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Surface durability of powder-forged roller treated by shot peening[†]

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Abstract

To investigate the influence of shot peening on the surface durability of powder-forged rollers, the case-hardened powder-forged rollers with a forging density of 7.5 g/cm^3 treated by the single shot peening and the double shot peening were fatigue-tested under a sliding-rolling contact condition. The surface roughness, the surface hardness and the surface compressive residual stress of the rollers were increased by the shot peening. In addition, the pores near the roller surface were deformed by the shot peening. The failure mode of all the test rollers was spalling due to subsurface cracking. The fatigue lives of all the test rollers were improved by the shot peening, and that of the test roller S08, which was shot-peened with the hardest steel shots in this experimental range, was especially improved. The surface durability of the test roller S08 was also most improved by the shot peening. Cracks became difficult to occur and propagate under the roller surface since the pores near the roller surface were deformed by the stronger shot peening. In this study, double shot peening, which generally restrains the increase in surface roughness, was not particularly effective for the improvement in the surface durability of the powder-forged rollers, because the influence of tangential force on fatigue was not always great in a case of subsurface cracking.

Keywords: Roller; Powder-forged material; Shot peening; Surface durability; Hardness; Surface roughness; Pore

1. Introduction

Forging is the processing method for shaping metal by using compressive forces. In a case of forging for powder metal, it is often used in machine part production because it reduces production costs. Sintered material is of lesser intensity than conventional steel. However, powder-forged material is equivalent to conventional steel in fatigue strength [1]. On the other hand, shot peening is the surface treatment method for surface modification, and it is often used to improve the fatigue strength of machine parts. Shot peening is employed for conventional steel, but it is hardly employed for powder-forged material. Therefore, in this study, the powder-forged rollers treated by shot peening were fatigue-tested in order to investigate the influence of shot peening on the surface durability of the powder-forged rollers.

2. Test roller pair

2.1 Manufacture of test roller pair

A test roller pair employed in the roller tests consisted of the slower test roller and the faster mating roller with 60 mm in diameter. The manufacturing conditions of the test rollers are given in Table 1. Pre-alloyed metal powder was powder-forged into discs after sintering. Hot forging performed at a high temperature was employed in this study. The forging density of the powder-forged discs was 7.50 g/cm^3. The above discs were manufactured to the test roller as shown in Table 1. Meanwhile, the mating roller was made of chromium molybdenum steel (JIS:SCM415). The test rollers and the mating rollers were finish-ground after case hardening.

Young's modulus and Poisson's ratio of the test roller are 177 GPa and 0.28, and those of the mating roller are 206 GPa and 0.30, respectively.

2.2 Shot peening conditions for test roller pair

Table 2 shows the shot peening conditions for test roller pair. In this study, the finish-ground circumferential surfaces of the test roller pair were shot-peened at a roller rotational speed of 30 rpm by a centrifugal peening unit. S06 and D08 represent the test specimens treated by normal single shot peening and normal double shot peening, respectively. Double shot peening consists of primary shot peening and secondary shot peening. S08 and D17 represent the test specimens

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Table 1. Manufacturing conditions of test rollers.

		Test roller
Sintering	Powder type	0.2 % C, 0.2 % Mn, 0.5 % Ni, 1.0 % Mo, Balance Fe
	Particle diameter	Average 75 μm, Maximum 250 μm
	Mixing	0.20 % Graphite, 0.75 % Zinc stearate
	Compacting pressure	6.5 ton/cm^2
	Green density	6.89 g/cm^3
	Heat treatment	1403 K x 20 min, in N_2 gas
Forging	Compacting pressure	2.7 ton/cm^2
	Forging density	7.50 g/cm^3
	Heat treatment	1323 K x 30 min, in N_2 gas
Machining		Turning
Case hardening		1213 K x 4.5 hr, Oil cooling
Tempering		453 K x 1.5 hr, Air cooling
Finishing		Grinding

Table 2. Shot peening conditions for test roller pair.

