Improvement of tensile fatigue strength of duralumin plate with a hole by cavitation peening using opposed cavitating jets

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Introduction

Cavitation impacts at bubble collapses cause severe erosion in hydraulic machineries such as pumps and valves. However, the cavitation impacts can be utilized for mechanical surface treatment in the same way of shot peening. The peening method using cavitation impacts is called as “cavitation peening”, or “cavitation shotless peening” as shots are not required [1]. In case of conventional cavitation peening, cavitation bubbles are generated by injecting a high speed water jet into water, i.e., a cavitating jet. In order to treat a relatively thin plate, treatment of both surfaces at the same time would be useful, as convex curve of the plate induced by the peening could be reduced. Thus, peening effect using opposed cavitating jets [2] to treat both side at the same time should be examined.

In previous report [2], it was shown that the opposed cavitating jet could treat inner surface of a pipe which was placed in parallel to the cavitating jets. And also, when the opposed cavitating jets injected to the target, cavitation impacts at impinging area were enhanced, as the pressure at bubble collapse region was increased [3]. In order to enhance fatigue strength with a hole by cavitation peening using a single cavitating jet, a plate and/or attachment were required to make cavitation bubble collapse on the wall surrounding the hole with enhancing cavitation impacts, and it took time to treat. On the other hand, when the opposed jets were used, the bending fatigue strength and fatigue life of the duralumin plate with a hole was enhanced comparing with as machined specimen [2]. However, the fatigue strength and fatigue life of tensile test are not investigated.

Objectives

In the present paper, in order to demonstrate the improvement of tensile fatigue strength by cavitation peening using opposed cavitating jets, duralumin plate with a hole was treated by the opposed cavitating jets and tested by a tensile fatigue test. The residual stress on the surface surrounding wall was evaluated by an X-ray diffraction method in order to investigate the reason of the improvement of fatigue properties.

Methodology

Figure 1 illustrates the cavitating jet apparatus using opposed cavitating jets. The opposed cavitating jets were injected through a nozzles into water filled tank using plunger pumps, whose maximum injection pressure was 35 MPa and maximum discharge was 3.0×10^{-2} m^3/min, separately. The used nozzle for the cavitating jets was a nozzle with a cavitator and guide pipe and it was shown in Fig. 2. The nozzle throat diameter d was 2 mm, the throat diameter of cavitator d_c was 3 mm, the length L and the diameter D of outlet bore were 16 mm and 16 mm, respectively. The L and D were already optimized [4]. The distance from the cavitator to the nozzle plate and geometry of the guide pipe were also optimized [5]. The injection pressure p was chosen as 30 MPa in the experiment. The standoff distance which was defined by the upstream corner of the nozzle plate to the specimen, was chosen as optimum standoff distance at the condition. The specimen was placed at the middle of the opposed cavitating jets, and the specimen was moved. The processing speed by the jets was 1 mm/s, and the specimens were treated 5 times and 10 times, respectively. The processing time per unit length t_p was defined by the number of scan n and the processing speed v as shown in Eq. (1).

$$t_p = \frac{n}{v} \qquad (1)$$

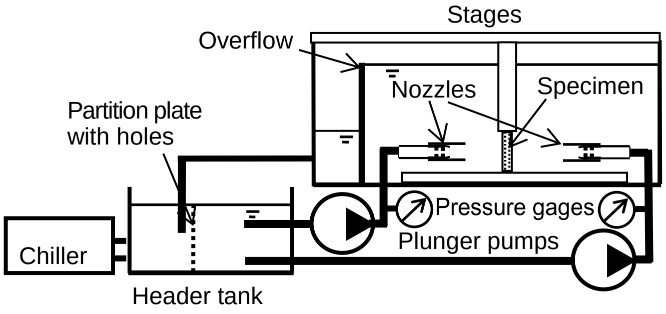


Fig. 1 Cavitating jet apparatus

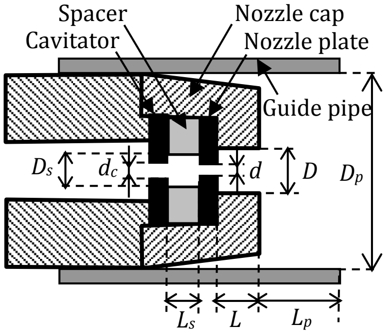


Fig. 2 Nozzle for cavitating jet

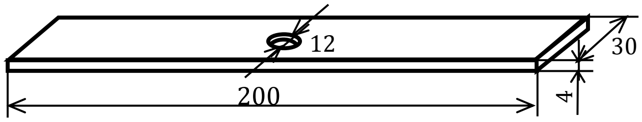


Fig. 3 Geometry of test specimen
(All dimensions quoted in mm)

