Research on Pitting Strength under Rolling Contact of a Structual Mild Steel

Takashi FUKUI* and Yoshio TOKIHIRO*

Abstract

Wear may be defined as the unwanted removal of solid material from rubbing surface and it contains diverse phenomena such as adhesive, abrasive, surface fatigue, seizing etc. But, in general, one of the these types of wear does not occur individually, but two or three types of wear occur together.

Therefore, wear mechanisms of metal have been already studied by many investigators for various material under the simple condition. But, there are few basic studies under the actual condition. In this paper, the present investigators have studied (friction speed and lubricating method are constant) the relationship of the Hertz's stress Pm on pitting of a structual mild steel with carbon 0. 118% preceded by normalized at 900°C through measurement of wear loss and observation of wear surface.

1. INTRODUCTION

Wear means the unwanted removal of solid material from rubbing surfaces. So far as the wear of metal against metal is concerned, many results of study1)~21), especially of study at laboratories have already been presented. From the viewpoint of its phenomena, wear can be classified thus : adhesive wear, abrasive wear, pitting, fretting, and corrosive wear. As for pitting, it is a phenomenon which is caused when the contact stress of a certain strength over the limit is repeated about 10^6 times. This phenomenon has much to do with such machine elements as antifriction bearing, gear, and rolling mill. (When this phenomenon spreads all over the surface of material, it is called spalling.) And pitting confines the conditions of usage and the endurance of materials. Therefore, in order to prolong the endurance of these mechanical elements, and to find the appropriate conditions of usage, it is important to analize the rolling conditions of these mechanical elements, the mechanism of pitting in various contact stresses, the characteristics of pitting of materials, and the influences of heat treatment, of surface finishing and of method of lubrication upon pitting.

As for the mechanism of pits' occurance under rolling contact, S. Way1), for example, presented long ago the result of his study. In his opinion, the repetition of contact stress causes cracks on the surface of the materials, owing to the fatigue of the materials ; and into the cracks penetrates lubricant whose pressure enlarges the cracks and causes pits. After him, Nishihara and Endo4) examined the same problem, applying various terms of fatigue fracture to rolling contact. They think that the mechanism of pits' occurance and the influence of lubricant can be explained by measuring the average of shearing stress or shearing strain energy from the surface to a certain depth. Besides, there is Kuroda's shearing-stress-amplitude-maximum theory18).

Anyway, all these investigators are of the same opinion that the starting point of pits lies at a certain depth from the surface of material.

Therefore, in this paper, the present investigator, taking these theories into consideration, made endurance tests of mild steel under the condition of lubrication and slide, and examined the conditions of pits' occurance under each contact stress, through means of measuring wear loss and

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* Mechanical Engineering cource, Yamaguch University Technical Jurior College

of the visual observation of the wearing surface.

2. TEST PIECES AND METHODS OF EXAMINATION

2. 1 Test pieces

As the test pieces, the commercial structural steel (SS 41) 45ϕ are normalized from 900°C×2hr. The chemical contents and mechanical properties of these test pieces are indicated in Table 1 ; the normalized structure in Fig. 1 ; the test pieces are finished by lathe as shown in Fig. 2. Fig. 12(a) shows the roughness curve of the surface of the test pieces which are measured by Kosaka's profilometer (length : 500 times, width : 10 times). (Both of the upper and the lower test pieces are the same in their roughness.)

Table 1 Chemical composition and mechanical properties of normalized test piece

Chemical composition								Mechanical properties		
C	Si	Mn	P	S	Cu	Ni	Cr	Yield point (kg/mm^2)	Tensile stress (kg/mm^2)	Hardness (Hv)
0.118	0.16	0.50	0.002	0.006	0.15	—	0.13	30	48	108

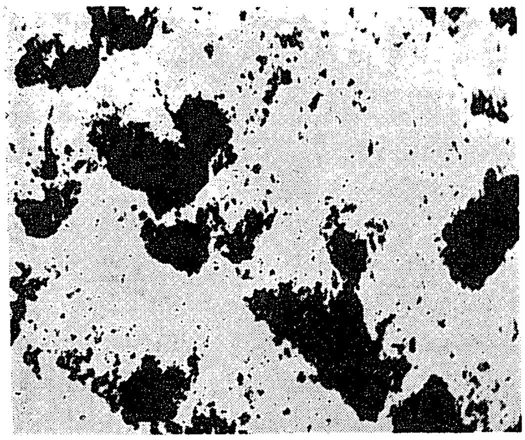


Fig.1 Microstructure of test piece normalized at 900°C for 2 hours Magnif. : ×400

