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Formation and progression of cavitation erosion surface for long exposure

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ABSTRACT

Cavitation erosion often causes the leakage of water in piping systems of industrial plants. Cavitation erosion tests were carried out for S15C carbon steel equivalent to pipe steel STPG370 in a stationary specimen test method using a vibratory apparatus specified by ASTM G32-03. Another test was performed using a cavitating liquid jet method according to ASTM G134-95 to simulate the flow condition. It was found that the maximum depth of erosion (MaxDE) increases with exposure time with a power of about 0.5 which is different from the ordinary power of 1.0. The distribution of the maximum depth of erosion pits was obtained by the extreme value analysis (Gumbel distribution) at every exposure time.

1. Introduction

A few studies have reported about the long-term cavitation erosion for long exposure [1]. Thiruvengadam et al. [2] emphasised the change in the rate of cavitation damage with the exposure time separated into four zones. The incubation zone is defined loosely as the time during which little or no weight loss occurs. The accumulation zone is where the erosion rate increases gradually. The attenuation zone is where the increasing rate reaches a peak in the accumulation zone and then begins to decline. The steady-state zone is where the rate of loss reaches a constant value after the attenuation zone. They reported that the erosion rate–time curve does not depend on the material and becomes a similar curve if the erosion rate and time are normalized by the maximum erosion rate and time when it reaches the maximum erosion rate. On the other hand, Plesset and Devine [3] and Hobbs [4] reported that a wide peak period can be defined as a steady-state stage based on experiments. Moreover, Shalnev et al. [5] divided the whole period into two stages that is an incubation zone and a steady-state zone. Thus, the method to evaluate erosion is different depending on the researchers, and the time of the experiments which is limited to about 40 h. A change in erosion rate in the steady-state stage defined by Thiruvengadam et al. [2] has not been clarified yet.

On the other hand, erosion of pipes used in industrial plants recently became a serious problem. Cavitation erosion has been studied generally by a vibratory method based on the ASTM (American Society for Testing and Materials) G32 standard [6]. However, there are some problems in the studies based on ASTM standards. At first, cumulative erosion is defined as the average erosion obtained by the mass loss of a test specimen, although the maximum depth is important for the leakage from a pipe. Secondly, the ASTM standard suggests that the erosion resistance should be evaluated as the time to reach 100 μm of the mean depth of erosion. Therefore, as far as we know, there is no data of erosion in millimeter range. Thirdly, the maximum rate of the erosion depth is assumed to change linearly with exposure time. Okada and Iwai [7] studied the progression of cavitation erosion on carbon steel for long exposure, but the maximum depth of erosion (MaxDE) was up to about 200 μm. Therefore, it is necessary to clarify the change in depth for deeper erosion.

In this study, vibratory cavitation erosion tests were carried out for a long exposure including deep erosion that is not specified in the ASTM standard. The materials were S15C carbon steel equivalent to actual pipe steel STPG370 and soft commercially pure aluminum A1070BD-F. Moreover, erosion test was carried out using a cavitating liquid jet apparatus in order to verify whether the vibratory test results can be applied to an actual flowing system. The test results were evaluated in terms of the maximum depth of erosion and the surface profile of the cross section by the observation of the cut test specimen after the experiment. A prediction method is proposed for long-term cavitation erosion.

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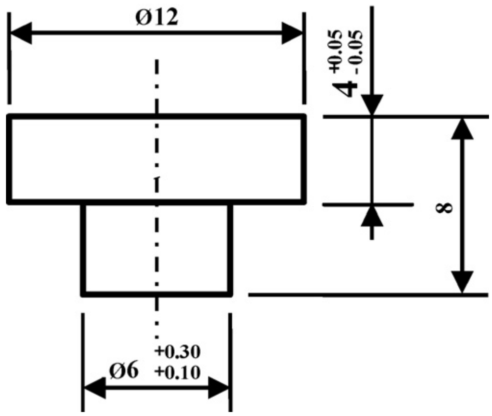

Fig. 1. Test specimen for cavitating liquid jet.

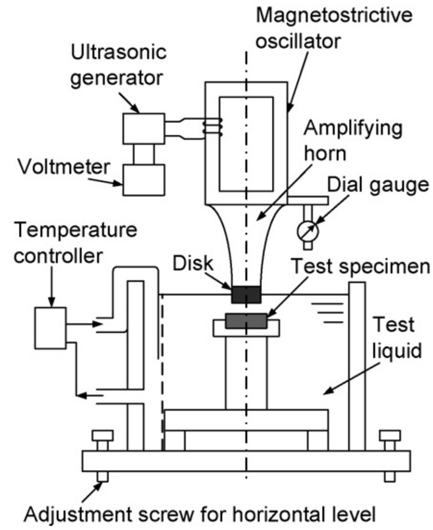

Fig. 2. Vibratory apparatus.

