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CAVITATING JET IN AIR USING MULTIPLE NOZZES

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ABSTRACT

Cavitating jet can be used for surface modification to improve fatigue strength as same way as shot peening. Peening method by means of cavitation impacts generated by the cavitating jet can peen the surface without the use of shot. Hence, it is a kind of shotless peening, and can be called "cavitation shotless peening." The cavitating jet in air was realized by injecting high-speed water jet into low-speed water jet, which was injecting in air, using a concentric nozzle. In order to treat wider area by using the cavitating jet in air for cavitation shotless peening, cavitating jet in air using multiple nozzles for high-speed water jet and a nozzle for low-speed water jet was investigated. The capability of the cavitating jet in air using multiple nozzles was measured by an erosion test using aluminum specimens. The treatment area using the cavitating jet in air using the multiple nozzles was three times wider than that of the cavitating jet in air of single nozzle at the present condition. It was revealed that the capability of the jet was increased with the injection pressure of the low-speed water jet. The fatigue strength of stainless steel was improved by cavitation shotless peening using the cavitating jet in air of multiple nozzles.

1. INTRODUCTION

Cavitating jet is useful for practical application such as surface enhancement as same way as shot peening and cleaning. Peening using cavitation impact at bubble collapse was named as "cavitation shotless peening (CSP)", as the shots of shot peening were not required. Introduction of compressive residual stress and improvement of fatigue strength by cavitation shotless peening were revealed (Soyama et al., 1996a; 1999; 2000; 2001; 2002; 2003; 2004a; 2004b; 2005). The cavitation impacts can also be useful for gathering impurities in silicon wafer (Soyama, 2000; Kumano et al., 2004a; 2004b), this technique was called "gettering," in device process.

In case of cavitation shotless peening and gettering using cavitation impacts, the cavitation was generated by a high-speed submerged water jet with cavitation, i.e., a cavitating jet. The cavitating jet is normally produced by injecting a high-speed water jet into water. Several researchers had tried to produce an artificially submerged jet in air by injecting a high-speed water jet into a concentric low-speed water jet for cutting rocks or cleaning (Vijet et al., 1978; Vickers et al., 1980; Vijet et al., 1992). In order to develop the efficiency of cavitating jet in air, the cavitating jet in air using multiple nozzles of high-speed water jets was investigated.

Soyama successfully generated suitable cavitating jet in air for cavitation shotless peening by injecting a high-speed water jet into a concentric low-speed water jet, which is injected directly into air without a water-filled chamber (Soyama, 2004b). According to an erosion test on a pure aluminum specimen, the performance of the cavitating jet in air depended on the injection pressure of the low-speed water jet, and the cavitating jet in air at the optimum injection pressure had a higher impact compared with both cavitating jet in water and normal water jet in air (Soyama, 2004b). Thus, it is necessary to investigate the ability of the cavitating jet in air for various pressure of the low-speed water jet.

A high-pressure water jet in air, which is normally used for cutting, can also peen the surface of metallic materials (Daniewicz, 1999; Rajesh, 2004). However, a very high injection pressure of more than 100 MPa is required for peening using a normal water jet in air. In the case of a cavitating jet, injection pressure of 20 or 30 MPa is enough for peening. Also, the area treated by a cavitating jet is 12 times larger than that of a water jet in air. From the point of view of efficiency, a cavitating jet is more suitable, since it can treat a larger area and do so at a low injection pressure. Altough peening by using water jet in water also investigated by other researchers (Hirano, 1996; Ramulu, 2002 & 2004), the cavitation should be considered (Soyama et al., 1996b & 1996c). The cavitating jet in air would have wider applications compared to the cavitating jet in water filled chamber.

In the present paper, the performance of the cavitating jet in air using multiple nozzles was investigated by erosion test. This assumes that the greater the mass loss, the greater the jet's capability. Specimens for the erosion test were made of pure aluminum (Japanese Industrial Standard JIS A1050). The stainless steel specimen made of JIS SUS316L was treated by cavitating jet in air using the multiple nozzles to reveal the improvement of fatigue strength.

