620.178.162.2

Effects of Surface Roughness and Running-in upon Pitting Fatigue in Rolling Contact Surface*

(2nd Report, Effects of Cyclic Work-Hardening)

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A study was conducted on the relationship between the increase in hardness due to rolling contact and the pitting fatigue limit. Results obtained are as follows: (1) Allowable contact stress, namely shakedown limit, for pure rolling elements made of steel which have work-hardening ability can be shown by $p_{j\max} = (0.42 \sim 0.89)H_B'$, where H_B' is Brinell hardness after an arbitrary number of rotations at the point where reversed shear stress caused by the contact stress is maximum. (2) Theoretical pitting fatigue limit can be shown by $p_w = 0.4 H_B' = 0.4C H_B$, where H_B is the Brinell hardness of the specimen before running, and the maximum value of C obtained from authors' experiment was about 2 in the case of carbon steel ($H_B = 160$). (3) It is better not to consider that the hardening in rolling contact is of fatigue hardening nature as in the case of rotating bending, because the increase in hardness caused by the cyclic plastic deformation at the subsurface of rolling element in this case is being performed under a hydrostatic pressure condition.

1. Introduction

It is said that pitting which occurs on rolling contact surfaces is caused by fatigue of material due to repeated contact stress. Because the surface where the force is transmitted from one body to another is the same place where the damage (pit) occurs, work-hardening (changes in physical properties) of material greatly affects the fatigue of material in rolling contact.

Explanations on the rolling contact fatigue limit described in the past publications^{(1)~(3)} indicate that the fatigue limit in rolling contact is comparable with the fatigue limit in compression or in twisting assuming that the changes in properties of materials are negligible. However, the authors' experimental results⁽⁴⁾ in which no pitting occurred at a Hertzian stress of $0.71 H_B$ could never be explained by these publications. Up to now, it is not clear as to whether or not the fatigue strengths of the work-hardened layers, which are produced by the repeated stresses at the surface and/or subsurface of rolling elements, are higher than those of layers which have not

undergone work hardening. Moreover, it is not clarified whether or not Miner's law (a law of linear cumulative damage)⁽⁵⁾ can be applied to rolling contact fatigue damage.

In the present investigation, when rollers work hardened by an original method under repeated stress were used, the pitting limit was elevated to a value higher than that mentioned in the previous report⁽⁴⁾. And, the effects of work-hardening at the surface and/or subsurface of the rollers on rolling contact fatigue are clarified.

2. Testing machine, test pieces and experimental conditions

The rolling contact fatigue testing machine used in the present experiments is the same as the one used in the previous experiments. Shapes and dimensions of the test pieces (rollers) are shown in Fig. 1. The bores of the rollers are tapered to a Morse taper No. 5 for preventing the run-out of rollers resulting from fretting corrosion which is apt to occur at the interface of the bore and shaft. The rollers were mounted tightly on the shaft, on which MoS_2 was applied, and the run-out and resulting hindrances during tests were avoided.

* Received 24th June, 1969.

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The outer surface (contact surface tested) was finished by grinding or superfinishing. The ground surfaces were of peak-to-valley roughnesses ranging from 3 to $5\mu\text{m}R_{\text{max}}$ and the superfinished surfaces, which were produced after grinding to a roughness of about $1\mu\text{m}R_{\text{max}}$, were of roughnesses ranging from 0.5 to $0.2\mu\text{m}R_{\text{max}}$. The rollers which mated with the pitting roller (160 Brinell hardness number H_B) were of two hardness grades: One was identical with the pitting roller [Fig. 1 (a), 0.45 % carbon steel, 160 H_B] and the other was made of a 0.45 %

Fig. 1 Dimensions of test rollers

carbon steel having hardnesses of 350 and 420 H_B . The mating rollers of 420 H_B were cylindrical in shape and 25 mm in length [Fig. 1 (b)].

Each of the experiments was started after confirming that the run-outs of rollers were less than $15\mu\text{m}$ (about $5\mu\text{m}$ in most cases). The rotational speed was increased to the designated value (3 570 rpm, unless specified) under no load. The load was increased up to the designated value within about 1 minute after the temperature of lubricating oil had reached 40°C . The following roller was freely driven by the driving roller. Differences in rotational speed of driving and following rollers were absent as confirmed with a numerical revolution meter and hence it was concluded that these rollers were under pure rolling. As lubricating oil a DTE Heavy Medium gear oil (trade mark of Mobil Petro, Ltd.) was used and it was flooded from a point 20 mm above the region of contact of the rollers at a flow rate of 1.4 l/min through a nozzle 8 mm in diameter.

