Fatigue Strength of Steel Rollers and Gears Treated by Cavitation Peening with Short Processing Time*

(A Case of Processing Time of 1 min and 5 min)

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Abstract

In this study, steel rollers and gears were treated by the cavitation peening with processing times of 1 min and 5 min, and they were fatigue-tested using a roller testing machine and a gear testing machine. The surface hardness and the compressive residual stress of the rollers and gears were increased by the cavitation peening, while, the surface roughness of the cavitation-peened rollers and gears was almost the same as that of the non-peened ones. As a result of the fatigue tests, the fatigue strength of the test specimens were improved by the increase in surface hardness due to the cavitation peening, and those without the increase in surface hardness were not increased so much. The fatigue strength of the cavitation-peened test specimens was similar to that of the shot-peened ones obtained by the previous fatigue tests. This study revealed that the cavitation peening is expected to put to practical use in the improvement in fatigue strength of steel gears.

Key words: Gear, Surface Treatment, Cavitation, Steel, Fatigue Strength, Pitting, Hardness, Surface Roughness, Normal Stress

1. Introduction

Shot peening (SP) is widely employed as a surface treatment method in the production of machine elements to improve their fatigue strength. The fatigue strength of steel gears has been discussed based on surface durability or bending strength⁽¹⁾. The surface durability of steel gears is the resistance of tooth surface to surface failure that is pitting, and the bending strength of them is the resistance of tooth to fatigue fracture initiated at or near root fillet. Some papers revealed that stronger shot peening provides the larger bending strength

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of steel gears⁽²⁾. And, the other papers revealed that the surface durability of steel gears depends on the SP conditions⁽³⁾. Thus, in this study, the fatigue strength of steel gears was discussed based on their surface durability.

In general, surface hardness and surface compressive residual stress are increased by the SP. At the same time, surface roughness is also increased by the SP. For this reason, the fatigue strength of some shot-peened steel gears increases due to the increase in surface hardness and surface compressive residual stress, and that of other ones decreases due to the increase in surface roughness. In other words, the main cause of the decrease in the fatigue strength of shot-peened steel gears is that the plastic deformation on the tooth surface due to shot impact leads to the increase in surface roughness.

On the other hand, cavitation peening (CP)⁽⁴⁾ is the peening by both the shock wave due to cavitation bubble collapse and the impact force due to micro jet. CP is effective for the increase in fatigue life of steel gears, because the increase in surface hardness and surface compressive residual stress is obtained with less increase in surface roughness⁽⁵⁾. Our previous study revealed that the fatigue life of cavitation-peened steel rollers increased with increasing processing time of the CP within a processing time of 30 min. After that, CP condition has been optimized to obtain the larger surface hardness and larger surface compressive residual stress⁽⁶⁾. Shorter processing time of surface treatment method for machine elements is important to promote greater efficiency and productivity. Therefore, in this study, the steel rollers and gears were treated by the CP with processing times of 1 min and 5 min, and they were fatigue-tested to investigate the effect of CP on their fatigue lives.

2. Test Specimens

2.1 Manufacture of Test Specimens

A test roller pair employed in the roller tests consists of the slower test roller and the faster mating roller with 60 mm in diameter. A spur gear pair which consists of the test pinion and the mating gear was employed in the gear tests. As shown in Table 1, the test rollers and the test pinions were made of chromium steel (JIS: SCr420), and the mating rollers and the mating gears were made of chromium molybdenum steel (JIS: SCM420). They were finish-ground after case hardening. Specimens R and G represent the test roller and the test pinion, respectively. Figure 1 shows the shapes and the dimensions of the test roller pair. The specification of the test gear pair is shown in Table 2. Here, the Young's modulus and the Poisson's ratio of the rollers and the gears are 206 GPa and 0.3, respectively.

