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Fatigue strength improvement of gears using cavitation shotless peening

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Peening, using cavitation impacts induced by bubble collapse, represents a novel surface enhancement technique for machine parts without involving conventional shot peening blasting. This is known as cavitation shotless peening, CSP. The improvement in the fatigue strength of a spur gear after CSP has been demonstrated. The fatigue strength of a gear treated with CSP was improved by about 60%, compared with that of a non-peened gear.

KEY WORDS: surface enhancement, fatigue strength, cavitation, shot peening, gear

1. Introduction

Cavitation normally causes severe erosion in hydraulic machinery such as pumps, valves and ship propellers due to the impacts produced on the collapse of cavitation bubbles. However, the cavitation impacts can be utilized for surface enhancement in a similar manner to convectional shot peening. Peening using cavitation impacts does not require shots as in shot peening. Thus, we refer to this process as 'cavitation shotless peening (CSP)'.

CSP makes use of a submerged high-speed water jet with cavitation, herein referred to as cavitating jet, to impact compressive residual stress on the surface of material. The intensity of cavitation impacts can be controlled by hydraulic parameters such as injection pressure and cavitation number [1–2]. CSP is also different from normal water-jet peening in air, in that normal water-jet utilizes the impacts of actual water droplets. Peening using a water-jet in air has been carried out using a plunger pump with a pressure capacity of over 100 MPa [3]. However, this is expensive in terms of operational cost. CSP offers alternative cheaper surface enhancement technique on metallic materials by using a plunger pump with a pressure capacity of 20–30 MPa [4–6]. The surface quality after peening affects the fatigue test results. The surface of materials treated by CSP is less rough compared to those treated by shot peening thereby contributing to longer fatigue life. CSP is capable of treating difficult-to-reach places such as the roots of gears. Soyama et al. have reported that, from results obtained from a rotating bending fatigue test [6], the improvement in fatigue strength of carburized steel using CSP is better than that of shot peened material. On the contrary, the residual compressive stress layer in specimen treated by CSP is thinner than that treated by shot peening. Thus, the rotating bending fatigue test was used to determine the S–N curves of non-peened and peened specimens.

In this study, we demonstrate the improvement of fatigue strength of gears using CSP. To confirm the initial test conditions, i.e., before gear production, a rotating bending fatigue test was carried out on carburized chrome–molybdenum alloy steel (Japanese Industry Standards JIS SCM420), round bar shaped, which is a representative for gear material. The bending fatigue test of gear was then carried out on spur gears. A comparison of spur gears in the non-peened and peened conditions, using shot peening and CSP, has been done to elucidate fatigue strength improvement. It is noted that this is the first report on the fatigue strength improvement of gears using CSP.

2. Experimental facilities and procedures

The cavitating jet apparatus was used for CSP. Details of the apparatus may be found in references [5–7]. The gear and specimen for the rotating bending fatigue test were both mounted in a water-filled chamber. The cavitating jet was injected vertically onto the round bar and gear specimen set-up. The gear and the round bar specimen were rotated during the cavitation treatment. The processing time per unit length, t_p, of specimen for the rotating bending fatigue test was

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Table 1.
CSP conditions.

	CSP 30M	CSP 50M
Injection pressure p_1 MPa	30	50
Tank pressure p_2 MPa	0.42	0.29
Cavitation number σ	0.014	0.0057
Nozzle diameter d mm	1.9	1.2
Standoff distance s mm	45	80
Arc height H_N mm (at 18 s/mm)	0.115	0.390
(Calculated arc height H_A mm)	(0.048)	(0.129)

defined as the ratio of the number of scans n to the scanning speed v;

$$t_p = \frac{n}{v} \tag{1}$$

The cavitation number, σ, a key parameter in cavitating jet, is defined by the injection pressure, p_1, the tank pressure, p_2 and the saturated vapor pressure, p_v as follows;

$$\sigma = \frac{p_2 - p_1}{p_1 - p_2} \cong \frac{p_2}{p_1} \tag{2}$$

σ can be simplified as indicated in Equation (2) because $p_1 \gg p_2 \gg p_v$. Absolute pressure values were used for the determining the cavitation number. From considerations of previous results [5–9], the conditions of CSP were selected as shown in table 1. Almen strips which are used for shot peening, were also used in CSP as a tool for measuring peening intensity. The arc height using an N-gage Almen strip and the corresponding conversion to A-gage values from calculation of the results of arc height are also shown in table 1 [10]. Table 2 identifies the shot peening conditions.