2. Materials and experimental procedure

2.1. Materials

S15C steel (0.15% carbon steel) was selected as a test material due to its chemical composition similar to that of carbon steel used in STPG370 (equivalent to ASTM A) pipes for pressure service. Commercially pure aluminum A1070BD-F (purity: Al ≧ 99.70%) was also used for the vibratory test of cavitation. Commercially pure aluminum A1070 was used for the cavitating liquid jet test. The chemical composition was similar to A1070BD-F. The chemical composition, the heat treatment and the mechanical properties are listed in Tables 1 and 2, respectively.

S15C was normalized by aircooling after being kept at 910 °C for 10 min. The materials were machined into specimen shape by a cutting machine. The size of test specimens of S15C and A1070BD-F was approximately 25 mm in diameter and 5 mm in thickness. A1070 was 12 mm in diameter and 4 mm in thickness as specified in the ASTM standard G134-95 [8] (Fig. 1). The test surface of specimens were buffing-finished by polishing with alumina powders (particle size of 0.3 μm) after being ground with grade 1200 emery paper. The Ra (arithmetical mean deviation of the surface) of the test surface was 0.15 μm for S15C test specimen, 0.30 μm for A1070BD-F and 0.37 μm for A1070, respectively.

2.2. Experimental procedure

Cavitation erosion tests were carried out by a stationary specimen method using a vibratory apparatus specified in ASTM G32-03 [6] and by a cavitating liquid jet method specified in ASTM G134-95 [8].

S15C and A1070BD-F were tested using the vibratory apparatus shown in Fig. 2. A disk of 16 mm in diameter made of erosion resistant SUS304 steel was screwed into the amplifying horn of the oscillator, and the test specimen was placed in close proximity to the vibrating disk. The distance between the disk and the specimen was 1 mm. The resonance frequency of the oscillator was 19.5 kHz, and the double (peak to peak) amplitude of the disk was 50 μm. After a vibrating disk was used for 10 h, every disk was replaced by a new one. Deionized water was used as test liquid, which was kept at 25 ± 1 °C with a temperature control device.

The test specimen was removed after predetermined time intervals, and weighed with a precision balance (sensitivity 0.01 mg) after being cleaned with acetone in an ultrasonic bath. The shape of the eroded surface was measured with a surface profile meter (Keyence Co. LT-8010, resolution of 0.1 μm and measurement interval of 2 μm). The maximum depth of erosion was measured by an observation of cross section of the tested specimen with an optical microscopy.

A1070 was tested using a cavitating liquid jet apparatus as shown in Fig. 3. The liquid was pressurized by a plunger pump. The cavitation number was kept at 0.025 (the upstream pressure was 17.4 MPa and the downstream pressure was 0.44 MPa), and the jet flow velocity was kept at 185 m/s [8]. The test specimen was placed at a stand-off distance (between the nozzle and the test surface of the specimen) of 15 mm [9], and the jet flow from the nozzle made of diamond of 0.4 mm in hole diameter impinged on the test specimen. The test liquid was tap water. The cavitation number σ shows the tendency for cavitation to occur in flowing streams of liquids, and is defined as follows.

$$\sigma = \frac{p_d - p_v}{p_u - p_d} \quad (1)$$

where: p_v = vapor pressure, p_d = downstream pressure, and p_u = upstream pressure.

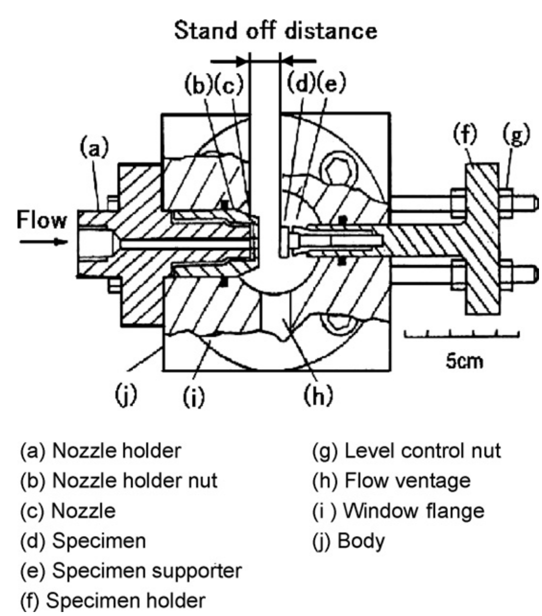

Fig. 3. Cavitating liquid jet apparatus.