Table 1 Manufacturing conditions of rollers and gears

Test roller pair	Test roller	Mating roller
	R	RM
Test gear pair	Test pinion	Mating gear
	G	GM
Material*	SCr420	SCM420
Heat treatment	Case hardening	
Finishing	Grinding	

*JIS G 4105 -1979

Fig. 1 Shapes and dimensions of test roller pair

In this study, the finish-ground circumferential surface of the test roller pair and the finish-ground tooth surface of the test gear pair were treated by the CP. CP uses a cavitating jet in water⁽⁷⁾. Two types of cavitating jets in water shown in Fig. 2 were employed in this study. One is formed by injecting a high-speed water jet into a water-filled chamber, and the other is formed by injecting a high-speed water jet into a low-speed water jet which is injecting in water. Tap water was used to produce both a high-speed and a low-speed water

jets. Table 3 shows the CP conditions for the test roller pairs and the test gear pairs. HL indicates the CP used both a high-speed and a low-speed water jets, and H indicates that used only a high-speed water jet. The processing time of the CP was 1 min and 5 min. The CP for the gears was treated in the same manner as that for the rollers shown in Fig. 2. During the CP, the rotational speed of the roller and the gear was 20 rpm. Here, NP represents the non-peened test specimens.

Table 2 Specification of test gear pair

	Test pinion	Mating gear
Module	mm	5
Standard pressure angle	deg.	20
Number of teeth	20	21
Addendum modification coefficient	0	-0.19
Tip circle diameter	mm	110.0
Center distance	mm	102
Face width	mm	5
Contact ratio		1.536

Fig. 2 Cavitation peening for roller

Table 3 Cavitation peening conditions for test specimens

Condition name		HL1	HL5	H5
High-speed water jet	Nozzle diameter d_H	2 mm		
	Injection pressure p_H	30 MPa		
	Standoff distance s_H	140 mm		80 mm
Low-speed water jet	Nozzle diameter d_L	50 mm		---
	Injection pressure p_L	0.02 MPa		---
	Standoff distance s_L	80 mm		---
$s_H - s_L$		60 mm		---
Processing time t		1 min	5 min	5 min
Rotational speed of roller and gear		20 rpm		

2.2 Surface Properties of Test Specimens

Figure 3 shows the surface photographs and the roughness curves of the test rollers and pinions before the fatigue tests. The surface photographs of the test rollers and the test pinions were taken by a scanning laser microscope or a stereoscopic microscope, respectively. The roughness curves of the test rollers were measured on the circumferential surface along their axial direction, and those of the test pinions were measured on the tooth surface along their tooth profile direction, using a surface roughness meter. Here, in the case of shot-peened test pinions⁽⁸⁾, the indentations due to steel shots appeared on the tooth surface, and the grinding marks on the tooth surface disappeared due to the SP. From the

surface photographs in Fig. 3, the grinding marks can be observed on the circumferential surface of the test rollers and the tooth surface of the test pinions. Also in the roughness curves, unlike SP, the large plastic deformation due to the CP did not appear on the cavitation-peened surface of most test specimens. However, the roughness curve of only the test roller R-H5 became slightly-rough compared to those of the other test specimens.

Fig. 3 Surface photographs and roughness curves of test rollers and pinions

Table 4 Surface properties of test rollers and pinions

Specimen	Test roller				Test pinion			
	R-NP	R-HL1	R-HL5	R-H5	G-NP	G-HL1	G-HL5	G-H5
R_a μm	0.08	0.07	0.12	0.24	0.31	0.28	0.30	0.31
R_z μm	1.20	1.10	1.38	2.13	2.34	2.14	2.26	2.42
HV	803	827	834	869	718	725	729	759
$(\sigma_x)_r$ MPa	-351	-551	-648	-1134	-369	-377	-451	-424
$(\sigma_y)_r$ MPa	-58	-216	-371	-649	-529	-554	-671	-873

