Influence of Work Hardening and Residual Stress Induced by Shot Peening on Pitting Strength

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Abstract

This study is to examine the influence of work hardening and compressive residual stress induced by shot peening on the pitting fatigue strength. Test specimens were prepared so that the surface roughness was made to be identical by grinding after two kinds of shot peening to various carburized steels.

As a result, the pitting strength increased with the peening intensity and the surface hardness was increased after tempering at 300 °C by shot peening. It was found that both increases in surface hardness before testing and compressive residual stress during testing contributed to the improving of the pitting strength. It is because the number of crack initiation in the material with both higher hardness and higher compressive residual stress was fewer, when pitting strength was compared between specimens having the same hardness after testing.

Keywords
Residual stress, Work hardening, Shot peening, Carburized materials, Pitting strength

1. Introduction

Shot peening has been applied generally to improve fatigue strength of carburized gear for automobile transmissions. In recent years, we have developed a technique to realize a surface hardness and compressive residual stress of 1000 HV or over and 1800 MPa or over, respectively, which enables miniaturized carburized gears for improving automotive fuel consumption rate. This process has significantly improved fatigue strength of gears at their dedendum [1,2]. Accordingly, it is anticipated that the status of breakage that is fatal to gear life may shift from dedendum fraction to tooth flank pitting damage. However, the pitting strength of materials given such high hardness and compressive residual stress has not been studied enough.

Incidentally, reports on the effect on pitting strength of shot peening are variously different; some conclude shot peening has improved pitting strength [3-6] and the other worsened [7]. An increase in surface hardness or compressive residual stress and that in surface roughness are mentioned as factors to improve and worsen strength, respectively. However, the effect of shot peening on pitting strength has not reached common agreement. Because the specimens used in these studies are varied simultaneously in factors attributing to material such as hardness, residual stress and surface roughness by shot peening.

Therefore, we prepared test specimens the surface roughness of which was made identical by grinding after two kinds of shot peening for various carburized steels, and tried to clarify the influence of work hardening and compressive residual stress induced by shot peening on pitting life. We estimated the pitting strength of materials given a high hardness and compressive residual stress of 1000 HV or over and 1800 MPa or over, respectively.

2. Experimental Methods

2.1 Test materials

Table 1 shows chemical composition of specimens used in this study. These include two types of steels: JIS Low-alloy case hardening steel SCM420H (J) and steel A with higher silicon content. Steel A has higher temper softening resistance than SCM420H and has

Table 1 Chemical composition (mass%).

Steel	No.	C	Si	Mn	Cr	Mo
SCM420H	J	0.20	0.25	0.80	1.17	0.16
SteelA	A	0.18	0.83	0.63	1.27	0.15

Table 2 Heat treatment conditions and carburizing properties.

No.	Conditions of heat treatment			Carburizing properties	
	C [mass%]	SZT	Tempering temperature [℃]	γ_R [vol.%]	Surface hardness [HV]
J	0.70	-	160	14.8	745
A1	0.75	-	160	23.2	747
A2		-	140	24.4	772
A2S		○	140	10.9	855

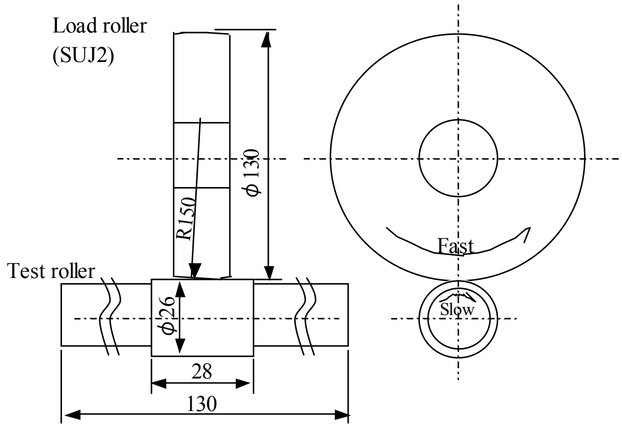


Fig.1 Schematic diagram of roller pitting testing specimen.

Table 3 Shot peening conditions.

No.	Shot material	Diameter [mm]	Density [g/cm3]	Hardness [HV]	Air pressure [MPa]	Coverage [%]
SP①	Steel	0.6	7.8	700	0.2	300
SP②	Zirconia	0.6	4.6	1000	0.2	300

Table 4 List of specimens.