In order to simplify the descriptions which

Table 1 Numbers given to the main experiments and their respective conditions

Numbers of experiment	Hardnesses of rollers (H_B , Brinell)		Roughnesses (μm , R_{max} , Before running)		Applied load kg	Hertzian stress kg/mm^2	Repetitions of contact (Rotations)	Number of pits
	Driver	Follower	Driver	Follower				
[1]	160	420	5	0.4	670	123	10^4	0
[2]	160	420	5	0.4	670	123	10^5	0
[3]	160	160	5	5	670	123	1.1×10^7	1 (Small, 6.8×10^6) 1 (Very large, 1.1×10^7)
[4]	160	420	5	5	120	52	1.6×10^7	Many
[5]	160	420	5	5	570	113	10^6	Many
[6]	160	420	5	5 0.3	200 670	67 123	10^6 5.7×10^5	0 Many
[7]	160	420	5	5 0.3	400 670	95 123	10^5 7.8×10^5	0 Many
[8]	160	420	5	5 0.3	400 620	95 118	10^5 7.96×10^5	0 Many
[9]	160	420 350	5	5 0.3	400 620	95 118	10^5 10^7	0 0
[10]	160	420	5	5 0.3	400† 620	95 118	10^5 2×10^7	0 0
[11]	160	420	5	5 0.3	200† 620 700	67 118 126	10^6 2×10^7 10^6	0 0 0
[12]	160	420	5	5 0.3	400† 670	95 123	10^4 1.2×10^6	0 Many
[13]	160	420	5	0.3	620	118	6×10^6	8
[14]	160 (160) ←	160 420	5	5 0.3	670 620	123 118	1.1×10^7 10^7	0 (0.175 mm Surface removal) 0
[15]	160 (160) ←	160 350	5	5 0.3	470 670	103 123	10^7 10^7	0 (0.25 mm Surface removal) 1 (Pitting crack)
[16]	160	160 420	5	5 0.3	470 670 750	103 123 130	10^7 10^7 10^7	0 (0.25 mm Surface removal) 0 0

† Rotated in the opposite direction (see Fig. 10)

follow, a number was given to each main experiment and the corresponding maximum Hertzian stresses, numbers of rotations, etc. are shown in Table 1.

3. Flow of texture and changes in hardness at contact stresses of over shakedown limit

3.1 Shakedown limit of work hardenable materials

K. L. Johnson calculated the shakedown limit of a system consisting of a rigid cylinder rolling on an elastic-perfectly plastic semi-infinite solid, and obtained the equation⁽⁶⁾,

$$p_{\max} = 4.0 \tau_k \quad (1)$$

where $p_{\max}$ is the limit of the maximum Hertzian stress which is allowable on the rolling contact surface; τ_k is yield stress in simple shear. He also pointed out⁽⁷⁾ that a surface layer $\delta = 0.5y$ in thickness moves in the direction of rotation of roller due to plastic deformation and that this movement accumulates as the number of contacts is increased when the Hertzian stress is over the limit $4.0\tau_k$. $2y$ is the Hertzian contact band and is given by Eq. (2) for the present experiments.

$$2y = \sqrt{\frac{32(1-\nu^2)P}{\pi E b \left(\frac{1}{r_1} + \frac{1}{r_2} \right)}} = 0.0268 \sqrt{P} \quad (\text{mm}) \quad (2)$$

where, P (kg) is the normal load applied on the roller. In the case of materials having work hardening property, the limit which is calculated by substituting the yield stress in simple shear (strain of nearly zero) into Eq. (1), i. e., $p_{\max} = 4.0 Y_E / \sqrt{3}$ and $p_{\max} = 4.0 Y_E / 2$ following the yield conditions of von Mises and Tresca respectively (Y_E = yield stress in simple tension or compression) does not give the lower limit of Hertzian contact stress at which the accumulative movement of the surface layer begins to occur. A value of τ_k in work hardenable materials increases along with the number of contacts and the resulting plastic deformation is sometimes visible and sometimes not visible under the microscope ($\times 400$) when $p_{\max} > 4.0 Y_E / (\sqrt{3} \sim 2)$. Therefore, an exact value of τ_k can only be obtained by measuring the hardness (yield stress) at a point $0.5y$ below contact surface.

