EFFECT OF CAVITATION SHOTLESS PEENING ON FATIGUE STRENGTH OF STEEL GEAR

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ABSTRACT

The purpose of this study is to investigate the effect of cavitation shotless peening (CSP) on the rolling contact fatigue strength of steel gears. The case-hardened steel rollers and gears treated by the CSP were fatigue-tested using a roller testing machine and a gear testing machine. The hardness and the compressive residual stress of the test rollers and gears were increased by the CSP. The work-hardened layer due to the CSP was in a range of a depth of about 0.5mm below the surface. While, the surface roughness of the peened rollers and gears was similar to that of the non-peened ones. In the fatigue tests, the rolling contact fatigue life of most peened rollers and gears was longer than that of the non-peened ones. This study revealed that the rolling contact fatigue strength of steel gears was improved by the increase in surface hardness due to the CSP.

KEY WORDS

Gear, Peening, Cavitation, Fatigue, Hardness

INTRODUCTION

The fatigue strength of steel gears is generally defined as the bending fatigue strength or the rolling contact fatigue strength, whichever is smaller (J.A.Collins, 2002). In the case of the bending fatigue strength of shot-peened gears, many research indicate that the bending fatigue strength increases as the arc height become larger (B-R.Hoehn, 2002). While, as for the influence of shot peening on the rolling contact fatigue strength of gears, there are the reports (D.V.Girish, 1997) on the decrease in rolling contact fatigue strength of shot-peened gears as well as the reports (M.Seki, 2007) on the increase in that. The main cause of the decrease in rolling contact fatigue strength of shot-peened gears is that the plastic deformation on the tooth surface due to shot impact leads to the increase in surface roughness. In other words, the rolling contact fatigue strength depends on the surface roughness as well as the peening effect.

This paper discusses the effect of cavitation shotless peening (CSP) on the rolling contact fatigue strength of steel gears. The CSP is the peening by cavitation impact, and does not require a shot (H.Soyama, 2005). This peening can introduce compressive residual stress into steel surface and improve the rotating bending fatigue strengths of steel (H.Soyama, 2000), (D.Odhiambo, 2003). Thus, it can be expected that the rolling contact fatigue strength of steel gears is improved by the CSP.

TEST SPECIMEN

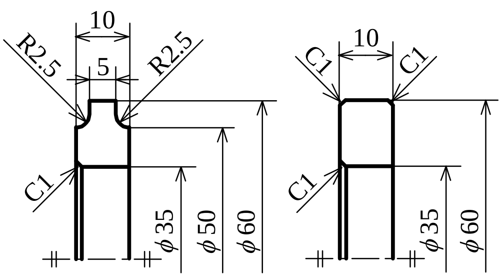
A test roller pair employed in the roller tests consists of the slower test roller and the faster mating roller with 60mm in diameter. As shown in Table 1, the test rollers and the mating rollers were made of chromium molybdenum steels, and were finish-ground after case hardening. Figure 1 shows the shapes and the dimensions of the test roller pair. A spur gear pair which consists of the test pinion and the mating gear was employed in the gear tests. The specification of the test gear pair is shown in Table 2. The gear pair had involute profile teeth, a module of 5mm, a standard pressure angle of 20deg. and a gear ratio of 20/21. As shown in Table 1, the test pinions and the mating gears were also made of chromium molybdenum steel, and were finish-ground after case hardening. In the fatigue tests, the test roller and the test pinion were set to be failed faster than the mating roller and the mating gear, respectively. Here, the Young's modulus and the Poisson's ratio of the rollers and the gears are 206GPa and 0.3, respectively.

Table 1 Manufacturing conditions of rollers and gears

Specimen	Test roller	Mating roller
	R	RM
Material*	SCM415	SCM420
Heat treatment	Case hardening	
Finishing	Grinding	

Specimen	Test pinion	Mating gear
	G	GM
Material*	SCM415	
Heat treatment	Case hardening	
Finishing	Grinding	

*JIS G 4105 -1979



(a) Test roller R (b) Mating roller RM

Fig.1 Shapes and dimensions of test roller pair

Table 2 Specification of test gear pair

	Test pinion	Mating gear
Module mm	5	
Pressure angle deg.	20	
Number of teeth	20	21
Addendum modification coefficient	0	-0.19
Tip circle diameter mm	110.0	113.1
Center distance mm	102	
Facewidth mm	5	22
Contact ratio	1.536	

