Improvement of Surface Durability of Case-Carburized and Hardened Gear by Shot Peening and Barrelling Processes

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ABSTRACT

In this investigation, a surface durability (pitting limit) of the case-carburized steel rollers with surface hardness of 750 Hv is examined under rolling/sliding conditions using a rolling contact fatigue testing machine. Two kinds of rollers which are finished to a surface roughness of about 0.2 $\mu m R_{max}$ or about 3 $\mu m R_{max}$ by a cylindrical grinding machine are used. To improve the surface durability, the shot peening and the barrelling processes are employed and they are compared to the non-treated surface. The processes of shot peening and barrelling can be applied to surfaces with complex configurations, such as gear. Each surface roughness of rollers finished by above machining methods is measured before/after load running and residual stresses are also detected by an X-ray diffraction method. Consequently, it is clarified that the surface durability of rollers whose surfaces are subjected to the barrelling process after the shot-peening process is improved.

KEYWORDS

Tribology, Gear, Surface Roughness, Fatigue Strength, Pitting, Scoring, Wear, Shot-Peening Process, Barrelling Process, Case-Carburized Steel

1. INTRODUCTION

A surface durability of the gear is also affected by the compressible residual stress besides the hardness and the surface roughness(1)-(3). If the sum of tooth surface roughnesses of a pair of gears is smaller than the oil film thickness between them, the metal contact is prevented, and as a result the surface durability (pitting limit) will be remarkably improved(4).

Though a configuration of the surface with modification of the tooth profile and/or the tooth-trace is very complicated, the shot peening and the barrelling processes can be applied to finish the gear with a complex surface. While the shot-peening process is generally utilized to improve the bending fatigue strength of the tooth root of a gear(5), in the present investigation the effect of the shot peening upon the surface fatigue strength of a case-carburized and hardened steel gear will be examined. In this report, the surface durability of the case-carburized and hardened steel roller is examined

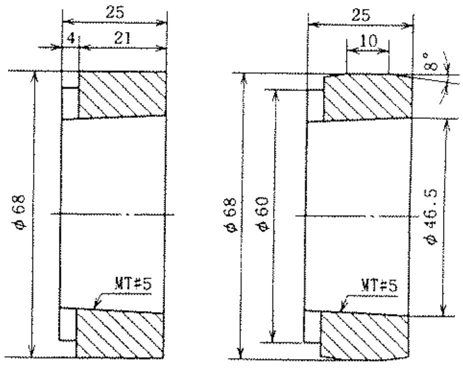


Fig. 1 Dimensions of rollers

using a highly loaded two rollers contact fatigue testing machine. It is well known that the surface and subsurface of the case-carburized and hardened steel roller have some compressive residual stress. First of all, all rollers are ground by a cylindrical grinding machine, thereafter some of them is shot peened and as a result of shot peening a compressive residual stress will be added to the surface and subsurface. And in addition to it, the surface durability of rollers barrelled after shot peening in order to improve the surface roughness is also examined.

Table 1 Chemical compositions of test rollers

Material	Chemical compositions (%)								
	C	Si	Mn	P	S	Ni	Cr	Mo	Cu
SCM822H	0.22	0.32	0.79	0.023	0.011	0.07	1.04	0.35	0.10

Table 2 Surface conditions of rollers

Group	Roughness of ground surface	Shot peening	Bar-relling
A	$R_{max} \fallingdotseq 0.2\mu m$	×	×
B	$R_{max} \fallingdotseq 3\mu m$	×	×
C	$R_{max} \fallingdotseq 3\mu m$	○	×
D	$R_{max} \fallingdotseq 3\mu m$	○	○