Specimen		Test roller						Mating roller
		Single shot peening		Double shot peening				
				D08		D17		M
		S06	S08	*1	*2	*1	*2	
Shot diameter	mm	0.6	0.8	0.8	0.3	1.7	0.3	0.2
Shot hardness	HV	600	700	600	700	400	600	700
Shot velocity	m/s	60						88
Peening time	sec	200	100	100	36	200	36	200
Projection amount	kg/min	100						
Arc height	mmA	0.465	0.635	0.540	0.230	0.705	0.215	0.235
Coverage	%	600		300				2200

*1: Primary shot peening, *2: Secondary shot peening

treated by single shot peening and primary shot peening with larger steel shots, respectively. Mating roller was also shot-peened as shown in Table 2. Here, the non-peened test roller is denoted as NP.

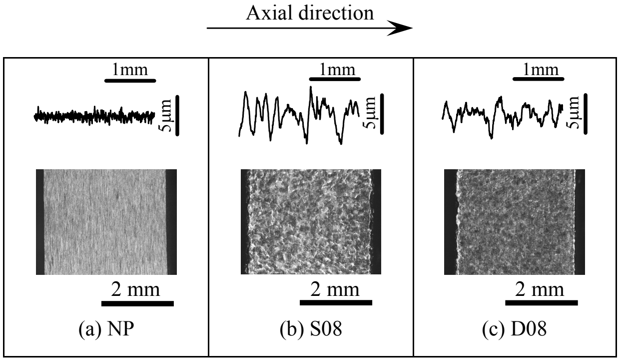
2.3 Surface properties of test roller pair

Fig. 1 shows the roughness curves and the surface photographs of the test rollers before tests. The grinding marks can be observed on the roller surface of NP. In contrast, on that of the shot-peened rollers the indentations due to steel shots appear, and the grinding marks disappear by the shot peening. Comparing the test rollers shot-peened with 0.8 mm steel shots, the surface roughness of D08 was smaller than that of S08.

Fig. 2 shows the cross sections of test rollers. Pores existed in the powder-forged rollers employed in this study. The pores near the roller surface were deformed by the shot peening.

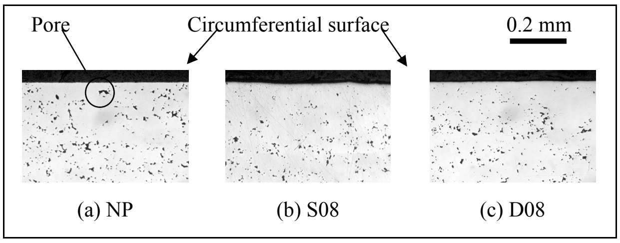
Fig. 3 shows the average hardness distributions of test rollers. The Vickers hardness was measured with a micro hardness tester under a measuring load of 0.98N for 30sec. The average hardness distribution was obtained from five measured hardnesses at each depth below the circumferential surface of roller. As shown in Fig. 3, the hardness near the circumferential surface of the test rollers was increased by the shot peening. The work-hardened layer due to the shot peening was in a range of a depth of about 0.3mm below the roller surface.

The residual stress distributions of test rollers are shown in



(a) NP (b) S08 (c) D08

Fig. 1. Roughness curves and surface photographs of test rollers.



(a) NP (b) S08 (c) D08

Fig. 2. Cross sections of test rollers.

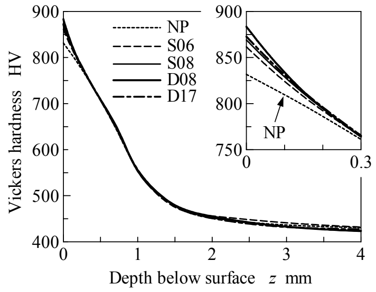


Fig. 3. Hardness distributions of test rollers.

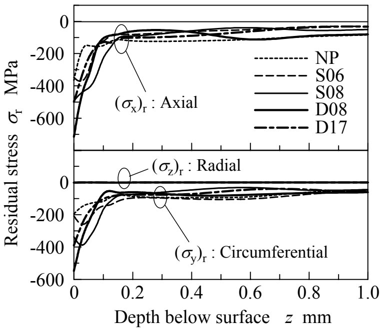


Fig. 4. Residual stress distributions of test rollers.