2. 2 Testing machine and methods of examination

As the wear testing machine, the Amsler type (the upper test piece : 200 rpm, the lower test piece : 220 rpm) is used. When the test pieces of the shape and dimension shown in Fig. 2 are used, relative sliding rate 10% and friction speed 0.46m/sec must be given. In order to keep a constant lubrication on the contact surface of the test pieces, kerosene is given at the rate of 1 cc/sec from the oil tank of the testing machine. Wear loss is measured every 300000 turns. After the test pieces are washed in benzine and alcohol and dried, the measurement is taken with a precision chemical balance and at the same time the visual observations of the test pieces is carried out. Consequently, when the wear loss of the test pieces gets remarkably great due to the pits of them , the examination is stopped. And when there is no pitting even after the contact of the test pieces is repeated many 10^7 turns, the examination is also stopped here. Judging from the results of these examinations, the relation between wear loss and the number of contact repetition is shown in diagrams, from which the limit strength of pitting of the used material can be judged.

2. 3 Computation of the maximum compressive stress and the width of contact area

In this computation, two cyrindalical test pieces of the same quality shown in Fig. 2 are used. When the test pieces are in elastic contact with each other, the maximum compressive stress (Pm) and the half width of contact area (b) are, owing to Hertz's elastic contact theory, given in the following formulas[2) :

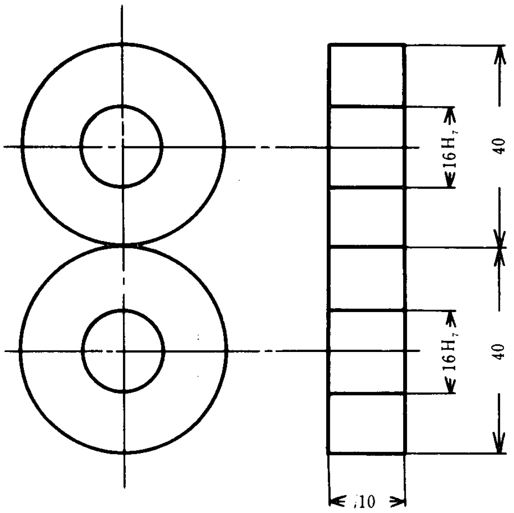


Fig. 2 Shape and dimension of test piece for wear test

$$Pm=\sqrt{\frac{m^2EP}{\pi(m^2-1)BR}}$$

$$b=\sqrt{\frac{4(m^2-1PR)}{\pi m^2BE}}$$

Symbols :

P : load given between the test pieces (kg)

E : Young's modulus (kg/mm^2)

$\frac{1}{m}$: poisson's ratio

B : width of the test pieces (mm)

R : radius of the test pieces (mm)

Pm and b which use this examination are shown in Table 2.

Table 2 Relationship of compression load (P), maximum compressive stress (Pm) and contact width (b)

P (kg)	170	130	100	80	60	40	25	9
Pm (kg/mm^2)	83.2	73	64	57.2	48.6	40.3	32	23
b(mm)	0.13	0.11	0.1	0.09	0.08	0 06	0.05	0 03

3. RESULTS

3. 1 Measurement of wear loss

The relation between wear loss and the number of contact repetition is shown in Fig. 3～Fig. 9 under the same lubrication and under the contact friction speed and sliding rate. These figures show that the greater the maximum compressive stress gets, the smaller the number of the contact repetition becomes. And as other articles[2,11,12)] show, the wear loss of the upper test piece is greater than that of the lower one. As the maximum compressive stress gets under 73 kg/mm^2 and the number of contact repetition is over 6×10^5 turns, wear loss reduces just a little. This tendency seems to be due to the influence of the components of oxide film and the thickness of the wearing surface.