2. TESTING ROLLER AND EXPERIMENTAL CONDITION

2.1 Testing roller

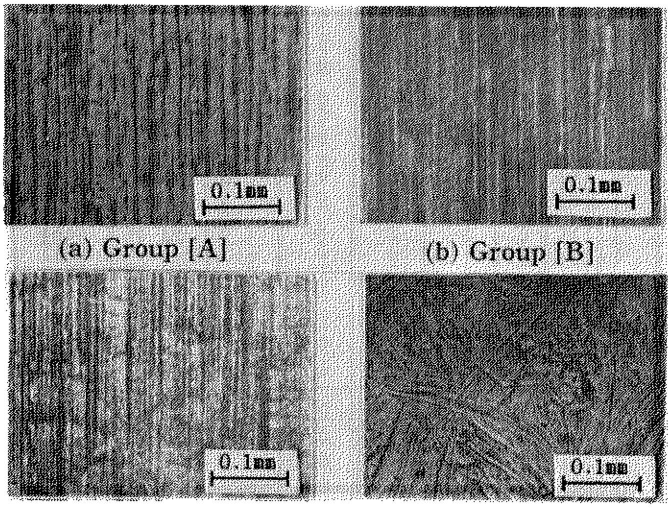
Figure 1 shows shapes and dimensions of test rollers. The outside diameter of rollers is ϕ68 mm and an effective face-width is 10 mm. The base material of test rollers is 0.22C-Cr-0.35Mo steel (SCM822H JIS steel). The steel roller is case-carburized at 1203 K (=930 ℃) and tempered at 433 K (=160 ℃). Table 1 shows chemical compositions of roller material. The depth of effective hardness over 513 Hv is about 2 mm from the surface. The load capacity running tests are performed using four groups of test rollers ([A]~[D]) as shown in Table 2. Surface roughnesses of rollers in Groups [A] and [B] had be respectively finished to $R_{max} \fallingdotseq 0.2\mu m$ ($0.1 \sim 0.2\mu m$) and $R_{max} \fallingdotseq 3\mu m$ ($2.5 \sim 4\mu m$) by a cylindrical grinding machine. The roller surface in Group [C] was ground by the grinding machine as same as one in Group [B] and thereafter shot peened in expectation of improving the surface durability by the effect of the

Table 3 Conditions of shot-peening process

Method	Shot material	Shot size(mm)	Hardness (Hv)	Pressure (MPa)	Arc height (mmA)	Coverage (%)
Air	RCW06PH	ϕ0.6	600	0.3	0.37	600

Table 4 Conditions of barrelling

Barrelling Material	Times (min)
Alundum	30



(c) Group [C] (d) Group [D]

Fig. 2 Surfaces of rollers before running the large compressive residual stress and the hardness on/below the surface by the shot-peening process. The roller surface in Group [D] was subjected to the barrelling process after shot peening in order to improve the surface roughness. Figures 2 and 3 show representative surfaces and surface roughnesses of four groups of rollers. Tables 3 and 4 show conditions of the shot-peening and the barrelling processes, respectively.

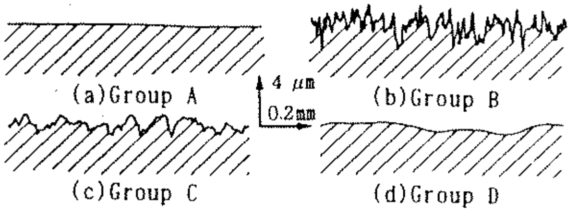


Fig. 3 Surface roughnesses of test rollers before running

Table 5 Properties of lubricating oils

Test oil	Density at 288 K g/cm^2	Fire point K	Pour point K	Viscosity mm^2/s		Viscosity index
				313 K	373 K	
Oil-Y	0.878	495	248	68	8.6	98
Oil-Z	0.886	509	253	150	14.8	97

2.2 Testing machine and running condition

Figure 4 shows the schematic drawing of a two rollers contact fatigue testing machine which has a high normal load of maximum 50 kN (6). The driver (faster roller) is rotated at about 1820 rpm and the follower (lower roller) is rotated to produce a specific sliding ratio of $\varepsilon_2 = (\omega_2 r_2 - \omega_1 r_1)/\omega_2 r_2 = -20$ % by controlling

