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세이빙기어의 굽힘피로강도 평가에 관한 연구

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A Study on the Evaluation of Bending Fatigue Strength in Shaving Gears

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Key words : Bending fatigue strength(굽힘피로강도), Shaving gear(세이빙기어), Hob(호브), Shaving(세이빙), Shot peening(쇼트피니싱), S-N Curves(S-N 곡선), Surface roughness(표면조도)

Abstract

This study deals with evaluation of bending fatigue strength in shaving gears. The saving gears were manufactured by processes that are currently used in most gears manufacturing companies. The test gears are hobbed, then the tooth surface are treated by a combination of shaving, carburizing and shot peening. The constant stress amplitude fatigue test is performed by using an electro-hydraulic servo-controlled pulsating tester. The S-N curves are obtained and illustrated.

In this study, the effect of shaving process and shot peening was investigated and evaluated quantitatively on the fatigue strength. The enhancement of fatigue strength due to shaving process and shot peening is clarified.

1. Introduction

Gears are some of the most frequently used power transmission devices in cars, airplanes, and industrial machines, and because of greater industrial development, there is an increasing demand for more efficient, high precision gears that are stronger and more powerful, yet smaller and lighter. Various research efforts have been advanced to design gears that meet these increasing demands and overcome the limitations facing the gear-manufacturing industry.

For example, since heavy-loaded, high-speed power transmission systems use gears that are surface-hardened by carburization, many studies have been conducted to determine precisely how surface-hardened gears and compression residual stress work together to strengthen gears against

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bending fatigue[1, 2]. Compression residual stress occurs the difference in temperature between the surface and the center of a gear.

Carburization, as recommended by AGMA[3] is the typical method used in the manufacture of power-transmission gears for cars, airplanes, and industrial machines.

Aida[4] and Retting[5] observed the effect of the hardness layer and residual stress by evaluating the fatigue strengths of gears carburized with various materials.

Nishikou[6] suggested a formula for estimating fatigue strength by calculating fatigue strength in carburized gears and high-frequency carburized gears. Unfortunately, these researchers employed hob-finished gears instead of shaving gears, which is most frequently used in the gear processing industry nowadays. And there is no research on the strength evaluation of shaving-treated gears.

The purposes of this paper are to evaluate the performance and applications of shaving gears, which are manufactured in the greatest number and to investigate the mechanical properties of the gears manufactured in conventional gear treatment processes so as to understand the effects of the shaving process and shot peening on compression residual stress of the gear's surface hardness layer and the teeth risk section.

In addition, fatigue tests were performed on gears in order to obtain bending fatigue strength and to observe the effects of the shaving process and shot peening on fatigue strength. Finally the mechanical properties of test gears used in this study were applied to the estimate formula[7] of gear fatigue strength so as to check if this formula may be applicable to the test gears.

2. The Properties of Test Gears

2.1 Test gears

The gear material in this study was SCM420 of KSD, whose chemical compositions were presented in Table 1. The chemical analysis of test gear material was commissioned to a test specialist. The dimensions of the test gears are shown in Table 2. Module m = 5 and teeth number z = 18 were selected in order to measure X-ray residual stress at teeth, and face width b = 8 mm was selected to allow for loading stress in the fatigue tester.

The gears were manufactured by first cutting 110 mm SCM420 into pieces and processing them into gear blanks on a lathe and into finished gears on hobbing and shaving machines. To prevent lateral carburization, 20㎛ copper-plating was performed on the gears before carburization. In the carburization treatment, the effective carburized depth was determined with reference to the recommendations by AGMA[3]. The

Table 1 Chemical compositions of SCM420(wt%)

SCM420	C	Si	Mn	P	S	Cu	Ni	Cr	Mo
Range	0.18 ~ 0.23	0.15 ~ 0.35	0.60 ~ 0.85	≤ 0.30	≤ 0.30	≤ 0.30	≤ 0.25	0.90 ~ 1.20	0.15 ~ 0.30
Measured	0.21	0.26	0.70	0.014	0.015	0.20	0.15	0.95	0.16

Table 2 Dimension of test gear

Module *m* [mm]	5
Number of teeth *z*	18
Face width *b* [mm]	8.0±0.01
Pressure angle [deg]	20
Teeth shape	Involute
Tip diameter [mm]	100
Finish	① Hobbed ② Hob & shaved
Material	SCM 420
Heat－treatment	See Fig. 2

Table 3 Code of test gear

Code	Surface－treatment process
HC	Hobbing→Carburizing
HSC	Hobbing→Shaving→Carburizing
HSCSP	Hobbing→Shaving→Carburizing →Shot peening

machining processes and the heat-treatment conditions for the test gears are presented in Figs. 1 and 2, respectively. Shot-peening was performed in order to investigate the effect of shot-peening on the fatigue strength of the gears.