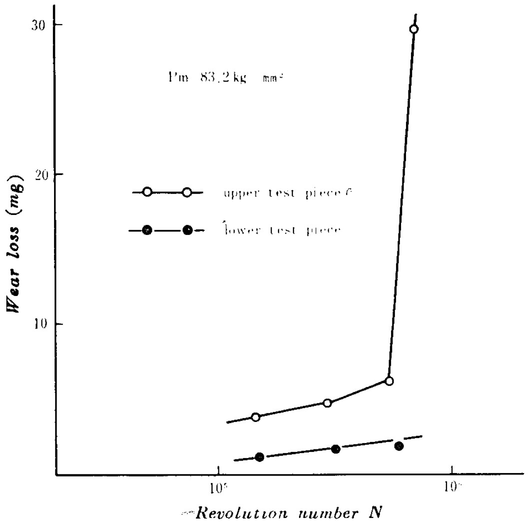


Fig. 3 Relation between wear loss and revolution number

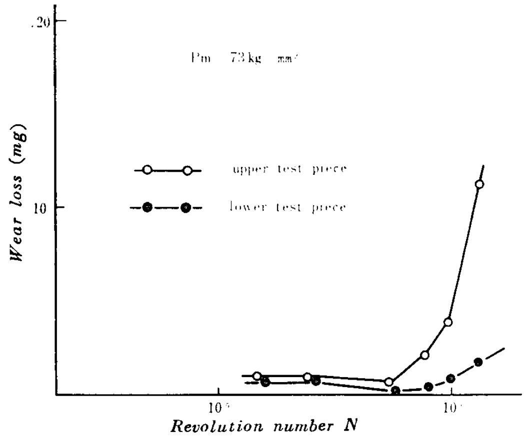


Fig. 4 Relation between wear loss and revolution number

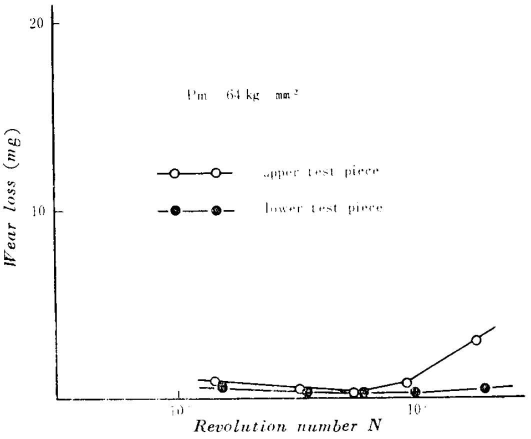


Fig. 5 Relation between wear loss and revolution number

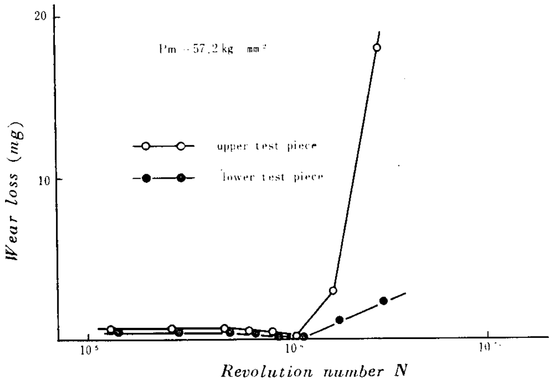


Fig. 6 Relation between wear loss and revolution number

