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Cavitation Shotless Peening for Improvement of Fatigue Strength

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1 Abstract

This paper gives an overview of the art, craft and science of "Cavitation Shotless Peening" as a new method of turning the traditional negative effects of cavitation in hydrodynamic machinery to more positive industrial applications.

Impact at cavitation bubble collapse can be used to improve the fatigue strength just as the same way as shot peening. Cavitation impacts can peen the surface without the use of shot. Hence, it is a kind of shotless peening, and herein termed as Cavitation Shotless Peening (CSP). The peened surface by CSP is less rough compared with shot peening, since there is no solid body collision involved. In the present study, cavitation impacts were produced by a submerged high speed water jet with cavitation, i.e., a cavitating jet. The cavitating jet differs completely from a normal water jet in air.

To explore the potentials of CSP as a means of inducing surface compressive residual stress and subsequently increasing fatigue strength of materials, silicon-manganese alloy (JIS SUP7) and an aluminum alloy (JIS AC4CH) specimens were peened by a cavitating jet. The residual stress was measured by an X-ray diffraction method.

Experimental results confirmed that the rotating beam ($R = -1$) fatigue strength of silicon-manganese alloy increased by 41% while that of aluminum alloy increased by 56% in comparison with non-peened specimens.

2 Introduction

When a liquid at constant temperature is subjected to a decreasing pressure below the saturated vapor pressure, liquid becomes gas. In viewpoint of phase transition from liquid to gas, cavitation has the same phenomenon as that of boiling. However, cavitation generates impacts at gas bubble collapse [1-2].

General research subjects on cavitation were focused on its negative effects such as erosion in engineering applications [3-6]. Soyama et al. proposed the peening method by cavitation impacts [7] and then proved the introduction of residual stress [8,9] and improvement of fatigue strength [10-13]. With CSP increase in roughness is negligible because of no solid body collisions and the operational costs are low. In the initial cavitating stage, there is plastic deformation at the sub-surface of the material without mass loss. Hence compressive residual stress can be obtained without morphological damage.

Figure 1 shows the schematic diagram of impinging jets both in air and in water. For the case of water jet in air, the pressurized water jet generates droplets of water around the potential core. When the droplets impinge the solid boundary, erosion is formed at the center of the jet. Thus, the eroded region of water jet in the air is smaller than the one produced by

3 Experimental facilities and procedures

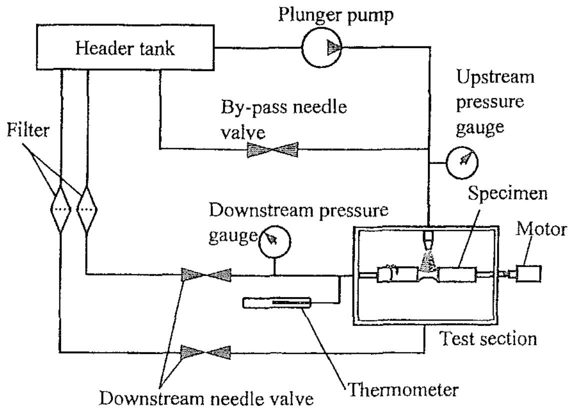


Figure 2. Cavitating jet apparatus

Figure 2 shows the experimental set-up used to peen both the silicon-manganese alloy (JIS SUP7) and aluminum alloy (JIS AC4CH). The test section was filled with water. A cavitating jet was passed through a nozzle of throat diameter 1.8mm. Tap water was used in the cavitating loop jet. The specimen was mounted horizontally across the test section to allow the cavitating jet to impinge it at 90 degrees. The plunger pump had a maximum pressure of 35MPa. The specimen was gradually rotated and scanned at a speed of 1mm/sec along its axis using a motor. The upstream and downstream pressures at the nozzle were controlled by the needle valves.

The main parameter of the cavitating jet was cavitation number σ, which is a measure of the resistance of the flow to cavitation [17]. With respect to nozzles and orifices, the flow velocity depends on the pressure difference between the upstream and downstream pressures. Thus the cavitation number is given by

$$\sigma = \frac{p_2 - p_v}{p_1 - p_2} \qquad \text{........(1)}$$

where p_1, p_2, and p_v are upstream, downstream and vapor pressures, respectively. Since $p_1 > p_2 > p_v$, Eq.1 can then be simplified as

$$\sigma = \frac{p_2}{p_1} \qquad \text{........(2)}$$

The standoff distance s was defined as the length from the upstream corner of the nozzle throat to the surface of the specimen under test. Thus, the optimum standoff distance s_{opt} was qualitatively determined by the erosion test. The specimen for the erosion test was made of pure aluminum (JIS A1050P). In the erosion test, the standoff distance was measured as the rate of cavitation erosion was varied. To determine the optimum scanning speed v_{opt}, the residual stress was measured at different exposure time per unit length, t. The exposure time per unit length is the ratio of number of scans n to scanning speed v.

$$t = \frac{n}{v} \qquad \text{........(3)}$$

The cavitation number σ of 0.014 and upstream pressure of 30MPa was used for both specimens. The exposure time t for silicon-manganese alloy (JIS SUP7) and aluminum alloy (JIS AC4CH) were 0.4mm/min and 30mm/min, respectively. The standoff distance s for JIS SUP7 was 55mm while for JIS AC4CH it was 60 mm.

