Improvement of Threshold Stress Intensity Factor Range of Stainless Steel by Cavitation Peening

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Abstract

In order to investigate the mechanism of improvement of fatigue strength of stainless steel by cavitation peening, a load controlled plate bending fatigue test machine was developed, and the threshold stress intensity factor range ΔK_{th} of stainless steel with and without cavitation peening was investigated. It was revealed that ΔK_{th} of stainless steel was improved from 3.88 MPa$\sqrt{\mathrm{m}}$ to 7.11 MPa$\sqrt{\mathrm{m}}$ by the cavitation peening. Note that the evaluation method of ΔK_{th} using the load controlled plate bending fatigue test with a notched specimen was useful to investigate effect of mechanical surface treatment such as cavitation peening and shot peening.

Keywords Stress intensity factor, cavitation peening, plate bending fatigue test.

Introduction

Cavitation impacts normally cause severe erosion in hydraulic machineries such as pumps and valves. However, the impacts can be utilized for peening as same way as shot peening. A peening method using cavitation impacts is called "cavitation shotless peening" [1], [2] as shots are not required, or it is simply called as "cavitation peening" [3]. Although it was already revealed that cavitation peening improved fatigue strength of metallic materials [1], [2], [4], [5], the mechanism of the improvement of fatigue strength by cavitation peening is not clear. There are two possible reasons for the improvement of fatigue strength of metallic materials by cavitation peening. One of them is a reduction of crack growth rate. The other reason is suppression of crack initiation. It is necessary to investigate effect of cavitation peening on the crack initiation and crack growth rate, in order to make clear the mechanism of improvement of fatigue strength of metallic materials by cavitation peening.

Although a measurement method of fatigue crack growth rates using compact tension specimen is standardized by ASTM E647-13 [6], it is very hard to evaluate crack growth of surface modified layer by using standard test method, as the thickness of the layer was too thin comparing with base material. It was shown that the crack propagation rate and the threshold stress intensity factor range ΔK_{th} of peened material can be evaluated by a load controlled plate bending fatigue test [7]. It is very useful to investigate the mechanism of the improvement of the fatigue strength by the peening whether the crack initiation and/or crack growth were suppressed by the cavitation peening.

In order to establish the cavitation peening, the improvement of the aggressive intensity of the cavitating jet, which was used for cavitation peening, is also very important. When the aggressive intensity was enhanced, the peening effect would be improved and/or the processing time would be shortened. These are very important for practical applications. Normally, a cavitating jet is generated by injecting a high speed water jet into a water filled chamber. This is a kind of cavitating jet in water. Note that in the case of the cavitating jet, the aggressive intensity of the jet using a large nozzle at low injection pressure is much larger than that of small nozzle at high injection pressure [8]. Soyama realized "a cavitating jet in air" without a water filled chamber, injecting a high speed water jet into a low speed water jet, which was injected into air without the water filled chamber, using a concentric nozzle [9], [10]. Recently, Soyama successfully enhanced the aggressive intensity of the cavitating jet by optimizing the nozzle geometry, i.e., nozzle outlet bore, cavitator and guide pipe [11], [12].

In the present paper, in order to investigate the mechanism of the improvement of fatigue strength of stainless steel by cavitation peening experimentally, stainless steel specimen was treated by cavitation peening using the enhanced cavitating jet, and □K_{th} of treated specimen by cavitation peening was evaluated by the load controlled plate bending fatigue test, comparing with non-peened specimen.

Experimental Apparatus and Procedures

Figure 1 illustrates a schematic diagram of cavitation peening system. A high speed water jet was pressurized by a plunger pump, whose maximum injection pressure was 35 MPa and maximum discharge was 3.0×10^{-2} m^3/min, and injected into a water filled chamber through a nozzle with a cavitator and guide pipe, which 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 8 mm and 8 mm, respectively. The L and D were already optimized [11]. The distance from the cavitator to the nozzle plate and geometry of the guide pipe were also optimized [12]. 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 each condition.

In order to evaluate aggressive intensity of the cavitating jet, Duralumin plate made of Japanese Industrial Standard JIS A2017-T3 was treated, and arc height of curvature of treated plate was measured as same way as Almen strip. The inverse of radius of curvature was used for the parameter of the aggressive intensity of the cavitating jet. The size of the plate was 50 mm in width, 200 mm in length and 5 mm in thickness, as it is necessarily to develop and collapse the cavitation bubble on the plate.