The surface roughness, the surface hardness and the surface residual stress of the test rollers and pinions are given in Table 4. The arithmetic average roughness R_a and the maximum height roughness R_z were obtained in the same manner as measuring the roughness curves shown in Fig. 3. The Vickers hardness was measured with a micro hardness tester under a measuring load of 0.98 N for 30 s. The average hardness distributions of the test rollers and pinions were obtained from five measured hardnesses at each depth below the circumferential surface of the roller and the tooth surface of the gear, respectively. The surface hardness was approximated as the hardness at a depth of 0 mm from their hardness distributions. The surface residual stress was measured according to the $2\theta\text{-sin}^2\psi$ method⁽⁹⁾ using CrK α -ray as characteristic X-ray. $(\sigma_x)_r$ and $(\sigma_y)_r$ of the rollers in Table 4 represent the surface residual stresses measured on the circumferential surface in the axial and the circumferential directions of the roller, respectively. In the case of the gear, $(\sigma_x)_r$ and $(\sigma_y)_r$ were measured at the working pitch point in the tooth trace and the tooth profile directions of the gear, respectively.

As can be seen in this table, the surface hardness and the surface compressive residual stress of most test rollers and pinions were increased by the CP. On the other hand, those of the test pinions G-HL1 and G-HL5 were not greatly increased by the CP. This may be because cavitation bubble collapse was not occurred successfully near the tooth surface⁽¹⁰⁾,

although CP uses cavitation bubble collapse. In the CP for a rotating roller, the circumferential surface was perpendicular to the cavitating jet direction, while, the tooth surface was not perpendicular to that in the CP for a rotating gear. Consequently, the increase in surface hardness and surface compressive residual stress due to the CP obtained in the gear was smaller than that obtained in the roller under the same CP condition. However, the cavitation impact due to the CP can hit a surface with narrow region, such as narrow steel tubes⁽⁴⁾ and elements of a steel belt for CVT⁽¹¹⁾. Some CP conditions, such as G-H5, can give the increase in surface hardness and surface compressive residual stress for the tooth surface of the gear, and they are effective for steel gears. In terms of surface roughness, R_a and R_z of only R-H5 were increased by the CP, and those of the other cavitation-peened test rollers and pinions were similar to those of the non-peened test rollers and pinions, respectively, as shown in Fig. 3.

In this study, the residual stress below the circumferential surface of the test rollers was also measured by removing the surface layer with electrolytic polishing⁽¹²⁾. Figure 4 shows the residual stress distributions of the test rollers. The residual stresses $(\sigma_x)_r$ and $(\sigma_y)_r$ below the circumferential surface of the rollers, shown in Fig. 4, were determined by modifying the measured residual stresses by the elastic calculation⁽¹³⁾, since the measured stresses were influenced by the removal of the surface layer. The residual stress $(\sigma_z)_r$ in the radial direction of the roller was determined by the elastic equations⁽¹³⁾. According to the results, the compressive residual stress near the circumferential surface of the test roller was also increased by the CP. The compressive residual stress layer due to the CP was in the range of 0.025 mm to 0.200 mm below the circumferential surface of the test rollers. While, as for the hardness distributions of the test specimens, the work-hardened layer due to the CP was in the range of 0.1 mm to 0.3 mm below the circumferential surface of the test rollers and the tooth surface of the test pinions. The effective case-hardened depths, where the hardness is 550HV, were about 1.2 mm for the test rollers, and were about 0.8 mm for the mating rollers. The effective case-hardened depths of the test pinions and the mating gears were 0.7 mm to 0.8 mm and 0.9 mm to 1.0 mm, respectively. Thus, it can be expected that the fatigue strength of the test specimens will be improved by the CP, because the CP gives the increase in hardness and compressive residual stress near the surface to the test specimens with less increase in surface roughness.