Table 3. Surface properties of test rollers and mating roller.

Specimen	NP	S06	S08	D08	D17	M
R_z μm	2.06	5.06	10.30	6.39	4.42	3.25
HV	831	867	898	935	918	874
$(\sigma_x)_r$ MPa	-365	-348	-492	-715	-498	-809
$(\sigma_y)_r$ MPa	-193	-207	-337	-548	-390	-615

Fig. 4. The residual stress was measured according to the 2θ-$\sin^2\psi$ method [2] using CrKα-ray as characteristic X-ray. For the stress analysis below the contact roller surface, an arbitrary point at the center of the roller surface was chosen as the origin, and the x, y and z coordinates were taken in the axial, circumferential and radial directions of the roller, respectively. The surface layer of the roller was removed by electrolytic polishing to measure the residual stress below the roller surface. The residual stresses $(\sigma_x)_r$ and $(\sigma_y)_r$ in the axial and the circumferential directions of the roller, shown in Fig. 4, were determined by modifying the measured residual stresses by the elastic calculation [3], 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 [3]. $(\sigma_x)_r$ and $(\sigma_y)_r$ of the shot-peened rollers were in compressive field in the surface layer. These compressive residual stresses were larger than those of NP. The compressive residual stress layer due to the shot peening was within about 0.1 mm in depth below the roller surface.

The surface roughness, the surface hardness and the surface residual stress of the test rollers and the mating roller are given in Table 3. The surface roughness R_z was measured along the axial direction on the circumferential surface. The surface hardness was determined from the hardness distribution on the cross section. $(\sigma_x)_r$ and $(\sigma_y)_r$ in Table 3 represent the surface residual stresses measured on the circumferential surface in the axial and the circumferential directions of the roller, respectively. As can be seen in Table 3, the surface roughness, the surface hardness and the surface compressive residual stress were mostly increased by the shot peening.

3. Test method and test result

3.1 Test method

The rolling contact fatigue tests of the rollers were performed using a spring-loaded type roller testing machine [4]. The maximum Hertzian stress $p_{\max}$ [5] was adopted as the standard of the loading between contact rollers. These roller tests were performed under a sliding-rolling contact condition. The circumferential velocity and the specific sliding of the test roller were 4.50 m/s and -25.7 %, respectively. Those of the mating roller were 5.65 m/s and +20.4 %, respectively. The relative radius of curvature of the test roller pair was 15 mm. The lubricating oil employed in the roller tests was EP gear oil (Kinematic viscosity: 190.9 mm^2/s at 313 K, 17.47 mm^2/s at 373 K). The flow rate of the supplied oil was about 1500 ml/min for the test roller pair. During tests, the oil temperature was adjusted to 313±4 K.

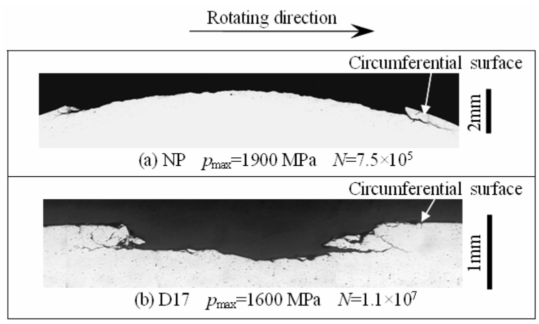


Fig. 5. Transverse sections of failed test rollers.

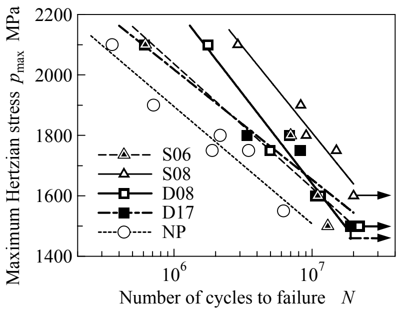


Fig. 6. $p_{\max}$-N curves of test rollers.

