J Mater Sci (2007) 42:6638–6641
DOI 10.1007/s10853-007-1535-8

Improvement of fatigue strength by using cavitating jets in air and water

H. Soyama

Received: 18 June 2006 / Accepted: 16 January 2007 / Published online: 1 May 2007

Abstract Peening method using cavitation impact at bubble collapse has been proposed. At the peening, cavitation bubble was normally generated by injecting a high-speed water jet into a water-filled chamber, i.e., a cavitating jet in water. In the present paper, the peening using a cavitating jet in air, which can generate the cavitation bubble without a water-filled chamber was investigated. It was revealed that the improvement of fatigue strength peened by the cavitating jet in air was better than that of the cavitating jet in water.

Cavitation impacts can be utilized for improving the fatigue strength of metallic materials [1, 2] in the same way as shot peeing, although they normally cause severe damage in hydraulic machinery. Peening using cavitation impacts is called ''cavitation shotless peening (CSP)'' [3–7], as shot is not used. In the case of CSP, cavitation bubbles are formed by injecting a high-speed water jet into a water-filled chamber producing a cavitating jet. Cavitation takes place in the shear layer around the jet. In the present paper, a cavitating jet using a water-filled chamber is designated as ''a cavitating jet in water (CJW)''. The development of CSP using a cavitating jet without a water-filled chamber will give rise to an expansion in the applications of CSP.

Recently, Soyama successfully produced CSP by means of ''a cavitating jet in air (CJA)'' using a concentric nozzle injecting a high-speed water jet into a low-speed one. This was expelled into the air and it was shown that the compressive residual stress introduced using CJA was greater than that of CJW [8]. One of reasons why the peening effect using CJA is better than CJW, is the interference between the high-speed and the low-speed water jets [9]. Thus, improvement of the fatigue strength using CJA is better than that of CJW. Since it has been reported that the improvement in the fatigue strength of soft and hard materials such as aluminum casting alloy and carburized chrome-molybdenum alloy steel is greater when using CJW rather than shot peening [5, 10], it would be interesting to study the fatigue strength of materials peened by CJA.

In this paper, the improvement found in the fatigue strength of metallic materials when using CJA instead CJW was investigated. Specimens made of stainless steel were peened by CJA and CJW and tested by a plate bending fatigue test.

Figure 1 illustrates the cavitating jet apparatus, which can be used for both CJA and CJW [9]. A sluice is set in tank A to enable CJW testing. For this the tank is filled with water. Figure 2 shows a schematic diagram of the test nozzle. The diameters of the nozzles for the high-and low speed water jets, d_H and d_L, were 1 mm and 20 mm, respectively. The nozzle of the low-speed water jet was taken off for the CJW test. In the apparatus, the nozzle was fixed and the specimen was scanned by moving the stage. The injection pressures of the high-and low-speed water jets, p_H and p_L, were measured with pressure transducers. In the paper, the pressure is given as the relative pressure. In the experiment, p_H was limited to 30 MPa by the maximum injection pressure of the plunger pump. As the performance of CJA depended appreciably on p_L, p_L was chosen to be 0.05 MPa which is the optimum condition [9].

The material used for the fatigue tests was stainless steel (Japan Industrial Standards JIS SUS316L). The chemical composition of the test specimens by percentage weight is shown in Table 1. The specimens were heat treated at

H. Soyama (✉)
Department of Mechanical Engineering, Tohoku University, 6-6-01 Aoba, Aramaki, Aoba-ku, Sendai 980-8579, Japan
e-mail: soyama@mm.mech.tohoku.ac.jp