The test gears were coded according to the applied processes, as presented in Table 3.

2.2 The measurement results of hardness and compression residual stress

Vicker's tester (FN-7) was employed for the hardness measurement of the test gears. As the preliminary procedures, the gears were cut into test pieces and mounted for polishing and lapping. Hardness distribution was measured in depth direction as shown in Fig. 3.

The measurement conditions were measurement load 300 gf and duration time period 10 sec. The measurement results on test gears are shown in Fig. 3. The maximum hardness(H_m), core hardness(H_c), and effective carburized depth(d_{eff}) of the test gears are presented in Table 4.

The effective carburized depth (deff) refers to the depth at which hardness reaches 550 Hv. Generally, the recommendations of AGMA[3] are applied in heat treatment. The effective

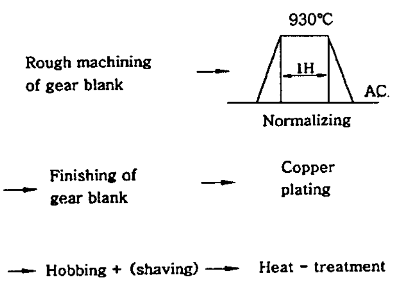

Fig. 1 Machining process of test gears.

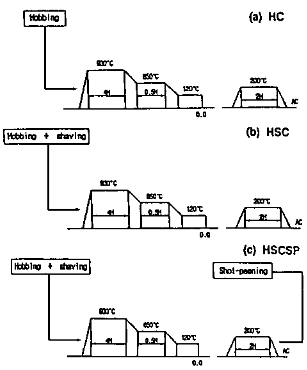

Fig. 2 Heat-treatment process of test gears

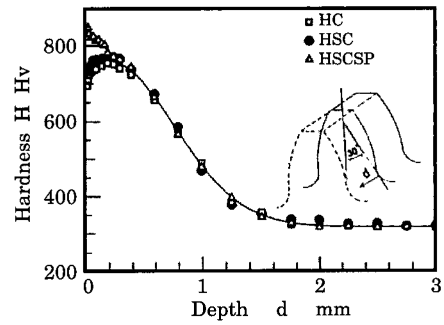

Fig. 3 Hardness distribution of test gears

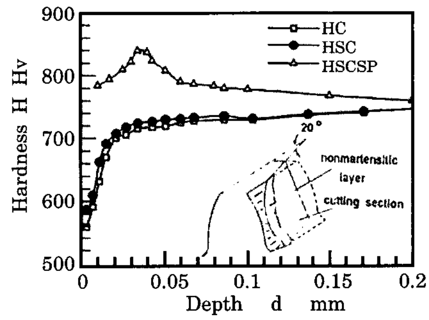

Fig. 4 Hardness distribution of non-martensitic layer in test gears

Table 4 Hardness & compressive residual stress of test gears

Code of test gear	H_s (Hv)	H_m (Hv)	H_c (Hv)	d_{eff} (mm)	σ_R (MPa)
HC	551	758	332	0.95	−302
HSC	580	782	334	0.94	−311
HSCSP	780	846	334	0.94	−486

H_s : Hardness of surface
H_m : Hardness of maximum
H_c : Hardness of core
d_{eff} : Depth of effective caburized
σ_R : Residual stress of surface

carburized depth for the test gears used in this study was found to be

between approximately 0.94 and 0.95 mm. To measure surface hardness (H_S) in the surface layer, test gears were cut off at the angle of 20 degrees, as is shown in Fig. 4, and the surface hardness was measured on the cut side.

In the case of HC gears, the surface hardness of the teeth risk section was found to decrease to 551 Hv. HSC gears showed a little more surface hardness than HC gears on the ultra-surface of risk section (H_S), as shown in Fig. 4, and used estimate values on a variety experimental results. The surface residual stress σ_R of all test teeth were measured by diffraction method(SMX-50). The measurement results(σ_R) are also shown in Table 4.

2.3 The surface roughness and metallography

A surface roughness gauge(Surfcome S70A) was employed to measure the surface roughness of the test gears. The ten point median height(Rz) and maximum height(Rmax) measurements on each