Fig. 4 Residual stress distributions of test rollers

3. Experimental Procedures

The rolling contact fatigue tests of the rollers were performed using a spring-loading type roller testing machine⁽¹⁴⁾. The load between the test roller and the mating roller was given by a compression spring. The maximum Hertzian stress $p_{\max}$ ⁽¹⁵⁾ was adopted as the standard of the loading between contact rollers. These roller tests were performed under the sliding-rolling contact condition⁽¹⁴⁾ given in Table 5. The test rollers were taken as the

slower rollers, and the mating rollers were taken as the faster rollers.

The operating fatigue tests of the gears were performed at a test pinion rotational speed of 1800 rpm using a power circulating type gear testing machine⁽⁸⁾. In this experiment, the test pinions and the mating gears were used as the driven gears and the driving gears, respectively. The load between the test pinion and the mating gear was given by a load lever and weights. The maximum Hertzian stress $p_{\max}^{(16)}$ at the working pitch point was adopted as the standard of the loading for the tooth meshing of a test gear pair.

The lubricating oils employed in the roller tests and the gear tests were ATF and EP gear oil, respectively. The properties of these lubricating oils are given in Table 6. These lubricating oils were pressure supplied to the engaging side of the roller pair and the gear pair from nozzles. The flow rate of the supplied oil was about 1500 ml/min for the roller pair and about 750 ml/min for the gear pair. The oil temperature was adjusted to 313 ± 4 K.

As described later, the roller tests were performed under the maximum Hertzian stress of 2000 MPa to 2400 MPa. The minimum oil film thickness by D.Dowson⁽¹⁷⁾, namely $h_{\min}$ was in the range of 1.7 μm to 1.8 μm for the test roller pair. Likewise, the gear tests were performed under the range of 2000 MPa to 2500 MPa. In the test gear pair, $h_{\min}$ was in the range of 0.9 μm to 1.3 μm during the fatigue tests.

While, the D value defined by P.H.Dawson⁽¹⁸⁾ was above 1 for all the test roller pairs and all the test gear pairs. In the calculation of the minimum oil film thickness and the D value, the oil temperature between the operating surfaces was taken as 313 K, which was the supplied oil temperature, in both the roller test and the gear test.

In this study, the fatigue lives N_f of the test rollers and the test pinions were defined as the total number of cycles when the percentage of the pitted area on a test roller pair and a test gear pair reached 5 percent, respectively. Those were also defined as the total number of cycles when the testing machine was automatically stopped by the vibration increase due to the especially large surface failure or the tooth breakage.

Table 5 Sliding-rolling contact condition for test roller pair

Rotational speed of slower roller	1432 rpm
Circumferential velocity of slower roller	4.50 m/s
Rotational speed of faster roller	1800 rpm
Circumferential velocity of faster roller	5.65 m/s
Specific sliding of slower roller	-25.7 %
Specific sliding of faster roller	+20.4 %
Sliding velocity	1.15 m/s

Table 6 Properties of lubricating oils

		ATF	Gear oil
Specific gravity	288/277K	0.8564	0.9022
Flash point	K	467	477
Pour point	K	---	260.5
Kinematic viscosity	313K	33.18	190.9
	$\times 10^{-6} \text{ m}^2/\text{s}$ 373K	7.225	17.74
Viscosity index		191	98
Total acid number	mgKOH/g	---	2.26

4. Experimental Results

4.1 Failure Mode of Test Specimens

Figure 5 shows the circumferential surface and the cross section of the failed test roller and the failed tooth of the test pinion. As shown in the cross section of the failed test roller, cracks originated on the circumferential surface, and then propagated in the rolling direction

of the test roller. In this study, the failure mode of all the test rollers was pitting due to surface cracking. The failure mode of the test pinions was also mainly pitting due to surface cracking. First, the pitting occurred near the working pitch point of the test pinion, and then spread over the dedendum flank with the increase in number of cycles. In some cases of the test pinions, the pitting increased in size locally near the working pitch point on a certain tooth, and then the crack, which originated at the pitting, reached the tooth root of the opposite flank, and finally the tooth breakage occurred. In the failure mode of the test specimens, no significant difference could be seen between the test specimens with and without the CP.