Table 1 Chemical composition of material under test

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
0.68	0.53	3.8	0.46	0.56	0.01	0.09	0.02	RE

Table 2 Mechanical properties of material

Yield stress	258 MPa
Tensile strength	410 MPa
Elongation	21.7 %

The specimens made of duralumin Japanese Industrial Standards JIS A2017-T3 with a hole were treated opposed cavitating jets, and tested by a tensile fatigue test comparing with as machined specimen and the result of treatment using a single cavitating jet [6]. Tables 1 and 2 show chemical composition and mechanical properties of material under test. Figure 3 illustrates the geometry of the fatigue test specimen. The thickness and the width of the specimen were 4 mm and 30 mm, respectively. The specimen had a hole, whose diameter was 12 mm, in the center. The corner of the specimen was rounded by R = 1 mm. The tensile fatigue test was carried out with the frequency of 30 Hz and the stress ratio between the maximum tensile stress, $\sigma_{\max}$, and the minimum tensile stress, $\sigma_{\min}$, was 0.1.

The residual stress on the surface of the wall surrounding a hole was measured by an X-ray diffraction using a $\sin^2\psi$ method. The direction of the residual stress in the walls was around the circumference of the hole. Kα X-rays from a tube with a Cr target operated at 35 kV and 40 mA were used. The X-rays were directed through a 0.8 mm diameter collimator and an incident monochromator. The lattice plane, (h k l), used was the Al (3 1 1) plane and the diffraction angle without strain was 139 degrees. The diffraction ring from the specimen was detected at ψ = 0, ±20.3 deg, ±29.3 deg, ±36.9 deg, ±43.9 deg and ±50.8 deg using a 2D-PSPC.

Results and analysis

In order to reveal the improvement of fatigue properties of duralumin plate with a hole by the opposed cavitating jets, Fig. 4 illustrates the relation between the maximum tensile stress $\sigma_{\max}$ and the number of cycles to failure N_f. At $\sigma_{\max}$ = 170 MPa, although the number of cycles to failure N_f of as machined specimen was 2.00×10^5, that of specimen peened by the opposed jets at t_p = 5 s/mm was 7.04×10^5, and that of peened by the jets at t_p = 10 s/mm was 5.01×10^5. Namely, cavitation peening using the opposed jets enlongated the fatigue life by 3.5 times and 2.5 times, respectively. On the other hand, N_f treated by the single cavitating jet with a special fixture for 4 min was 4.18×10^5, and that of 8 min was 8.62×10^5 [6]. The equivalent processing time of t_p = 5 s/mm was 150s, and that of t_p = 10 s/mm was 5 min. Thus, it can be concluded that the cavitation peening using the opposed jets improved the tensile fatigue strength, and the proposed method is simpler and quicker than that of the single jet.

In order to investigate the reason of the improvement of fatigue properties, Fig. 5 shows the fracture surface and the aspect of inner wall surrounding the hole after the tensile fatigue test at $\sigma_{\max}$ = 170 MPa. As shown in Fig. 5 (b) and (c), the plastic deformation pits are observed on the surface of the wall surrounding the hole. Even though the surface of the wall was placed to the parallel to the jets axis, the cavitation impacts produced the plastic deformation pits on the surface of the wall. It seems that the crack initiated in the wall surrounding the hole at as machined specimen and cavitation peened specimen at t_p = 5 s/mm. On the other hand, in the case of t_p = 10 s/mm, the crack initiated at