2. EXPERIMENTAL FACILITIES AND PROCEDURES

Figure 1 shows the experimental set up for the cavitating jet in air. Figure 2 illustrates the schematic diagram of a nozzle for the cavitating jet in air by using multiple nozzles. The test nozzle consists of multiple nozzles for the high-speed water jet and a nozzle for the low-speed water jet. The cross sectional shape for the low-speed water jet was rectangular. Figure 3 shows two types of nozzle for the cavitating jet in air. Figure 3 (a) shows the straight type. The nozzles for the high-speed water jet were set straight on the line. The nozzles for the high-speed water jet in Fig. 3 (b) were set alternatively. The multiple high-speed water jets from the nozzles of both types were injected into the low-speed water jet. The nozzle of the high-speed water jet whose diameter d_H = 0.47 mm, 0.52 mm, 0.55 mm and 0.60 mm were tested. The effects of nozzle pitch s_p for the high-speed water jet was also examined. Three type of nozzle for the straight type was tested at s_p = 10 mm, 15 mm and 20 mm. The inner width of the nozzle of low-speed water jet was about 16 mm. The standoff distance *s* was defined by the distance between the nozzles of the high-speed water jets and specimen. The injection pressure of the high-speed water jet p_H and that of a low-speed water jet p_L were controlled by opening the valve. The injection pressures p_H and p_L of the nozzles were measured by pressure transducers. In the present paper, the pressures are relative pressures. The high-speed water jet was pressurized by a plunger pump. The low-speed water jet was pressurized by a submerged turbine pump. The specimen was set perpendicularly to the jet axis. Tap water was used in the cavitating jet loop.

The exposure time of specimens made of pure aluminum (Japanese Industrial Standard JIS A1050) to the jet was kept constant at 10 minutes. The mass loss Δm was measured. In order to measure the jet capability in the erosion test, both the aluminum specimen and the nozzle were fixed.

The stainless steel specimen, JIS SUS316L was scanned by moving the specimen at defined standoff distance in front of the cavitating jet. The thickness of specimen was 2 mm. The exposure time t_s to the jet was defined as the exposure time per unit length from the scanning speed *v* as follows:

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

where *n* is the number of scans. The fatigue strength of specimen was investigated by a plane bending fatigue test of plate.

The cavitation number σ, which is a key parameter for a cavitating flow, was defined by p_H and p_L and the saturated vapor pressure p_v as follows;

$$\sigma = \frac{p_L - p_v}{p_H - p_L} \cong \frac{p_L}{p_H} \tag{2}$$

In the case of a cavitating jet, the cavitation number can be simplified as in Eq (2) because $p_H \gg p_L \gg p_v$. Absolute pressure was used for the calculation of the cavitation number.

3. RESULTS

3.1 Treatment area of a Cavitating Jet in Air Using Multiple Nozzles

Figure 4 shows the erosion pattern induced by the cavitating jet in air using multiple nozzles for the high-speed water jet. For the reference, the erosion pattern of a cavitating jet in air using a single nozzle for the high-speed water jet is shown in Fig. 5. Figure 4 (a) shows the erosion pattern induced by the cavitating jet using the straight type multiple nozzle at s_p = 10 mm, d_H = 0.52 mm, p_H = 18 MPa, p_L = 0.06 MPa, s = 12.5 mm. Figure 4 (b) shows the erosion pattern using nozzle of wider s_p at 20 mm. Both erosion patterns revealed typical erosion pattern induced by the cavitating jet in air (see Fig. 5). The main erosion region was a ring produced by the cavitation impacts and the center was also eroded by the impacts of droplets as same as normal water jet in air. The width of the erosion pattern of multiple nozzles was over 60 mm, although that of single nozzle was 20 mm. This means that the multiple nozzles can be useful for surface modification, cleaning and so on. The diameter of the ring of both s_p = 10 mm and 20 mm were nearly same. When the distance between the nozzles of the high-speed water jet was closer, the ring became a rather rectangular shape. At d_n = 10 mm, the parts of the ring which was close to next ring was dim. The reason might be that shear intensity around the jet at these parts would be weak and then the cavitation intensity was also weak. On the other hand, the erosion at the top and bottom area along the log span directionally in Fig. 4 (a) was severe. As the distance between the ring erosion region at s_p = 10 mm was closer that of s_p = 20 mm, the nozzle of s_p = 10 mm was better for the cavitation shotless peening. In order to treat the surface as uniformly as possible, the alternate type was tested to reduce the region without erosion. Although the erosion of outside region of the ring was developed, the pitting pattern was not uniform. The number of pits between the nozzles was small. The mass loss of the alternative type was at 10 minutes 42 mg and that of the straight type was 49 mg. Thus, the straight type nozzle of s_p = 10 mm was chosen.