The authors give the shakedown limit $p_{j\max}$ of work hardenable materials, which corresponds to Eq. (1), as,

$$p_{j\max} = 4.0 \frac{(Y_E \sim Y')}{\sqrt{3} \sim 2} \quad (3)$$

where, Y' is the yield stress in simple compression after arbitrary number of contacts at the point $0.5y$. In order to give $p_{j\max}$ as a function of Brinell hardness number, it must be noted that the resistance in plastic deformation (yield pressure) is $3Y$, and is not $3Y_E$ or $3Y'$, because there is an appreciable amount of plastic deformation at the point where the ball (indenter) is impressed. There is an appreciable difference between the yield stress in simple compression Y' of the material subjected to cyclic plastic deformation and the yield stress of the same material at the margin of Brinell indentation Y , where a definite amount of plastic deformation ($\approx 20d/D\%$, d = diameter of indentation, D = dia. of indenter)⁽⁸⁾ is observed. For instance, the yield stress Y of an annealed mild steel is about twice the yield stress $Y_E (= Y')$ and is nearly equal to the tensile stress σ_B . In elastic-perfectly plastic and/or fully work hardened materials, $Y_E = Y' = Y = \sigma_B$. By putting $Y_E/Y = j$, Eq. (3) is rewritten as Eq. (4).

$$p_{j\max} = \frac{4.0j}{\sqrt{3} \sim 2} \frac{1.15H_B'}{3} \quad (4)$$

$$= (0.77 \sim 0.89) H_B' \quad (5)$$

$$= (0.77 \sim 0.89) j H_B' = C' H_B'$$

$$= (0.42 \sim 0.89) H_B' \quad (6)$$

where, H_B' is the Brinell hardness number at the point $0.5y (= \delta)$ where the material is work-hardened. The shakedown limit of an elastic-perfectly plastic material is given by Eq. (5) as a function of H_B' . In the case of annealed steel, the limit is given by Eq. (6) because the value j is in the range 0.55 to 1. The value C would approach 0.89 as the value of H_B'/H_B becomes greater because the stress-strain curve of work hardened steel seems to converge to the curve of an elastic-perfectly plastic material. Therefore, the movement of surface layer which is imagined from the case of elastic-perfectly plastic materials or K. L. Johnson's theory would stop after a small number of stress repetitions as a result of increase in yield stress even when the Hertzian stress corresponding to the load applied is over the shakedown limit calculated using the yield stress Y_E in simple compression before running. However, the movement would not stop and continuation of running would become impossible due to changes in contact surface when the load exceeds a certain limit.

3.2 Stress repetition and flow of texture

The minimum value of shakedown limit, just over which plastic deformation begins to occur, is in the range 58 to 67 kg/mm² which is

obtained by substituting the yield stress $Y_E = 29$ kg/mm² in Eq. (3). From the experiments, the maximum value of shakedown limit, just over which plastic deformation at the point $\delta = 0.5y$ accumulates along with the repetitions of contact and results in stopping of the running test, is about 123 kg/mm² in the case of 0.45% carbon steel. In the above experiments the rollers of 160 H_B and $5\mu\text{m}R_{\text{max}}$ were used in combination with ones of 420 H_B and $0.4\mu\text{m}R_{\text{max}}$.

Figure 2 shows changes in texture of the softer roller in transverse section at the center of width after 10^4 rotations; etching reagent used is 5% nitric acid in alcohol. In Fig. 2, there is no appreciable change in texture within the region from the contact surface to the depth 0.1 mm. However, there is a trace of plastic deformation at the subsurface in the range 0.1 to 0.5 mm below the contact surface. It is also understood that a surface layer of 0.1 mm in thickness had moved in the direction of roller rotation by about 0.5 mm during 10^4 rotations. The texture after 10^5 rotations becomes as shown in Fig. 3. It is seen from Fig. 3 that the texture at about 0.25 mm below the contact surface has slid so as to make an angle of 64 degrees with the radial direction and has resulted in a 0.8 mm movement of surface layer of about 0.1 mm in thickness in the direction of roller rotation. It was estimated from the authors' experiments that the movement of surface layer at the Hertzian stress 123 kg/mm² would not stop even after running in excess of 10^5 rotations although the work hardening due to repetitions of contact stress is progressive. However, whether or not the movement of the surface layer actually