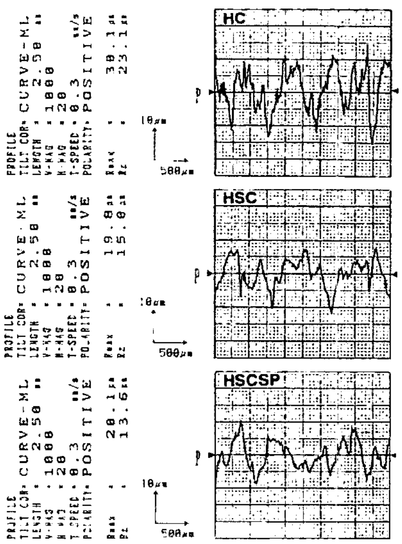

Fig. 5 Comparison of the surface roughness on test gears

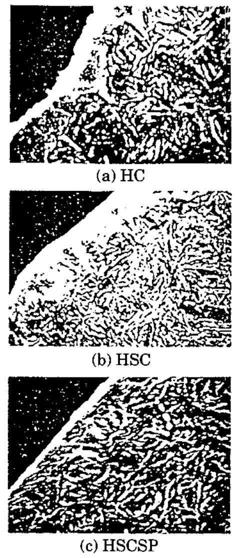

Fig. 6 Photography of test gears by SEM

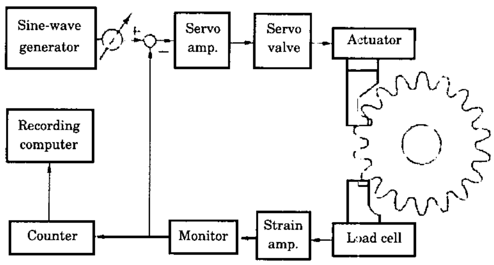

Fig. 7 System of bending fatigue tester

of the HC and HSC test gears are presented in Fig. 5. As shown in Fig. 5, the gears that underwent hobbing and shaving showed 30 to 35% better Rmax and Rz than hobbing gears.

The teeth of the test gears were cut off, ground, and processed in 3% ethanol etching in order to observe the metallography on a SEM. As is observed in Fig. 6, an 11 to 16μm thick defect on surface was found in the vicinity of the teeth risk section, and shaving gears showed better surface conditions than hobbing gears.

3. Bending Fatigue Tests

3.1 Equipment for bending fatigue tests

A high speed electric-hydraulic servo-controlled fatigue tester(with a constant loading weight of 2,500 kgf, an operating frequency of 40 Hz, and hydraulic pressure 210 kgf/㎠) was employed for bending fatigue tests on the gears. The details of the test are shown in Fig. 7.

3.2 The relation between the test weight load and the actual stress of the teeth risk section

The weight load in the fatigue test was established as the maximum actual stress on the teeth S(MPa). The normal weight loaded by the tester was defined as Pn(kgf) and the maximum tension actual stress on the teeth as S(MPa). The formula (1) calculates the 2-dimensional finite element method on fractured teeth by fixed standard rack tool[7].

$$S = \frac{1}{0.102}\,\frac{P_n}{bm}\left[a_1\left(\frac{1}{z}\right)+a_2\left(\frac{1}{z}\right)^3+3.50\right] \exp\left[\left\{2.50\left(\frac{1}{z}\right)-0.50\right\}\frac{\lambda_p}{m}\right] \quad (1)$$

where b is face width, m is module, z is teeth number, λ_p is the distance from the tooth tip at center cycloid to loading point (mm), a_1 is 2.50, and a_2 is 2600.

When the dimension of the test gears (m=5, z=18, b=8mm, λp=0.8 mm) is applied to formula (1), the result is formula (2).

$$S(MPa)=37.8\frac{P_n}{bm}=0.945\,P_n \quad (2)$$

In this study formula (2) was utilized to calculate the relation between test load and the actual stress on the teeth risk section.

3.3 The result of the fatigue test and discussion

As recommended by the ISO[8] gear strength calculation formula, a non-fraction repeat-loading number was designated as $N \geq 3\times10^6$ because the life coefficient of the heat-treated test gears was 1.0 at $N=3\times10^6$. An electric-hydraulic servo fatigue tester was employed to conduct fatigue test on HC, HSC and HSCSP gears and the inclination part and horizontal part of the S-N curve were obtained based on the measurements and were presented in Fig. 8. The fatigue strength of the HC, HSC and HSCSF type gears was calculated by $\sigma_u=S_0+\Delta d$ in the staircase method[9], where So refers to the stress level value at the initiation of the test and d is the interval between the stress level values. Coefficient Δ is calculated as the ratio between the distance of stress level value (d), fatigue strength, and standard deviation (σ).

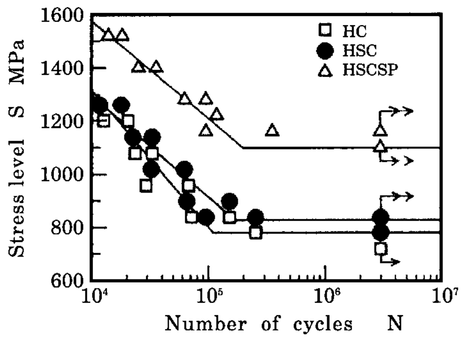

Fig. 8 S-N curve of test gears

Table 5 Estimation example of fatigue strength by staircase method

Code of gear	S_0 MPa d MPa	Experimental results	Fatigue strength σ_u(MPa)
HC	S_0=780 d=60	x x ○ ○ ○	Δ=−0.08 σ_u=775
HSC	S_0=780 d=60	x ○ x ○ ○	Δ=1.12 σ_u=847
HSCSP	S_0=1,080 d=60	x ○ x ○ ○	Δ=0.31 σ_u=1,099
Note) X : Break before $N=3\times10^6$ ◯ : Not break at $N=3\times10^6$			