Table 3 CSP conditions for rollers and gears

Condition name	W1P3T3	W2P3T01	W2P3T02
Injection type	Water		
Nozzle diameter mm	1	2	
Injection pressure MPa	30		
Processing time min	30	1	2

Condition name	W2P3T05	W2P3T1	W2P3T3
Injection type	Water		
Nozzle diameter mm	2		
Injection pressure MPa	30		
Processing time min	5	10	30

CSP is the peening using the cavitating jet in water (D.Odhiambo, 2003) or the cavitating jet in air (H.Soyama, 2005). The peening using the cavitating jet in water was used in this study. Table 3 shows the CSP conditions for the rollers and the gears employed in this study. Two types of nozzle A and B were used to produce the cavitating jet. Nozzle type B is a modified nozzle for the high-speed water jet to obtain the greater peening effect, compared with the case of nozzle type A. Nozzle type A was used only in the CSP for the test pinion. The condition names were marked by the different injection type, nozzle diameter, injection pressure and processing time. During the CSP, a rotational speed of the roller and the gear was 60rpm for nozzle type A and 20rpm for nozzle type B. Here, non-peening is denoted as NP. In this study, the mating gear was peened under the condition W1P3T3 using nozzle type A, and the mating roller was not peened.

Figure 2 shows the surface photographs and the roughness curves of the test rollers before the fatigue tests. The surface photographs were taken by a scanning laser microscope. The roughness curves were measured on the circumferential surface along the axial direction using a surface roughness measuring machine. In the specimen shown in this figure, B placed before a hyphen represents the peening by using nozzle type B. It can be confirmed from this figure that the surface photographs and the roughness curves of the test rollers were hardly changed even after the CSP. Also in the case of the test pinions, there is no clear difference between those with and without the CSP, and the grinding marks could be still observed on the tooth surface of the peened test pinions.

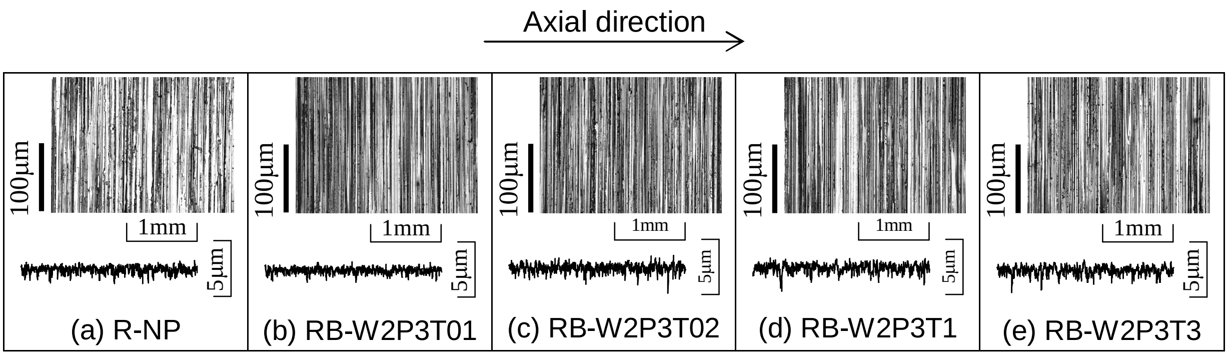


Fig.2 Surface photographs and roughness curves of test rollers

Table 4 Surface properties of test roller pair and test gear pair

Specimen	Test roller					Mating roller
	R-NP	RB-W2P3T01	RB-W2P3T02	RB-W2P3T1	RB-W2P3T3	RM
R_z μm	3.17	2.08	2.59	3.08	3.61	2.22
H_V	737	793	804	844	874	788
$(\sigma_x)_r$ MPa	-375	-969	-1098	-1187	-1016	-378
$(\sigma_y)_r$ MPa	-164	-285	-504	-672	-815	-140

Specimen	Test pinion				Mating gear
	G-NP	GA-W1P3T3	GA-W2P3T3	GB-W2P3T05	GM
R_z μm	2.36	2.06	1.97	2.21	2.30
H_V	715	726	760	783	709
$(\sigma_x)_r$ MPa	-385	-675	-474	-661	-635
$(\sigma_y)_r$ MPa	-657	-781	-733	-856	-848

x : Axial direction of roller, Tooth trace direction of gear
y : Circumferential direction of roller, Tooth profile direction of gear