No.	AS VCQT	VCQT +SP①	VCQT +SP②
J	○	○	○
A1	○	○	○
A2	—	—	○
A2S	—	—	○

Table 5 Roller pitting test conditions.

Surface pressure	3.0 GPa
Rotating speed	1500 rpm
Slip ratio	-60%
Lubricant oil	CVT Fluid
Oil temp.	90 ℃
Oil quantity	2.0 L/min

excellent in pitting resistance [8]. These materials were machined to the test rollers shown in Fig. 1 (ϕ26.04 mm×130 mm) and were carried out carburizing treatment and shot peening treatments as stated hereinafter. In this experiment, area to be tested (sliding surfaces) of the specimens were ground by 20 μm to eliminate the influence of shot peening on the surface texture and finished the test roller diameter to ϕ26.0 and surface roughness to Ra≒0.10 μm.

The heart treatment conditions and carburizing properties applied to each steel grade are as shown in Table 2. In this study, we controlled heat treatment conditions by steel type to vary pre-shot peening hardness and amount of retained austenite (γ_R) that had a significant influence on post-shot peening hardness and compressive residual stress. All the carburizing treatment were conducted under a non-oxidative atmosphere (VCQT).

SCM420H (J) scored 745 HV Vickers hardness of carburized case, 0.7 mass % for subsurface carbon concentration and approximately 15-vol% for the amount of γ_R. The case hardness of steel A were changed by tempering at 160℃ (A1) and 140℃ (A2) (A1:747 HV, A2:772 HV). In addition, sub-zero treatment (SZT) at -80℃×7.2 ks to A2 was applied prior to the tempering treatment in order to increases the case hardness (A2S:855HV) by decreasing the amount of γ_R in carburized case. Among these materials experimentally prepared in this study, the hardness of steel A2 and A2S had more than 750 HV. Steel A2 and A2S meet conditions [1,2] that can give a hardness of 1000 HV or over and compressive residual stress of 1800 MPa or over by combining with shot peening of SP②.

The surface hardness of the specimens was measured by using micro Vickers hardness tester (load 2.94 N). The carbon concentration and the amount of γ_R were determined by using Electron Probe Micro-Analyzer (EPMA) and X-ray diffractometer, respectively.

2.2 Shot peening condition

Shot peening conditions are as shown in Table 3. In order to vary hardness and compressive residual stress after shot peening, the shot media used for shot peening treatment was SP① with a hardness of 700 HV and SP② with a hardness of 1000 HV. The shot peening treatments were performed by using direct-pressured air-peening-machine.

And the area of peening was only the sliding surface of the test roller. The residual stresses of the specimens were measured by using X-ray diffraction method.

The lineup of specimens is as shown in Table 4. The materials were combined with the shot peening conditions as shown in Table 4 to vary hardness and residual stress. Among these combinations, A2-SP② and A2S-SP② meet the process conditions [1,2] that can give a hardness of 1000 HV or over and compressive residual stress of 1800 MPa or over.

2.3 Pitting fatigue test

The pitting life was evaluated by the pitting test on roller pitting (RP) tester shown in Fig 1. The pitting test conditions are shown in Table 5. The load roller is the quenched and tempered bearing steel (SUJ2).

3 Experimental Results

3.1 Surface properties of specimens

The surface properties of the test specimens are as shown in Table 6. This table also shows the results of the hardness and residual stress after tempering at 300 ℃×10.8 ks.

The surface hardness of SCM420H fluctuated depending on presence or absence of shot peening and shot peening intensity as we expected. The surface hardness of pre-shot peening treatment, SP① and SP② scored 745 HV, 920 HV and 948 HV, respectively. As to the surface hardness of the steel A, the material tempered at 160 ℃ (A1) was almost equivalent to SCM420H (J) of the same treatment condition. Both of the specimens tempered at a low temperature of 140 ℃ (A2) and subzero-treated (A2S) showed a high hardness of approximately 1050 HV by shot peening treatment of SP②.

SCM420H and steel A1 were given a surface compressive residual stress of approximately 800 MPa and 1300 MPa by shot peening treatments of SP① and SP②, respectively. A2-SP② showed a high compressive residual stress of approximately 1800 MPa, which was in accordance with our test results [1,2] hereto. As a result, we succeeded in making the test specimens with equalized surface roughness while varied in hardness and residual stress.

