PEEN FORMING OF DURALUMIN PLATE BY USING A CAVITATING JET IN AIR

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ABSTRACT
Cavitation impacts at bubble collapse normally cause severe damage in hydraulic machineries. However, cavitation impact can be utilized to improve fatigue strength the same way as shot peening. In the present paper, the possibility of cavitation impact for peen forming was investigated. Peen forming is used to make curvature of main wing of airplanes. Cavitation impacts were produced by a cavitating jet in air, which was injected low-speed water jet and high-speed water jet into air by using concentric nozzle. It was concluded that convex curve of duralumin plate was produced by the cavitating jet in air.

INTRODUCTION
Impacts induced by cavitation bubble collapse causes cavitation erosion and noise in hydraulic machineries such as pumps, valves and screw propellers. However, cavitation impacts can be used for surface modification to improve fatigue strength [1-4] and to introduce compressive residual stress of metals [5-7] the same way as shot peening. The cavitation impacts for surface modification were produced by a high-speed submerged water jet with cavitation, i.e., a cavitating jet in water. The region and impact intensity were controlled by hydraulic parameters such as upstream pressure, nozzle size etc.

The cavitating jet differs completely from a normal water jet in air. The remarkable difference between a cavitating jet and a water jet in air is the size of the treated area. The cavitating jet can treat an area 12 times wider than that of a water jet in air [8]. The great advantage of surface treatment by using a cavitating jet is that the peened surface is less rough compared with shot peening, since there are no solid body collisions involved [3]. This means that the remarkable effects of peening can also be produced in soft metals.

Soyama and Saito [9] developed a cavitating jet in air, which is suitable for the surface treatment, by injecting a high-speed water jet into a low-speed water jet. The cavitating jet in air can treat large machinery components, which could not be accommodated into the water chamber.

Peen forming is a metal forming process used for making curvature on plates. The peen formed surface using shots were damaged due to the solid collision. For the case of cavitation impacts, the surface of soft materials was not damaged.

In the present paper, in order to demonstrate the possibility of the peen forming by using a cavitating jet in air, ability of the cavitating jet was measured by using an erosion test using aluminum specimen, and then the peen forming of plate made of duralumin was investigated at several conditions.

NOMENCLATURE
\[ d_H = \text{throat diameter of nozzle of high-speed water jet} \]
\[ d_L = \text{throat diameter of nozzle of low-speed water jet} \]
\[ h = \text{arc height} \]
\[ n = \text{number of scan} \]
\[ p_H = \text{injection pressure of high-speed water jet} \]
\[ p_L = \text{injection pressure of low-speed water jet} \]
\[ p_v = \text{saturated vapor pressure of test water} \]
\[ R = \text{radius of curvature} \]
\[ R_s = \text{surface roughness} \]
\[ s_H = \text{standoff distance between nozzle of high-speed water jet and surface of specimen} \]
\[ s_L = \text{standoff distance between nozzle of low-speed water jet and surface of specimen} \]
\[ t = \text{exposure time to jet per unit length} \]
\[ \nu = \text{scanning speed} \]
\[ \sigma = \text{cavitation number} \]
\[ \sigma = \frac{p_L - p_v}{p_H - p_L} \]

EXPERIMENTAL FACILITIES AND PROCEDURES
Figure 1 illustrates the experimental set up of the cavitating jet in air for peen forming. The test nozzle consists...
of a nozzle for the high-speed water jet and a nozzle for the low-speed water jet. Both nozzles were set in a concentric configuration. The diameter of the nozzle for the high-speed water jet $d_H$ was 1 mm and the diameter of nozzle for the low-speed water jet $d_L$ was 20 mm. 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 absolute pressures. The specimen was set perpendicularly to the jet axis. The standoff distance $s_H$ is defined as the distance from the upstream corner of the nozzle throat of the high-speed water jet to the surface of the test specimen. The standoff distance $s_L$ is defined as the distance from the outlet of the nozzle of the low-speed water jet to the surface of the test specimen. In the present experiment, the distance $s_H - s_L$ was fixed at 7.5 mm. Tap water was used in the cavitating jet loop.

The key parameter for a cavitating jet was cavitation number $\sigma$. The cavitation number was defined by the injection pressure of the high-speed water jet $p_H$ and that of a low-speed water jet $p_L$ and saturated vapor pressure $p_v$ as follows:

$$\sigma = \frac{p_L - p_v}{p_H - p_v}$$

(1)

In the case of a cavitating jet, the cavitation number can be simplified as in Eq. (1) because $p_H \gg p_L \gg p_v$.

The exposure time $t$ to the jet is defined as the exposure time per unit length from the scanning speed $v$ as follows:

$$t = \frac{n}{v}$$

(2)

where $n$ is the number of scans. At the present experiment, the nozzle was fixed and specimen for peen forming was moved by a motor at constant speed.

In order to investigate the capability of the jet, the mass loss induced by erosion was measured. This assumes that the greater the mass loss reveals the greater the jet’s capability. Specimens for the erosion test were made of pure aluminum (Japanese Industrial Standard JIS A1050). The exposure time of specimens to the jet was constant at 3 minutes. The mass loss was measured at a constant injection pressure $p_H = 20$ MPa. In order to optimize the cavitating jet in air, the mass loss was measured as the standoff distance $s_H$ and the injection pressure of the low-speed water jet $p_L$ was varied. To measure the jet capability at the erosion test, specimen made of aluminum was fixed and the nozzle was also fixed.

