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Scaling study of cavitation pitting from cavitating jets and ultrasonic horns

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ABSTRACT

Cavitation erosion prediction and characterization of cavitation field strength are of interest to industries suffering from cavitation erosion detrimental effects. One means to evaluate cavitation fields and materials is to examine pitting rates during the incubation period, where the test sample undergoes localized permanent deformations shaped as individual pits. In this study, samples from three metallic materials, an Aluminum alloy (Al 7075), a Nickel Aluminum Bronze (NAB) and a Duplex Stainless Steel (SS A2205) were subjected to a vast range of cavitation intensities generated by cavitating jets at different driving pressures and by an ultrasonic horn. The resulting pitted sample surfaces were examined and characterized with a non-contact 3D optical scanner and the resulting damage computer-analyzed. A statistical analysis of the pit population and its characteristics was then carried out. It was found that the various cavitation field strengths can be correlated to the measured pit distributions and that two characteristic quantities: a characteristic number of pits per unit surface area and unit time, and a characteristic pit diameter or a characteristic pit depth can be attributed to a given "cavitation intensity level". This characterization concept can be used in the future to study the cavitation intensity of the full scale and to develop methods of full scale predictions based on model scale erosion data.

1. Introduction

Evaluation of a new material's resistance to cavitation erosion often relies on comparative laboratory studies involving accelerated erosion tests. This is the case because scaled erosion tests are either not possible, too slow, or because cavitation erosion scaling is still not fully understood scientifically. Accelerated erosion tests to evaluate a material or select one material among several, by definition, involves subjecting material samples to a cavitation field that produces measurable erosion over a short period of time. This, almost by definition, involves a different type of cavitation erosion than what is present in the actual cavitation field the tested material is destined to be subjected to. Casually, the laboratory determined ranking of the materials in the accelerated erosion tests is practically assumed to hold in the real application field. However, evidence exists that this may not always be the case, since some materials at least react differently to cavitation fields of different strength [1–4].

Fundamentally, the mechanical process of cavitation erosion results from successive individual and collective cavity collapses, which generate local high amplitude, short duration loads. The overall picture is that bubble nuclei in the liquid grow explosively in low pressure regions forming cavitation bubble clouds [5–9]. These subsequently collapse generating very high local pressures and temperatures [10,11]. In addition, when the bubbles collapse very close or at the material surface, micro reentrant jets from bubble large deformations vector towards the material and impact its surface [12–15]. When the pressure loads exceed the elastic limit of the material, the material undergoes permanent deformations leaving microscopic pits [16]. This initial incubation period of the material response to the erosion cavitation flow field does not involve any mass loss. With repeated impacts, hardening of the material surface layer develops, the deformation of the material accumulates, and finally micro-failures occur resulting in material removal and thus weight loss.

One method to investigate a portion of the above dynamics is to conduct pitting tests, i.e. short duration tests during the incubation period, where isolated (not overlapping) pits can be

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Nomenclature

N	number of pits (#/mm^2/s)
N^*	characteristic number of pits (#/mm^2/s)
τ	characteristic time parameter (s)
D	pit diameter (μm)
D^*	characteristic pit diameter (μm)
V	pit volume (μm^3)

identified and characterized [1]. By doing so, the material is used as a recorder of the *highest pressures* in the cavitating field, since each material acts as a high pass filter and records as pits only the cavitating field pressure peaks at the material surface that exceed its yield stress and plastically deform permanently. Observation of pits for the purpose of evaluating the cavitation field intensity dates back to the early 1900s when Parsons and Cook [17] observed the depth and dimensions of the pitted areas, and researchers reported the pitting location relative to the cavitation cloud shape and statistics such as the number and the depth of pitting [18–20]. Knapp [19–21] introduced the idea that the pits could be used to understand the intensity of the cavitation field. Similar ideas of observing pits to represent the cavitation field was used in hydraulic turbine cavitation erosion studies [22], where it was found that the cavitation aggressiveness in the full scale is more severe than that of the model scale. Recent studies using pitting tests includes the use of thin copper foil in order to capture relative small magnitude impacts [23], analysis of pitting to determine the impact loads for a modeling effort for ductile metals [24], evaluation of flow aggressiveness in the study of hydraulic turbine flows [25], and applications to the erosion studies of marine propellers [26,27]. With the advance of modern imaging and micro-measurement technologies, recent studies reveal more details of the pit shapes and statistics [28,29]. However, these studies did not provide a unified description of the cavitation field based on the pitting tests.