3.2 Surface properties of specimens after tempering

Generally, it is known that the pitting resistance of tooth flanks increases with 300 ℃ tempering hardness [8]. Accordingly, we investigated the influence of thermal addition on hardness and residual stress after shot peening treatment.

The correlation of the surface hardness with tempering temperature is as shown in Fig. 2. The tempering hardness of SCM420H increased with the shot peening intensity (SP②＞SP①＞VCQT), which is the same as tendency of the hardness before testing. The tempering hardness of steel A1 was higher than that of SCM420H (J) of the same treatment condition. This tendency accorded with our test results [9] using high silicon steel.

Table 6 Surface properties of specimens.

Steel	No.	Before testing						After 300℃ tempering		
		Surface roughness Ra [μm]	Surfce carbon content [mass%]	Retained austenite [vol.%]	Surface hardness [HV]	Surface residual stress [MPa]	Max. residual stress [MPa]	Surface hardness [HV]	Surface residual stress [MPa]	Max. residual stress [MPa]
SCM420H	J-VCQT	0.12	0.70	14.8	745	-95	-517	603	-113	-113
	J-SP①	0.08		3.2	920	-826	-1293	720	-240	-377
	J-SP②	0.07		0.0	948	-1191	-1828	771	-555	-572
Steel A	A1-VCQT	0.15	0.75	23.2	747	-247	-247	675	-149	-291
	A1-SP①	0.09		5.3	963	-750	-1477	823	-392	-487
	A1-SP②	0.06		1.4	989	-1345	-1893	913	-765	-1005
	A2-SP②	0.06		0.0	1057	-1853	-2121	917	-987	-987
	A2S-SP②	0.07		2.6	1056	-1243	-1895	930	-677	-1039

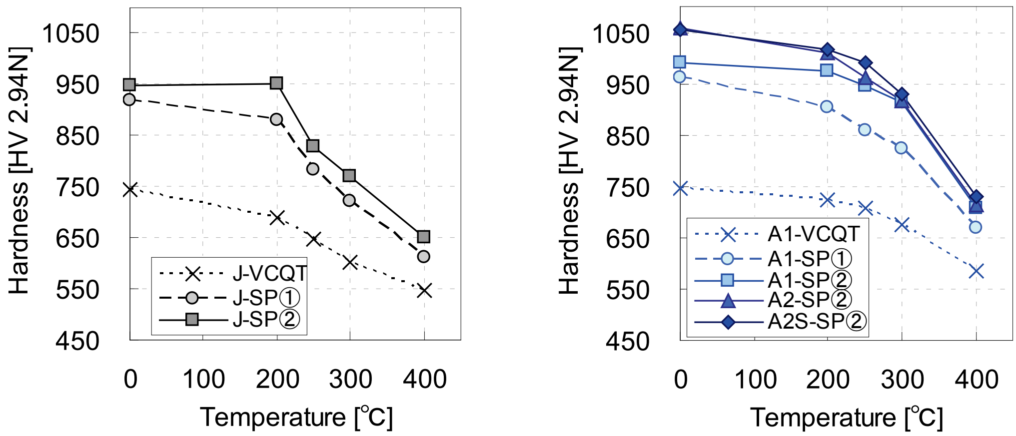


Fig.2 Surface hardness change in accordance with tempering temperature.

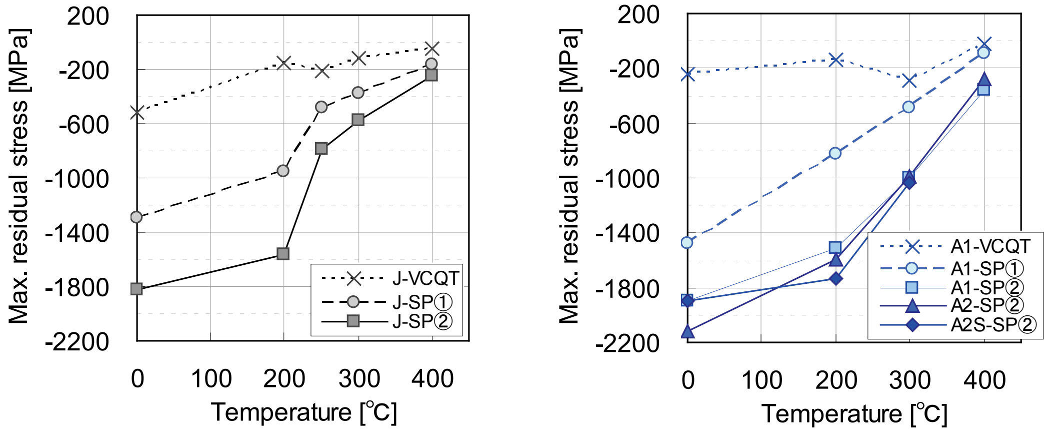


Fig.3 Maximum residual stress change in accordance with tempering temperature.

