Structure of a High-Speed Water Jet and the Damage Process of Metals in Jet Cutting Technology*

Ryōji KOBAYASHI**, Takakage ARAI**
and Hiroshi YAMADA***

This paper is mainly concerned with the dynamic structure of high-speed water jets, the damage process of metallic materials and a microscopic comparison of cavitation damage. The experimental conditions were an injection pressure of 30 to 90 MPa and a nozzle inner diameter of about 1 mm. Materials tested included aluminum, mild steel and stainless steel. The instantaneous behavior of the impact pressure was measured using a pressure transducer. Comparisons among stroboscopic observations for the structure of water jet, axial variation of the impact pressure and mass loss of the material caused by the jet impact showed that an axial location where the water jet begins to break up is close to the location of the maximum mass loss of the material. We have made a detailed comparative observation of the damage process for a water jet and for the cavitation (magnetostrictive vibratory method) using a scanning electron microscope and found some distinct differences in the damage process.

Key Words: Fluid Mechanics, Multiphase Flow, Cutting, Nontraditional Processing, Water Jet, Erosion, Cavitation

1. Introduction

Erosion effects of high-speed water jets have been applied to nontraditional processing, cleaning technology, the dismantling of buildings, and the medical field. Basic research on the dynamic structure of such high-speed water jets and on the damage process of solid materials caused by impingement of the water jet is important for further progress of water jet technology. Yokota and Yamakado⁽¹⁾ considered the structure of a water jet by observing the damage patterns of metallic materials. Watson et al.⁽²⁾ showed a relation between the structure of a water jet produced by a water cannon and the impact pressure. Yanaida and Ohashi⁽³⁾ measured time-mean total pressures in a water jet by using a Pitot tube. The dynamic structure of the water jet and its relation to

the damage process of metallic materials have not been, however, clarified in detail.

With a view to improving the performance and the accuracy of water jet technology, the structure of the high-speed water jet was observed, and then a relation between the jet structure and the damage process of metallic materials by impingement of the water jet was investigated in the present paper. In addition, a comparative observation of the damage surface between the water jet and the cavitation was made, because it had been recognized since an experiment by Hobbs⁽⁴⁾ that there exists a close correlation between the damage resistances of metallic materials against the impact of liquid droplets and the cavitation attack.

2. Experimental Apparatus and Procedure

Figure 1 shows a schematic diagram of the experimental apparatus. Tap water, as the medium liquid, was pressurized in the range of 30MPa to 90MPa by a three-throw plunger pump and injected horizontally from the contraction nozzle into the atmospheric field. The injection pressure was measured by a pressure transducer at the inlet of the nozzle. Materials of the

* Received 21st July, 1987. Paper No. 86-1173 B

** Department of Mechanical Engineering II, Faculty of Engineering, Tohoku University, Aramaki-Aoba, Sendai, 980, Japan

*** Nippon Petrochemicals Co., Ltd., 1-3-1 Uchisaiwai-cho, Chiyoda-ku, Tokyo, 100, Japan

test specimen adopted in the present investigation were aluminum (A1050P), mild steel (SS41) and stainless steel (SUS 304). The aluminum specimens were of 50 mm square and 10 or 5 mm thickness. The other specimens were of 50 mm square and 5 mm thickness. The mass of each specimen was measured using a chemical balance before and after each damage test, and the mass loss M of the specimen was obtained from the difference between them. Relative positions of the test specimen to the nozzle exit could be set up optionally by use of a three-dimensional traverse apparatus. The nozzle was made of tool steel. A detailed geometry of the nozzle exit is illustrated in Fig. 1. The nozzle exit was of $d=1.11$ mm in inner diameter. The ratio of the cylindrical length l to the exit diameter d was about 4 and the conical angle ϕ was about 13° . The structure of the water jet was observed by a method of shadow photography using a stroboscope with a flashing time of $0.8 \mu\text{s}$. Time variations of impact pressures by impingement of the water jet were measured by another pressure transducer in a circular disk which had a pressure measurement hole of 1 mm in diameter. The disk was made of stainless steel. We were careful to set the pressure measurement hole at the center of the water jet. Microscopic structures of damaged surfaces were observed by a scanning electron microscope (SEM).