In this paper, we model the pit statistics as an attempt to identify parameters that characterize the aggressiveness of a cavitation field. Three different materials, an Aluminum alloy, a Nickel Aluminum Bronze, and a Duplex Stainless Steel were subjected to vastly different intensities of cavitation field generated by acoustic horn [30] and by DynaJets® cavitating jets [4,31,32] at different driving pressures. These were provided by the Naval Surface Warfare Center, Carderock Division. The pit population and sizes resulting from the tests in these different cavitation fields were analyzed and statistically processed. Based on this analysis, we propose a model that describes the pitting statistics with a small number of parameters, which in the future can be used to define the cavitation field intensity level. The above three materials are the same three materials used in Franc et al. [33], and results in this paper can be used as a comparative study with [33] of various cavitation erosion generation methods. The study described in this paper is an effort to deduce a relationship between the cavitation field intensity and the pitting statistics. This is a part of an on-going rather large effort, in which we are investigating experimentally and modeling numerically the erosion process in order to relate the material erosion to the cavitation field intensity in a predictive manner.

2. Experimental setup and procedure

In order to study cavitation erosion in a controlled environment and in an accelerated manner, several laboratory techniques to generate cavitation have been used in the past. These techniques include the utilization of ultrasonic vibration to generate the cavitation, cavitation flow loops with strong separating flows, rotating disks, venturi cavitating flows, vortex generators, and submerged cavitating jets. Some of these techniques were standardized and resulted in American Society for Testing and Materials (ASTM) Standards [30] such as G-32 "*Test Method for Cavitation Erosion Using Vibratory Apparatus*" and G-134 "*Test Method for Erosion of Solid Materials by a Cavitating Liquid Jet*". In this study, the ultrasonic test method following G32 and cavitating jet tests were conducted at Dynaflow to investigate the incubation period. The time evolution of the weight loss of the three considered materials was documented in [32].

2.1. Ultrasonic cavitation erosion testing

We followed in our test the prescribed ultrasonic cavitation tests ASTM G-32 method [30]. The cavitation is generated by a vibratory device employing a magnetostrictive ultrasonic horn. The acoustic horn was operated at 20 kHz with a peak-to-peak amplitude of 50 μm. The amplitude was set using a bifilar microscope and maintained at that value throughout testing. The samples were held in place with fixed sample holders inside a 2000 ml beaker filled with distilled water and with the horn tip submerged 12 mm beneath the free surface. The beakers were immersed in a water bath maintained at 25 ± 2 °C. In the "*alternative*" G-32 test configuration (also known as a *stationary specimen method*), the horn tip is placed at a small distance from the stationary material sample, here at 0.5 mm below the tip of the horn, and the cavitation cloud was generated in between the two. We used 25.4 mm × 25.4 mm square samples of the material to be tested.

The temperature, liquid beaker volume, horn tip submergence beneath the free surface, frequency, and amplitude of the oscillations are all prescribed by the ASTM G-32 method. In the direct G32 method the cavitation cloud collapses in a hemispherical way toward the material, while in the modified method, the cavitation bubble cloud collapses in a cylindrical way. It is well known from previous studies [34] that the cloud cavitation collapsing cylindrically is much less erosive than the hemispherically collapsing cavitation clouds, thus the alternative methods produce less erosive results than the direct method.

Usually, for mass loss tests, the procedure is to expose the sample to cavitation for a given period of time, stop the test, remove the sample, and record weight to enable measurement of weight loss as a function of time. The sample is then returned for additional testing. In the pitting tests, only one interval of above mass loss test was conducted. The samples were polished up to a mirror like surface so that the surface scan conducted later will have less noise from the existing roughness of the surface. The facility at Naval Research Laboratory (NRL) was used to polish the samples. The specimens were prepared using SiC metallographic papers, starting with 240 grit and increasing fineness of 400, 600, 1200 and 1500, followed by diamond slurry polishes of decreasing grit diameter of 10, 3, 1 and.01 μm. The final step in polishing was performed on a vibratory polisher for a period of 12 h. The polished samples were kept individually in a container, and the surface was not touched by any other objects until the beginning of the test. As soon as the test is completed, the sample was dried completely by air blower and then stored individually in a container. The tested surface was not touched until it was examined by the optical scanner.