The treated region of the cavitating jet in air using multiple nozzles was investigated by means of a pressure sensitive film. Figure 6 revealed the treated region at s_p = 10 mm, d_H = 0.52 mm, p_H = 18 MPa, p_L = 0.06 MPa, s = 12.5 mm, t_s = 0.12 m/min. The dark color region shows the treated region, as the color of the films was changed by the cavitation impact. The width of the treated region was about 60 mm. The color of the film was almost uniform. It can be said that the developed nozzle can treat the region of 60 mm in width.

3.2 Capability of a Cavitating Jet in Air Using Multiple Nozzles

The mass loss induced by the cavitating jet was measured, as it assumed that mass loss corresponded to the capability of the cavitating jet. Figure 7 illustrates the mass loss as a function of the injection pressure of high speed waste jet of the cavitating jet in air. In the present condition, the mass loss increased concurrently with the injection pressure of the high-speed water jet. Namely, the ability of the cavitating jet increased with the injection pressure. It seemed that the increase of mass loss was going to be saturated.

Figure 8 illustrates the mass loss as a function of injection pressure of the low-speed water jet using the straight type multiple nozzle at d_H = 0.52 mm, p_H = 18 MPa, s = 15 mm changing with s_p = 10 mm, 15 mm and 20 mm. For all cases, The mass loss increase with p_L. As the mass loss induced by the single nozzle had a peak at certain p_L as the cavitation did not take place at very high injection pressure of the low-speed water jet. Thus, the ability of the cavitating jet in air using multiple nozzles also had optimum injection pressure of the low-speed water jet. This means that the injection pressure of the low-speed water jet was also an important parameter. The mass loss was largest at nozzle of s_n = 10 mm. This fact revealed that the distance between the nozzles of multiple high-speed jets was also an important parameter. s_p = 10 mm was chosen for the following experiments.

Jet power was defined by the injection pressure and flow rate. At constant jet power, the high-injection pressure can be used at small nozzle and the injection pressure was low at large nozzle. Figure 9 illustrates the maximum mass loss for each nozzle diameter d_H. The mass loss at each nozzle diameter was measured changing with injection pressure of high-and low-speed water jet and standoff distance at 10 mm, 15 mm and 20 mm. For the case of d_H = 0.47 mm, the mass loss had maximum at p_H = 27 MPa, p_L = 0.06 MPa, s = 15 mm. For the case of d_H = 0.52 mm, the mass loss had maximum at p_H = 18 MPa, p_L = 0.06 MPa, s = 15 mm. For the case of d_H = 0.55 mm, the mass loss had maximum at p_H = 8 MPa, p_L = 0.06 MPa, s = 15 mm. For the case of d_H = 0.6 mm, the mass loss had maximum at p_H = 9.6 MPa, p_L = 0.06 MPa, s = 15 mm. In any way, the mass loss had a maximum at d_H = 0.52 mm. When the cavitation number at each condition was calculated, the cavitation number was 0.006 at d_H = 0.47 mm; 0.009 at d_H = 0.52 mm; 0.02 at d_H = 0.55 mm; 0.017 at d_H = 0.6 mm. The cavitation number at optimum condition was increased with the nozzle diameter.