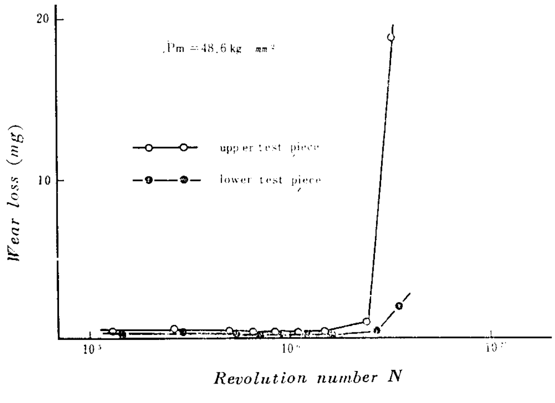


Fig. 7 Relation between wear loss and revolution number

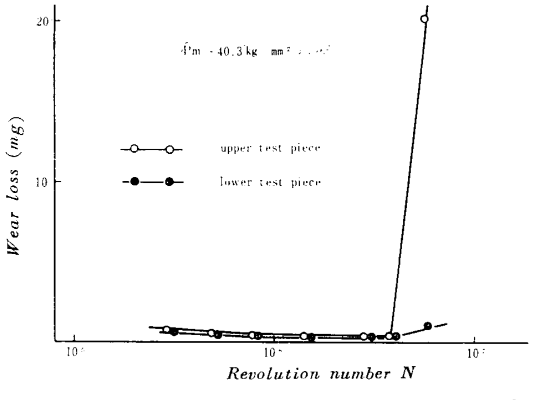


Fig. 8 Relation between wear loss and revolution number

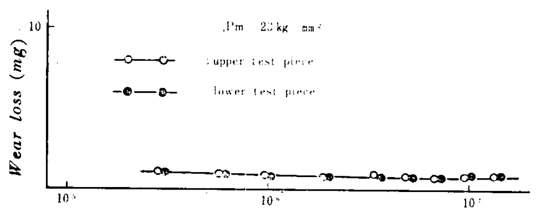


Fig. 9 Relation between wear loss and revolution number

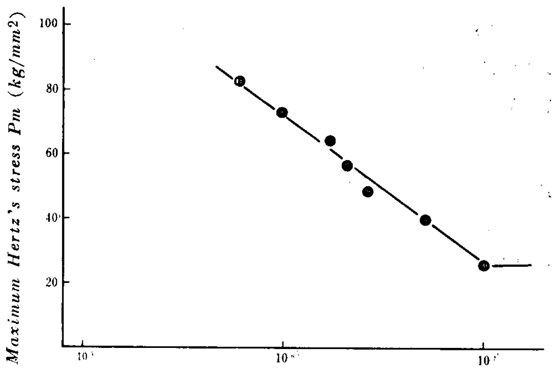
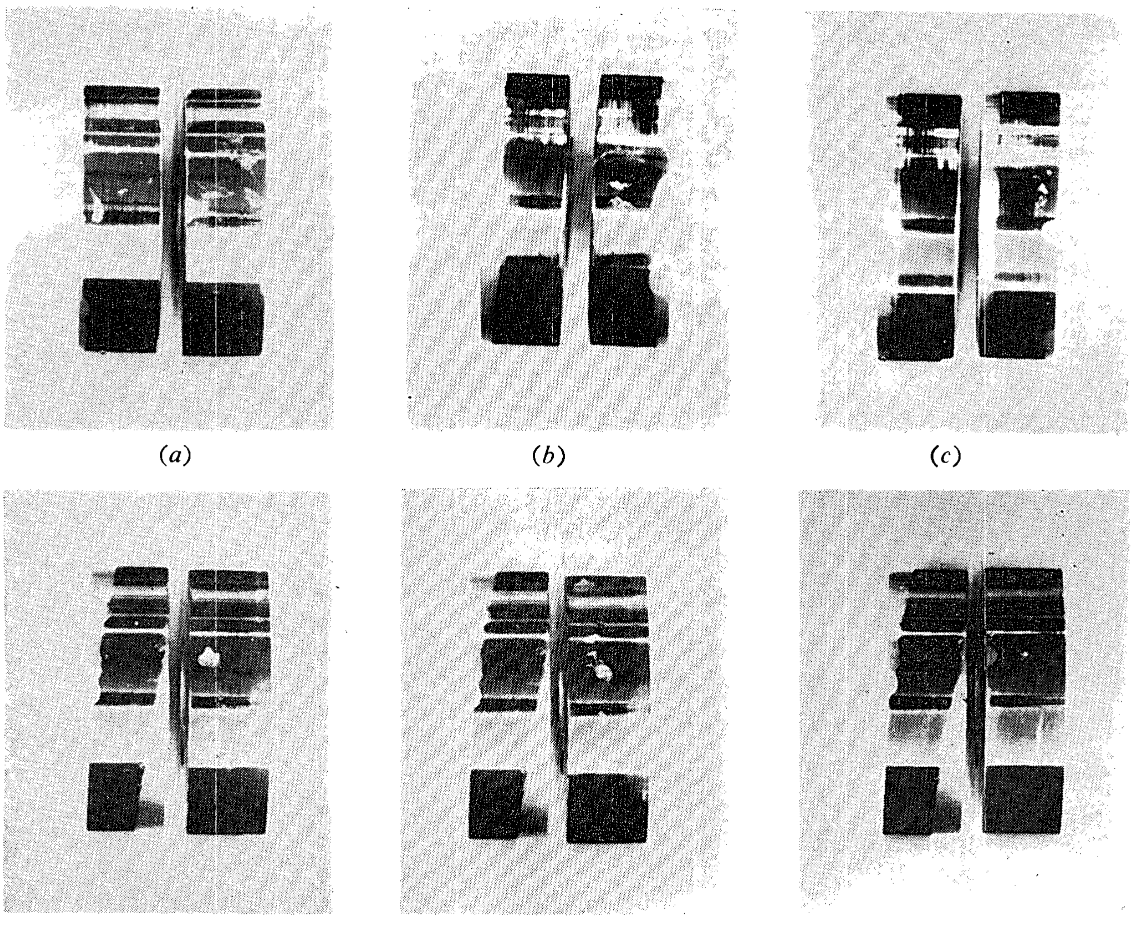


