Suitable Region of High-Speed Submerged Water Jets for Cutting and Peening*

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In order to establish useful techniques of cutting, drilling, peening and flushing by high-speed submerged water jets, we systematically observe the eroded surface on aluminum-alloy specimens in relation to the characteristics of cavitating jets, especially for the impinging jet through lucite specimens, for several types of nozzles. The impulsive pressures induced by the cavitating jets are also measured by means of pressure-sensitive film. It is concluded that the erosion characteristics are quite different in two typical standoff distances, i.e., the 1st and the 2nd peak. Cylindrical, small and deep pits predominantly occur at the 1st peak, while small lots of plastic deformations predominantly occur in the 2nd peak. Therefore, the 1st peak is suitable for cutting, while the 2nd peak is suitable for peening.

Key Words: Cavitation, Nozzle, Erosion, Jet, Impulsive Pressure, Peening

1. Introduction

Recently, high-speed submerged water jets have been successfully applied to cut marine structures and conduct sea-bottom drilling, in addition to surface-treatment uses such as cleaning, flushing and peening. In order to improve the capacity of such jets and the accuracy of working, however, it is absolutely necessary to establish precise techniques to control the stress range, i.e., the range of the impulsive pressures

on the working surface, with respect to the standoff distance. Of course, since the stress is directly related to the jet structures, we also must investigate the complex jet structures carefully.

In the literature, there are some reports on submerged-jet erosion tests⁽¹⁾, which are similar in technique to those for jets in air, on the most suitable nozzle geometry for marine-structure cutting^{(2),(3)}, on the effects of the horn downstream from the nozzle throat⁽⁴⁾, and on the effects of ambient pressure and air content through cavitation-noise measurements⁽⁵⁾. However, the jet structure and the marked effects of the controlling factors such as the nozzle geometry are not completely known for the submerged jets of present interest, and the impulsive pressure distributions have not yet been clarified with respect to the standoff distance. As expected, the cavitation nuclei^{(6),(7)} in the test water, one of the dominant factors of cavitation, may considerably affect the jet structures. In the previous papers^{(8),(9)} therefore, we carefully observed the cavitation aspects around the submerged water jet without any impinging specimen (called a "free jet"), by means of high-speed photography, and also clarified the time-dependent

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behavior of the inflow nuclei accompanying the jet flow and the ambient nuclei being within the test tank. In particular, we made the interesting observation that the secondary cavitation which arose within the upstream nozzle, i.e., the low-erosive streamer cavitation⁽¹⁰⁾, as expected supplied a considerably large amount of powerful nuclei into the downstream-main-cavitation and forced the cavitation to become severely erosive cavitation^{(11),(12)}, resulting in a marked increase in the cutting capacity of the jet.

In this paper, therefore, in order to clarify the mechanism of the impinging erosion, we systematically observe the jet structures and the eroded surfaces on aluminum-alloy specimens, for several types of test nozzles, in consideration of the cavitation-nuclei distribution, and in relation to the characteristics of cavitating jets. By comparing the impulsive-pressure-distributions⁽⁸⁾ for the free jets with the present erosion-mass-loss distribution, the following interesting facts are found. The eroded surface characteristics near the 1st peak are quite different from those of the 2nd peak. Clearly, at the 1st peak, a cylindrical, small and deep erosion trace appears in the core region. At the 2nd peak, however, numerous plastic deformations occur in the annular region around the jet boundary. Therefore, the 1st peak is suitable for cutting, while the 2nd peak is most suitable for peening.

2. Experimental Apparatus

Figure 1 shows the experimental setup described

Fig. 1 Experimental setup

elsewhere⁽⁸⁾. In order to keep the cavitation nuclei, a dominant factor of such a cavitation, as uniform as possible for the entire experimental range, the test water is sampled from a 180 m³-capacity underground reservoir ①, in which the water has been stored for a long time so as to be saturated by air naturally. Two straightening vanes ⑪ are set downstream from the test nozzle ⑨ to prevent reentry of bubbles occurring around the nozzle within the measuring tank of 1.84 m³ in volume. In fact, the nuclei distribution scarcely changes with respect to time, even when violent cavitation takes place downstream from the nozzle, as was previously shown⁽⁹⁾.