Table 6 Conditions and results of main experiments

No. of Exp.	Group	Roughness, μm R_{max} Before		After		Normal load kN/cm	p_{max} MPa	N_2 $\times 10^6$	T_2 K	Number of pits		Wear mg	
		Dri.	Fol.	Dri.	Fol.					Dri.	Fol.	Dri.	Fol.
[1]	A	0.2	0.2	0.4	0.3	29.48	2500	6.9	-	0	Many	2	324
[2]	A	0.1	0.1	0.1	0.1	27.17	2400	7.1	391	1	1	0	162
[3]	A	0.1	0.1	0.1	0.1	26.06	2350	7.8	283	0	1	0	4
[4]	A	0.1	0.1	0.1	0.1	24.95	2300	10.0	283	0	0	0	1
[5]	B	2	2.5	2	2	29.48	2500	0.05	-	Scoring		79	169
[6]	B	3	3	1	1.5	24.95	2300	10.0	294	0*1	0*1	23	5
[7]	B	4	3	2	2	22.83	2200	0.01	395	Scoring		12	10
[8]	B	2	1.5	0.8	0.8	20.80	2100	7.7	398	0*1	9*1	1	35
[9]	B	4	2.5	2	1.5	20.80	2100	10.0	396	0*1	0*1	6	22
[11]	C	3	2	1	1.2	24.95	2300	10.0	403	Scoring*2		42	68
[12]	C	1.5	2	1	1	22.83	2200	0.4	409	Scoring		491	273
[13]	C	2	2	1.5	1	22.83	2200	10.0	401	0*1	0*1	17	34
[14]	D	1	1	1	1.2	27.17	2400	10.0	378	0*1	0*1	8	3
[15]	D	1	1	0.8	0.5	24.95	2300	10.0	390	0	0	0	2
[16]	D	1	0.8	0.5	0.5	22.83	2200	10.0	378	0	0	1	0
[17]	D	0.5	1.0	0.3	0.6	29.48	2500	6.6	409	0	1*1	1	70
[18]	D	0.5	0.8	0.2	0.2	28.30	2450	10.0	411	0	0*1	5	5
[19]	D	0.5	0.5	0.3	0.2	27.17	2400	10.0	402	0	0	1	0
[20]	D	0.6	0.6	0.4	0.4	24.95	2300	10.0	397	0	0	0	0

Dri.; Driver Fol.; Follower *1; Micro-pitting *2; Mild scoring
N_2; Revolutions of follower T_2; Surface temperature after running

a gear ratio of power circulating gears. Here ω_1 and ω_2 are angular velocities of the driver and the follower, r_1 and r_2 are their radii, respectively. The friction torque is also measured from a strain gauge affixed on a diving shaft through slip rings and a friction coefficient is calculated using the friction torque, the applied normal load and a little compensating coefficient concerned to the bearing loss.

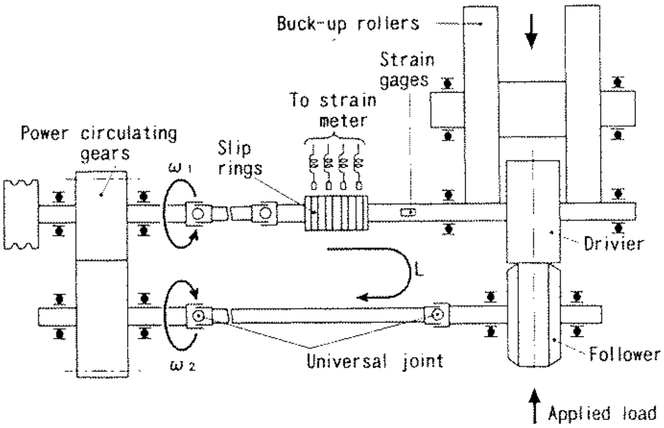
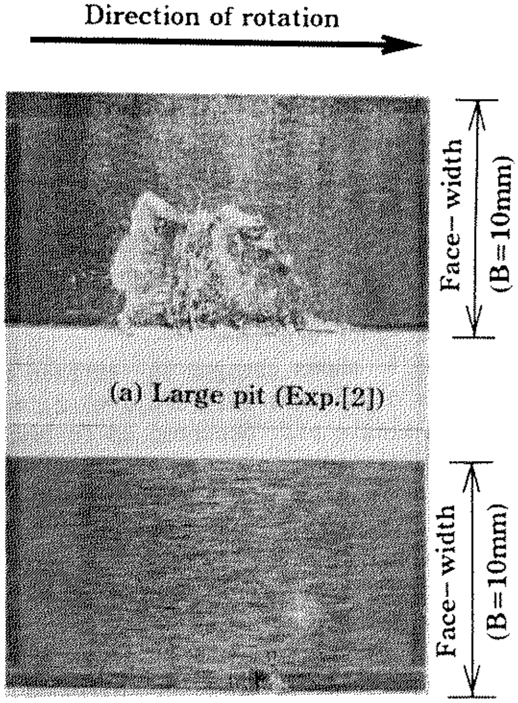