In order to demonstrate peen forming, duralumin (JIS A2027) was chosen as tested material. The thickness of specimen was 1.2 mm and 3 mm. The heat treatment of test specimen was T6 for the specimen of 3 mm in thickness. The curvature made by peen forming was measured by a surface profilometer.

**RESULTS**

In order to show the capability of the cavitating jet in air, the mass loss $\Delta m$ induced by the jet as a function of standoff distance $s_H$ with varying low-speed water jet injection pressure $p_L$ is shown in Fig. 2. The upstream pressure was 20 MPa. For each condition, the mass loss increases with standoff distance and then decreases. That is, there is a maximum mass loss at a certain standoff distance, which is called the optimum standoff distance, as for a normal cavitating jet in a water-filled chamber. The optimum standoff distance was about 30 or 35 mm at the present conditions.

The capability of the cavitating jet in air was also changed by the injection pressure of low-speed water jet. Figure 3 shows...
the mass loss at optimum standoff distance as function of the injection pressure of low-speed water jet $p_L$. The mass loss is increased with the injection pressure of low-speed water jet to its peak and then decreased. This results shows that the jet capability has an optimum injection pressure of low-speed water jet. At the present study, it is 0.15 MPa in absolute pressure. The mass loss at optimum condition was about 18 times larger than that of low $p_L = 0.12$ MPa. This means when the cavitating jet was used at out of suitable range, the jet capability would be very weak. The cavitation number at this condition is about 0.0075. This value is lower than that of previous report [10]. The facility used for present study of cavitating jet in air is different from previous report. The inlet shape and nozzle geometry for low-speed water jet is different. In case of cavitating jet in water-filled chamber, the cavitation intensity has a maximum at 0.014. This means that the optimum cavitation number of the cavitating jet in air is slightly lower than that of cavitating jet in water.

Figure 4 shows the schematic diagram of the cavitating jet in air and the erosion pattern on aluminum specimen induced by the cavitating jet in air at optimum condition, $p_H = 20$ MPa, $p_L = 0.15$ MPa, $s_H = 30$ mm. The main eroded area is a ring region with an inner diameter of 10 mm and an outer diameter of 20 mm. Ring erosion is formed by cavitation cloud hitting the surface which then spreads out to form ring vortex before cavitation collapse. At the center of the jet, small erosion took place, as the droplets from the high pressure water hit the region producing erosion as same as normal water jet in air. Figure 4 reveals that thus direct cavitating jet in air was successfully produced. When the nozzle and the specimen were fixed, the erosion pattern is not uniform as Fig. 4.

However, when the nozzle scanned the surface, the pit distribution peened by a scanning-type cavitating jet was uniform. This is advantageous for the purposes of peen forming.

Figure 5 shows the convex curve by peen forming using the cavitating jet in air. The cavitating condition was $p_H = 20$ MPa, $p_L = 0.15$ MPa and $s_H = 30$ mm, because the mass loss had a maximum at this condition. The scanning speed was chosen as 160 mm/min. Although curvature was increasing with processing time per unit length, the curvature was already saturated at the speed 160 mm/min. The thickness of peened specimen was 1.2 mm. It is clear that the cavitating jet made convex curve of duralumin plate.

Figure 6 reveals the morphology of peened surface of the test specimen in Fig. 5. A lot of pits induced by cavitation impacts were shown on the surface. The pit size ranged from 20 $\mu$m to 40 $\mu$m. The pattern of surface finish was shown on the surface of pits. Thus, these pits were plastic deformation pits without mass loss. The surface roughness $R_a$ of the specimen in Figs. 5 and 6 was 0.85 $\mu$m.

Figure 7 illustrates the curvature changing with the injection pressure of low-speed water jet. The thickness of peened specimens was 1.2 mm. In Fig. 7, the data of the mass loss in Fig. 3 was also put in together. The scanning speed was chosen as 160 mm/min for every cases. The standoff distance at each condition was chosen as the optimum standoff distance which was determined by the erosion test. The curvature increased with the injection pressure of low-speed water jet and then gradually decreased. Thus the optimum injection pressure of low-speed for peen forming is slightly larger than that of erosion test. Although the difference of capability of the jet
measured by erosion test between \( p_L = 0.15 \text{ MPa} \) and \( p_L = 0.12 \text{ MPa} \) was about 18 times, the difference of curvature between two cases was about twice.

Figure 8 illustrates the curvature and mass loss as a function of standoff distance. The curvature increased with standoff distance then decreased. The curvature had an optimum standoff distance, which is further than that of erosion test. These results revealed that the optimum peen forming condition might be slightly different from that of erosion test.

When the duralumin plate of 3 mm in thickness was peened by the cavitating jet in air, at \( p_H = 20 \text{ MPa} \), \( p_L = 0.15 \text{ MPa} \) and \( s_H = 35 \text{ mm} \), \( v = 21.8 \text{ mm/min} \), the obtained radius of curvature was 4.1 m. The radius of curvature of main wing of airplane for peen forming is about 3 to 5 m. Thus the cavitating jet can be useful for peen forming.

**CONCLUSIONS**

In order to demonstrate the peen forming by using a cavitating jet in air, the plates made of duralumin were exposed to the cavitating jet in air then the curvature of tested plate was measured at various conditions. Obtained results were summarized as follows:

1. The cavitating jet in air, whose injection pressure of high-speed water jet was 20 MPa, can be used for the peen forming.
2. The optimum condition of the cavitating jet in air for peen forming was slightly different from that of erosion test.
3. The injection pressure of low-speed water jet and standoff distance was one of parameters for peen forming by a cavitating jet in air.

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