The test material used in the rotating bending fatigue test was JIS SCM420. The geometry of the cylindrical test specimen was made to conform to JIS Z2274, as shown in figure 1. After carburizing, the surface was polished with emery paper grade 1500. The surface roughness after shot peening was R_a = 1.25 μm for SP1 and R_a = 0.90 μm for SP2. In order to avoid notch effects on the shot peened surface during the fatigue test, the surface was polished after shot peening. The surface roughness of the shot peened specimen after polishing was R_a = 0.08 μm, the surface roughness of specimen treated by CSP without polishing was R_a = 0.11 μm. The rotating bending fatigue test of round bar were conducted using a sinusoidal load of frequency 50 Hz and load ratio $R = -1$, at room temperature.

Table 2.
Shot peening conditions.

	SP1	SP2	SP3
Shot diameter d_s mm	0.6	0.1	0.3
Arc height H_A mm	0.55	0.33	0.20

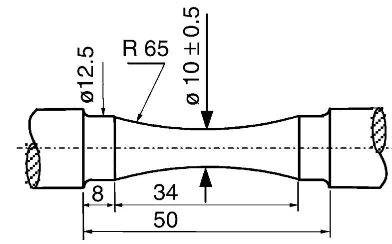

Figure 1. Geometry of specimen for rotating bending fatigue test.

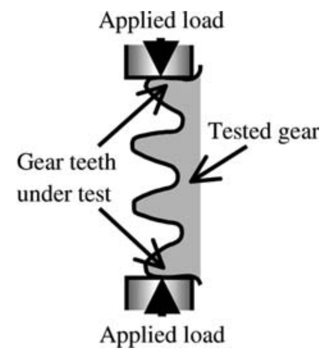

Figure 2. Schematic diagram of the bending fatigue test of gear teeth.

The spur gear tested by the bending fatigue test had the following dimensions; outside diameter was 78 mm and the root circle diameter was 68 mm. The gear had 32 teeth and the face-width was 11 mm. The chemical composition of the gear material corresponded to JIS SNCM420, which was enriched with nickel, rather than the JIS SCM420 alternative. The gear was finished by grinding after vacuum carburizing. Figure 2 illustrates the schematic of the gear fatigue test set-up, permitting bending fatigue test of the gear teeth. The gear was fixed between a stator, incorporating a load cell, and an actuator which applied the load.

3. Results

Figure 3 shows the results of a rotating bending fatigue test. The peening time per unit length of both CSP 30M and CSP 50M was 20 s/mm. Applying Little's method [11] of estimating the median fatigue limit at 10^7cycles, the stress magnitudes in specimen treated by CSP 30M and CSP 50M was 937 MPa and 903 MPa, respectively. The fatigue limit of non-peened specimen was 849 MPa. Thus, specimen peened with CSP 30M and CSP 50M exhibited increase in fatigue limit by 88 and 54 MPa, respectively with respect to the non-peened

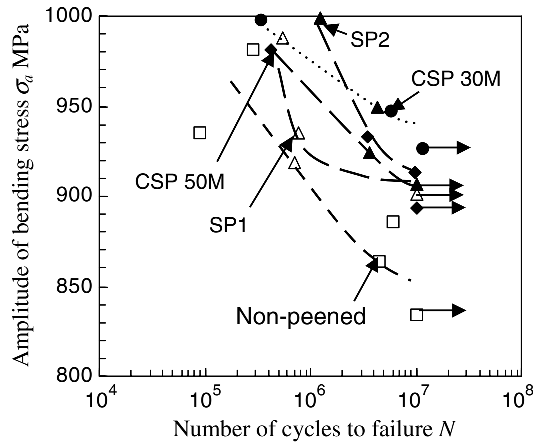

Figure 3. S-N curve of rotating bending fatigue test of the round bar specimen.