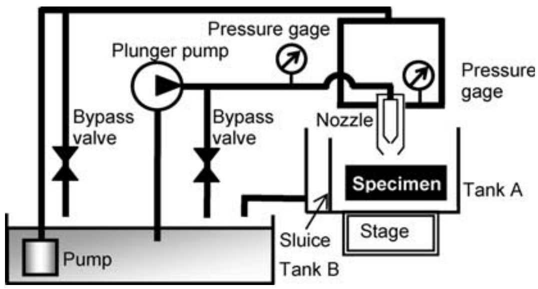

Fig. 1 Cavitating jet apparatus

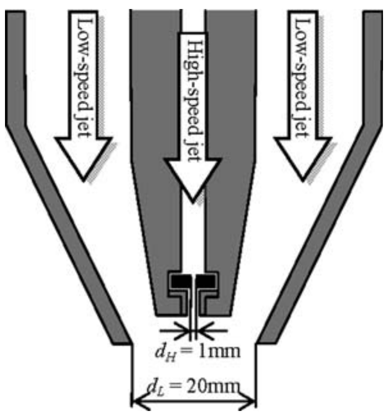

Fig. 2 Schematic diagram of the test nozzle

Table 1 Chemical composition of stainless steel JIS SUS316L (weight %) used in the tests

C	Si	Mn	P	S	Ni	Cr	Mo
0.010	0.19	1.66	0.033	0.016	12.03	16.92	2.01

1,080 °C and then water-quenched. The yield strength and tensile strength were 216 and 530 N/mm^2, respectively. The material had an elongation of 58% and a hardness of 138 HB. In order to investigate the fatigue strength, a plate bending fatigue test (R = –1) was carried out. Figure 3 illustrates the geometry of the specimens used for the

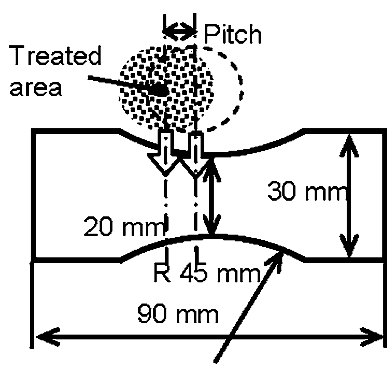

Fig. 3 Geometry of the specimens used for fatigue test

fatigue tests. The thickness of the specimens was 1.88 mm. The specimen treated by CJA was scanned at a constant speed v = 1 mm/s, and then moved stepwise with a constant pitch of 4 mm.

For both CJA and CJW, the peening effects, such as the introduction of compressive residual stress, varied with standoff distance, which is the distance from the test nozzle to the specimen. The residual stress on the surface was measured as a function of the residual stress, σ_R, using an X-ray diffraction method. A Cr tube operated at 30 kV and 8 mA was used for producing Kβ X-rays. The width of the slit was 4 mm and the angle of the solar slit was 1°. X-rays were counted for 4 s at each step using a scintillation counter at angles of ψ = 10°, 20.8°, 28.1°, 34.3°, and 40°. Here, ψ is the angle between the normal to the specimen surface and the normal to the diffractive face. The orientation was the (311) plane of γ-Fe. The diffractive angle 2θ without strain was chosen as 148.5° and the stress factor used for the X-ray diffraction method was –369.5 MPa/deg. The diffractive angle was determined by the half value method and the residual stress was calculated using the $2\theta - \sin^2\psi$ method, i.e., the gradient of the line from five points on the diagram using the method of least squares.

Figure 4 shows the residual stress, σ_R, as a function of standoff distance, s, for CJA and CJW. For all cases, the specimen was scanned at v = 1 mm/s. For both CJA and CJW, a compressive residual stress that varied with s was introduced. For the case of CJA, the maximum compressive residual stress was about 450 MPa occurring at s = 35 mm. On the other hand, the compressive residual stress for CJW had two peaks, one of about 180 MPa at s = 30 mm and a second one of –160 MPa at s = 65 mm. As σ_R dropped markedly to –65 MPa at s = 35 mm, the tests with the specimen nearer to the nozzle was set to be at s = 25 mm in this study. CJA can introduce large compressive residual stress compared with CJW.