In order to make clear the optimum standoff distance, the mass loss was measured changing with the stand off distance at s_p = 10 mm, d_H = 0.52 mm, p_H = 18 MPa, p_L = 0.06 MPa. Figure 10 illustrates the mass loss curve. The mass loss had a peak at s = 12.5 mm. Thus following cavitating condition was chosen for the cavitation shotless peening of stainless steel;

Nozzle type : Straight type
Pitch of the nozzle for the high-speed water jet : s_p = 10 mm
Diameter of the nozzle for the high-speed water jet : d_H = 0.52 mm
Injection pressure of the high-speed water jet : p_H = 18 MPa
Injection pressure of the low-speed water jet : p_L = 0.06 MPa
Cavitation number : σ = 0.009
Standoff distance : s = 12.5 mm

3.3 Improvement of Fatigue Strength by a Cavitating Jet in Air Using Multiple Nozzles

Figure 11 illustrates the S-N curve of stainless steel without and with cavitation shotless peening by cavitating jet in air using multiple nozzles. The scanning time t_s was 20 s/mm and 40 s/mm. In order to avoid the initiation of fracture from the weak point between the main treated region, the specimen at t_s = 40 s/mm was treated by t_s = 20 s/mm after treated t_s = 20 s/mm and moved half pitch, i.e., 5 mm. The fatigue strength at $N = 10^7$ was obtained by Little's method (Little, 1972). The fatigue strength without peening was 279 MPa. The fatigue strength with cavitation shotless peening by cavitating jet in air using multiple nozzles was 295 MPa at t_s = 20 s/mm, and 303 MPa at t_s = 40 s/mm, respectively. All specimen of t_s = 20 s/mm failed at the region between main treated region of the each high-speed water jet. It can be concluded that the cavitation shotless peening by cavitating jet in air using multiple nozzles can improve fatigue strength about 9 % compared with the non-peened specimens.

4. CONCLUSIONS

In order to develop the nozzle, which can treat wider area, for cavitation shotless peening, the cavitating jet in air using multiple nozzle of high-speed water jet was investigated. The capability of the jet was tested by the erosion test, for various injection pressure of high-and low-pressure, the pitch of the nozzle, the diameter of nozzle size and standoff distance region. It can be concluded that the injection pressure of the high- and low-speed water jet, the distance of the nozzle of high-speed water jet and the nozzle pitch were important parameters. In the present experiment, the test condition were as follows; straight type nozzle, s_p = 10 mm, d_H = 0.52 mm, p_H = 18 MPa, p_L = 0.06 MPa, s = 12.5 mm, respectively. The fatigue strength with the cavitation shotless peening by cavitating jet in air using multiple nozzles improved about 9 % compared with the non-peened specimens.

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NOMENCLATURE

d_H	=	nozzle diameter of high-speed water jet
n	=	number of scans
p_H	=	injection pressure of high-speed water jet
p_L	=	injection pressure of low-speed water jet
p_v	=	vapor pressure of test water
s	=	standoff distance from nozzle to impinged surface
s_p	=	nozzle pitch for the high-speed water jet
t_s	=	processing time per unit length $t_s = \frac{n}{v}$
v	=	scanning speed
Δm	=	mass loss
σ	=	cavitation number $\sigma = \frac{p_2 - p_v}{p_1 - p_2} \cong \frac{p_2}{p_1}$