Fig. 4 Schematic drawing of two rollers testing machine

As a lubricant, two kinds of mineral-type oils (Oil-Y, Oil-Z) for lubricating the gear are used. Table 5 shows properties of lubricating oils. The viscosities of oils are 68 mm^2/s and 150 mm^2/s at 313 K, respectively. The lubricant is regulated to a temperature of 323±2 K and flooded to a contact area between a pair of rollers at a ratio of about 1.4 L/min. A condition of an oil film between rollers is continuously measured during running by an electric-resistance method which an impressed voltage between rollers is 150 mV. The surface temperature of the follower is directly measured after running. As a running test is performed at a Hertzian maximum pressure of p_{max}=2000 MPa using Oil-Y, the theoretical oil film thicknesses calculated from Dowson's equations (7) are $h_{min}=0.8\mu m$ at the surface temperature of T_s=323 K (=50 ℃) and $h_{min}=0.2\mu m$ at T_s=393 K (=120 ℃), respectively.

3. EXPERIMENTAL RESULTS

Table 6 shows results of main experiments including surface roughnesses of test rollers before/after running and contact pressures, etc. It is well known that a pitting (spalling) limit of a case-carburized and hardened steel is not determined up to $N_2=10\times10^6$ revolutions(8). However, in this research the pitting limit up to $N_2=10\times10^6$ revolutions is investigated despite of its existing or not. Experiments [1]-[16] are lubricated with Oil-Y and Exps.[17]-[20] are lubricated with Oil-Z.



(b) Initial pit (Exp.[3])

Fig. 5 Pit occurred on follower

3.1 Pitting limit of case-carburized and hardened steel

First of all, running tests using rollers with the surface roughness of $R_{max} \fallingdotseq 0.2\mu m$ were performed in order to investigate the surface durability of the corresponding case carburized and hardened steel roller (Exps. [1]-[4]). Experiment [1] was performed at a Hertzian pressure of $p_{max}=2500$ MPa. A large pit (spalling) occurred on the surface of the follower after $N_2=6.9\times10^6$ revolutions. At $p_{max}=2400$ MPa, a large pit (spalling) as shown in Fig. 5(a) also occurred after $N_2=7.1\times10^6$ revolutions (Exp. [2]). And, at the Hertzian pressure of $p_{max}=2350$ MPa, a small pit as shown in Fig. 5(b) occurred after $N_2=7.8\times10^6$ revolutions (Exp. [3]). This initial pit will soon grow to the large pit as shown in Fig. 5(a) because an applied load is extremely high. However, at $p_{max}=2300$ MPa, not a single pit occurred up to $N_2=10\times10^6$ revolutions (Exp. [4]). Figure 6 shows a S-N curve of the case-carburized and hardened test rollers with the surface roughness of $R_{max} \fallingdotseq 0.2\mu m$. From above results, it is suggested that the pitting limit of rollers with the surface roughness of $R_{max} \fallingdotseq 0.2\mu m$ will be a range of $p_{max}=2200\sim2300$ MPa.