Fig. 5 Observations of failed test roller and test pinion

4.2 Relations between Maximum Hertzian Stress and Fatigue Life

Figures 6 and 7 show the relations between the maximum Hertzian stress $p_{\max}$ and the fatigue life N_f of the test rollers and the test pinions obtained by the fatigue tests, respectively. The arrows in Fig. 6 indicate that the percentage of the pitted area in a test roller pair did not reach 5 percent or no fatal surface failure occurred on the circumferential surface, when the number of cycles of the test roller exceeded 2×10^7 cycles. P_B in Fig. 7 represents that the tooth breakage due to pitting at the working pitch point occurred.

From Fig. 6, the fatigue lives of all the test rollers were increased by the CP, and those of the test roller R-H5, which is designated by a circle with dot, were extremely increased. Also in Fig. 7, those of the test pinion G-H5, which is designated by a square with dot, were longer than those of the other test pinions. However, those of the test pinions except for G-H5 were not greatly increased by the CP. This result can be understood from the fact that the increase in surface hardness and surface compressive residual stress due to the CP was not completely obtained for the test pinions G-HL1 and G-HL5 as shown in Table 4.

Fig. 6 $p_{\max}$ - N_f curves of test rollers

Fig. 7 $p_{\max}$ - N_f curves of test pinions

4.3 Evaluation of Fatigue Strength by Vickers Hardness and Normal Stress

As previously noted, the failure mode of the test rollers and pinions employed in this study was pitting due to surface cracking. Thus, tangential normal stress σ_y was considered

because it became maximum on the surface⁽¹⁹⁾. In the calculation of this tangential normal stress on the contact surface, x - y - z coordinate system was taken in the same direction as measuring the surface properties of the test specimens. Tangential normal stress σ_y on the circumferential surface of the test roller and that at the working pitch point on the tooth surface of the test pinion were calculated under this coordinate system using the analytical method by J.O.Smith⁽²⁰⁾.

As in the case of the case-hardened steel rollers and gears employed in the previous papers^{(8), (19)}, the maximum amplitude $[A(\sigma_y/\sqrt{3} \text{ HV})]_{\max}$ of the ratio of tangential normal stress σ_y to Vickers hardness HV was calculated by neglecting the effect of mean stress on fatigue and by assuming that the material strength of the test specimens is proportional to their initial hardness. In the following paragraph, the fatigue life and the fatigue strength of the test rollers and pinions were discussed by the maximum amplitude $[A(\sigma_y/\sqrt{3} \text{ HV})]_{\max}$ ⁽²¹⁾. For calculating this tangential normal stress σ_y , the surface residual stress of the test specimens shown in Table 4 was considered. Here, the tangential normal stress σ_y on the surface was influenced by the surface residual stress, while, the stress amplitude $A(\sigma_y)$ on the surface was not influenced by the surface residual stress. Consequently, discussing by the maximum amplitude $[A(\sigma_y/\sqrt{3} \text{ HV})]_{\max}$ was not considered the effect of the surface residual stress. This evaluation method was the same as the previous paper^{(8), (21)}.

Figures 8 and 9 show the relations between the maximum amplitude $[A(\sigma_y/\sqrt{3} \text{ HV})]_{\max}$ and the fatigue life N_f of the test rollers and pinions, respectively. Here, the effect of hardness does not appear by using this evaluation method. Compared with Figs. 6 and 7, the curves of the cavitation-peened test rollers and pinions shown in Figs. 8 and 9 are nearly coincident with those of the non-peened test roller and pinion, respectively. In the case of shot-peened test pinions, the plots of most shot-peened ones in the $[A(\sigma_y/\sqrt{3} \text{ HV})]_{\max}$ - N_f curves laid beneath those of the non-peened ones, since the influence of the surface roughness appeared⁽⁸⁾. On the other hand, the influence of the surface roughness did not appear in Figs. 8 and 9. Therefore, it can be understood from this that the fatigue lives of the cavitation-peened test rollers and pinions were directly improved by the increase in surface hardness due to the CP.