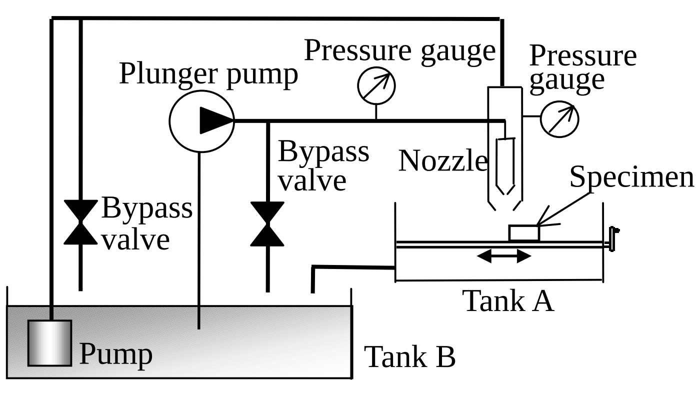


Fig. 1 Schematic diagram of apparatus of cavitating jet in air for CSP

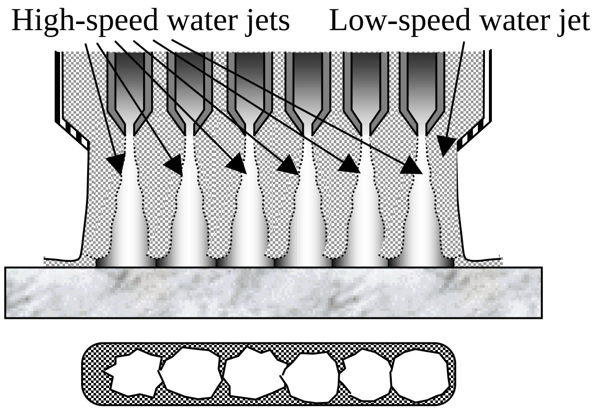
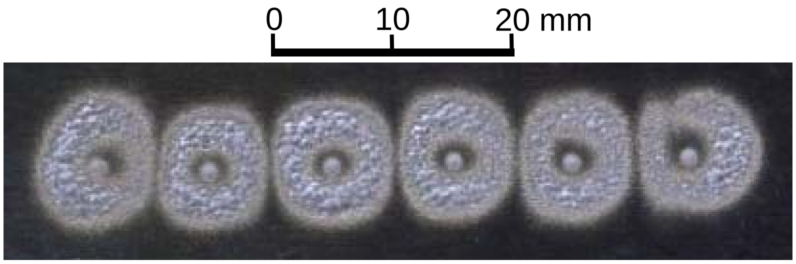


Fig. 2 Schematic diagram of multiple nozzles

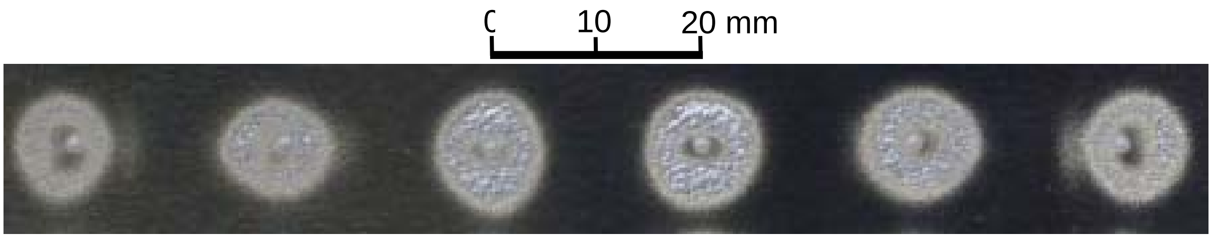
(a) Straight type

(b) Alternate type

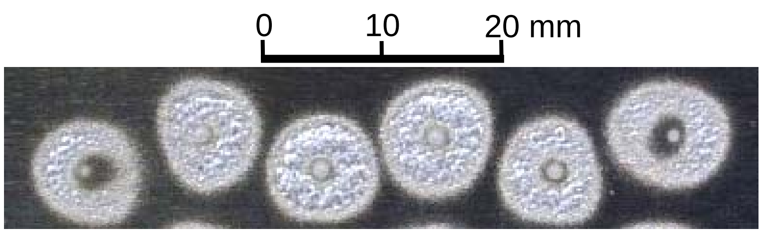
Fig. 3 Multiple nozzles for cavitating jet in air



(a) Straight type, s_p = 10 mm, d_H = 0.52 mm, p_H = 18 MPa, p_L = 0.06 MPa, s = 12.5 mm



(b) Straight type, s_p = 20 mm, d_H = 0.52 mm, p_H = 18 MPa, p_L = 0.06 MPa, s = 15 mm



(c) Alternate type, s_p = 10 mm, d_H = 0.52 mm, p_H = 16 MPa, p_L = 0.1 MPa, s = 15 mm