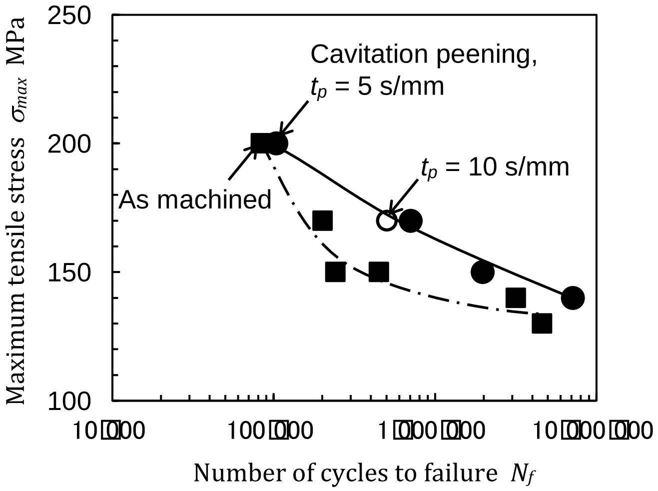
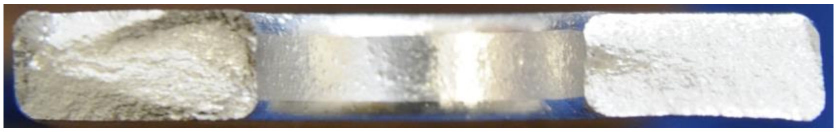


Fig. 4 S-N curve obtained by tensile fatigue test

(a) As machined specimen, σ_{max} = 170 MPa, $N = 2.00 \times 10^5$



(b) Cavitation peened specimen, t_p = 5 s/mm, σ_{max} = 170 MPa, $N = 7.04 \times 10^5$

(c) Cavitation peened specimen, t_p = 10 s/mm, σ_{max} = 170 MPa, $N = 5.01 \times 10^5$

Fig. 5 Aspect of fracture surface and wall surround the hole

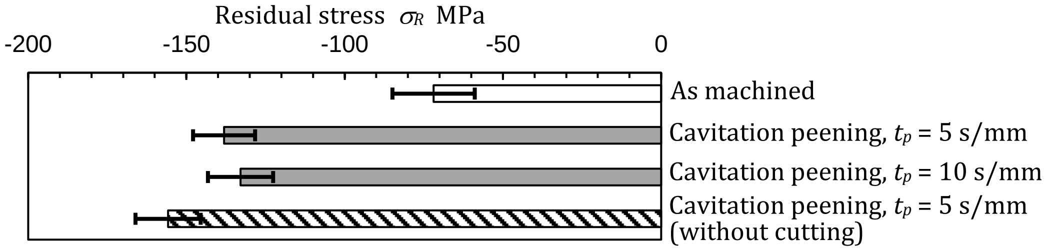


Fig. 6 Residual stress on the surface surround a hole

the corner. It would be expected that the surface roughness around the corner was too rough due to the over peening. This is one of the reasons why the fatigue life at t_p = 10 s/mm was slightly shorter than that of t_p = 5 s/mm.

As one of main factors of the improvement of fatigue properties is the residual stress, Fig. 6 shows the residual stress on the wall surrounding the hole. In the case of as machined specimen, the compressive residual stress was introduced by the drilling to make the hole. Regarding our previous report [7], the thickness of the compressive residual stress layer of as machined specimen was about 60 μm. In the case of cavitation peened specimen, the residual stress was -138 ± 10 MPa at t_p = 5 s/mm and -133 ± 10 MPa at t_p = 10 s/mm. Both of them were the residual stress of the fractured surface in Fig. 5 (b) and (c) after the fatigue test. When the residual stress was measured before the fatigue test without cutting, it was -156 ± 10 MPa at t_p = 5 s/mm. Namely, cavitation peening using the opposed cavitating jets can introduced compressive residual stress. Considering previous report [7], it was expected that the compressive residual layer was about 150 μm.

Conclusions

In order to demonstrate the utility of cavitation peening using the opposed cavitating jets, a tensile fatigue test was carried out using the duralumin plate having a hole with and without cavitation peening. It was revealed that the opposed cavitating jet improved the fatigue life of the duralumin plate with a hole by introducing compressive residual stress into the surface on the wall surrounding the hole.

Acknowledgements

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