The shape of specimen was designed according to the Japanese Industrial Standards (JIS Z2274), as shown in Fig. 3. The chemical compositions of experimental specimens were as shown in Tables 1 and 2. The silicon-manganese alloy (JIS SUP7) was heat-treated at 1103K for 20 minutes and quench hardened at 673K for 40 minutes. This gave Rockwell hardness H_{RC} of 51. The aluminum alloy (JIS AC4CH) was solution-treated at 813K for 5 hours and allowed to age at 443K for 3 hours.

For the purpose of comparing the peening effect between shot peening and CSP, an N-type Almen strip, 76mm x 19mm x 0.8 mm thick was scanned at a speed of 20mm/min. Then the arc height was measured using an Almen gauge according to the required standard [18]. For the aluminum alloy (JIS AC4CH), the shot peened material was SB8PM with conditions as shown in Table 3. The conditions were decided with reference to the results of Masaki et al. [19].

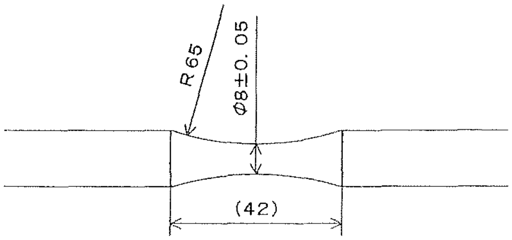


Figure 3. Geometry of test specimen for rotating bending fatigue test

Table 1 Composition of JIS SUP7 by weight %

C	Si	Mn	P	S	Ni	Cr	Al
0.6	2.0	0.88	0.16	0.12	0.01	0.14	0.03

Table 2 Composition of JIS AC4CH by weight %

Si	Fe	Mg	Ti	Sr	Al
6.97	0.08	0.43	0.17	0.009	bal

Table 3 Shot peening conditions for JIS AC4CH

Project amount (kg/min)	Shot Pressure (MPa)	Peening time (sec)	Standoff distance (mm)	Arc height (mmA)	Coverage (%)
15	0.1	45	200	0.29	300

4 Results

Figures 4(a) and 4(b) shows the relation between the stress amplitude σ_a and the number of cycles to failure N obtained from rotating bending fatigue tests for JIS SUP7 and JIS AC4CH, respectively. For JIS SUP7, at higher stress amplitude the CSP and non-peened specimen had similar life. Using Little's method on estimating the median fatigue limit [20], CSP specimen had an increase of 281.6 MPa in fatigue limit, which is 41%. Optimization conditions for silicon-manganese alloy (JIS SUP7) are yet to be published for comparison with other peening methods.

From Fig. 4(b) it can be seen that specimen peened by CSP had highest fatigue limit at N equals 10^7. Considering the non-peened specimen as the reference point, the CSP specimen had an increase of 56% in fatigue limit while the shot peened specimen gave an increase of 20%.

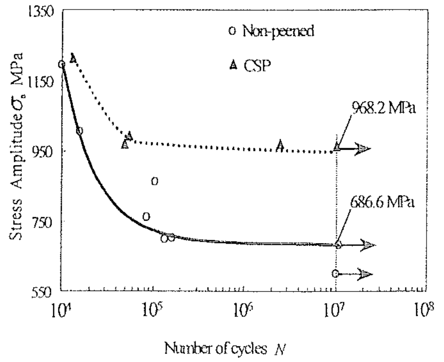


Figure 4(a). Cyclic stress curves for JIS SUP7

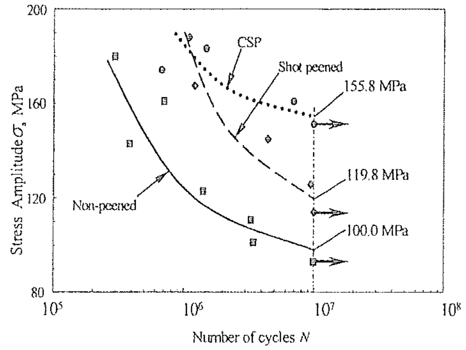
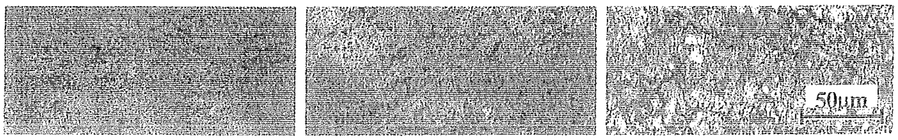