The tank, which is made of clear lucite to allow flow visualization, is first filled with the water by a centrifugal pump ⑥ through four support nozzles ⑩. The water is pressurized for the high-speed water jet by a plunger ② whose maximum injection pressure is 70 MPa, and is horizontally injected from the test nozzle ⑨ after passing a 3-way directional valve ③. The injection pressure P_1 is precisely measured by the pressure transducer ⑧ at the adapter ⑦ which holds the nozzle.

Figure 2 shows the configuration of three test nozzles. The conical nozzle, generally utilized for jet cutting, and the cylindrical nozzle are selected to investigate the effects of the throat-inlet shape, while the horn A nozzle is expected to activate the cavitation significantly so as to increase the turbulence of the injected water⁽²⁾. For all the nozzles, which are made of stainless steel SUS 304, the throat is 1 mm in diameter D and 4 mm in length l .

3. Experimental Procedure

We have followed similar procedures to those of the previous experiments, for jet visualizations, measurements for cavitation induced impulsive pressures

Fig. 2 Test nozzles

P_{sh} and for cavitation nuclei, as described elsewhere^{(8),(9)}. The pressures P_{sh} are measured by using pressure-sensitive film⁽⁸⁾. For the free jet, the film is fixed parallel to the jet, at a radial distance y of 5 mm from the jet axis, while it is perpendicularly fixed at $x/D=100$ for the impinging jet. The injection time t is fixed at 5 min for both cases at $P_1=30$ MPa.

The very high-speed characteristics of cavitation are carefully observed by using a xenon flash lamp whose exposure time is about 1 μ s. Figure 3 illustrates the flow-visualization system for the impinging-jet cavitation against a vertical solid specimen, in which the cavitation is observed through lucite instead of the specimen, by a kind of reflectance method.

The aluminum-alloy specimens A1050PH24, whose tensile strength ranges from 94 MPa to 127 MPa, are used for the erosion tests. Each specimen is 100 mm $\times$ 70 mm in surface area, 9 mm thin and about 165 g in initial mass. The high-speed water jet impinges against the specimen mounted perpendicular to the central axis of the jet. The erosion tests are carried out for various standoff distances x/D between the nozzle exit and the specimen surface. For comparison with the previous results⁽⁸⁾ for the free jet, the

Fig. 3 Flow visualization system

Fig. 4 Erosion curve (aluminum alloy)

impinging erosion tests are carried out at the injection pressure $P_1=30$ MPa and within the injection time $t=5$ min. After 5 min of the impinging test, the mass loss from the specimen is precisely measured with an accuracy of 0.1 mg.

4. Results and Discussion

4.1 Suitable regions for cutting and peening

Figure 4 illustrates typical erosion curves, i.e., the relationship between the standoff distance x/D and the mass loss Δm measured at $P_1=30$ MPa and within $t=5$ min, while Fig. 5 shows the P_{sh} distributions along the free jet measured by using the pressure-sensitive films⁽⁸⁾, for comparison. Notice here that the erosion curves are quite different from the P_{sh} -distribution curves, clearly showing a marked difference in erosion mechanism between the free and the impinging jet. For all erosion curves, Regions I, II and III are clearly seen: the mass loss Δm starts from zero and increases with x/D in Region I; it takes a maximum in Region II where it is very close to the 1st peak for the free jets; and it is very small in Region III at $x/D \geq 50$, where the 2nd peak is expected to be. Figure 5 shows two distinct peaks with respect to the distance x/D , as expected. We call them the 1st and the 2nd peak⁽⁸⁾.