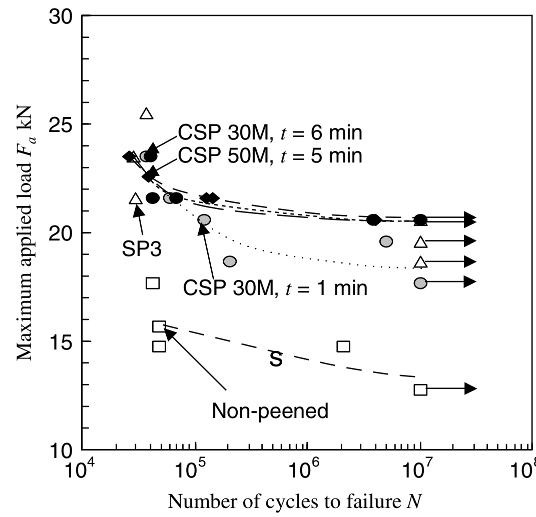

Figure 4. S-N curve of bending fatigue test of gear teeth.

specimen. CSP carried out using larger nozzle at low injection pressure produced better results than those employing a small nozzle at high injection pressure at the same flow rate. The fatigue limit of shot peening was 910 MPa in SP1 and 915 MPa in SP2. In the present evaluation, the highest fatigue limit was obtained from the specimen peened with CSP 30M.

The residual stress at the surface was measured in order to investigate the reason for the improved fatigue strength. The residual surface stress of CSP 30M and CSP 50M was −840 MPa and −750 MPa, respectively. The shot peened specimens SP1 and SP2 had surface residual stress of −840 MPa and −1090 MPa, respectively. The main reason of improvement in fatigue strength stemmed from the introduction of compressive residual stress. However, there was no significant distinction in residual stress values between the peened specimens after CSP and shot peening. The arc height of CSP 30M was very small compared with that of the shot peening conditions. Even though the ratio of the arc height of CSP 30M to SP1 and SP2 were 1/11 or 1/6, respectively, the fatigue strength of samples treated with CSP 30M was better than those of shot peened. Despite the fact that the arc height and the residual stress are amongst the parameters which are responsive to the peening intensity, it was necessary, to conduct the fatigue strength tests of samples treated with different peening methods.

Figure 4 shows the results of the bending fatigue test of gear teeth. The peening times, t, of CSP 30M were either 1 min or 6 mins. The peening time with CSP 50M was 5 mins. The estimated median fatigue limits at 10^7 cycles using Little's method [11] of non-peened, CSP 30M (t = 1 min), CSP 30M (t = 6 min), CSP 50M and SP3 specimens were 13 kN, 18 kN, 21 kN, 21 kN and 21 kN, respectively. The fatigue strength of the gear treated by CSP was significantly improved compared to the non-peened gear. Comparing the results of t = 1 min and t = 6 min with CSP 30M, the peening time of 1 min at CSP30M condition was too short to yield significant improvement. This suggests that a further improvement in fatigue strength might be obtained by an increase in the peening time using CSP. At present, the improvement in fatigue strength after CSP is the same as that after shot peening. The fatigue strength of a gear treated using either CSP or shot peening improved by approximately 60% with respect to a non-peened gear.

4. Conclusions

In order to evaluate the improvement of the fatigue strength of a spur gear after CSP, rotating bending fatigue test of round bar was carried out on carburized chrome–molybdenum alloy steel (JIS SCM420), which is a representative material for gears. The bending fatigue testing of gear teeth was investigated. It was established that fatigue strength of gear specimen treated by CSP improved by about 60% relative to that of non-peened gear. Similar improvement was obtained by gear specimen treated by shot peening. The residual stress and the arc height are measures of peening intensity. The actual fatigue test on gears was carried out to compare the fatigue strengths obtained with different peening methods.

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