The tested specimen to evaluate ΔK_{th} was made of stainless steel JIS SUS316L. The geometry of the specimen is shown in Fig. 3. The pre-crack was made on the specimen by using a milling machine after cavitation peening in order to avoid deformation of crack by cavitation impacts. The fatigue crack was developed by a plate bending fatigue test machine as shown in Fig. 4. The applied bending stress σ_a was obtained from bending moment M, width of the specimen W and thickness of the specimen using following Eq. (1).

$$\sigma_a = \frac{6\,M}{W\,t^2} \qquad (1)$$

Stress intensity factor range ΔK was calculated by using Newman-Raju Equation [13] as follows.

$$\Delta K = \Delta\sigma_a \sqrt{\pi\, b}\,\frac{J}{\phi}\,S\,H \qquad (2)$$

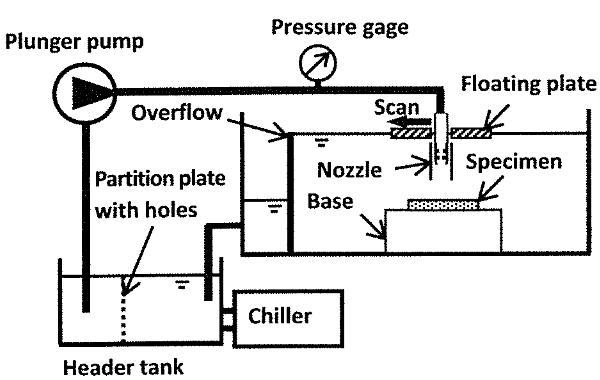

Fig. 1 Schematic diagram of cavitation peening system

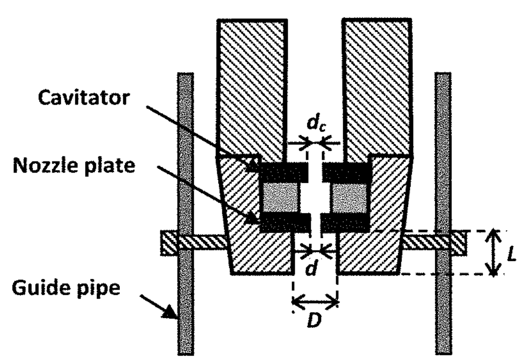

Fig. 2 Nozzle geometry

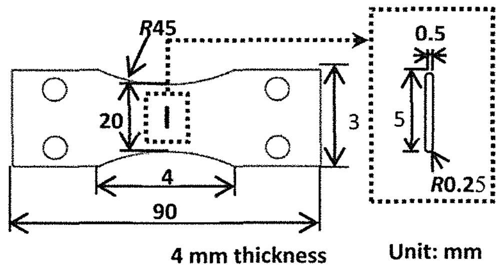

Fig. 3 Geometry and dimensions of specimen for plate bending fatigue test

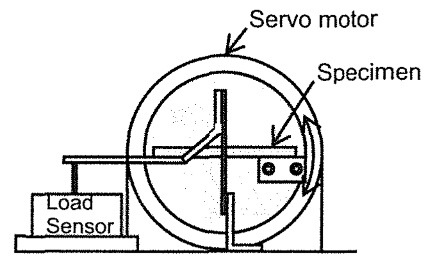

Fig. 4 Schematic of load controlled plate bending fatigue tester

Here, b was crack depth from the surface, $\Delta\sigma_a$ was $2\sigma_a$, J, ϕ, S and H were shape factors. Although the crack propagated three dimensionally, the crack depth b was estimated by the crack length $2a$ on the surface during the fatigue test. Then the following relation between the crack length $2a$ and the crack depth b was obtained by the observation of crack shape.

$$b = 0.801 \times \log_e \{(1.845 \times 2a) - 7.854\} \tag{3}$$

Note that the relation between the crack length and the crack depth were the same for the specimen with and without cavitation peening.
In order to obtain ΔK_{th}, K-decreasing processes in fatigue crack growth test were carried out. During K-decreasing test, ΔK_{th} depends on the decreasing rate, and too large decreasing rate made a delay of crack growth, then the load was decresed gradually. The ΔK_{th} was defined as ΔK at $da/dn = 10^{-10}$ m/cycle.
The processing time per unit length t_p was defined by the following equation.

$$t_p = \frac{n}{v} \tag{4}$$

Here, n was number of process and v was the process speed.