The correlation of the maximum residual stress with tempering temperature is as shown in Fig. 3. For all the test specimens, the compressive residual stress decreased significantly at a temperature of 200 ℃ or over. However, the compressive residual stress tempered at 300 ℃ differed depending on the combination of material with shot peening. When comparing between different shot peening intensities, compressive residual stress after tempering at 300 ℃ showed higher in the order of shot peening intensity (SP②＞SP①＞VCQT). For the specimens of SP②, the compressive residual stress scored approximately 1000 MPa at the maximum. On the other hand, when comparing between different materials, the attenuation of compressive residual stress after tempering for steel A of high silicon grade showed tended to be less than SCM420H. This tendency accorded with Fukuoka's test result [4] using high silicon steel. The surface properties when tempered at 300 ℃ of A2-SP② and A2S-SP② having high hardness and high compressive residual stress were almost on a par with those of A1-SP②. This result indicates that application of low-temperature tempering or subzero treatment, one of the processes giving high hardness and high compressive residual stress, doesn't have a significant influence on hardness and residual stress after tempered at 300 ℃ following shot peening.

3.3 Results of pitting test

The relationship between the surface hardness after tempering at 300 ℃ and pitting life is as shown in Fig. 4. The surface residual stress after tempering at 300 ℃ was also shown in this Fig.4. All the steel types improved in pitting life due to shot peening with a pitting life for SP② longer than that for SP①. For A2-SP② and A2S-SP②, no pitting occurred even after 4×10^7 cycles. As to the specimens increased in tempering hardness by shot peening, its pitting life increased with 300 ℃ tempering hardness. However, when sorting by shot peening, pitting life of SP② tended to show longer than that of the identical tempering hardness of SP①. This result suggests that the surface compressive residual stress of more than 500 MPa help improve the pitting life. Incidentally, the specimens before shot peening treatment (VCQT) showed longer life as compared to SP① with the identical tempering hardness, which induced a result that cannot be explained by the residual stress at 300 ℃. Therefore, we tried to clarify these reasons by comparing the post-testing hardness with the 300 ℃ tempering hardness.

3.4 Surface properties of specimens after testing

In order to verify the reasonability of the correlation of pitting life with 300 ℃ tempering hardness, we investigated the surface properties after testing. The relationship between the surface hardness after testing and pitting life is as shown in Fig. 5. The surface residual stress after testing was also shown in Fig.5. The post-testing hardness of the VCQT specimens is higher than the 300 ℃ tempering hardness. This tendency was different from Fig.4 that is sorted according to the 300 ℃ tempering hardness. This increment of hardness is attributed to the influence of work hardening caused by the thrust force of the roller over the test surface. When pitting life was compared between specimens having the same hardness after testing, the pitting life improved with the shot peening intensities (SP②＞SP①＞VCQT) and accorded with intensities of the compressive residual stress after testing.

Fig. 6 shows an example of the changes in hardness with the number of cycles for the sample after shot peening treatment (A1-SP①). Hardness tends to decrease with the number of cycles and does not decrease in a short period of time down to 300 ℃ tempering hardness. Fig. 7 shows the SEM microphotographs of sliding surface layers for SCM420H-

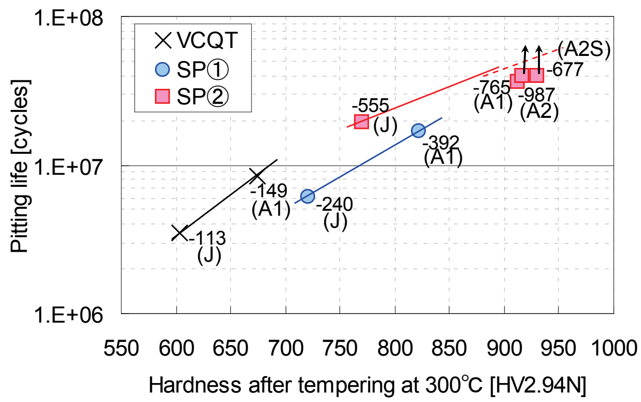


Fig.4 Relationship between surface hardness after tempering at 300 ℃ and pitting life.

