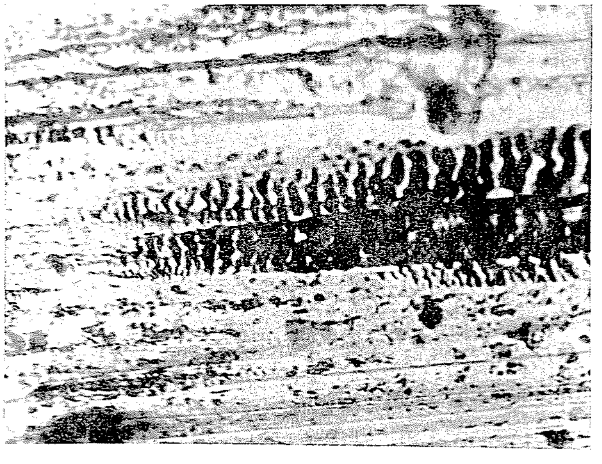

Fig. 12

The study of the surfaces of the test cylinders worn in the Reichert machine led to the following observations:

Cylinder I (Load: 2 kp)

Fig. 10 shows the inlet area of the wear track. Fine grooves can be clearly seen which are formed by the surface irregularities of the rotating ring, and by microscopic impurities introduced by the ring.

Cylinder II (Load: 20 kp)

The worn surface is much greater. Fig. 11 shows the edge of the worn surface. The fine grooves have merged, quite significant smooth areas can be seen, but among the relatively smooth areas seriously damaged parts are present (dark spots on the pictures), which could be formed by tearing out of material. These damaged parts are very uneven. In the middle of Fig. 11, a surface formation can be seen, which points to the cracking of the smooth surface.

Cylinder III (Load: 30 kp)

The character of the surface is similar to that observed in the case of cylinder II. The cracking of the material surface is increased (Fig. 12), protruding of the material at the edge of the track is more pronounced and the material particles torn out of the flattened areas or delaminated as a consequence of the spread of cracks are larger (Fig. 13).

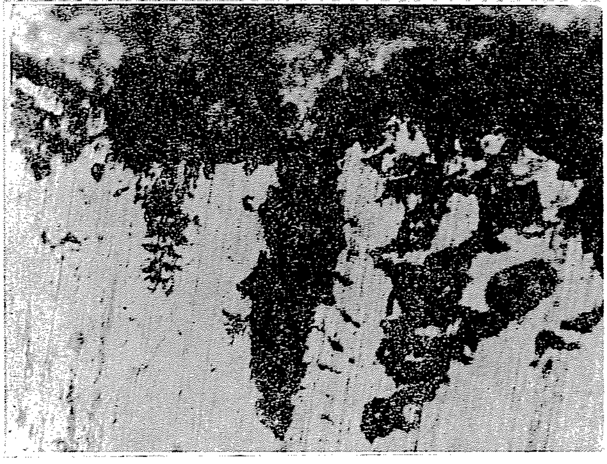

Fig. 13

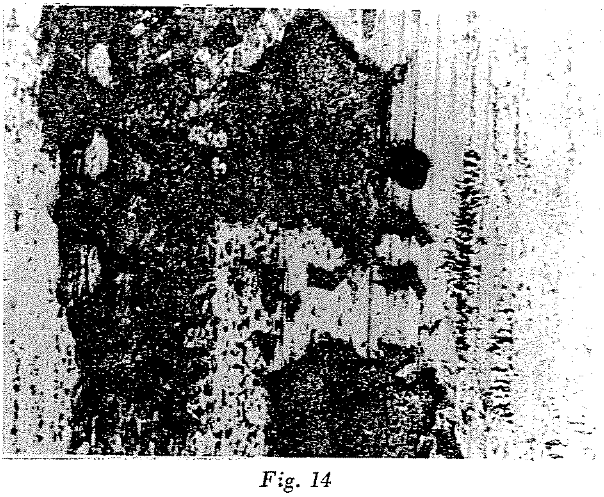

Fig. 14

Cylinder IV (load: 40 kp)

The damaged areas increase, which points to the tearing out of comparatively large particles of material and to the spread of cracks (Fig. 14). Wear grooves can hardly be seen, and those occurring are very shallow. At the outlet end of the wear track, the spread of cracks could clearly be seen.