Fig. 10 S—N diagram for rolling contact of test pieces tested by various load



(*a*) (*b*) (*c*)

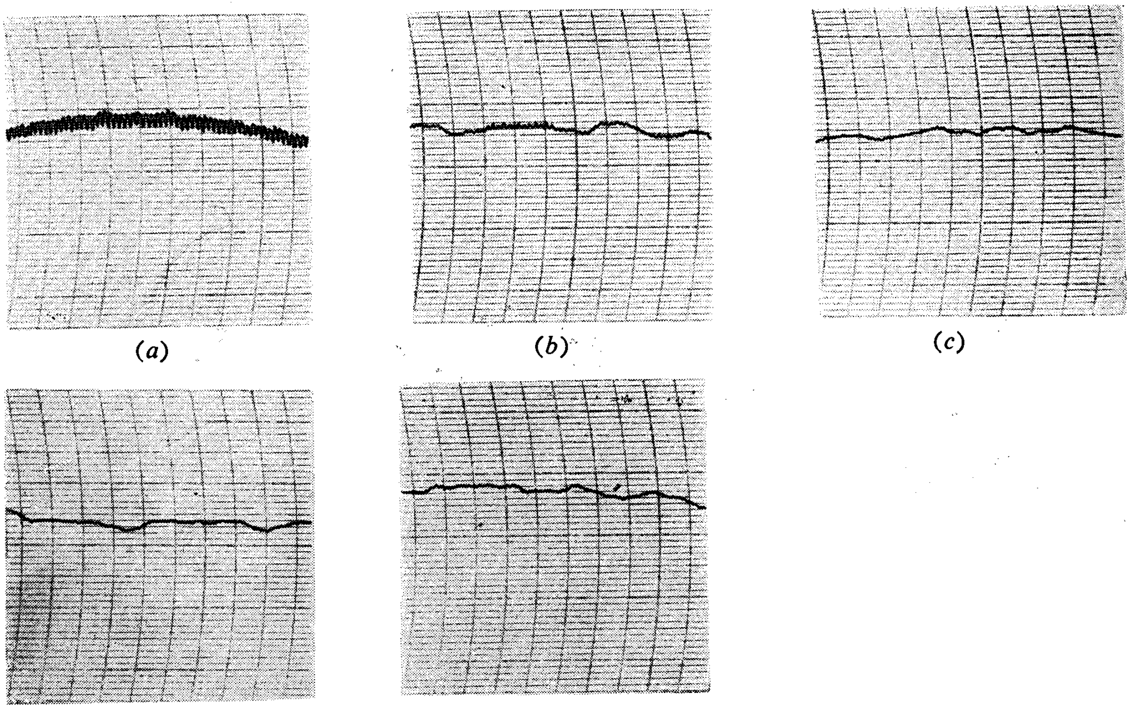
(*d*) (*e*) (*f*)

Fig. 11 Photographs of pit come to found on the surface of test piece (where : left=lower test piece, right=upper test piece)

(*a*) *Pitting by* $Pm=83.2kg/mm^2$, *revolution number* 5.5×10^5
(*b*) *Pitting by* $Pm=73kg/mm^2$, *revolution number* 7.8×10^5
(*c*) *Pitting by* $Pm=64kg/mm^2$, *revolution number* 1.1×10^6
(*d*) *Pitting by* $Pm=57.2kg/mm^2$, *revolution number* 1.6×10^6
(*e*) *Pitting by* $Pm=48.6gk/mm^2$, *revolution number* 2.7×10^6
(*f*) *Pitting by* $Pm=40.3kg/mm^2$, *revolution number* 4.0×10^6

Fig. 10 shows the relation between the maximum compressive stress and the number of contact repetition which is kept until pits begin to come about. It tells that the limit strength of pitting is 23 kg/mm^2 (the maximum compressive stress computed in Table 2). Fig. 11 is shown the pictures of pits which seem to be due to fatigue. Judging from these results, it is possible to say that the greater the maximum compressive stress gets, the greater pits become and that there is a clear correlation between the time when pits begin to come about and the time when wear loss increases suddenly.