In this study, the roller testing machine was automatically stopped when the vibration transducers fixed on the machine acted by the vibration increase due to the large surface failure. The fatigue life N of test rollers was defined as the total number of cycles when the testing machine was automatically stopped.

3.2 Failure mode

Fig. 5 shows the transverse sections of the failed test rollers. The micropits on the roller surface occurred at the early stage of the roller tests. Eventually, however, a fatal separation on part of the roller surface occurred as shown in Fig. 5. The ultimate failure mode of all the test rollers employed in this study was spalling due to subsurface cracking. Their failure depths ranged from 0.2 mm to 0.6 mm below the roller surface.

3.3 Fatigue life

Fig. 6 shows the $p_{\max}$-N curves of the test rollers obtained in the roller tests. The arrows in this figure indicate that no fatal surface failure occurred on the roller surface when the number of cycles of test roller exceeded 2×10^7 cycles. The fatigue lives of all the test rollers were improved by the shot peening, and those of S08 were especially improved. S08 was shot-peened with the hardest steel shots in this experimental range. The fatigue life of S08 was more than eight times that of NP under $p_{\max}$=2100 MPa, and more than four times under $p_{\max}$=1750 MPa.

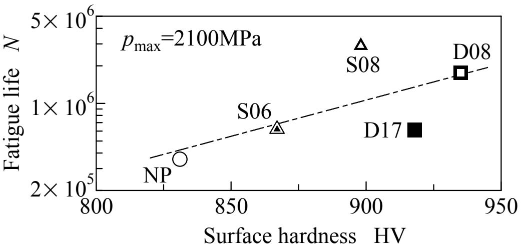


Fig. 7. Relations between fatigue life and surface hardness.

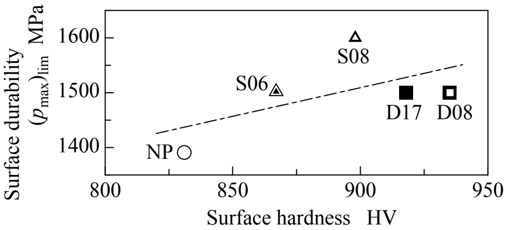


Fig. 8. Relations between surface durability and surface hardness.

3.4 Surface durability

The subsurface cracks of the test rollers employed in this study propagated parallel to the roller circumferential surface, and the roller surface layer finally separated. Cracks propagated to the roller surface through the work-hardened layer due to the shot peening just before a fatal separation on the roller surface occurred. Thus, the results of this roller tests are comparatively affected by the work-hardened layer due to the shot peening.

In this study, the surface durability $(p_{max})_{lim}$ of the test roller was defined as the maximum Hertzian stress p_{max} at 2×10^7 cycles. Fig. 7 shows the relations between N and surface hardness, and Fig. 8 shows the relations between $(p_{max})_{lim}$ and surface hardness. In general, the rolling contact fatigue life and strength increases with the increase in hardness except in the case of too large surface roughness [6]. From these figures, the fatigue life and the surface durability of the test rollers have a tendency to increase with the increase in surface hardness. This may be because the results of this roller tests are affected by the work-hardened layer due to the shot peening.

Spalling due to subsurface cracking generally depends on shear stress amplitude below the surface [1]. In contrast, it does not depend heavily on tangential force between contact surfaces and surface roughness, since shear stress amplitude is not affected so much by tangential force and surface roughness. In this study, the surface roughness R_z of S08, which was the largest in surface durability, was five times larger than that of NP.

Therefore, the spalling crack became difficult to occur and propagate within the work-hardened layer due to the stronger shot peening, because the pores near the roller surface were deformed and the hardness near the roller surface was increased by the stronger single shot peening. Double shot peening, which restrains the increase in surface roughness, was less effective than single shot peening in this roller tests, since tangential forces between contact rollers have little influence on spalling failure.

4. Conclusions

In this experimental range, it is proposed that stronger single shot peening, which increases hardness near the roller surface, has to be selected in order to improve the surface durability of case-hardened powder-forged rollers with a forging density of 7.5 g/cm^3.

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