The surface roughness, the surface hardness and the surface residual stress of the rollers and the gears are given in Table 4. The surface roughness of the gears was measured on the tooth surface along the tooth profile direction, and that of the rollers was obtained in the same manner as at measuring the roughness curve shown in Fig.2. The surface hardness was determined from their hardness distributions. The surface residual stress was measured according to the 2θ-$\sin^2\psi$ method (The Society of Materials Science, 1982) using CrKα-ray. As can be seen in Table 4, the surface hardness and the surface compressive residual stress of the test rollers and the test pinions are increased by the CSP. In particular, those of the test rollers increase with the increase in processing time of the CSP. In the case of the test pinions, those of the test pinion peened using nozzle type B were larger than those peened using nozzle type A. The work-hardened layer due to the CSP was in a range of a depth of about 0.5mm below the surface. Thus, it can be expected that the rolling contact fatigue strength of steel gears will be improved by the CSP, because the CSP gives the peening effect to the test specimens without significant change in the surface roughness.

EXPERIMENTAL PROCEDURES

The rolling contact fatigue tests of the rollers were performed using a spring-loading type roller testing machine (K.Fujita, 1977). The load between the test roller and the mating roller was given by a compression spring. The maximum Hertzian stress p_{max} (K.L.Johnson, 1987) was adopted as the standard of the loading between contact rollers. These roller tests were performed under a sliding-rolling contact condition (K.Fujita, 1977). The lubricating oil employed in the roller tests was ATF.

The operating fatigue tests of the gears were performed at a test pinion rotational speed of 1800rpm using a power circulating type gear testing machine (M.Seki, 2007). The test pinions were used as the driven gears in this experiment. The load between the test pinion and the mating gear was given by a load lever and weights. The maximum Hertzian stress p_{max} (D.W.Dudley, 1962) at the working pitch point was adopted as the standard of the loading for the tooth meshing of test gear pair. The lubricating oil employed in the gear tests was EP gear oil.

In this study, the fatigue lives 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.

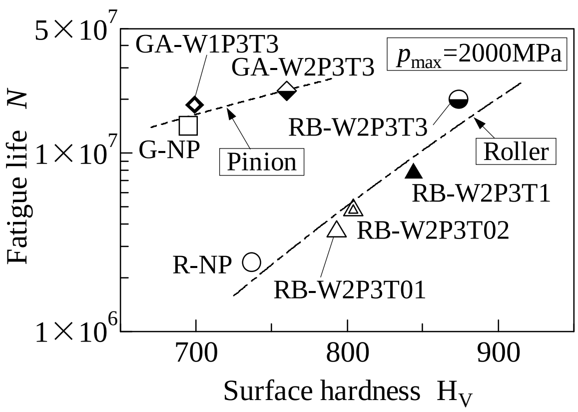


Fig.3 Relationship between fatigue life and surface hardness of test rollers and pinions

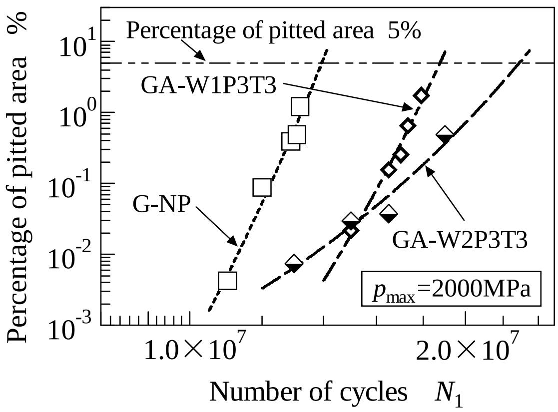


Fig.4 Change in percentage of pitted area on a test gear pair during gear tests

EXPERIMENTAL RESULTS

Figure 3 shows the relationship between the fatigue life and the surface hardness of the test rollers. The fatigue lives were obtained by the roller tests performed under p_{max}=2000MPa, and the surface hardness is given in Table 4. The failure mode of all the test rollers employed in this study was spalling due to subsurface cracking. Their failure depth was in a range of a depth of about 0.5mm below the roller surface. The relationship between the fatigue life and the surface hardness of the test pinions are also shown in this figure. The fatigue lives of the test pinions were the result of the gear tests performed under p_{max}=2000MPa. The failure mode of the test pinions employed in this study was mainly pitting due to surface cracking. As can be seen in this figure, the fatigue lives of the test rollers and the test pinions were improved by the CSP. Moreover, it is obvious from this figure that the fatigue lives increase with the increase in surface hardness. As shown in Fig.2 and Table 4, the surface roughness was not increased so much by the CSP. Therefore, it could be considered that the fatigue life of all the peened rollers and pinions increased, unlike in the case of the shot peening.