Fig. 8 $[A(\sigma_y/\sqrt{3} \text{ HV})]_{\max}$ - N_f curves of test rollers

Fig. 9 $[A(\sigma_y/\sqrt{3} \text{ HV})]_{\max}$ - N_f curves of test pinions

4.4 Relations between Fatigue Strength and Surface Hardness

Figure 10 shows the relations between the fatigue strength and the surface hardness of the test rollers and pinions. In this study, the fatigue strength $(p_{\max})_{\lim}$ of the test roller and pinion was defined as the maximum Hertzian stress $p_{\max}$ at 2×10^7 cycles life, and the surface hardness is given in Table 4. The result obtained in this study is shown in Fig. 10 (a), and that of the shot-peened test specimens obtained by our previous fatigue tests^{(8), (19)} is shown in Fig. 10 (b). The processing time of the CP employed in this study was 60 s and 300 s, and the peening time of the SP shown in Fig. 10 (b) was 200 s. Closed circles and squares shown in this figure indicate the results of non-peened test roller and pinion,

respectively. The difference between the largest fatigue strength of the peened test specimens and the fatigue strength of the non-peened test specimens is also shown in this figure.

Fig. 10 Relations between fatigue strength and surface hardness of test rollers and pinions

It can be seen from Fig. 10 (a) that the fatigue strength of the test rollers and pinions increased with increasing their surface hardness except for G-HL5. This tendency agreed with the result that the fatigue lives of the cavitation-peened test specimens were improved by the increase in surface hardness due to the CP, which was discussed in the preceding section. The fatigue strength of G-HL1 and G-HL5 was not greatly increased by the CP, since their surface hardness was similar to that of G-NP.

On the contrary, the fatigue strength of the shot-peened test specimens did not increase with increasing their surface hardness. This is due to that the increase in surface roughness due to the SP resulted in the decrease in fatigue strength. Stronger SP provides larger hardness and larger compressive residual stress, and also provides larger surface roughness. Thus, in a case of SP, larger surface hardness caused by stronger SP does not lead to larger fatigue strength, and the fatigue strength of shot-peened test specimens is negatively affected by their surface roughness.

In a case of CP, larger surface hardness obtained by CP leads directly to larger fatigue strength, because CP does not induce the increase in surface roughness. The processing time of the CP employed in this study was similar to the peening time of the SP shown in Fig. 10 (b). Comparing Fig. 10 (a) with Fig. 10 (b), the fatigue strength $(p_{\max})_{\lim}$ of the cavitation-peened test specimens was similar to that of the shot-peened ones. Therefore, CP is expected to put to practical use in the improvement in fatigue strength of steel gears.

5. Conclusion

In order to investigate the effect of CP on the fatigue strength of steel gears, steel rollers and gears were treated by the CP with processing times of 1 min and 5 min, and then were fatigue-tested using a roller testing machine and a gear testing machine. The following points can be concluded.

- (1) The surface hardness and the surface compressive residual stress of the test specimens were increased by the CP, and those of some test pinions were not increased so much.
- (2) The grinding marks could be observed on the surfaces of the cavitation-peened test specimens. And the surface roughness of most cavitation-peened test specimens was similar to that of the non-peened ones.
- (3) The fatigue life and the fatigue strength of the test specimens were improved by the increase in surface hardness due to the CP, and those without the increase in surface hardness were not increased so much.
- (4) The fatigue strength of the cavitation-peened test specimens was similar to that of the shot-peened ones.
- (5) This study revealed that CP is expected to put to practical use in the improvement in

fatigue strength of steel gears.

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