Based on these observations, the course of wear in this case can be characterized by the following processes. At light loads, the irregularities of the surfaces and the particles introduced between the moving surfaces form fine grooves. These are flattened under increasing load, the grooved surface contacts the opposite one at more and more points, so that the contact will gradually turn into a 'plane on plane' type. During the contact, significant friction heat is evolved. Subsequently, probably owing to mechanical and thermal stresses cracks begin to form in the smooth surfaces. After the spread of cracks, the material delaminates.

Electron microscopic study of the worn test specimens and discussion of the observations

After the microscopic observation, an electron microscopic study was made in order to obtain — by utilizing the greater magnifications — a more accurate picture of the surface morphology, also allowing a better interpretation of the microscopic observations.

The study was carried out using a transmission electron microscope type EM-5, which gives a maximum resolution of 20 Å. Its magnification range is 1000—10,000×. Since the surface of the test pieces could not be studied directly by transmission electron microscopy, a suitable method of replica preparation had to be chosen. The two-stage replica technique has been preferred to the one-stage method, because in case of the latter, the removal of the thin-layer replica would have been extremely difficult. In the first stage, a relatively thick plastic print of the surface is prepared, which can be easily removed from the surface and is easy to handle.

This print, the so-called intermediate replica gives the negative structure of the original surface (a protuberance in the original surface is an indentment in the replica and *vice versa*).

In the second stage, a positive print is prepared from the intermediate replica, suitable for examination in the electron microscope. In this study, the second-stage replica was prepared by vaporization of carbon in high vacuum onto the negative print. The resulting amorphous carbon film is thin, but stable and gives a good resolution. All the second-stage carbon replicas obtained in this way were observed and photographed at 50 kV accelerating voltage, with a magnification of 7800 ×. The pictures published here were prepared with a further magnification of 2 × from the negative plates so that the total magnification of these pictures is uniformly 15,600 ×.

Discussion of the pictures

The same order will be followed here as in the discussion of light microscopic pictures. The pictures taken from the balls from the four-ball machine will be discussed first.

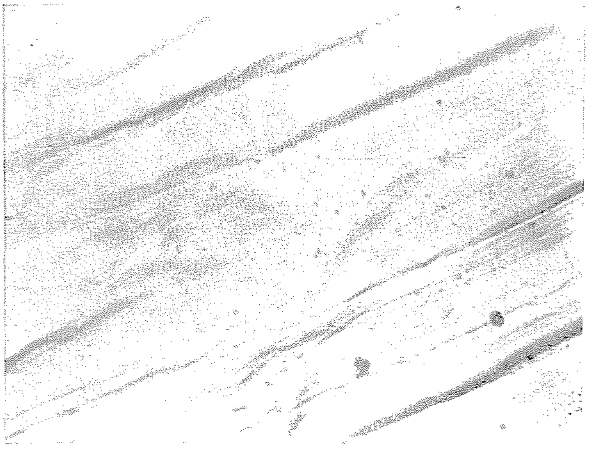

Fig. 15

Ball 1. (Load: 100 kp)

Figure 15 clearly shows that the surface is quite smooth, no severe damage or seizure can be observed. The wear grooves which are not deep are clearly visible.

Ball 2. (Load: 200 kp)

Figure 16 shows a surface which is slightly more grooved than that of Ball 1, but the condition of the two surfaces is essentially the same.

Ball. 3. (Load: 220 kp)

Figure 17 shows the fine cracks in a surface flattened by plastic deformation. Figure 17. is considered to be a highly characteristic picture, demonstrating the advantage of electron microscopy. The cracks in Fig. 17 cannot be seen by conventional microscopy, yet they are of great importance in the mechanism of wear. Figure 17 shows also small secondary irregularities present on a surface which appeared smooth by conventional microscopic observation (compare with certain areas in Fig. 7).