3. Results and Discussion

3.1 Mass loss by jet impact

Figure 2 shows the mass loss M of aluminum

Fig. 1 Schematic diagram of experimental apparatus

Fig. 2 Mass loss M against distance x/d from nozzle exit (effect of injection pressure P_0)

specimen in relation to the distance x/d from the nozzle exit. The exposure time t_0 is 60 s. It is seen from the figure that the mass loss becomes maximum at $x/d \approx 700$ and the mass loss curve has two peaks for higher magnitude of the injection pressure P_0 . We call them the first peak and the second peak, respectively. The distance from the nozzle to the second peak location has a tendency to increase slightly with increasing P_0 . Figure 3 gives the same relations as Fig. 2 for mild steel and stainless steel at $P_0=70$ MPa and $t_0=300$ s, compared with aluminum at 70MPa and 60s. The figure shows that the first peak does not appear on the mass loss curve for mild steel and stainless steel under such experimental conditions. It can be said that the ranking of this damage resistance of metallic materials against the impact of water jet is the same as the one against cavitation⁽⁵⁾. Attention should be paid to the location of the second peak in Fig. 2, where it is noted that the location x/d did not change for all the test materials. This means that the appearance of the peak is closely related to the structure of the water jet.

3.2 Structure of water jet and damage patterns

Figure 4 shows the structure of the water jet over the range from the nozzle exit to the location of the second peak for $P_0=50$ MPa. Figure 5 represents the damage patterns of aluminum at various locations x/d

Fig. 3 Mass loss curve for different materials

Fig. 4 Structure of water jet ($P_0=50$ MPa)

for the exposure time 60 s. In the region from the nozzle exit to the first peak ($x/d=180$), the jet is continuous, there are small droplets around the jet, and the damage makes a petal-like pattern. In the other region between the first peak and the second peak, there exist large scale deformations of the water jet, and the damage is the most remarkable at the center of the jet. At a location x/d near to the second peak, the deformation reaches the jet center, where the water jet breaks up into water lumps and droplets, as shown in Fig. 4(d).

3.3 Impact pressure

The fact that the mass loss M becomes maximum at the second peak location rather than near the nozzle means that the damage of materials is caused not by the dynamic pressure but by the impact pressure. For this reason, we measured time variations of the impact pressure by using the pressure transducer and considered the characteristics of the impact pressure in relation to the structure of water jet. Figure 6 shows the maximum, average and minimum values of the impact pressure at various locations x/d for $P_0=50$ MPa. Figure 7 shows one of the frequency spectra of the impact pressure, in which it is noted that there exists a peak frequency of about 2.5 kHz at $x/d=270$, which is much larger than the pressure fluctuation due

to the plunger pump. Such a peak frequency was observed in the region where the water jet makes a large-scale deformation, while there was no peak frequency in the other regions near the nozzle and where the water jet broke up into lumps. The mechanism of such periodic oscillations is not yet clear.

As found from Fig. 6, the maximum value of the impact pressure remains constant from $x/d=0$ to 500. It means that the jet holds a constant velocity in that region. The following can be said from a comparison among Figs. 2, 4 and 6. In a region near the nozzle, the amplitude of the impact pressure is small, where the mass loss M is also small. In the region where the large-scale deformation is observed, both the impact pressure amplitude and the mass loss increase. The location where the water jet breaks up into lumps is followed by the second peak of the mass loss curve. It could, therefore, be said that the mass loss has a close relation with the structure of the water jet and the amplitude of the impact pressure.

3.4 Effects of incident angle

Figure 8 shows relations of the mass loss M to the incident angle θ of water jet, where M_0 denotes the mass loss for $\theta=0^\circ$ (normal to the surface of the test specimen). The experimental results for the second peak agree well with a curve of $\cos \theta$. This indicates that the mass loss depends on the normal component of the jet velocity to the specimen. The curve for the first peak has the maximum value of M/M_0 at θ of about 10° . There thus exists a clear difference between

Fig. 5 Patterns of damage (Al, $P_0=50$ MPa, $t_0=60$ s)

Fig. 6 Impact pressure

Fig. 7 Frequency spectrum of impact pressure

Fig. 8 Variations of mass loss M depending on incident angle θ for the first and second peaks (Al)

the two curves for the first peak ($x/d=180$) and the second peak ($x/d=720$). It could be said that the damage of material at the location of the first peak is caused by the excavation force due to water flowing radially after impinging on the specimen surface, while that near the second peak depends strongly on the impact pressure due to the impinging of water lumps and droplets.