Experimental Results

Figure 5 illustrates the aggressive intensity of the cavitating jet with and without cavitator and guide pipe. In Fig. 5, the aggressive intensity was revealed by the inverse of curvature of peened Duralumin plate. The optimized cavitator enhanced the aggressive intensity about two times larger than that of the jet without cavitator. The optimized guide pipe also increased the aggressive intensity about two times larger than that of the jet without guide pipe. When both cavitator and guide pipe were used, the aggressive intensity of the jet was about four times larger than that of jet without cavitator and guide pipe, as cavitator feed cavitation nuclei to the jet and the guide pipe enlarged the cavitation cloud of the jet [12].
In order to investigate ΔK_{th}, the load controlled plate bending fatigue test was carried out.

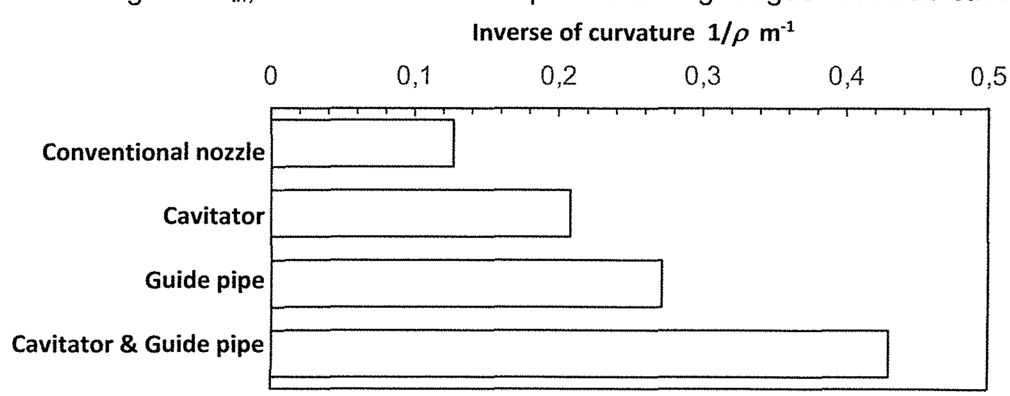

Fig. 5 Effect of cavitator and guide pipe on aggressive intensity of the cavitating jet