Ball 4. (Load: 360 kp)

A seriously damaged surface can be seen in Fig. 18. The surface roughness is great. The area seen in Fig. 18 is probably the side or 'slope' of a wear groove

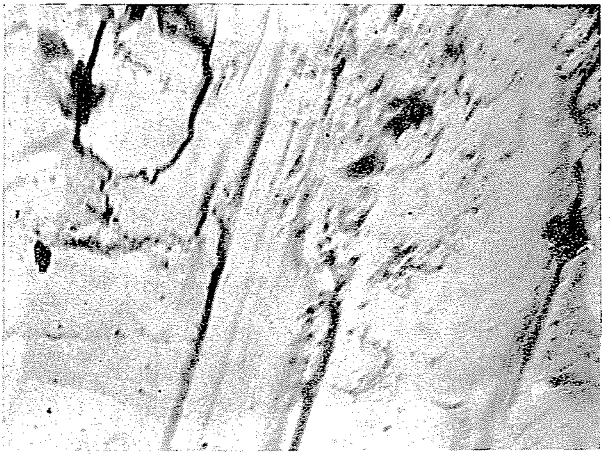

Fig. 16

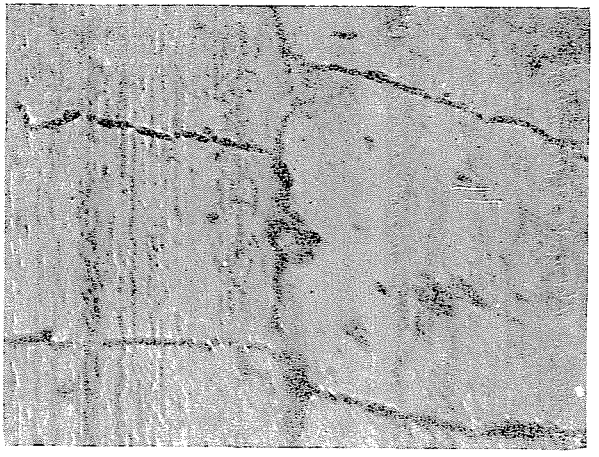

Fig. 17

(compare with Fig. 8). This picture demonstrates the large depth of focus of the electron microscope.

Ball 5. (Load: 380 kp)

Figure 19 shows severe wear appearing in the form of delamination. It is a consequence of the shadowing that the parts with bright edges emerge from the surface. This electron microscopic picture probably shows a magnification of the area seen in Fig. 9.

We now pass to the discussion of the electron microscopic pictures taken from the surfaces of the cylinders worn in the Reichert apparatus.

Cylinder I (Load: 2 kp)