3. 2 Roughness of wear surface



(a) (b) (c) (d) (e)

Fig. 12 Relation between roughness and revolution number at $P_m=48.6 kg/mm^2$
Magnif. : $(10\times500\times3/4)$

(*a*) *Revolution number*$=0$
(*b*) *Revolution number*$=3.9\times10^5$
(*c*) *Revolution number*$=5.8\times10^5$
(*d*) *Revolution number*$=7.7\times10^5$
(*e*) *Revolution number*$=9.7\times10^5$

As an example, Fig. 12 shows how the roughness of wearing surface change when the primary roughness of the test pieces is kept constant and the maximum compressive stress is also kept constantly 48.6 kg/mm^2. (The measurement is taken in the same way as the primary roughness is measured.) As the number of contact repetition increases, the surface distinctly gets smooth and the roughness of it decreases. And the repetition gets over about 6×10^5 turns, there can be recognized little change in the surface. By the way, as for the other stresses, almost the same tendency can be recognized, and it is possible to get the same conclusion that there is a correlation between the quantity of wear loss and the roughness of the surface.

3. 3 Hardness under the worn surface

Fig. 13 is shown the hardness under the worn surface of the test pieces when the endurance

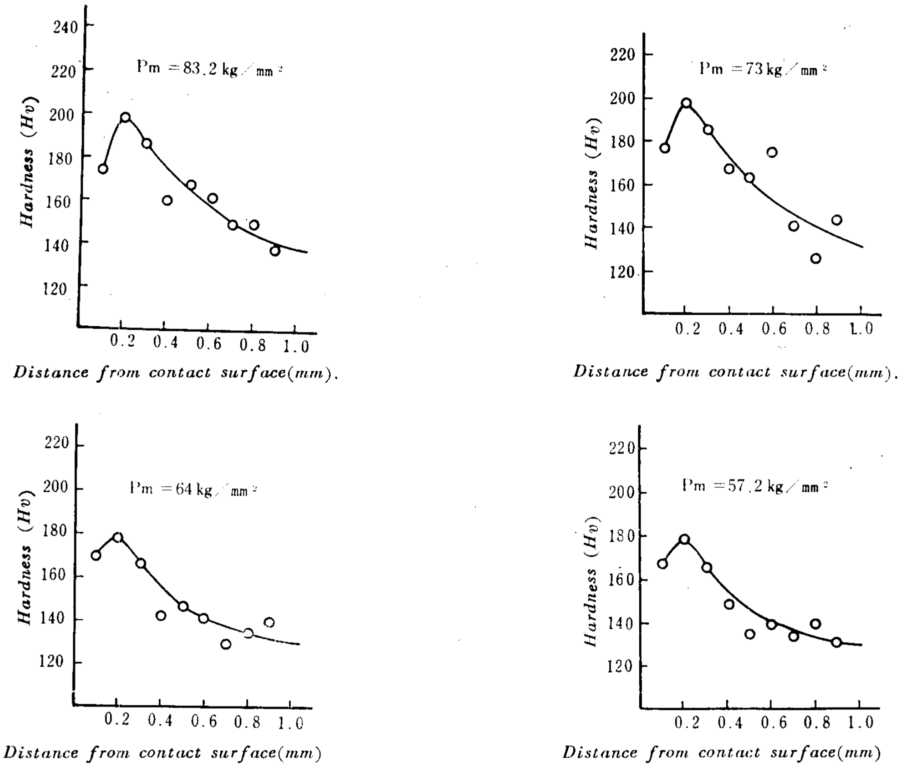


Fig. 13 Effect of contact load on the microhardness near the surface of test piece(in microvikers)

test is stopped. (The measuring apparatus : Leitz's microhardness tester, measuring load : 200 g and holding time : 30 sec.) This figure shows that although there is a little difference in matrix hardness, the greater the maximum compressive stress gets, the greater the ratio of the hardness due to the number of contact repetition becomes. Therefore the depth as which the maximum of hardness lies is about 0.15~0.25 mm from the worn surface. In case of other stresses, the same tendency can be recognized.