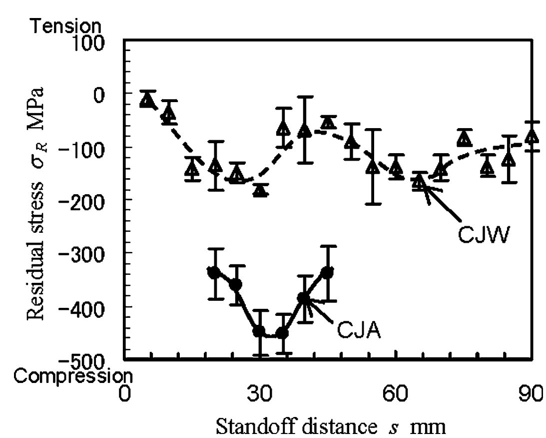

Fig. 4 Introduction of compressive residual stress as a function of standoff distance

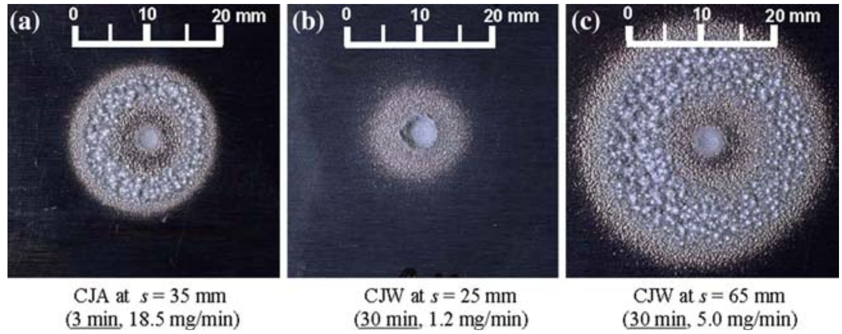

Fig. 5 Erosion pattern on aluminum specimens induced by CJA and CJW. (**a**) CJA at s = 35 mm (3 min, 18.5 mg/min). (**b**) CJW at s = 25 mm (30 min, 1.2 mg/min). (**c**) CJW at s = 65 mm (30 min, 5.0 mg/min)

In order to clarify the peening mechanism at each peak for CJA and CJW, the erosion patterns on pure aluminum specimens is shown in Fig. 5. The difference in performance between CJA and CJW was remarkable, with the test time for CJA being 3 min and that for CJW being 30 min. For all three cases, erosion at the center of the jet was observed. This erosion is induced by droplets in the high-speed water jet striking the surface in the same way as in a normal water jet, i.e., by a water jet in air that is normally used for cutting material. The erosion at the center for CJW at s = 25 mm is the largest; thus, it can be concluded that the compressive residual stress was introduced mainly by the impact of droplets. In the case of CJA and CJW at s = 65 mm, the erosion pattern has a ring structure, which is the typical pattern induced by a cavitating jet. With a cavitating jet, cavitation bubbles strike the surface and then spread out across the surface and collapse. As the impact force is produced as the bubble collapses, the main area of erosion takes place at a certain distance from the center of the jet. This is why the cavitating jet produces a ring erosion pattern. In the case of CSP, the processing time was short [11]; thus, erosion was not observed on the surface. The outer diameter of the ring erosion is about 20 mm for CJA and about 32 mm for CJW at s = 65 mm. The width of the jet for CJW can develop to a larger size than that of CJA, as the high-speed water jet breaks through the low-speed water jet for CJA. When the performance of the jet is gauged by the amount of material removed, the CJA performs three times better than CJW at s = 65 mm, as the mass loss rates were 18.5 mg/min for CJA and 5.0 mg/min for CJW at s = 65 mm.