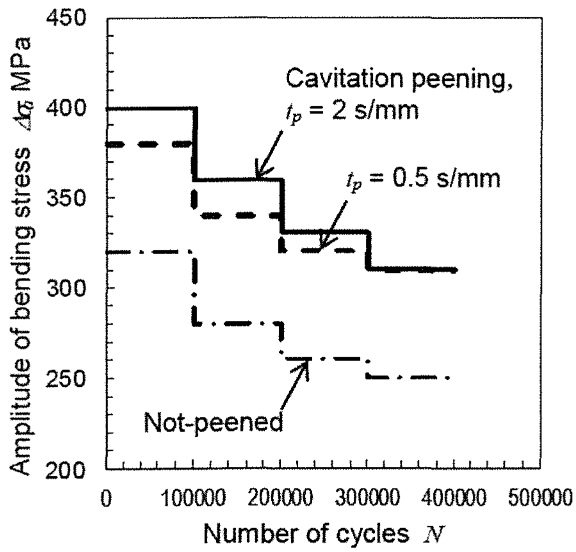

Fig. 6 Amplitude of bending stress changing with number of cycles

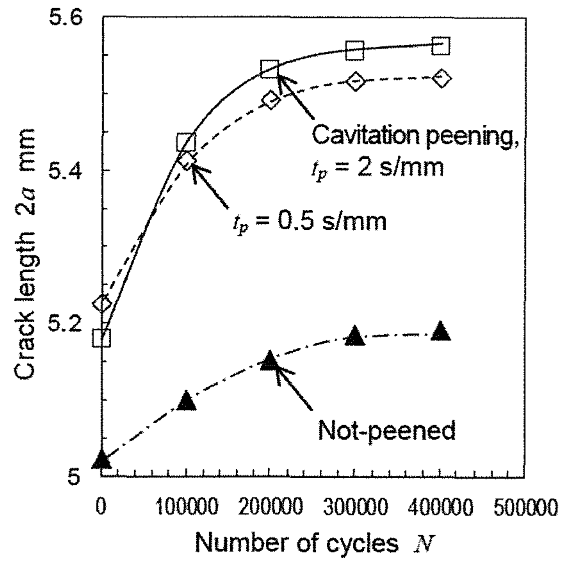

Fig. 7 Crack length changing with number of cycles

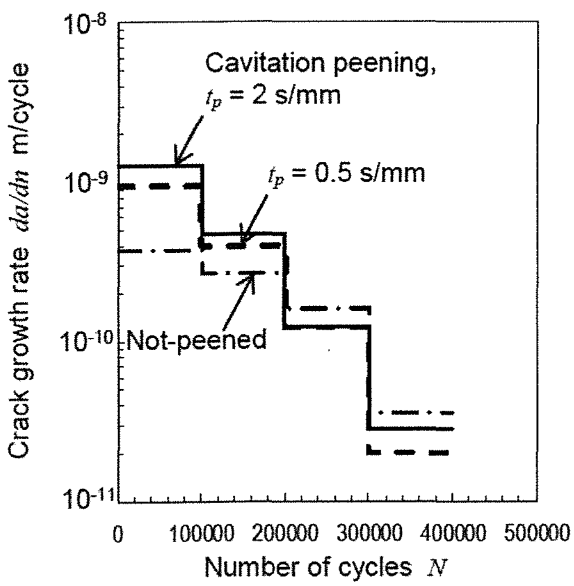

Fig. 8 Crack growth rate changing with number of cycles

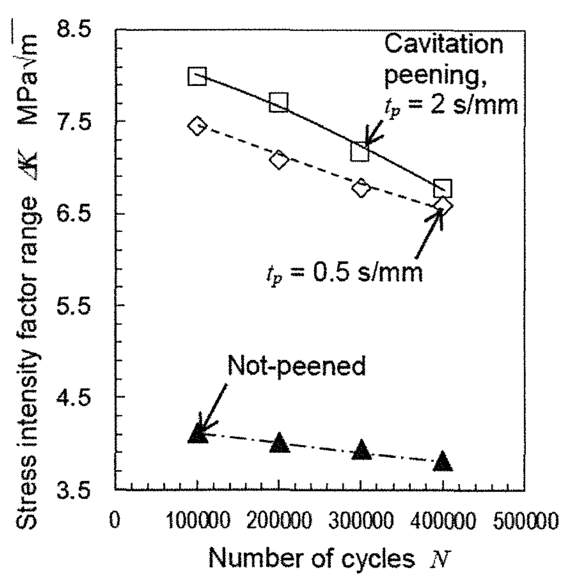

Fig. 9 Stress intensity factor range changing with number of cycles

At the test, the crack length of the non-peened specimen and that of treated specimen by cavitation peening at t_p = 0.5 s/mm and 2 s/mm were measured at each 100,000 cycles. The amplitude of bending stress $\Delta\sigma_a$ was decresed as shown in Fig. 6, in order to keep the decreasing rate at constant as possible. Figure 7 illustrates crack length $2a$ as a function of number of cycles. In Fig. 8, The crack growth rate da/dn was calculated from the results of Fig. 7, and stress intensity factor range ΔK was shown in Fig. 9.
Figure 10 illustrates the relation between the stress intensity factor range ΔK and the crack growth rate da/dn. The ΔK and da/dn were the data of Figs. 8 and 9, respectively. As shown in Fig. 10, the relation between ΔK and da/dn of non-peened was shifted to right hand side by the cavitation peening. In other words, when the relation of non-peed one was compared with that of cavitation peening, da/dn at the equivalent ΔK was suppressed by cavitation peening, and ΔK at the equivalent da/dn was increased by cavitation peening. The threshold