Fig. 4 Erosion pattern induced by cavitating jet in air using multiple nozzles

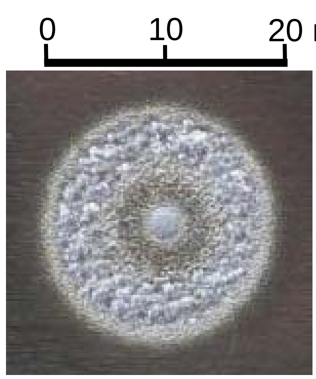


Fig. 5 Erosion pattern induced by cavitating jet in air using single nozzle
(d_H = 1 mm, p_H = 30 MPa, p_L = 0.06 MPa, s = 35 mm)

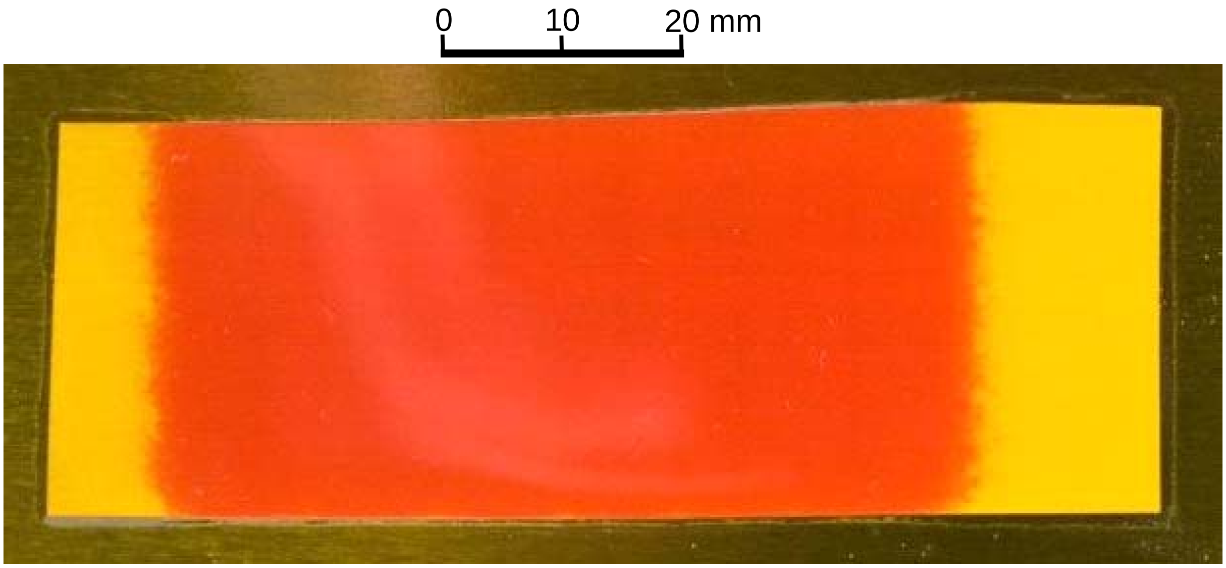


Fig. 6 Treatment area by cavitating jet in air using multiple nozzle measured by pressure sensitive film (straight type, s_p = 10 mm, d_H = 0.52 mm, p_H = 18 MPa, p_L = 0.06 MPa, s = 12.5 mm, t_s = 0.12m/min)