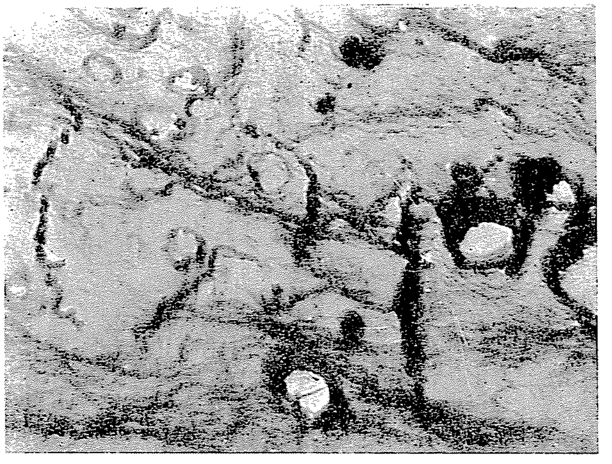

Fig. 18

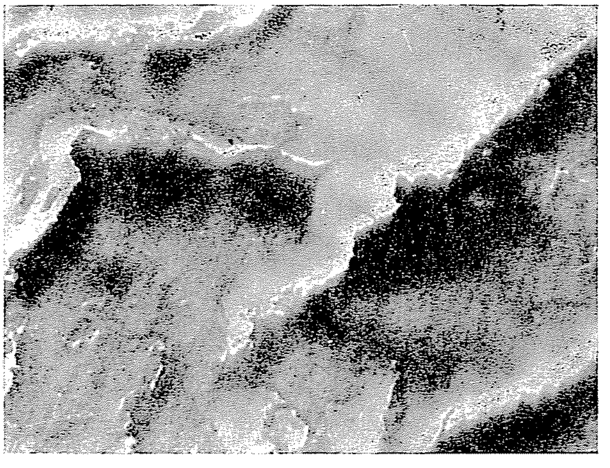

Fig. 19

A magnification of the fine grooves shown in Fig. 10 can be seen in Fig. 20. What is seen in the middle of the picture is probably the embedding place of the wear particle responsible for ploughing the shown groove. The particle itself cannot be observed in the picture, it was apparently removed in further wear or in the preparation of the cleaning replica.

Cylinder II (Load: 20 kp)

Figure 21 is a very interesting picture, since the boundary between a relatively smooth and a severely damaged area (as shown on Fig. 11) can be seen.

Cylinder III (Load: 30 kp)

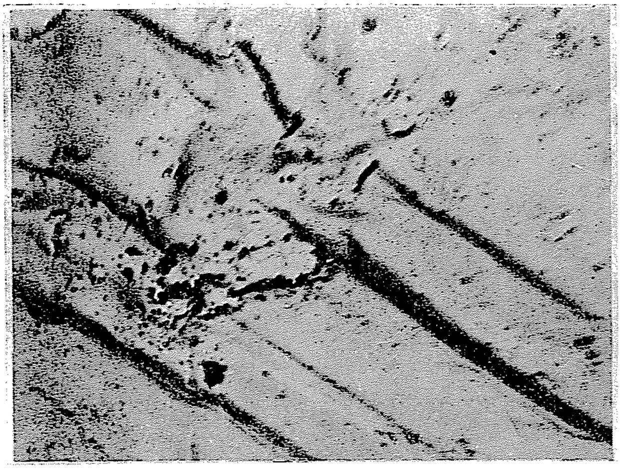

Fig. 20

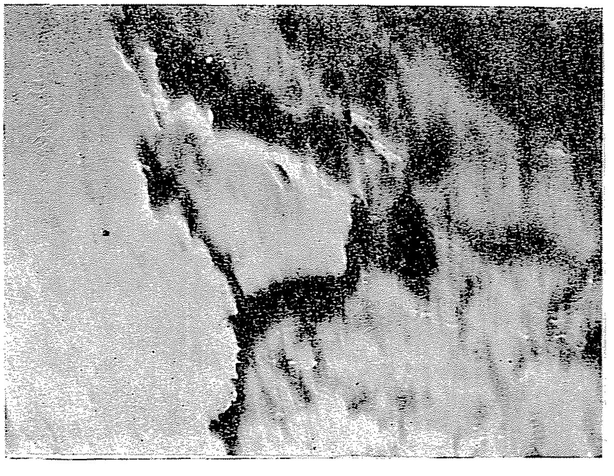

Fig. 21

Figure 22 shows a cracked surface being in the state of delamination. The vaporization shadow points to a well-defined difference in the level of the two depicted areas. A wear scratch can be seen very clearly in Fig. 23. It is interesting to observe the tracks of splintering occurring at the formation of the main scratch and resulting in the formation of small secondary scratches beginning at the main scratch.

Cylinder IV (Load: 40 kp)

A deep crack can be seen in Fig. 24 which shows the roughness of the 'smooth' surfaces seen in the pictures taken by conventional microscopy. Very fine wear grooves can also be seen on this 'smooth' surface. Figure 24 corresponds well e.g. to the area in the centre of Fig. 13 where the 'smooth'