3.5 Time dependence of damage pattern at the first peak

The damage pattern at the second peak is conical in shape and remains unchanged as the exposure time t_0 increases, while the damage pattern at the first peak, the petal pattern, varies with exposure time. Figure 9 shows the damage patterns at various exposure times at the first peak ($x/d=180$) for $P_0=70$ MPa. As seen in photos (a) and (b), the central circular area remains unchanged, and its annular region is

Fig. 9 Time dependence of damage pattern (Al, $P_0=70$ MPa, $x/d=180$)

Fig. 10 SEM observations of damaged surface

selectively eroded to form the petal pattern. The central residual area decreases gradually (Photo(c)) and disappears finally (Photo(d)). After a long exposure time, the damage is the most remarkable at the center of the water jet (Photo(e)). This process was observed in the range from $x/d=90$ to 270. The erosion time in which the central residue disappears becomes shorter with the distance from the nozzle. For example, the erosion time was about 120 s for $x/d=90$, 20 s for 180 and 1 s for 270.

3.6 Microscopic observation of the damaged surface.

The surfaces of the aluminum specimen damaged by the water jet and by the cavitation were observed microscopically by using the scanning electron microscope (SEM) and were compared in Fig. 10. Photos (a) and (c) show the effects of the water jet for $P_0=30$ MPa at $x/d=630$. Photos (b) and (d) show the effects of the cavitation using a magnetostrictive vibratory method. Photo (a) shows that plastic deformations have already occurred on the metal surface at a short exposure time $t_0=1$ s (that is, during the incubation period), while Photo (c) for $t_0=60$ s gives an information that the size of water lumps was of the order of $100 \mu\text{m}$ in magnitude. As seen in Photo (b) for cavitation, plastic deformations of the order of $10 \mu\text{m}$ in magnitude are already observed at a short exposure time $t_0=10$ s in the incubation period. Photo (d) shows that the irregularity produced by the collapsing of cavitation bubbles is of the order of $10 \mu\text{m}$. Figure 11 shows the cross section of a damaged aluminum specimen at the second peak location and its expanded view. Figure 11(a) indicates that the damage was caused by the impingement of the lumps and droplets. Moreover, we observed cross cracks, as shown in Fig. 11(b), which are produced by the high static pressure.

4. Conclusions

The present results are summarized as follows.

(1) There exist two peaks on the mass loss curve representing the relation between the mass loss M caused by impinging of the water jet and the distance x/d from the nozzle to the test specimen. The location

Fig. 11 Cross-sectional view of damage

x/d for the second peak remains unchanged for different materials. This indicates that the generation of the second peak has a close relation to the structure of the water jet.

(2) The second peak of the mass loss appears at the axial location where the water jet breaks up.

(3) The mechanism of damage by the water jet varies with the distance from the nozzle to the specimen. The excavation force of the water jet plays an important role at the first peak, while the impact force due to impingement of lumps and droplets is important at the second peak.

(4) The comparative observation showed that the microscopic structure of solid surface damaged by the water jet is similar to the one by cavitation. Both the structures seem to be caused by impact fracture. Size of the surface irregularities depend on the size of

impinging lumps, droplets and collapsing bubbles.

References

- (1) Yokota, A. and Yamakado, N., On the Damage of Solids by a High-Velocity Water Jet and the Structure of the Jet, *Trans. Jpn. Soc. Mech. Eng.*, (in Japanese), Vol. 33, No. 249 (1967), p. 723.
- (2) Watson, A. J., Williams, F. T. and Brade, R. G., Impact Pressure Characteristics of a Water Jet, *Proc. 6th Int. Symp. Jet Cutting Technology*, Guildford, (1982), p. 93.
- (3) Yanaida, K. and Ohashi, A., Flow Characteristics of Water Jets in Air, *Proc. 5th Int. Symp. Jet Cutting Technology*, Hanover, (1980), p. 33.
- (4) Hobbs, J. M., Practical Aspects of Cavitation, *NEL Rep.*, No. 229 (1966).
- (5) Kobayashi, R., Cavitation (Erosion), *Turbomachinery* (in Japanese), Vol. 3, No. 4 (1975), p. 774.