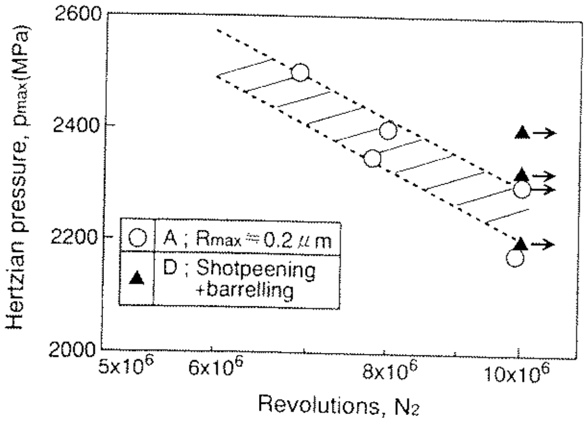


Fig. 6 S-N curve

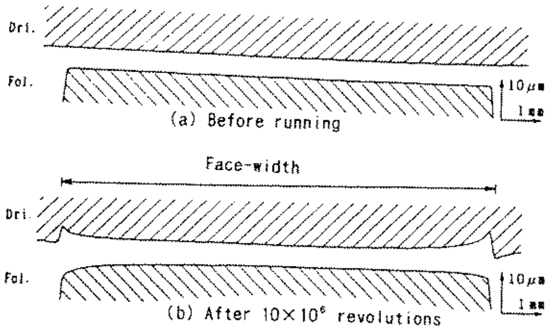


Fig. 7 Changes in surface roughness (Group [A], Exp. [4], p_{max}=2300MPa)

Figure 7 shows changes in surface roughnesses of rollers with $R_{max} \fallingdotseq 0.2\mu m$ which not a single pit occurred up to $N_2=10\times10^6$ revolutions at $p_{max}=2300$ MPa. Since the sum of surface roughnesses of a pair of rollers equals nearly to a theoretical oil film thickness, surface roughnesses in the central region of the face-width before/after running don't almost change. This means occurrence of non-metal contact. But profiles in both sides of face-width have changed markedly. Therefore it is confirmed that changes in profiles of Exp. [4] as shown in Fig. 7 have been produced by plastic deformation without wear as referring a "Wear" column in Table 6. Here, a quantity of wear is measured precisely within ±1 mg.

The surface durability of rollers in Group [B] finished to the surface roughness of $R_{max} \fallingdotseq 3\mu m$ by the cylindrical grinding machine was examined (Exps. [5]-[9]). When the running test is performed at a Hertzian pressure of $p_{max}=2500$ MPa, a scoring occurred immediately after starting of running (after about $N_2=50\times10^3$ revolutions) with white smoke and abnormal noise (Exp. [5]). In Exp. [6] no pitting occurred up to $N_2=10\times10^6$ revolutions at $p_{max}=2300$ MPa. In Exp. [7] the scoring occurred at $p_{max}=2200$ MPa. At the low Hertzian pressure of $p_{max}=2100$ MPa, not scoring but pitting occurred after $N_2=7.7\times10^6$ revolutions (Exp. [8]). It may be strange that the pitting didn't occur at

p_{max}=2300 MPa (Exp. [6]), but the pitting occurred at p_{max}=2100 MPa (Exp. [8]). Then the same test was repeated after exchanging test pieces only, and neither pitting nor scoring occurred up to $N_2=10\times10^6$ revolutions (Exp. [9]). As a scoring is liable to occur under the $R_{max}>h_{min}$ condition, it is difficult to examine exactly the pitting limit. However, it may boldly say that from above results the surface durability of the roller ground to $R_{max}\fallingdotseq 3\mu m$ will be about p_{max}=2100 MPa.

Figure 8 shows changes in surface roughnesses before/after running in Exp. [9] which neither pitting nor scoring occurred. The surface roughness after running become smaller than half of one before running and configurations of asperities of the surface roughness becomes round to some extent. From this fact there must be an existence of micro-EHL oil film. It is suggested that the changes in profiles and roughnesses of roller surfaces as shown in Fig. 8 were produced by both plastic deformation and wear.

3.2 Effectiveness of shot-peening process

Experiments [11]-[13] of Group [C] were performed using the roller shot peened after grinding. In Exp. [11], although rollers pressed at the Hertzian pressure of p_{max}=2300 MPa were possible to run to $N_2=10\times10^6$ revolutions, the abnormal wear which might be produced by the occurrence of mild-scoring has occurred in both sides of the face-width as shown in Fig. 9. Generally, a scoring will occur at an early stage of the load running and it will progress rapidly with abnormal noise and smoke. On the contrary, when a mild-scoring occurs, an adhesion between rollers will progress slowly without abnormal noise and smoke. In this experiment, both abnormal noise and smoke weren't appeared at all as the mild-scoring phenomena.

And, the experiment [12] performed at p_{max}=2200 MPa had a scoring at $N_2=0.4\times10^6$ revolutions. This scoring didn't occur at an early stage of running and it took a lot of time until scoring occur with big noise and white smoke. As the result of this test, a lot of quantities of wear produced by the adhesion. In Exp. [13] at p_{max}=2200 MPa, neither pitting nor scoring occurred up to $N_2=10\times10^6$.