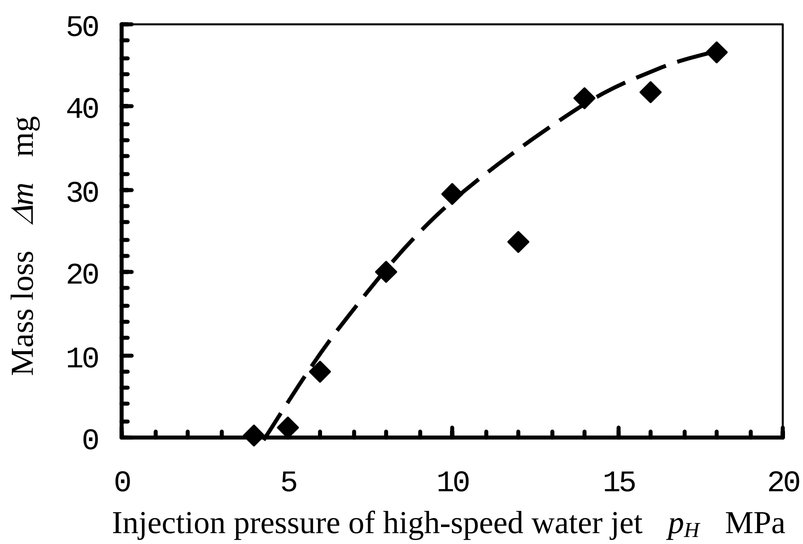


Fig. 7 Mass loss as a function of injection pressure of high-speed water jet (straight type, s_p = 10 mm, d_H = 0.52 mm, p_L = 0.06 MPa, s_p = 15 mm)

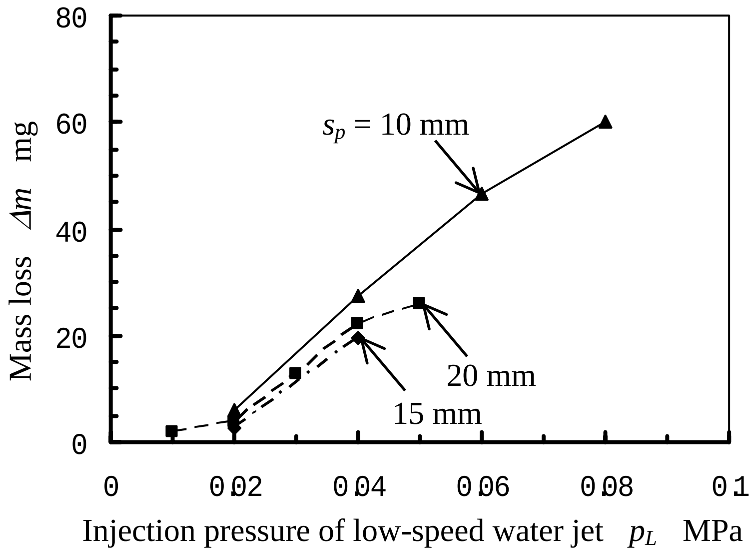


Fig. 8 Mass loss as a function of injection pressure of low-speed water jet
(straight type, d_H = 0.52 mm, p_H = 18 MPa, s = 15 mm)

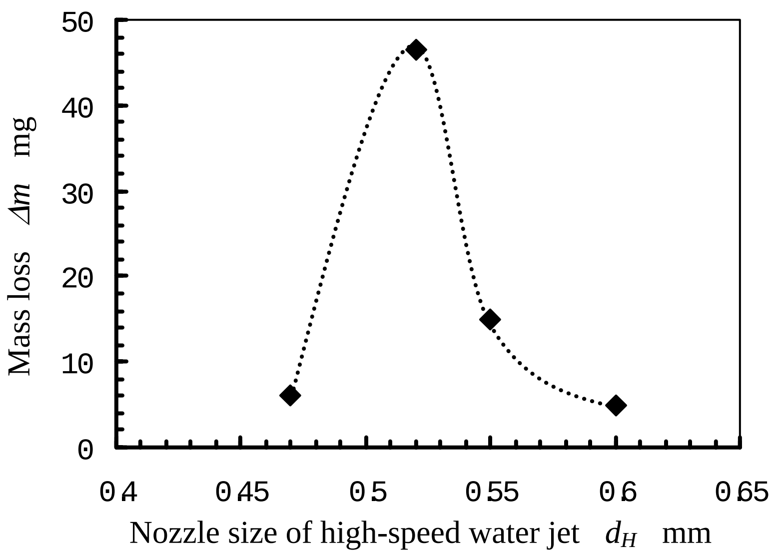


Fig. 9 Mass loss as a function of nozzle size of high-speed water jet
(straight type, s_p = 10 mm, p_L = 0.06 MPa, s = 15 mm)