In Fig. 4, it is surprising that all nozzles result in exceptionally high mass loss Δm at $x/D=15 \sim 20$ near the 1st peak. In the following, let us consider the reason why Δm , i.e., the impulsive pressures P_{sh} , significantly increase here. In order to show the essential features of the free jets, Fig. 6 illustrates eight typical high-speed photographs of the cavitation aspects around the free jet, which are randomly taken for the cylindrical nozzle at the injection pressure $P_1=30$ MPa.

Of course, for the submerged jet, the jet itself as well as the vorticity in the shear layer along the jet boundary, which is said to be the main cause of erosion, are more rapidly damped than for the jet in air. Clearly, near $x/D \approx 50$ where P_{sh} is locally

Fig. 5 Impulsive-pressure-distribution of free jet

minimum, since the cavitation clouds clearly break down in Fig. 6, the water-column structure with very high boundary vorticity drastically shifts the water-mass structure of low vorticity there.

As expected, from the bubble size or number of distribution, the size as well as the number of large powerful nuclei supplied into the low pressure region markedly change with the distance x/D depending on the kind of jet. The size rapidly increases with x/D . At $x/D \leq 50$, since there are a few small nuclei, P_{sh} values at 1st peak result from very high vorticity with a few small nuclei, while P_{sh} values near 2nd peak result from comparably weak vorticity with numerous large nuclei. Such a deduction can explain well the fact that the bubble clouds, which are as large as those near the 2nd peak, less frequently occur near the 1st peak than near the 2nd peak (see Fig. 6(h)), and also

Fig. 6 Cavitation bubble clouds around free jet ($P_1=30$ MPa, cylindrical nozzle)

explain the tendency of the P_{sh} distribution as shown in Fig. 5.

For such an impinging jet, as the cavitation characteristics on the impinging surface are shown in Fig. 9, the number of large recirculating bubbles from the impinging surface significantly increases, especially at a short distance x/D . And they are supplied into the above-mentioned high-vorticity, low-pressure region, resulting in severely erosive cavitation^{(10),(11)}, as the erosion traces clearly showed.

Surprisingly, Fig. 4 indicates that the mass loss Δm has a maximum near $x/D=15$ for all nozzles, while there is no peak at the 2nd peak as it was seen in Fig. 5 and Δm monotonously decreases with increasing x/D . It is therefore clear that the impinging jet is quite different from the free jet in erosion mechanism. For example, near the 2nd peak, where P_{sh} is lower than 130 MPa of the tensile strength of the test aluminum alloy, as expected, the mass loss resulting from P_{sh} higher than 130 MPa does not occur, but considerably remarkable plastic deformations resulting from P_{sh} lower than 130 MPa occur. Near the 1st peak in Region II, on the contrary, the impulsive pressures P_{sh} in the impinging jet must be two or three times higher than those in the free jet, because remarkable mass loss occurs results there. Such a fact suggests that such high pressures are found only in the impinging jet with water-column structure in Region II where the recirculating nuclei are powerful. In short, for the submerged impinging jet, the working characteristics or the impulsive pressures are quite different between the 1st and 2nd peaks points.

It is also remarkable from the viewpoint of nozzle injection characteristics that the order of nozzles in the plot of Δm near 1st peak is not equal to that in the plot of P_{sh} (see Figs. 4 and 5). For example, the Δm value is the highest for the cylindrical nozzle, in which the severely erosive cavitation is expected to occur considering the behaviors of the secondary cavitation arising within the nozzle⁽⁹⁾, and it is about twice as high as that of other nozzles. However, the P_{sh} value for the horn A nozzle is the highest. Namely, the fast demonstrates the difference in erosion mechanism between the 1st peak and the 2nd peak.