3.3 Micro-pitting

When the surface durability of the case-carburized and hardened steel is investigated,

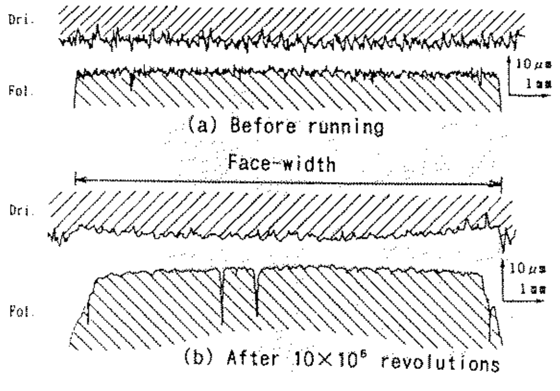


Fig. 8 Changes in surface roughness (Group [B], Exp. [9], p_{max}=2100MPa)

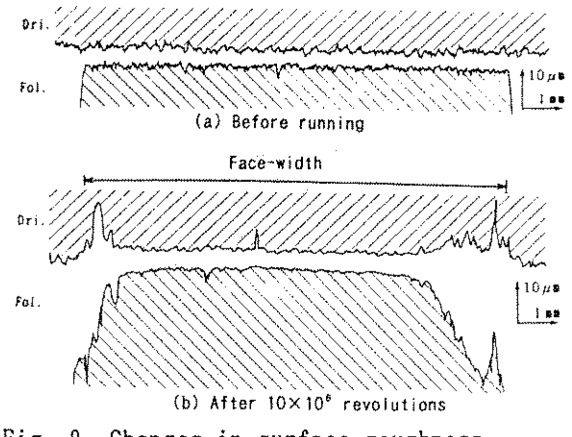


Fig. 9 Changes in surface roughness (Group [C], Exp. [11], p_{max}=2300MPa)

a micro-pitting which is called as "frosting" or "cloudy" may become a subject of discussion in addition to large pitting (spalling)(9). When the sum of surface roughnesses of a pair of rollers is appreciably greater than the oil film thickness between them, the micro-pitting as shown in Fig.10 may occur. However, in the present experiments a lot of micro-pitting didn't occur so as the roller surface will be looked cloudy. The mark (*1) in "Number of pits" column of Table 6 shows the fact that the micro-pitting was observed on the surface after running. It is recognized that in Table 6 this mark is almost found in the case of Groups [B] and [C] which the sum of surface roughnesses is markedly greater than the theoretical oil film thickness.

3.4 Effectiveness of barrelling process

Experiments [14]-[20] of Group [D] were performed using rollers with the processes of shot peening and barrelling after grinding. Here, Exps. [17]-[20] were lubricated using Oil-Z whose viscosity is about twice as large as Oil-Y.

In Exp.[14] neither pitting nor scoring occurred up to $N_2=10\times10^6$ revolutions even at a Hertzian pressure of $p_{max}=2400$ MPa. Figure 11 shows changes in surface roughnesses before/after running. The height of the surface roughness after running is lower about half than one before running and profiles in both sides of the face-width change greatly. As shown in Table 6, the quantity of wear is a little even at highly Hertzian pressures such as $p_{max}=2300\sim2400$ MPa.

Next, the load capacity running test was performed using Oil-Z with a high viscosity.

Fig. 10 Micro-pitting

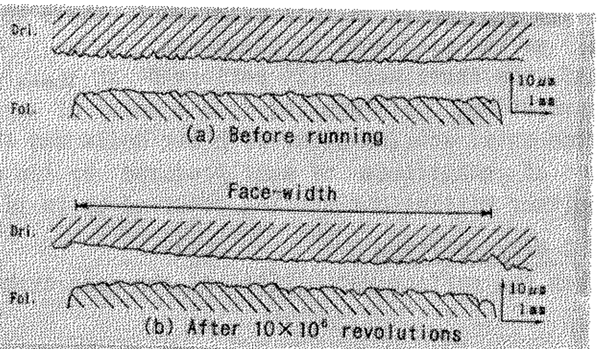


Fig. 11 Changes in surface roughness (Group [D], Exp.[14], p_{max}=2400MPa)