As shown in Table 5, the fatigue strength of each of the gear types was calculated as the average value of five repeated test measurements. The fatigue strength for the HC and HSC gears were 776 MPa and 835 MPa, respectively. The test found that the HSC gears showed approximately 8% greater fatigue strength than the HC gears. This may have been because the shaving process contributed to such improved surface properties as surface hardness and roughness, thereby, adding to fatigue strength.

The fatigue strength for the HSCSP gears obtained 1,098 MPa The shot-peening treated gears (HSCSP) showed 32 to 41% greater improvement in fatigue strength than the non-shot-peening-treated test gears (HC and HSC gears).

4. Strength Estimation by the Fatigue Strength-estimation Formula

The following is the estimation formula for fatigue strength σ_u(MPa) that is obtained from the bending fatigue test on SCM420 carburized gears[10],

$$\sigma_u = \sigma_{uc} + \sigma_{usc} + \sigma_{uR} = f(H_c) + g(H_s - H_c) + h(\sigma_R) = (257 + 1.17Hc) + 3.1\exp[0.0097(H_s - H_c)] - 0.5\sigma_R \quad (3)$$

where $H_c(H_v)$ is core hardness, $Hs(H_v)$ is surface hardness, and σ_R (MPa) is the compression residual stress of the teeth surface. σ_{uc}=f(H_c), σ_{usc}=g($H_s - H_c$), and σ_{uR}=h(σ_R) refer, respectively, to the fatigue strength of the test piece prior to carburized, the increase in fatigue strength due to the surface hardness layer, and the increase in fatigue strength due to compression residual stress. In order to research the effect of the gear manufacturing process method and the surface treatment process method on fatigue strength, σ_{usc} and σ_{ur} were calculated and were presented in Fig. 9. The fatigue strength mechanism by manufacturing process method and the surface treatment process method may be described as the increase in σ_{usc} and σ_{uR} as shown in Fig. 9. This increase in σ_{usc} and σ_{uR} may be attributed to the fact that the surface treatment generated surface hardness layer and the compression residual stress resulted in the improvement in surface hardness and compression residual stress. The measurement results of hardness and compression residual stress in Table 4 were applied to the above estimation formula, and they were compared to the test results, as shown in Fig. 10.

The estimation values were found to be approximately the same as the test results, and estimate deviation was 2 to 6%. This means that

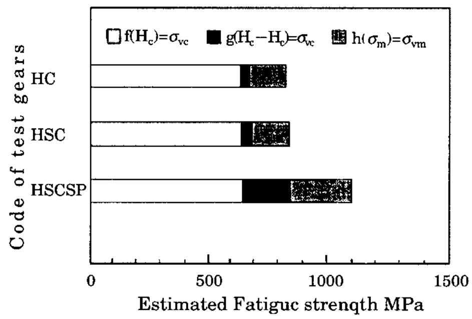

Fig. 9 Contributions of hardened layer and residual stress to fatigue strength

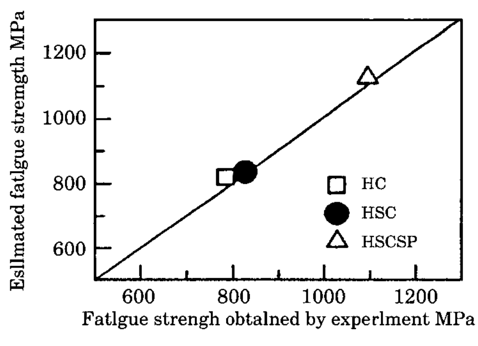

Fig. 10 Comparison between estimated fatigue strength with experimental results

the above formula (3) can be safely applied to the test gears used in this study.

5. Conclusion

The results of this study are as follows;

(1) The surface roughness (Rmax, Rz) of shaving gears (HSC) was found to show 30 to 35% greater improvement than that of non shaving-treated gears (HC).

(2) The shot-peening treated gears(HSCSP) showed 34 to 41% greater surface hardness and 56 to 60 % higher compression residual stress than HC and HSC gears. Therefore, shot-peening treatment tended to lead to improvement in the surface hardness layer

(3) The fatigue strength was found to be 8% higher in HSC gears than in HC gears, and shot-peening treated gears (HSCSP) showed approximately 32 to 41% greater improvement in fatigue strength than HC and HSC gears.

(4) The estimate formula for fatigue strength was found to be applicable to the test gears of this study, and estimate deviation was between 2 and 6 %.

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