To show the radial aspects of P_{sh} for the impinging jet, Fig. 7 illustrates the radial distribution of P_{sh} and the corresponding pressure-sensitive film map for the horn A nozzle measured at $x/D=100$, $P_1=30$ MPa, $t=10$ s. As shown in the erosion pattern in Fig. 8, is relatively low not only in value but also in occurrence frequency in the central portion of $y/D \approx 0$. The fact that P_{sh} of the horn A nozzle is the highest corresponds well to the fact that the plastic is the most severe in Fig. 8(c). In short, the horn-part of the nozzle is said

Fig. 7(a) Radial impulsive pressure of impinging jet ($P_1=30$ MPa, horn A nozzle)

Fig. 7(b) Pressure-sensitive-film-map ($P_1=30$ MPa, horn A nozzle)

Fig. 8 Erosion pattern ($P_1=30$ MPa, aluminum-alloy, (a) conical nozzle, (b) cylindrical nozzle, (c) horn A nozzle)

to activate the erosive cavitation in the jet boundary, making this nozzle suitable for peening. Since the plot of $(P_{sh})_{max}$ in Fig. 4 is very similar to that in Fig. 7 for the horn A nozzle, the impulsive pressures are almost independent of the direction. Such a nature is said to be favorable for peening.

In short, according to the geometry, one nozzle is most suitable for cutting to produce very high impulsive pressures, while the other nozzle can be suitable for peening to produce comparatively low impulsive pressures.

4.2 Erosion characteristics

Figure 8 illustrates the erosion pattern for three types of nozzles in Regions I, II and III. In the nearest region to the nozzle, i.e., in Region I of $x/D=5$, where the water column continuously impinges on the specimen, as expected, a slightly eroded, discolored circular area ("core") about 2 mm in diameter is observed in the central portion on the specimen surface, and several plastic deformation rings develop concentrically around the core. The rings may result from high-speed impingement of the ringlike bubble clouds, which developed along the water column. The deformations are expectedly smaller and shallower than those in Region III, but the deformed area is much wider than that in Regions II and III, because the higher jet velocity results in a much higher radial velocity along the test surface. In Region II, a deep cylindrical erosion area appears. This area is assumed to result from direct impingements of large droplets which developed along the jet axis, resulting in the severe erosion. Around this area, we can observe a small amount of not only erosive pits accompanied with detectable mass loss but also annular plastic-deformation area as observed in Region III. With increasing x/D , this cylindrical area reaches a maximum size at $x/D=15\sim 20$, and then decreases gradually. In the intermediate region between Regions II and III, as expected, the cylindrical area and the deformation coexist.

In Region III, however, a large amount of plastic deformation without measurable mass loss is uniformly observed within a wide annular region like a doughnut, which might result from high impulsive pressures caused by the ringlike vortex cavitation.

Judging by the mass loss and the eroded surface characteristics, the directly impinging droplets play an important role on the cutting power of the jet, i.e., the mass-loss-rate. And Region II, where very high impulsive pressures concentrate within a very narrow circular region, is said to be suitable for cutting, while Region III where number of relative low impulsive pressures widely uniformly distribute and where the impulsive pressures widely distribute with respect to

x/D so as to control the working capacity easily, is said to be the most suitable for peening.

4.3 Flow behaviors of the impinging region

In general, the impinging flow may be divided into the following three regions⁽¹³⁾: (i) the free-jet region before impingement, (ii) the wall-jet region after impingement where the jet flows rapidly along the specimen surface, and (iii) the impinging-jet region, the transient region between the two. In the impinging-jet region, of course, a very large pressure gradient must be present along the surface and the jet axis, because the flow direction changes very rapidly. In order to clarify such transient behaviors in the impinging-jet region through a clear lucite specimen, we attempt to visualize the characteristics of the impinging jet. Figure 9 illustrates the characteristics for the three nozzles at a typical injection pressure $P_1=30$ MPa, for three typical standoff distances $x/D=5, 15$ and 100 , which correspond to Regions I, II and III, respectively. In particular, for the case of $x/D=100$ suitable for peening, we attempt to make stereo-observations simultaneously from the x - and the y -direction through the lucite specimen and the side-window.

For a very short impingement case without measurable mass loss at $x/D=5$, as expected, we can clearly observe a circular core about 2 mm in diameter on the jet axis, showing the typical continuous column impingement without measurable mass loss.