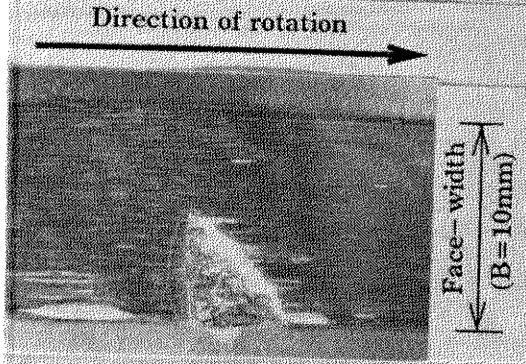


Fig. 12 Pit ocurred at p_{max}=2500MPa (Group [D], Exp.[17])

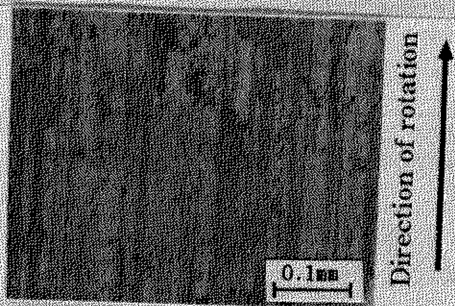


Fig. 13 Surface of rollers after running (Group [D], Exp.[19], p_{max}=2400MPa)

The running at an appreciably high Hertzian pressure of p_{max}=2500 MPa became impossible due to large pitting as shown in Fig. 12 after N_2=6.6×10^6 revolutions (Exp. [17]). However, when the running test was performed at a Hertzian pressure lower than p_{max}= 2450 MPa, neither pitting nor scoring occurred up to N_2=10×10^6 revolutions (Exp. [18]). Figure 13 shows the follower surfaces at p_{max}=2400 MPa after running in Exp. [18]. Distributions of hardnesses on/below surfaces in both contact regions and non-contact regions after N_2=10×10^6 revolutions at p_{max}=2400 MPa are shown in Fig. 14. The hardness was measured using a micro-vickers hardness testing machine with a weight of 500 g. Although the hardness of the surface after grinding was about 720~750 Hv, the hardness of the surface with the shot peening and the barrelling processes has increased to 800~850 Hv. Furthermore, the surface hardness after running has increased than that before running.

3.5 Friction coefficient

Figure 15 shows changes in friction coefficients obtained when running tests were performed at p_{max}=2300 MPa. When the height of the surface roughness is markedly higher than the oil film thickness and neither pitting nor scoring occurred, the friction coefficient was large and a lot of quantities of wear were produced (refer to Table 6).
Although asperities of the surface roughness of the roller have become round by the shot peening process after grinding, many quantities of wear were yet produced even when neither pitting nor scoring occurred. When the barrelling process was applied after shot-peening process, neither pitting nor scoring occurred almost, the friction coefficient became low, and the quantity of wear became slightly.