Figure 6 reveals the results of the fatigue tests for CJA, and CJW at s = 25 mm and 65 mm. A S–N curve of a non-peened specimen is also plotted in Fig. 6. As the area treated using CJA is only 20 mm, the specimen was scanned 10 times at v = 1 mm/s, and moved stepwise five times with a pitch of 4 mm. Thus a width of 36 mm (36 mm = 20 mm + 4 mm × 4 times) was treated by CJA and processing time per unit length was 50 s/mm. The processing time for 32 mm width corresponded to 40 s/mm, which was equal to the CJW condition. As the specimen peened by CJA without the stepwise movement had broken beyond the peened area, the specimen was scanned and moved step wisely. As the peened area was 32 mm in width for CJW at s = 65 mm, the specimen treated using CJW was scanned forty times at v = 1 mm/s, i.e., 40 s/mm. Although the peened area for CJW at s = 25 mm was small, a crack occurred in the peened area, since there had been scarcely any improvement in the fatigue strength. The specimen peened by CJA did not break until after 10^7 cycles of bending stress with an amplitude of σ_a = 350 MPa, whereas the number of cycles to failure in similar tests for specimens peened by CJW was 2×10^5 for s = 25 mm and 5×10^5 for s = 65 mm. The fatigue strengths at 10^7 cycles obtained by Little's method [12] were 360 MPa for CJA, 327 MPa for CJW at s = 65 mm, 292 MPa for CJW at s = 25 mm and 279 MPa for the non-peened specimen. The compressive residual stress introduced in the fatigue specimens in the above mentioned processing times were about 600 MPa for CJA, 540 MPa for CJW at s = 65 mm and 400 MPa for CJW at s = 25 mm. In actual fact, in every case the compressive residual stress introduced became almost saturated after 10 s/mm. Although the residual stress of CJW at

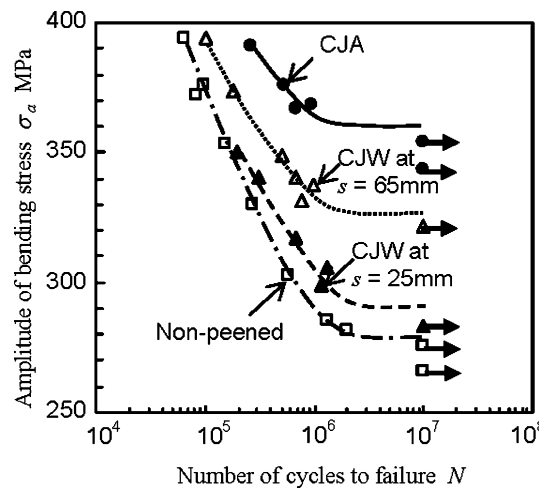

Fig. 6 Improvement of fatigue strength peened by CJA and CJW

s = 25 mm was nearly the same as that at *s* = 65 mm, the improvement in the fatigue strength over the non-peened specimen was much larger. It was noted that the fatigue strength was scarcely improved for CJW with the target close to the nozzle, despite the fact that a compressive residual stress was introduced. It can be concluded that peening by CJA improves the fatigue strength more than peening by CJW.

References

1. Soyama H (2000) JSME Int J 43A:173
2. Soyama H, Kusaka T, Saka M (2001) J Mater Sci Lett 20:1263
3. Macodiyo DO, Soyama H, Saka M (2003) J Mater Sci Lett 22:115
4. Soyama H, Sasaki K, Odhiambo D, Saka M (2003) JSME Int J 46A:398
5. Odhiambo D, Soyama H (2003) Int J Fatigue 25:1217
6. Soyama H, Macodiyo DO, Mall S (2004) Tribology Lett 17:501
7. Soyama H, Macodiyo DO (2005) Tribology Lett 18:181
8. Soyama H (2004) Trans ASME J Eng Mater Technol 126:123
9. Soyama H (2005) Trans ASME J Fluids Eng 127:1095
10. Soyama H (2006) Metal Finishing News 7–2:48
11. Soyama H, Park JD, Saka M (2000) Trans ASME J Manuf Sci Eng 122:83
12. Little RE (1972) ASTM STP 511:29