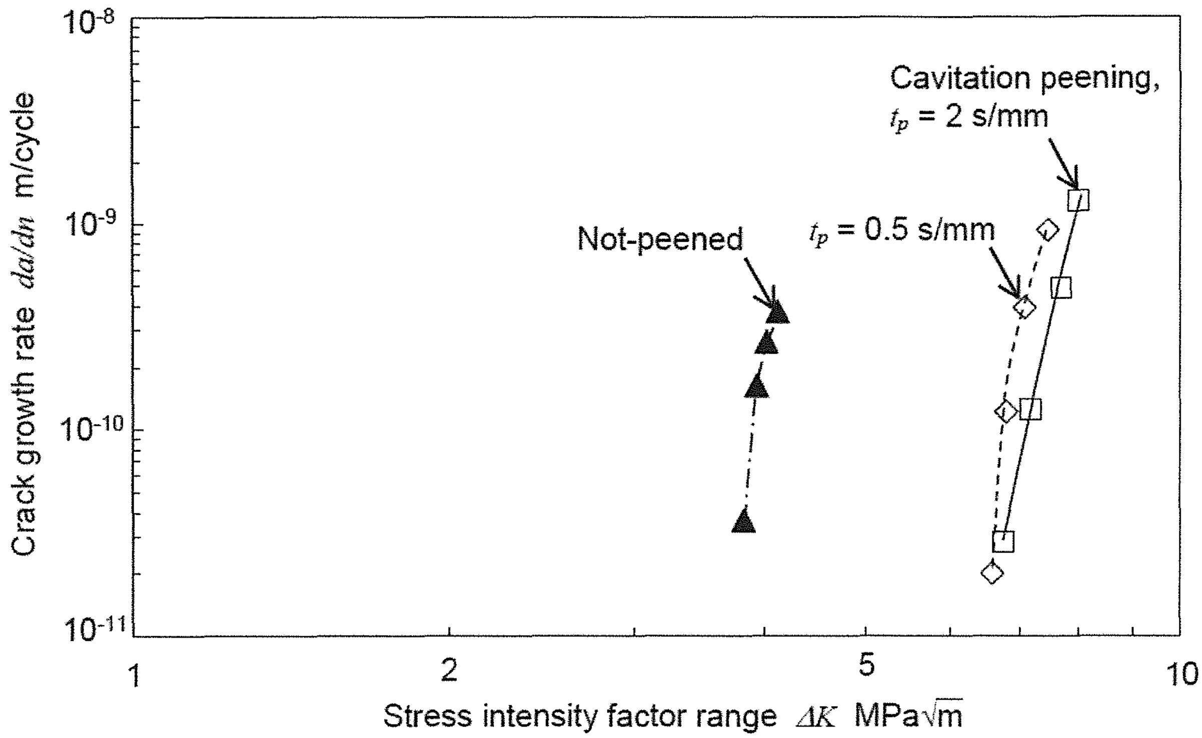

Fig. 10 Improvement of threshold stress intensity factor range ΔK_{th} by cavitation shotless peening

stress intensity factor range ΔK_{th}, i.e., ΔK at da/dn = 10^{-10} m/cycle, of non-peed specimen was 3.88 MPa$\sqrt{\mathrm{m}}$. On the other hand, ΔK_{th} of cavitation peened specimen at t_p = 0.5 mm/s and 2 mm/s were 6.76 MPa$\sqrt{\mathrm{m}}$ and 7.11 MPa$\sqrt{\mathrm{m}}$, respectively. Cavitation peening made ΔK_{th} 1.8 times larger than that of non-peed specimen. Namely, cavitation peening reduced crack initiation well as the suppression of crack growth rate. Note that the used load controlled plate bending fatigue test with a notch can evaluate threshold stress intensity factor range of surface modification layer of the specimen by cavitation peening. The proposed method would be useful to evaluate threshold stress intensity factor range of surface modified layer by the other mechanical surface treatment such as shot peening.

Conclusions

In order to investigate the mechanism of the improvement of fatigue strength of metallic materials by cavitation peening, the aggressive intensity of the cavitating jet, which was used for cavitation peening, was enhanced and the threshold stress intensity factor range ΔK_{th} of stainless steel JIS SUS316L with and without cavitation peening was evaluated. The main results were summarized as follows.

1. The optimized cavitator and the optimized guide pipe enhanced the aggressive intensity of the cavitating jet about four times larger than that of the jet without the cavitator and the guide pipe.
2. The ΔK_{th} of stainless steel specimen treated by cavitation peening was improved about 1.8 times larger than that of non-peened one.

Acknowledgements

This work was partly supported by JSPS KAKENHI Grant Number 24360040 and The New Technology Development Foundation. The author thanks Mr. M. Mikami, technician, and Mr. N. Kumagai, graduate student, Tohoku University for their help with the experiment.

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