Clearly, the column very rapidly shifts into a very thin water layer and radially spreads out from the core. Downstream from the thin spreading layer, the vortex-ring cavitation occurs with frequent cycles growth and collapse, resulting in fairly high impulsive pressures and measurable plastic deformations on the specimen. Stationary starlike or polygonal bubble clouds stationary are observed with wide annular regions 15, 30 and 60 mm in diameter, characterizing the wall-jet region. At the outside of the clouds, fine vortex-ring cavitation bubbles randomly occur in a multiplex manner, as in Region III. On the line from the core to the apexes of the bubble clouds, we can often observe several fairly large spherical bubbles. Occurrence of such bubbles clearly shows us that the bubble clouds and/or the nuclei are sufficiently supplied into the low-pressure region within the vortex rings developing in the shear layer along the jet boundary in the free-jet region. Then, why does the thin spreading layer develop in a starlike manner? We conclude that when the length of the layer increases locally, the flow velocity around the layer tends to increase, and the corresponding pressure tends to decrease, so that the length of the layer increases further. Thus, the trail of the layer is very rapidly locally lengthened just like a jet. Such a local elongation continues until the above-mentioned pressure reduction balances the pressure rise due to impingements of the above-mentioned fairly large

Fig. 9 Characteristics of bubble clouds on the impinging surface ($P_1=30$ MPa, (a) conical nozzle, (b) cylindrical nozzle, (c) horn A nozzle)

spherical bubbles.

Even in Region II near the 1st peak of $x/D=15$, we can observe the circular core 3~4 mm in diameter and the starlike or the polygonal bubble clouds. In this region, however, since not the continuous water column but discrete massive water particles intermittently impinge against the specimen, the resulting erosion becomes more severe than that in Region I. Expectedly from the fact that much jet-energy is absorbed at the impinging portion, the core considerably deforms and the bubble clouds become smaller. Then, the erosive vortex cavitation much more powerfully develops and collapses even near the core, resulting in much erosion.

Finally, in Region III of $x/D=100$, number of bubble clouds resulted from the vortex cavitation stochastically impinge against the specimen, especially within an annular region 30~40 mm in diameter, resulting in marked deformation area on the aluminum specimen. In the wall-jet region, however, most of the huge number of fine bubbles within the bubble clouds disappear as the ambient pressure becomes higher, and the vortex-ring cavitation alone remains as shown in Fig. 9. With an increase in radial distance from the core, such a cavitation once rapidly grows and then collapses.

From the side view, we can observe the vortex cavitation developed helically along the jet boundary, implying the existence of very intermittent, very high vortex flows along the jet. In short, the impulsive pressures are said to be maximum at the standoff distance x/D where the vortex-ring cavitation develops the most violently. For example, for the conical nozzle, the bubble clouds as well as the vortex-ring cavitation are the weakest among those of the three test nozzles, so that the vorticity in the flow field is the lowest. This corresponds well to the fact that the cutting capacity of this nozzle is the lowest.

5. Conclusion

In order to establish useful techniques of cutting and peening by high-speed submerged water jets, we systematically investigated the jet structures and the eroded surfaces of aluminum-alloy specimens for several types of nozzles. The obtained results are summarized as follows:

(1) With respect to the standoff distance x/D , the impulsive-pressure characteristics can be divided into two regions. One is Region II, suitable for cutting, where very high concentrated impulsive pressures distribute. The other is Region III, suitable for peening, where comparatively low impulsive pressures widely and uniformly distribute.

(2) The cutting or peening capacity, i.e., the

impulsive pressures, strongly depends on the nozzle geometry. For example, the cylindrical nozzle results in maximum mass loss on the specimen, while the horn A nozzle results in maximum plastic deformations.

(3) The annular plastic-deformation region almost corresponds to the region where the largest vortex-ring cavitation bubbles collapse. The core and the thin spreading layer are closely related to the water jet structure, and depend on the standoff distance x/D .

(4) In Region III, the impulsive pressures are almost independent of the direction, especially for the horn A nozzle.

(5) The cavitation nuclei as well as the recirculating cavitation bubbles play an important role in making the cavitation very erosive.

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