Fig. 2 Microphotograph of pitting roller rotated through 10^4 rotations at a Hertzian stress p_{max} of 123 kg/mm² ($=0.77 H_B$)

ceases could not be investigated because ripples, large in amplitude, occurred on the contact surface. The above-mentioned estimation was confirmed by the results of Exp. [6], in which the occurrence of rippling was prevented by a method proposed by the authors. For instance, one of the pits which occurred in Exp. [7] was in the shape of an equilateral triangle having a side length of about 9 mm (the width of roller is 10 mm).

3.3 Increase in hardness due to repetition of rolling contact stress

Figure 5 shows changes in hardness H_V of the rollers having an initial hardness of 160 H_B which were rotated through 10^4 , 10^5 , 5.7×10^5 , 1.2

Fig. 3 Microphotograph of pitting roller rotated through 10^5 rotations at a Hertzian stress p_{max} of 123 kg/mm² ($=0.77 H_B$)

Fig. 4 Microphotograph of pitting roller rotated through 10^6 rotations at a Hertzian stress of 67 kg/mm² and then rotated through further 5.7×10^5 rotations at a Hertzian stress of 123 kg/mm²

$\times 10^6$ and 1.1×10^7 rotations at a Hertzian stress of 123 kg/mm^2 . Micro-Vickers hardness H_V was measured by applying a load of 1 kg in all the experiments described in this paper. The rollers which rotated through 5.7×10^5 and 1.2×10^6 rotations at a Hertzian stress of 123 kg/mm^2 ($=0.77 H_B$) were obtained by adopting the method proposed by the authors, i.e., the roller of $160 H_B$ and $5 \mu\text{m} R_{\text{max}}$ was combined with the roller of $420 H_B$ and $5 \mu\text{m} R_{\text{max}}$ during the early stages of running under a smaller Hertzian stress and thereafter the harder roller was replaced with one having a smoother surface ($0.3 \mu\text{m} R_{\text{max}}$) and then rotated at a larger Hertzian stress (see Table 1). When soft and hard rollers were in combination, the running test could not be continued up to 10^7 rotations due to pitting. Therefore, the roller which was rotated through 1.1×10^7 rotations was one of the rollers in the combination which had no hardness difference. As clearly understood from Fig. 5, an increase in hardness per one rotation of roller becomes rapidly smaller with the increase in number of rotations. Pertinency of Eq. (6) showing the shakedown limit for work hardenable materials will be checked by using Fig. 5. Because the ratio of the Brinell hardness at a point 0.17 mm ($=0.5y$) to the Hertzian stress ($p_{\text{max}} = 123 \text{ kg/mm}^2$) is 0.54 ($=123/230$) and fairly larger than the minimum value of C' ($=0.42$), it is concluded that the forward movement of surface layer

would definitely continue during short period of running after 10^4 rotations. In the case of 10^5 rotations, the resulting ratio is 0.49 ($=123/250$) which is a little greater than the minimum value of C' . However, it is not clear as to whether or not the movement of the surface layer could continue because the value C' in Eq. (6) must have become greater than the minimum one ($=0.42$) due to the work hardening at the subsurface. From the results (Figs. 2~4), which show that this movement is existent at 10^5 rotations and over, it was found that plastic deformation could occur at a certain stress smaller than the yield stress which is obtained by testing the resistance to plastic deformation in one direction (hardness test) because the stress in rolling contact is cyclic.

K. L. Johnson proposed $\tau_k \doteq H_V/16$ for calculating the shakedown limit of work hardenable materials⁽⁹⁾. The Hertzian stress obtained by using this relation is $p_{j\text{max}} \doteq 0.7 H_B'$ and is 161 kg/mm^2 in the case of Figs. 2~4. The authors' result showing that plastic deformation can occur at a Hertzian stress of $0.49 H_B'$ can not be explained using K. L. Johnson's method.

