Wear 386–387 (2017) 99–105

Contents lists available at ScienceDirect

Wear

journal homepage: www.elsevier.com/locate/wear

Time-resolved observations of pit formation and cloud behavior in cavitating jet

N. Fujisawa[a,*], T. Kikuchi[b], K. Fujisawa[a], T. Yamagata[a]

[a] Flow Visualization Research Center, Niigata University, Japan
[b] Graduate School of Science and Technology, Niigata University, Japan

ARTICLE INFO

Keywords:
Cavitation
Erosion
Pit
Shadowgraph
Cavitating jet
Time-resolved observation

ABSTRACT

Time-resolved observations of pit formation and cloud structure in a cavitating jet are carried out to understand the erosion mechanism of a cavitating jet issuing from a converging and diverging nozzle in a still water environment. Pit formation is detected by a sensor made of gold film (0.2 μm in thickness) glued to a transparent glass plate, and the number and size of the pits are evaluated from digital image analysis. High-speed camera shadowgraph imaging allows observation of the cloud structure in the cavitating jet, which captures the cavitation cloud collapse combined with the time-difference analysis. The radial distribution of pits is in close agreement with the erosion depth distribution evaluated from the weight-loss profiles of an aluminum specimen in a cavitating jet. The pit distribution in the cloud collapse is well reproduced in the time-difference analysis. Furthermore, simultaneous observations of the pit and cloud structures show that pits are formed on the wall at the instant of cloud collapses during the periodic behavior of the cavitating jet.

1. Introduction

A cavitating jet is a high-speed submerged water jet accompanying the bubble formation in the shear layer of the jet. This flow configuration has been a topic of interest for the fabrication, cutting, and peening of metal materials in industrial engineering. The cavitating jet research field explores the highly erosive nature of the cavitating jet. Although the erosive nature arises from the cavitation cloud collapse near the wall [1], the erosion mechanism of the cavitating jet is not clear due to the complexity of the cloud behavior in a very short period of time, which is difficult to access experimentally.

The erosion mechanism of a cavitating jet is closely related to the periodic formation of the cavitation cloud in the jet that is created by the flow instability of the sudden expansion of the downstream flow of the orifice section in the conversing and diverging nozzle [2–5]. The periodic growth of the cavitation cloud is due to the occurrence of a reentrant jet in the entrance region of the orifice section [6–8]. When a cavitation cloud develops along the shear layer, the reentrant jet is created against the flow through the orifice, which is followed by the pinching-off behavior of the cloud and periodic shedding from the orifice section [9,10]. Shedding of the cavitation cloud triggers the formation of a new cloud and growth of the cloud along the shear layer, which results in the periodic growth of the cloud downstream of the orifice section. The cavitation cloud can collapse in a relatively high-pressure region downstream of the nozzle, and this generates the impulsive forces on the wall to damage the target metal materials in the cavitating jet; however, this has not been confirmed yet. The cavitating jet issuing from the converging and diverging nozzle indicates a series of periodic behaviors further downstream that consist of growth, shrinking, separation, and shedding of the cavitation cloud [3,7,8,11,12]. As a result of cavitation cloud collapse near the wall, impulsive forces act on the wall, as measured by the piezoelectric sensors [13–17].

The erosion characteristics of the cavitating jet have been evaluated by measuring the weight-loss characteristics of the wall materials in the cavitating jet [18–21]. This method is not popular owing to the necessity of extremely long testing times required to assess the erosion rates of materials. The observation of pits in the incubation period of the wall material is one alternative method to evaluate the erosion rate of the wall materials in a very short period of time [14,22]. On the other hand, the observation of cavitation pits using a thin metal sensor provides a convenient method with the potential to evaluate erosion rates and study the mechanism of pit formation in literature [23–30]. Most research has carried out qualitative observations of the spatial distribution of cavitation erosion [23–27]. The most popular pit sensor used in literature is thin aluminum of thickness of the order of 10 μm, which is attached to the wall using adhesive tape.

In recent years, quantitative information regarding cavitation pits,

---

* Corresponding author.
E-mail address: fujisawa@eng.niigata-u.ac.jp (N. Fujisawa).

http://dx.doi.org/10.1016/j.wear.2017.06.006
Received 2 April 2017; Received in revised form 11 June 2017; Accepted 12 June 2017

such as the number and size of the pits, is obtained from digital image analysis, which allows the study of the physical mechanism of cavitation erosion over the hydrofoil. More recently, simultaneous observations of the number of pits and the cavitation structure have been performed, and the structure responsible for the cavitation erosion is examined for cavitation erosion in the hydrofoil. The result indicates that the irregular shape of the cavitation cloud in the hydrofoil is responsible for the cavitation-pit formation and the cavitation erosion over the hydrofoil [28]. The relationship between these has not been studied with the cavitating jet, which is the topic of interest in this study.

Understanding the relationship between pit formation and cloud structure in a cavitating jet is vital to understand the physics behind cavitating-jet erosion. Therefore, simultaneous observations of the cavitating-jet structure and the acceleration pulse on the wall are carried out using shadowgraph imaging and an acceleration pulse measurement with an acceleration sensor [31]. The experimental results indicate that the cloud collapse of the cavitating jet occurs at the instant of acceleration-pulse generation on the test specimen. Therefore, cavitating-jet erosion can be generated at the instant of the cloud collapse, which results in the impulsive forces on the wall by the micro-jet mechanism (Fig. 1). However, the observation of cloud collapse from the side of the cavitating jet could not reproduce the peak position of the erosion rate correctly obtained from the weight-loss measurement, which suggests further study is required for the mechanism of cavitating jet erosion.