The Change in the percentage of the pitted area on a test gear pair during the gear tests is shown in Fig.4. Although the percentage of the pitted area increased during the gear tests, the increasing rate of the pitted area was decreased by the CSP. In particular, the increasing rate of the pitted area decreased with the increase in surface hardness due to the CSP. It can be considered from this figure that the pitting cracking was restrained by the CSP, because it occurred within the peened layer.

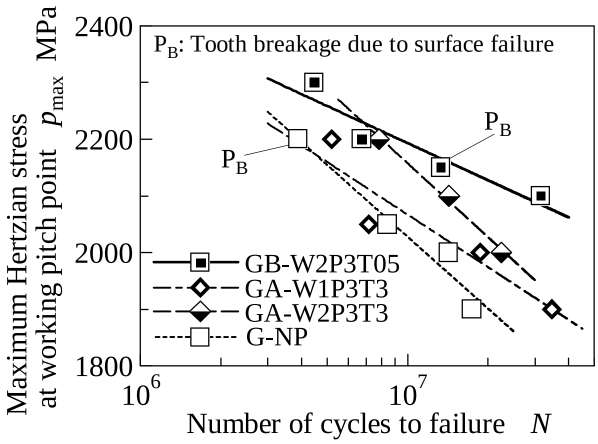


Fig.5 p_{max}-N curves of test pinions

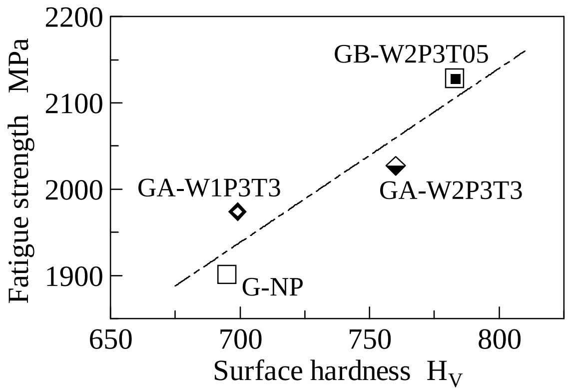


Fig.6 Relationship between fatigue strength and surface hardness of test pinions

Figure 5 shows the relationship between the maximum Hertzian stress p_{max} and the fatigue life of the test pinions obtained by the gear tests. Also in this figure, it can be understood that the fatigue lives of most test pinions were improved by the CSP. Specially, the fatigue lives of GB-W2P3T05 were much longer than those of the other test pinions. Here, the surface hardness of GB-W2P3T05 was the highest among the test pinions as shown in Table 4. Thus, it could be said as in Fig.3 that the fatigue life of the peened test pinions became longer as the surface hardness became higher.

Figure 6 shows the relationship between the fatigue strength and the surface hardness of the test pinions. In this study, the rolling contact fatigue strength, namely the fatigue strength of the test 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. It can be seen from this figure that the fatigue strength of the test pinions increases with the surface hardness. As previously noted, shot peening often causes the decrease in rolling contact fatigue strength of steel gears because of the increase in surface roughness. However, in the case of the CSP which does not cause the increase in surface roughness, the increase in surface hardness due to the CSP led directly to the increase in the rolling contact fatigue strength. Therefore, these facts indicate that the CSP is good for the increase in rolling contact fatigue strength of steel gears, because the peening effect is obtained with less increase of the surface roughness.

CONCLUSIONS

The hardness near the surface and the surface compressive residual stress of the test rollers and the test pinions were increased by the CSP. While, the surface roughness of the peened rollers and pinions was similar to that of the non-peened ones. As a result of the fatigue tests, the rolling contact fatigue life of most test rollers and test pinions was improved by the increase in surface hardness due to the CSP. In addition, the rolling contact fatigue strength of the test pinions was also improved by the same factor. It follows from these that CSP is a superior surface treatment method for improving the rolling contact fatigue strength of steel gears, because the peening effect is obtained with less surface roughness change.

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