4. Calculated pitting limit for work hardenable materials

It is found, from the authors' experiments, that the movement of the surface layer stops after a short period of running and that the increase in hardness at the subsurface (where the reversed shear stress is maximum) does not stop until about 10^7 rotations. Pitting seems to occur after the movement of surface layer has stopped but while the hardness at the subsurface is increasing due to repetition of the stress. The theoretical pitting limit can be derived by taking into consideration the authors' experimental result which shows that the allowable Hertzian stress on a roller is one half the shakedown limit obtained by using the hardness H_B' at the subsurface. It is assumed in the present paper that pitting occurs after a certain number of revolutions after the reversed shear stress $\tau_{s\text{max}}$ ($=0.25 p_{\text{max}}$) at a point $0.5y$ below the contact surface has reached a certain limit. Although this limit of shear stress has not yet been found, it is assumed to be equal to the fatigue limit τ_w in reversed twisting under non hydrostatic pressure. For steels, the relation between the fatigue limit τ_w and the tensile strength is approximately given by

$$\tau_w = 0.29 \sigma_B \quad \dots\dots\dots (7)^{(10)}$$

In the present level of study, there is no definite

Fig. 5 Relation between work hardening and number of repetitions of contact stress

evidence as to whether or not Eq. (7) is applicable to materials which are fully work hardened. However, it is assumed in this paper that Eq. (7) is usable in the calculation of the theoretical pitting limit. By substituting $\sigma_B = 0.35 H_B$ (for steel)⁽¹¹⁾ into Eqs. (1) and (7), theoretical pitting limit p_w is obtained.

$$p_w = 4.0 \tau_w = 4.0 \times 0.29 \times 0.35 H_B' = 0.406 H_B' \quad \dots\dots\dots (8)$$

Next, comparison is made between the pitting limit obtained from calculations and the one obtained by experiments. In the case of Exp. [3] (curve *e* in Fig. 5), the calculated and experimental results seem to be in disagreement because the calculated pitting limit is 140 kg/mm² and hence pitting should not occur in the experiment at a Hertzian stress of 123 kg/mm². When $p_w > p_{max}$, it seems much more likely that the pitting is caused by a micro crack which is produced at the contact surface due to repetition of metallic contact between the two contacting surfaces. Based on this argument, it can be concluded that, in the case of experiments conducted by past investigators, the crack which caused pitting first appeared at the contact surface (not subsurface) because the pitting limits obtained were in the range 0.2 to 0.35 H_B , which also agrees with one of the experimental results of authors. In Exp. [6], pitting has occurred because the calculated pitting limit p_w is 120 kg/mm² which is a little smaller than the Hertzian stress of 123 kg/mm² on the rollers in the experiment. Conformability of Eq. (8) was also checked in Exps. [9], [10], [11], and [14]. It is inconvenient to calculate p_w using Eq. (8) because the hardness H_B' at the subsurface must be measured. Equation (8) can be rewritten as a function of initial Brinell hardness as follows.

$$p_w = 0.4 C H_B \quad \dots\dots\dots (9)$$

where, C is a constant which has to be determined by experiment and varies with the hardness and the kind of material. In the case of a soft material such as an annealed 0.45 % carbon steel, C is about 2 as confirmed by the authors' experiments. Therefore, the maximum Hertzian contact stress allowable on a roller of a soft (160 H_B) 0.45 % carbon steel in pure rolling is about 130 kg/mm².

It is obvious that the harder the material the smaller the constant C becomes and approaches unity. Therefore, it should not be imagined that the maximum allowable contact stress (Hertzian stress) increases along with hardness for materials undergoing work hardening at the subsurface only (rollers having a

mirror finished surface). In the rollers with rougher surfaces, p_w is proportional to the initial Brinell hardness as confirmed by many past investigators.

5. Effects of surface roughness on pitting limit and shape of pit

5.1 Cases in which the harder roller is rougher

It is not impossible to prevent the occurrence of pitting in most cases when the harder roller is rough ($h_{min} < R_{max1}$) and is combined with a softer roller. For instance, the continuation of running tests becomes impossible due to an increase in number of pits which occurred after 1.6×10^7 and 10^6 rotations in Exps. [4] and [5] respectively. The increases in hardnesses of surface and subsurface of the rollers used in these experiments are shown in Fig. 6 and these results suggest that there is an intimate relation between pitting and work hardening of surface. It is important to note that the surface hardness of the roller rotated under a smaller load but for a longer time is greater than that of the roller rotated under reversed conditions. In the case of Exp. [4], it is impossible to think that

Fig. 6 Changes in hardness of pitting rollers in combination with a harder and rougher roller (420 H_B , 5 $\mu m R_{max}$).

pitting cracks growing into pits had occurred as a result of fatigue of the material at the subsurface where the maximum (reversed) shear stress occurred because the Hertzian stress $p_{\max}$ produced in this experiment was only 52 kg/mm^2 ($=0.33H_B$). Actually, there were no cracks arrested in the subsurface when the roller was cut and observed under a microscope at a magnification of 100.