4. CONSIDERATIONS

As the Fig. 3 ~ Fig. 9 show, the wear loss of the upper test pieces is always greater than that of the lower one. From this point of view, following considerations will be given. Relative sliding rate is 10%. To be exact, however, the sliding rate of the upper test piece is 11% ; that of the lower test piece 10%. Generally speaking, it is true sliding rate has nothing to do with pitting. As for the change of the ratio of sliding rate below 10%, however, they are, as Nishihara and Kobayashi[2] maintain, closely related to each other, because on that occasion the coefficient of friction increases remarkably. And the wear loss of the upper test piece is usually greater than that of the lower one. Because of unlike rolling direction, the sliding direction of each test piece is different ; in the upper test piece there is tensile stress in tangential direction on the side where there is oil pressure ; and S. Way[1], and Nishihara and Endo remark, when cracks are produced by fatigue, lubricant can easily penetrate into the crack. Therefore, as Fig. 11 shows, there can be found much more pits in the upper test piece than in the lower one. Except when the maximum compressive stress is 83.2 kg/mm^2, the quantity of wear loss gets smaller, when the number of contact repetition is more than 6×10^5. And the smaller the maximum compressive stress gets, the more noticeable this tendency becomes. It is because of the blackish oxide film which has been produced in the course of the test. According to Yoshimoto and Tsukizoe[14], the component of this film seems to be Fe_3O_4. In the initial stage of this test, too, as they affirm, the temperature of the wear surface seems to have already risen up to the melting point, at least, in some point, speaking of the organizing process of the oxide film, the film is produced evenly all over the surface in the case of pure iron; which as the carbon contents increase, pearlite begins to appear in the matrix. And between the two phases the discrepancy of the qualities of oxygen in demand and of oxygen combined begins to arise, so that the oxide film can not be produced evenly all over the surface. As the results, between the two phases are produced gaps, which allow the penetration of oxygen into them. Therefore, the gaps between the crystals and structures are easy for oxygen to penetrate and much oxide is produced there.

In addition, the film is more porous than that which is produced by means of direct oxidation, because in such oxides as humidity and sulpher which are contained in lubricant exert influence upon the creation of this film[3)].

Speaking of the roughness of the indented surfaces, they are covered with a oxide film and get quite even after a certain number of contact repetition. This phenomenon seems, as Nakamura affirms, to be due to (1) the fact that the powder of wear loss which is sheared buring the contact repetition fills the concaves of the surface and welds with them with the heat of the melting point which generates during the contact repetition, (2) the fact that the powder which has undergone hard working is so apt to oxidate that oxide films are easily produced over the surface, and (3) the fact that the protuberances, if not sheared, get partly so heated that they become the so-called "melting state," which promotes the plastic deformation of them and makes the surface even. As for the hardness of the test piece under the worn surface, as Fig. 13 shows, the maximum hardness layer lies at the depth of 0.15~0.25mm. And contrary to any theories as to pitting, which we have referred to so far, which affirm that the maximum hardness layer lies at the depth of 0.56~0.76 b. the hardness distribution of the test piece shows the same tendency as that of the surface rolling, which Ōkoshi and Sata[16)] point out. It is (1) because, as Fig. 11 shows, the two test pieces do not contact wholly with each other, so that the edge effect is strong, and the stress distribution at the edges approximate to secondary stress; and (2) because the relative sliding rate of the test pieces is so much as 10%, so that compared with the case of no slide, the maximum stress increase 14%, and the point at which the compressive stress comes to its maximum lies within the depth of 0.1 mm.

Therefore, if one of the two test pieces is given such working as chamber in order to remove the edge effect, the point of the maximum compressive stress confirms approximately to the value of calculation on paper.

5. SUMMARY

The results obtained may be summarised as follows:

(1) Maximum compressive stress 23 kg/mm^2 is the limit strength of pitting.

(2) In case that wear loss raises suddenly, pitting of test piece is apparent.

(3) In case that maximum compressive stress is below 73 kg/mm^2, wear loss slightly reduces at about 6×10^5 revolution number.

(4) It seems that temperature of local wear surface nearly raises at melting point at the beginning of the experiment.

(5) Hardened layer owing to repeat contact stress exists 0.15~0.25mm under the wear surface. But, it seems effect of burnishing.

(6) Initial roughness of wear surface is smoothed through comparative few repetition of the contact stress, then the roughness becomes constant. The degree of constant roughness of

the surface depends on the test condition.

Acknowledgement

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