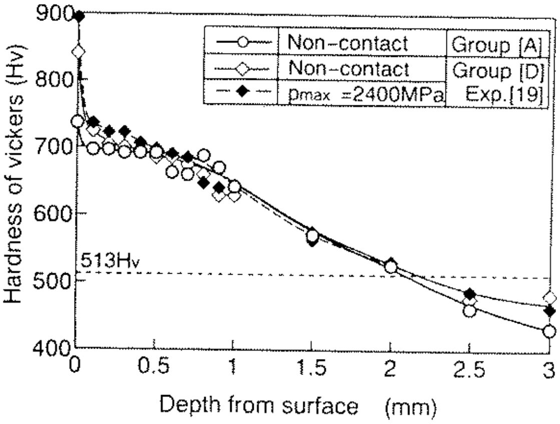


Fig. 14 Distributions of hardnesses

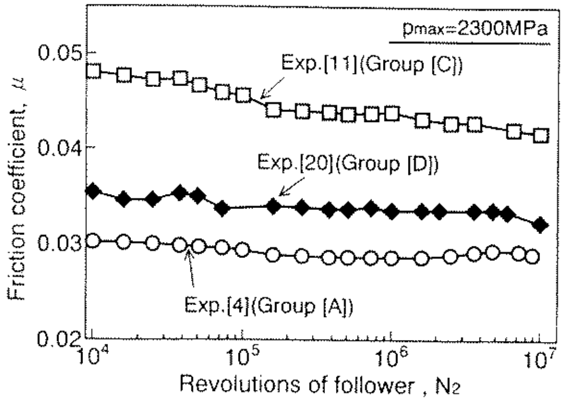


Fig. 15 Changes in friction coefficients

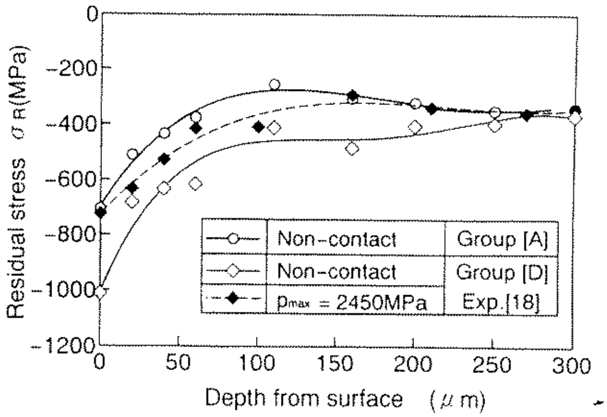


Fig. 16 Distributions of residual stresses

3.6 Compressive residual stress

One purpose of the present investigation is to improve a surface durability by the shot-peening process or other hardening process which induce generally some large compressive residual stress. Figure 16 shows distributions of residual stresses in both contact region and non-contact region of the driver after running in experiment [18] using a pair of rollers barrelled after shot peening. A residual stress was detected at a crystallographical plane (211) by an X-ray diffraction method with Cr-Kα rays. The compressive residual stress σ_R on/below the surface with the shot-peening process has increased than one of the non-treated surface. It is shown that the compressive residual stress on/below the surfaces decrease after running and it brings close to the residual stress of the surface without the shot-peening process. As a result, it is considered that the compressive residual stress will not contribute appreciably to the improvement of the surface durability.

4. CONSIDERATION

When the shot-peening process is applied to the surface of the steel roller, the radii of curvature of asperities of the surface roughness become large and the compressive residual stress increases. The asperity of the surface roughness after grinding is very sharp at the top as shown in Fig. 3(b). If it is shot peened after grinding, the asperity of the surface roughness will slightly become round as shown in Fig. 3(c). However, it is certified that even if the compressive residual stress has increased, an improvement of the surface durability will not be expected in the case that some high asperity which should become the trigger of the occurrence of either pitting or scoring remain. The surface durability of rollers barrelled after shot peening is appreciably improved (Exp.[14]-[20]). This main reason will be due to remove the trigger of the occurrence of both pitting and scoring. This fact is confirmed from the fact that the friction coefficient become low and the quantity of wear is not almost observed.
From the above fact, it is concluded that when the shot-peening process is applied to improve a bending fatigue strength of the gear tooth, it is very important to use the barrelling process after the shot-peening process in order to improve the surface roughness. The barrelling process is an effective way in order to lower the surface roughness of gears, since it can be easily applied to machine elements with the complex profile.

5. CONCLUSION

(1) In the present experiments, the pitting limit of the case-carburized and hardened steel roller ground to the surface roughness of $R_{max} \fallingdotseq 0.2\mu m$ is about $p_{max}=2200\sim2300$ MPa.
(2) Under $R_{max} > h_{min}$ condition, as the surface temperature increases highly for metal contacts, a scoring occurs often.
(3) The surface durability of rollers isn't improved by only the shot-peening process after grinding, nevertheless it has an increased compressible residual stress on/below the surface.
(4) When the barrelling process is introduced after shot peening in order to improve the surface roughness, neither pitting nor scoring occurs up to $N_2= 10\times10^6$ revolutions even at a very high Hertzian pressure of $p_{max}=2450$ MPa.

(5) Under $R_{max} > h_{min}$ condition, even when neither pitting nor scoring occurred, a lot of quantities of wear are produced. But the wear decreases appreciably when the barrelling process is employed. Therefore, it is confirmed that the barrelling process is an effective way in order to improve the surface durability of gears.

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