5.2 Cases in which a harder, rough roller is replaced with a smoother one during the experiment

In order to find out the effects of work hardening at the surface on rolling contact fatigue damage, experiments were conducted under the conditions that only the contact surface was work hardened at an early stage of running

Fig. 7 Changes in surface roughness of rollers used in Exp. [10]

Direction of rotation at $p_{\max}=95 \text{ kg/mm}^2 \rightarrow$
 $\leftarrow$ Direction of rotation at $p_{\max}=118 \text{ kg/mm}^2$

Fig. 8 Microphotograph of pitting roller rotated through 10^5 rotations at a Hertzian stress $p_{\max}$ of 95 kg/mm^2 in the opposite direction and then rotated through further 2×10^7 rotations at a Hertzian stress of 118 kg/mm^2 ($=0.74H_B$) in the normal direction

(corresponds to the condition that the pits can occur at a smaller Hertzian stress) and the load was increased along with replacement of the roller for preventing the continuation of work hardening at the surface (Exps. [6]~[12]).

In the case of Exp. [6], the driving roller of $5 \mu\text{m} R_{\max}$ $160 H_B$ was in combination with a following roller of $0.5 \mu\text{m} R_{\max}$ $420 H_B$ and rotated through 10^8 rotations at a Hertzian stress of 67 kg/mm^2 . Then the follower roller was replaced with a smoother one ($0.3 \mu\text{m} R_{\max}$, $420 H_B$) and thereafter the load was increased to the value in Exp. [3] and the combination was rotated through another 5.7×10^5 rotations until the continuation of running became impossible due to the occurrence of many pits resulting in a loud noise. In the case of Exp. [7], the initial load was made greater than that in Exp. [6], but the duration of running was shorter (10^5 rotations) because running became impossible at about 6×10^5 rotations under this load ($p_{\max}=95 \text{ kg/mm}^2$). In Exp. [8] too, the continuation of running up to 10^7 rotations was impossible in spite of the fact that the load was made smaller than in Exp. [7] after the replacement of roller. The life of roller in Exp. [8] was shorter than that of the roller ($160 H_B$, $5 \mu\text{m} R_{\max}$) which was in combination with a harder but smoother roller ($420 H_B$, $0.3 \mu\text{m} R_{\max}$) and rotated under the identical load from the commencement of running (Exp.

Direction of rotation at $p_{\max}=67 \text{ kg/mm}^2 \rightarrow$
 $\leftarrow$ Direction of rotation at $p_{\max}=118 \text{ kg/mm}^2$
 and 126 kg/mm^2

Fig. 9 Microphotograph of pitting roller rotated through 10^6 rotations at a Hertzian stress of 67 kg/mm^2 in the opposite direction and then rotated through further 2×10^7 rotations at $p_{\max}=118 \text{ kg/mm}^2$ and 10^6 rotations at $p_{\max}=126 \text{ kg/mm}^2$ in the normal direction (Exp. [11])

[13]). However in Exp. [9], when the hardness of following roller was decreased by $70 H_B$ from the value in Exp. [8], the work hardened roller could rotate under a load of 620 kg until 10^7 rotations without producing even a single pit because the difference in hardness of rollers was smaller than that in Exp. [8] and this combination seemed to run under the condition similar to that in Exp. [3].

From the experiments mentioned above and the flow of texture shown in Figs. 2 to 4, it was inferred that the direction of plastic flow at and near the surface affected the formation of pits. Therefore, a new experiment was carried out in which the directions of roller rotation in the first and second stages of running were opposite (Exps. [10]~[12]). In Exp. [10], not even one pit occurred under a load of 620 kg until 2×10^7 rotations. Also in Exp. [11], no pitting occurred. Figure 7 shows the surface roughness of rollers used in Exp. [10] before and after running. Figures 8 and 9 show the textures of transverse section at the center of face width in Exps. [10] and [11]. It is clearly seen from Figs. 8 and 9 that the directions of plastic flow at and near the surface are opposite while the plastic flow is in the same direction in the case of Fig. 4 (seen dimly from Fig. 4). Experiment [12] was performed to compare it with Exp. [7] and also to see the effects on rolling contact fatigue of the plastic flow and work hardening due to cyclic contact stress, due to which the material became anisotropic. If pitting cracks

were to occur at the surface in the direction of plastic flow, the lubricating oil would be enclosed in the course of rolling contact in the case of Exp. [7] and would not be enclosed in the case of Exp. [12], i.e., the cracks would not grow into pits in the latter case. However, only a longer life (1.5 times) was obtained in the latter case and occurrence of pitting could not be prevented.