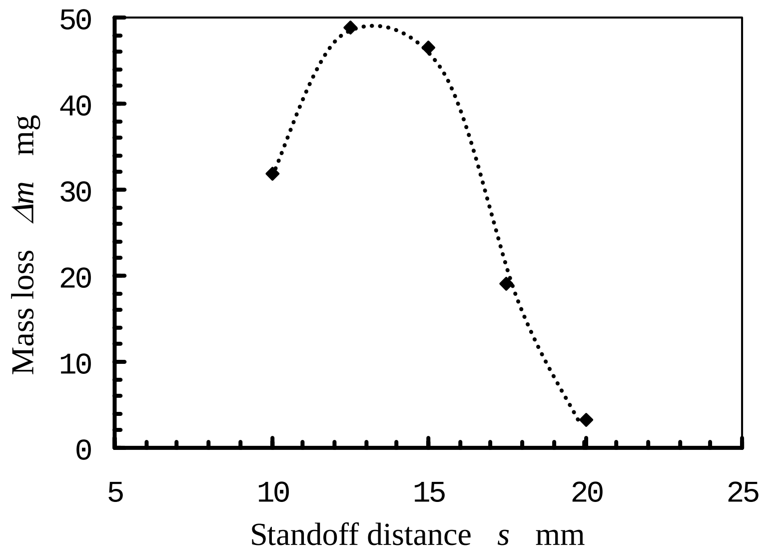


Fig. 10 Mass loss as a function of standoff distance (straight type, s_p = 10 mm, d_H = 0.52 mm, p_H = 18 MPa, p_L = 0.06 MPa)

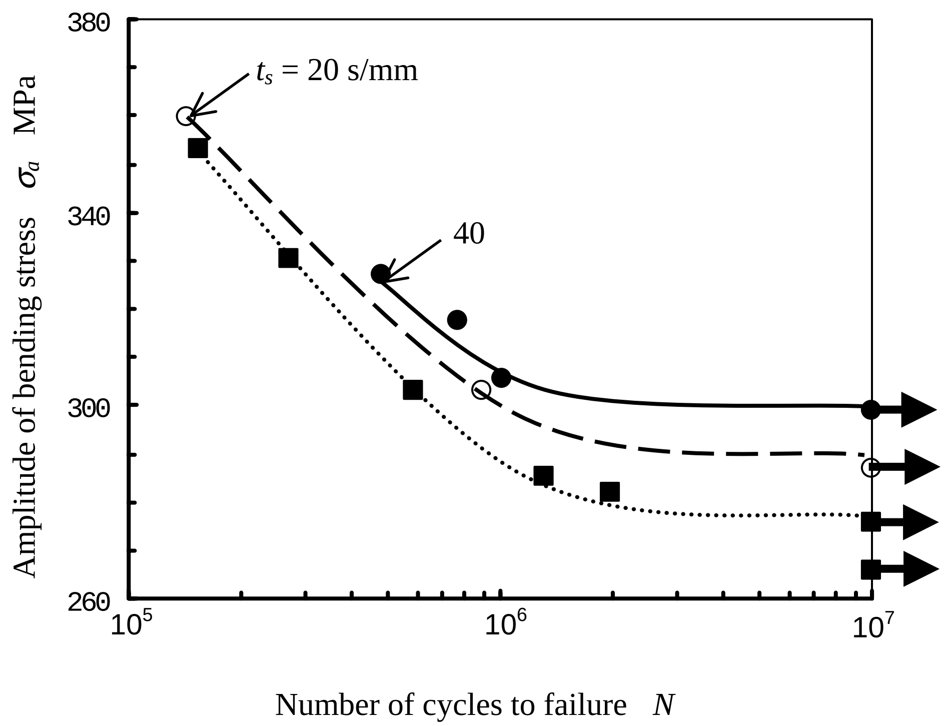


Fig. 11 Improvement of fatigue strength of stainless steel by cavitating jet in air using multiple nozzle for high-speed water jet (straight type, s_p = 10 mm, d_H = 0.52 mm, p_H = 18 MPa, p_L = 0.06 MPa, s = 12.5 mm)