Figure 4(b). Cyclic stress curves for JIS AC4CH



(a) Non-peened

(b) Cavitation shotless peening (Arc height H_N= 0.32 mm)

(c) Shot peening (Arc height H_N= 0.15 mm))

Figure 5: Surface morphologies of Almen strip

Figure 5 shows the surface morphology of Almen strip for the non-peened, CSP and shot peened specimens. Since there is no material loss and no particle bombardment, the surface of CSP specimen had a better quality finish than the shot peened one.

5 Conclusions

Impact by cavitation bubble can be used to improve the fatigue strength of materials. To demonstrate the increase in fatigue strength, a new technology, Cavitation Shotless Peening (CSP), reversing the negative engineering effects has been carried out. The impacts were produced by a cavitating jet. The specimens tested were silicon-manganese alloy (JIS SUP7) and aluminum alloy (JIS AC4CH). The key points are summarized as follows:

1. CSP increased the fatigue strength of silicon-manganese alloy by 41% and for the aluminum alloy by 56 % in comparison to the non-peened specimens.
2. There was no significant material loss and thus the surface finish of specimens peened by CSP had better results compared to shot peening.

6 Acknowledgements

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7 References

1. F.R. Young, Cavitation, Imperial College Press, 1999, p.4.
2. C.E. Brenen, Cavitation and Bubble Dynamics, Oxford University Press, 1995, p.21.
3. H. Soyama, Y. Ito, K. Uranishi, H. Kato and R. Oba, Proc. 15th IAHR Symp., 1990, Paper No. H 4.
4. H. Soyama, H. Kato and R. Oba, Proc. 3rd Inter. Conf. Cavitation, 1992, 103 – 110.
5. H. Soyama, R. Oba and H. Kato, Proc. Inter. Conf. Cavitation, 1992, 225 – 232.
6. H. Soyama, S.R. Lee, M. Tonasaki, K. Uranishi, S. Saito, T. Okamura, H. Kato and R. Oba, Proc. 3rd Inter. Symp. Cavitation, 1998, 135 – 140.
7. K. Sato, H. Soyama, Y. Yamauchi, T. Ikohagi, R. Oba and R. Oshima, Proc. of 11th Inter. Conf. on Jet Cutting Techn., 1992, 413 – 424.
8. H. Soyama, J.D. Park and M. Saka, Trans. ASME, Journal of Manuf. Science and Eng., 2000, 122, 83 – 89.
9. H. Soyama, T. Kusaka and M. Saka, Proc. of 6th Inter. Conf. on Residual Stresses, 2000, 1, 674 – 681.
10. H. Soyama, JSME International Journal, 2000, Ser. A, 43, 173 –178.
11. H. Soyama, T. Kusaka and M. Saka, Journal of Mater. Science Letters, 2001, 20, 1263 – 1265.
12. H. Soyama, K. Sasaki, H. Kumano, and M. Saka, Mater. Science Research International, Special Technical Publication, 2001,1, 216 – 219.
13. H. Soyama, K. Saito and M. Saka, "Improvement of Fatigue Strength of Aluminium Alloy by Cavitation Shotless Peening", Trans. ASME, Journal of Eng. Mater. Technology, 2002, 124, (in press).
14. H. Soyama, Y. Yamauchi, Y. Adachi, K. Sato, T. Shindo and R. Oba, JSME International Journal, 1995, Ser. B, 38, 245 – 251.
15. H. Soyama, Y. Yamauchi, K. Sato, T. Ikohagi, R. Oba and R. Oshima, Experimental Thermal and Fluid Science, 1996, 12, 411 – 416.
16. H. Soyama, A. Lichtarowicz, T. Momma and E.J. Williams, Trans. ASME, Journal of Fluids Engineering, 1998, 120, 712 – 718.
17. H. Soyama, A. Lichtarowicz and T. Momma, Proc. of 1996 ASME Fluids Engineeering Division Summer Meeting, 1996, 415 – 422.
18. H. Soyama, H. Kumano, K. Saito and M. Saka, Proc. of APCFS & ATEM '01, JSME/MMD, 2001, 2, 1047 – 1050.
19. K. Masaki, T. Matsumura and Y. Ochi, Proc. of the 2001 Annual Meeting of JSME/MMD (in Japanese), 2001, No. 01-16, 259 – 260.
20. R.E. Little, ASTM STP 511, American Soc. for Testing and Materials, 1972, 29 – 42.