5.3 Location of pitting cracks and shapes of pits

There is no doubt that in the case of soft materials (in which pitting occurs at a Hertzian stress of about $0.3 H_B$) pitting cracks occur first at the surface. However, when pitting occurs or does not occur according to circumstances at a Hertzian stress of about $0.75 H_B$, there is a strong suspicion that the pitting cracks may be occurring first at the subsurface where the reversed shear stress is maximum. There are no pitting cracks arrested in the subsurface of the rollers which are rotated under the same conditions from the beginning to the end of running (cases in which the surface of roller was not work hardened at the beginning of running). Under the particular running condition in which the surface of roller was work hardened in the first stage of running (Exp. [7]), a single pitting crack lying parallel to the surface was observed at the subsurface as shown in Fig. 12. Pits which occurred under this running condition are nearly rectangular in shape and

Fig. 10 Changes in hardness of pitting roller in Exp. [10]

Fig. 11 Changes in hardness of pitting roller in Exp. [11]

are different from the one shown in Fig. 13 (b), which occurred under usual running conditions. Pits which occurred under larger loads corresponding to a Hertzian stress of over shakedown limit (i.e., $>0.4H_B$) were large in size, and the corresponding pitting cracks were supposed to have occurred at the subsurface (of course, this is not conclusive) and spread in the direction of plastic flow toward both inner and outer sides, resulting in pits as shown in Figs. 13 (c) and (d), for Exps. [6] and [8] respectively. Although, the inclinations of the contours of pits on the left side are different as seen in Figs. 13 (c) and (d), their directions perfectly agree with the directions of plastic flow.

6. Methods for elevating the pitting limit

6.1 Miner's law on rolling contact fatigue

The authors believe that the Miner's law is not applicable to rolling fatigue (pitting) because the changes in material properties (hardness) at the subsurface due to the cyclic stress are different at each different magnitude of applied load, i.e., the work hardening at the subsurface is done under hydrostatic pressure caused by contact stress. Especially, overloading in contact can elevate the pitting limit if it does not cause appreciable changes in the contours of the contact surface and also if its repetitions are small

Fig. 12 A pitting crack arrested in subsurface and lying nearly parallel to the contact surface (Exp. [7])

Fig. 14 Changes in surface roughnesses of rollers used in Exp. [14]

in number.

6.2 Removal of surface layer after running

The resistance to fatigue of the work hardened layer at the subsurface of used rollers seemed to have increased because the work hardening was produced under hydrostatic pressure

(a) Exp. [7]

(b) Exp. [4]

(c) Exp. [6]

(d) Exp. [8]

Fig. 13 Representative shapes of pits which occurred on pitting rollers

caused by the contact stress. Therefore, a new experiment was conducted, in which the surface layer of used rollers was removed by grinding 0.2 mm in thickness and then the rollers were run under loads greater or smaller than the previous ones (Exps. [14]~[17]). In Exp. [14], after 1.1×10^7 rotations at a Hertzian stress of 123 kg/mm^2 , the surface of roller was removed by an amount of 0.175 mm (corresponds to $\delta = 0.5y$) and then the roller was rotated through 10^7 rotations at a Hertzian stress of 118 kg/mm^2 without producing a single pit. The changes in surface roughness of the roller in Exp. [14] are shown in Fig. 14. The decrease in surface roughness was small because the work hardened layer produced by earlier running had been exposed by the removal of the surface layer. Therefore, the ratio, $D' = (R_{\max 1}' + R_{\max 2}')/h_{\min}$ which is based on the roughness after running-in, becomes about 4, and hence, the running condition in Exp. [14] falls into the category in which the pitting cracks occur first at the surface due to metallic contact between the rollers. The reason why pitting did not occur in Exp. [14] could be ascribed to the fact that the constant C corresponding to C' in Eq. (6) is about 0.33 when the Hertzian stress is expressed by the relation $p_{\max} = CH_B''$ based on the Brinell hardness H_B'' after running. That is, the proportional coefficient obtained ($C=0.33$) corresponds approximately to the maximum value in the