The purpose of this paper is to study the erosion mechanism of a cavitating jet through a couple of experiments, such as the erosion loss measurement, pit and cloud collapse observations using a high-speed camera. The visualization of the pits are made by a thin gold film glued to a wall material to understand the pit formation process in the cavitating jet, while the cloud collapse is observed by the shadowgraph imaging combined with time-difference analysis. Furthermore, simultaneous observations of the pit and cloud structure are made for examining the relationship between pit formation and cloud collapse.

2. Experimental method and procedure

2.1. Experimental setup

The experiments were carried out in a water tank with a horizontal cross-sectional area of 400 mm × 400 mm and a height of 400 mm, which is illustrated in Fig. 2(a). The tank is made of an acrylic resin for flow visualization. The cavitating jet of water issuing from a converging and diverging nozzle spreads into a still water environment. The working fluid water is kept at 25 °C. The nozzle used in this experiment is shown in Fig. 2(b), which is designed with reference to the converging and diverging nozzle for generating the periodic behavior of the cavitating jet [5]. It consists of converging and diverging sections separated by an orifice plate 0.8 mm in diameter with 2.4 mm thickness.

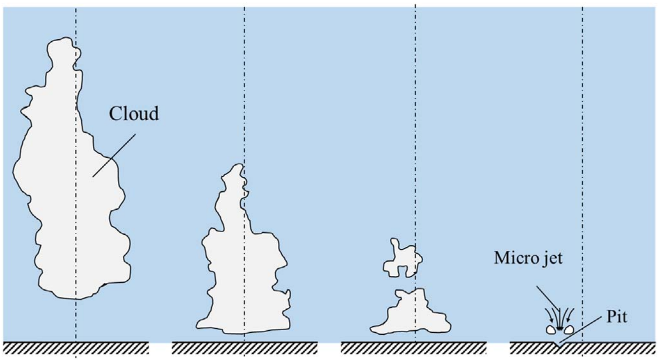

Fig. 1. Illustration of cloud collapse and pit formation.

The nozzle is located 150 mm deep from the water surface, so that the cavitation coefficient σ ($= 2(p - p_v)/\rho U^2$) in this experiment is $\sigma = 0.021$ (p: pressure, p_v: vapor pressure, U: velocity at nozzle exit, ρ: density of water). Note that the flow through the nozzle is driven by a plunger pump, where a filter is attached to eliminate dust in the working fluid. Most of these experiments were conducted at a pressure of 12 MPa. The mean velocity at the nozzle exit is set to 98 m/s, which is obtained from the discharge coefficient of the nozzle, i.e., 0.8, and the volume flow rate of water. It should be noted that the axial coordinate is taken by z, while the planar coordinates normal to the jet axis are denoted by x and y, respectively.

2.2. Characterization of cavitation erosion

The erosion characteristics of the cavitating jet were evaluated using a circular aluminum specimen (A1070) 40 mm in diameter with a thickness of 8 mm, which was placed normal to the jet axis for various standoff distances from the nozzle exit $y_s = 5$–40 mm. Note that the test surface was polished by buffing, which results in the RMS surface roughness 0.1 μm measured by roughness meter. The weight loss was measured at 5 min and later 10 min intervals with the aid of a high precision weight meter with an accuracy of 0.01 mg. The non-dimensional erosion rate V_m ($= dE_v/Qdt$) was evaluated with reference to the liquid droplet impingement test [32,33], where E_v is the erosion volume in a unit time t, and Q is the volume flow rate of the cavitating jet. The non-dimensional erosion rate V_m was obtained from the gradient of the erosion volume E_v versus the flow volume Qt of the cavitating jet.

The radial distribution of the erosion depth on the specimen surface was measured using a laser displacement sensor over the specimen surface, and the mean surface depth distribution was obtained from 8 measurements for every 15° assuming axisymmetry of the erosion depth profile. Note that the spatial resolution of the laser displacement sensor was 1 μm.

2.3. Observation of pit formation

Pit formation on the test surface was evaluated with a thin gold film of 0.2 μm thickness, which was glued to a glass plate with an adhesive of acrylic modified silicone resin, as shown in Fig. 3. The gold film sensor was fabricated from a pure gold by hammering as thin as 0.2 μm [34]. The observation was made through the glass plate using a high-speed camera (Fig. 1(a)). The gold film is thin enough to respond to the pit formation from the cloud collapse of the cavitating jet, while it is strong enough not to be torn out by the impulsive forces of the cavitation erosion. The selection of this sensor was due to the high sensitivity of the film to impact forces. It should be mentioned that the aluminum film of 10 μm thickness with an adhesive tape of 50 μm thickness has been tested as a typical sensor for pit observation in literature. However, this selection was not successful in this cavitating jet operating at 12 MPa, because the aluminum film was torn out by the impact of the cavitating jet. Furthermore, the aluminum film glued to the glass plate by instant adhesive did not respond to the impulsive forces in the cavitating jet. These results suggest that the thickness of the sensor and the adhesive are influential on the response to the impulsive forces. Therefore, the gold-film sensor used in this test was adhered to the glass plate to make the total thickness as small as possible, which was less than 10 μm in thickness.

The observation of pit formation was carried out using a high-speed CMOS camera (FASTCAM MINI AX2, 1024 × 1024 pixels with 8 bits) operating at 2000 frames/s with an exposure time of 8 μs and the pit images were captured by the camera for 5 s to perform a statistical analysis of the number of pits and size. The target area of the sensor was 22 mm × 22 mm, and the images were captured by a camera with a lens of 75 mm focal length. Therefore, the spatial resolution is 21 μm/pixel, which is fine enough to observe the pitting. The camera was located 150 mm from the sensor. The illumination was provided by a