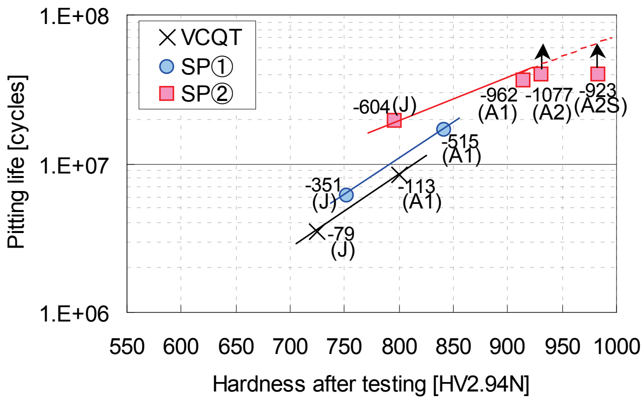


Fig.5 Relationship between surface hardness after testing and pitting life.

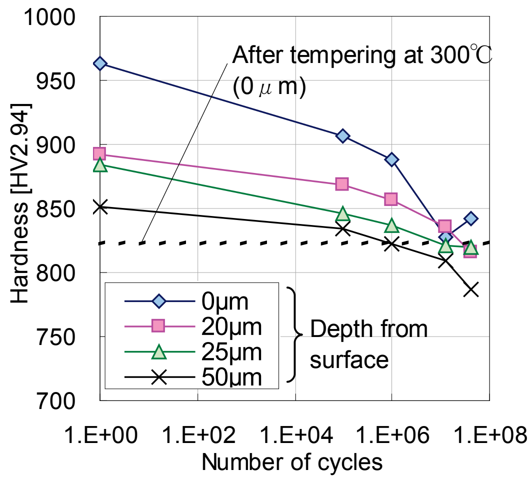
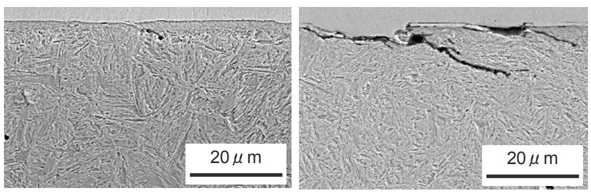


Fig.6 Change in hardness with the number of cycles (A1-SP①).



(a) J-SP②
Nf=19,163,968

(b) A1-VCQT
Nf=8,435,506

Fig.7 SEM microphotographs of specimens after testing.

SP② and A1-VCQT that have same hardness after testing. The cracks of SCM420H-SP② have fewer and shorter than that of A1-VCQT. This result indicates that initiation and propagation of pitting cracks are inhibited for SCM420H-SP② more than for A1-VCQT. In Kanisawa's study, the results of their examination on the behavior of crack propagation for the specimen with shot peening demonstrated that compressive residual stress had an effect to inhibit propagation of crack [6]. Therefore, the effect to inhibit crack propagation identified in Fig. 7 can be explained by the effect of compressive residual stress.

For all of these reasons, it was found that shot peening treatment helped improving pitting life by the effect not only increasing hardness after tempering and hardness at normal temperatures but also preserving compressive residual stress in a high-temperature environment.

4 Discussion and Conclusions

In this study, we investigated the influence of the work hardening and the residual stress induced by shot peening on the pitting strength. The results are as follows.

1) The 300 ℃ tempering hardness increases with shot peening intensities (SP②＞SP①＞VCQT). Also with the shot peening treated material, pitting life is influenced by the 300 ℃ tempering hardness.
2) For the improvement in pitting life, increase in tempering hardness due to shot peening is effective as well as increases in hardness at normal temperatures and in compressive residual stress. Increase in hardness has an effect on improving crack initiation resistance and increase in compressive residual stress has an effect on inhibiting crack propagation by preserving the stress in a high-temperature environment.
3) The high silicon steel given a hardness of 1000 HV and compressive residual stress of 1800 MPa significantly improved in pitting life. This was because silicon has an effect to inhibit not only decrement of hardness during testing but also attenuation of compressive residual stress.

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