relation, $p_w \doteq (0.2 \sim 0.35)H_B''$, which is obtained by replacing H_B in the experimental pitting limit $p_w = (0.2 \sim 0.35)H_B$ with the Brinell hardness H_B'' after running. The above-mentioned fact can be taken as strong evidence showing that the work hardened layer at the subsurface is not weak in fatigue strength. Figure 15 shows the hardnesses of the roller in Exp. [14]. In Exp. [15], a surface layer 0.25 mm in thickness of following roller was removed after 10^7 rotations under a load 470 kg and then, the roller was mounted on the driving shaft in combination with a roller of $350 H_B$ and $0.3 \mu\text{m} R_{\max}$. The surface hardness of the roller after running was about $260 H_V$ which was softer than that in Exp. [14] because the removed layer was greater in thickness. Therefore, the surface roughness after running was smaller than that in Exp. [14] as shown in Fig. 16. Although no pits occurred, a single pitting crack was observed on

Fig. 15 Hardnesses of pitting roller used in Exp. [14]

Fig. 16 Changes in surface roughness of pitting roller used in Exp. [15]

Fig. 17 Hardness of pitting roller used in Exp. [15]

the roller. Figure 18 shows the hardnesses of the roller used in Exp. [16]. Changes in roughness of the roller are shown in Fig. 19 and they indicate the interesting fact that the surface roughness improved by running-in does not deteriorate again on further running of 2×10^7 rotations.

From the experimental results mentioned in this section, it is imagined that the load-carrying capacities of gears may become greater when a small amount of the surface layer of teeth is removed after running.

Fig. 18 Hardness of pitting roller used in Exp. [16]

Fig. 19 Changes in surface roughness of pitting rollers used in Exp. [16]

7. Conclusions

The shakedown limit of work hardenable materials such as a $160 H_B$ 0.45 % carbon steel which is the maximum value of Hertzian stress allowable on the rolling contact surfaces was calculated, and then, an equation showing the theoretical pitting limit (based on experiments) which is applicable to the rollers having the cyclic work-hardened layers was obtained. The results obtained are as follows:

(1) The shakedown limit can be given by the relation, $p_{j\max} = (0.42 \sim 0.89) H_B'$; where H_B' is the Brinell hardness number at the subsurface after an arbitrary number of rotations.

(2) Therefore, even when the rollers are rotated under a load corresponding to a Hertzian stress of over the shakedown limit (i.e., $p_{j\max} \geq 0.42 H_B$, in the case of a $160 H_B$ carbon steel) which is calculated using the yield stress in a simple compression test on work hardenable materials, macroscopic forward movements of the surface layer would cease after a short period of running in most cases. The shakedown limit of a $160 H_B$ 0.45 % carbon steel roller was about $0.77 H_B$.

(3) The theoretical pitting limit is $p_w = 0.4 H_B'$. The pitting limit of $160 H_B$ 0.45 % carbon steel was about $0.75 H_B$.

(4) When pitting occurred at a Hertzian stress less than $0.4 H_B$, there would be observed a layer appreciably work hardened and pitting cracks at the contact surface.

(5) By using a new roller obtained by removing the surface layer of the roller rotated through 10^7 rotations, thus bringing to the contact surface the location of $\tau_{z\max}$, where the hardness was increased to about twice the initial value, a running test up to 10^7 rotations was made under the condition in which the pitting cracks can be supposed to appear first at the contact surface. However, no pitting occurred at a Hertzian stress of $p_{\max} = 0.33 H_B''$ ($= 118 \text{ kg/mm}^2$), where H_B'' is the Brinell hardness number at the contact surface (subsurface in the previous running).

(6) The pitting limit obtained from many past investigations was about $p_w = (0.2 \sim 0.35) H_B$, but the coefficient of H_B obtained from the authors' experiment is nearly equal to the maximum value 0.35 if it is assumed that $H_B = H_B''$. This would give strong support to the opinion that work hardened layers produced by repeated contact stress are not weak in rolling contact fatigue because hardening at the

subsurface progresses under hydrostatic pressure.

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