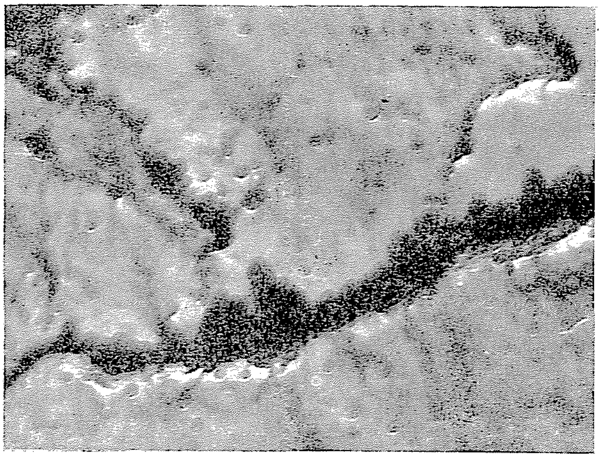

Fig. 22

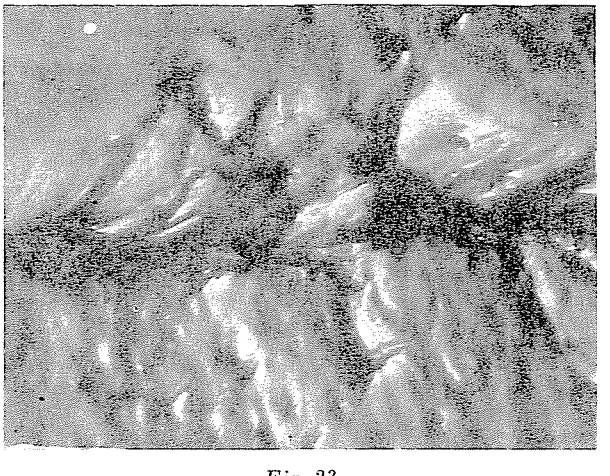

Fig. 23

surfaces are penetrated by fine cracks. Summarizing what has been said it can be stated that the electron microscopic pictures support the wear mechanism assumed on the basis of conventional microscopic observations as described in the foregoings. One supplementary remark should be added: formation and spread of cracks and delamination presumably have a greater role in the mechanism of wear than could have been thought on the basis of conventional microscopic observation.

Electron microscopy allowed to observe the formation of cracks and the delamination of the surface also on the balls worn in the four-ball apparatus. This phenomenon could not be seen by conventional microscopy. Thus, based on the additional information provided by electron microscopy, it is necessary to supplement the wear processes described in the discussion of conventional microscopic pictures inasmuch that formation of cracks and delamination occurs also on the balls of the four-ball apparatus before welding takes place. The mechanism of wear is thus similar in the two testing apparatuses in spite

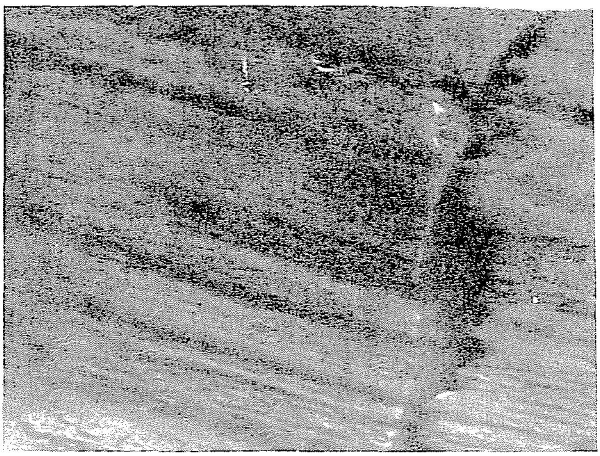

Fig. 24

of their different geometry. The combined application of conventional and electron microscopy has been found definitely advantageous. Conventional microscopy gives valuable informations in itself, but additional electron microscopic observations help in obtaining more accurate knowledge on the condition of worn surfaces.

Summary

The surfaces of test specimens from the four ball and the Reichert wear testing apparatus have been studied by conventional and electron microscopy. For electron microscopy, a two-stage replica technique has been applied. Based on the microscopic observations, the following phenomenological description can be given for the wear processes occurring in both apparatuses. At light loads, fine scratches and grooves are formed, broadening and merging at increased loads. Thus, the contact will gradually become plane-on-plane type. Subsequently, probably owing to mechanical and thermal stresses, cracks begin to form in the "smooth" surfaces. After the spread of cracks, the material delaminates.

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