

Material and velocity effects on cavitation erosion pitting

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ABSTRACT

Cavitation erosion during the incubation period was investigated via pitting tests conducted on three different materials: an Aluminum alloy, a Nickel Aluminum Bronze alloy and a Duplex Stainless Steel. Pitting tests were conducted in a cavitation tunnel in the velocity range 45–90 m/s at a constant cavitation number. The test section was made of a straight nozzle 16 mm in diameter discharged into the radial 2.5 mm space between two flat walls. Cavitation appears in the form of a toroidal cavity attached to the nozzle exit and damage on the samples facing the nozzle is concentrated in a circular ring centered in the cavity closure region. The exposure time was adjusted to avoid pit overlapping. The material surface was examined using a conventional contact profilometer which allowed us to identify the pits, count them, and measure their main characteristics such as depth, surface area, and volume. From these the pitting rate, the coverage rate, and the depth of deformation rate were defined. Pits were classified according to their diameter. For all materials and operating conditions, pitting rate appears to follow an exponential law in relation to the pit diameter. This law depends upon two parameters only, which were identified as the coverage time τ (i.e. the time required for the surface to be covered by erosion pits) and a characteristic pit diameter δ , which corresponds to the pits whose contribution to the coverage process is the highest. Scaling laws for pitting were derived accounting for both material properties and flow velocity, and a procedure to make pitting test results non-dimensional is proposed. The influence of the material on pitting test results was analyzed. It is shown that the damage is not correlated in simple terms with the elastic limit determined from conventional tensile tests and it is conjectured that other parameters such as the strain rate might play a significant role and should be included in the analysis. The effect of flow velocity on both parameters τ and δ was analyzed and a classical power law was found for the influence of the flow velocity on pitting rate for all three materials. Finally, some analysis and discussion is given concerning distributions of pit volume and pit depth.

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1. Introduction

This paper is devoted to the incubation period of the cavitation erosion process which precedes material removal and mass loss. During incubation, damage is characterized by small isolated plastic indentations on the material surface. Each pit is expected to be produced by a cavitation bubble collapsing close to the wall. It is well-known since Lord Rayleigh's work in 1917 that a vapor bubble can actually generate very high loads capable of damaging solid walls when collapsing [1].

Pitting tests have been recognized very early as a helpful technique to estimate the "Cavitation Intensity" as introduced first by Knapp in the 1950s [2,3]. The idea behind pitting tests is to use the material itself as a kind of sensor which will reveal the impact

loads due to bubble collapses, at least the most intense ones. Pitting tests are an alternative to the use of conventional pressure sensors which may be damaged by cavitation and which do not necessarily meet the required conditions for an accurate measurement of the impact loads in terms of rise time and resonant frequency in particular.

Although pitting tests appear as an attractive option to quantify the impact loads, no validated procedure is available yet. Estimating loads from pitting tests requires accurately understanding the material response to the impact load and, by an inverse technique, infer the characteristics of the loads from the measured geometric characteristics of the pits. The high strain rates involved with a pit formation together with the most likely triaxial loading makes this inverse procedure quite difficult. In addition, the material response at the microscopic scale of the collapsing bubble may be affected by multiple parameters such as microstructure, grain size, modes of plastic deformation, etc. The use of pitting tests for the quantification of cavitation intensity is still the subject of investigations and the present work is a contribution to this general objective.

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Nomenclature

D	pit equivalent diameter based on pit flat surface area
D^*	non-dimensional pit equivalent diameter (Eq. (11))
D_{max}	maximum equivalent pit diameter (see Table 3)
e	engineering strain
E	modulus of elasticity
h	pit depth
K_Y	parameter of the Ramberg–Osgood constitutive equation
m_Y	parameter of the Ramberg–Osgood constitutive equation
N	pitting rate per unit exposure time and unit surface area
N^*	non-dimensional pitting rate (Eq. (10))
n	probability density function (Eq. (5))
β	coverage rate
β^*	non-dimensional coverage rate (Eq. (14))
γ	depth of deformation rate
δ	characteristic pit equivalent diameter (Eq. (4))
ε	true strain
$\dot{\varepsilon}$	strain rate
ε_e	elastic deformation
ε_p	plastic deformation
ε_U	ultimate strain
σ	true stress or cavitation number
σ_U	ultimate tensile strength
σ_Y	elastic limit
τ	coverage time
ν	pit volume

The incubation period and associated pitting has been studied by many investigators using various experimental devices. Cavitation tunnels [4,5] produce cavitation erosion in a flowing liquid whereas vibratory systems [6–12] generate cavitation erosion in an almost stagnant liquid. Other devices have been developed for special purposes such as vortex cavitation generators [13,14], the Hopkinson bar type impact device [15], the magnetic impact testing machine [16], the rotating disk cavitation apparatus [17,18] or submerged cavitating jet devices [19–22]. Some of these techniques were standardized and resulted in American Society for Testing and Materials (ASTM) Standards 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”. Most of these techniques produce a large spectrum of bubbles of various sizes, at various distances from the eroded sample with possible collective effects which may affect the erosive potential of each individual bubble due to its interaction with the neighboring ones.

Detailed experimental studies have also been made on a single bubble collapsing in a static fluid in order to analyze the basic mechanisms of cavitation damage such as the formation of a high-speed liquid jet and the emission of shock waves. The resulting damage can be much more complex than a unique circular pit because of the formation of the re-entrant jet and a torus like structure which may break up into smaller bubbles whose collapse may cause additional pits of smaller size [23,24].

In the present work, pitting is generated in a cavitation loop. The loop is operated at high enough velocity and pressure in order to be able to investigate cavitation erosion on resistant materials within reasonable exposure times. Because of the large number of bubbles produced simultaneously, the investigation is based on a statistical analysis of erosion pits. Pitting tests have been made on three different materials in order to investigate the influence of the material on pitting results. The influence of the flow velocity

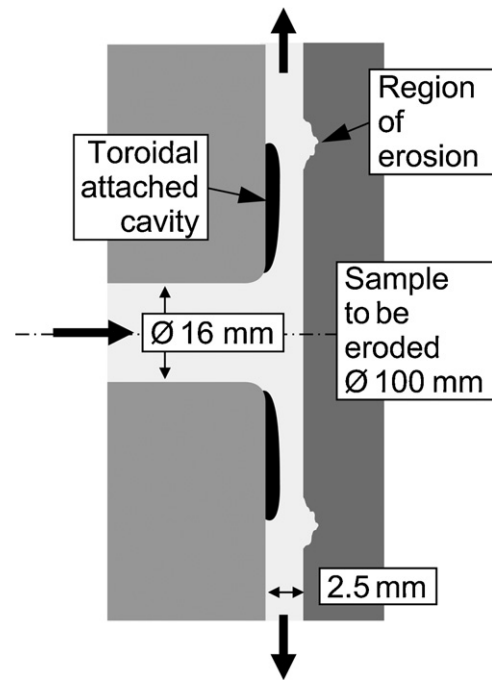


Fig. 1. Sketch of the test section.

is also investigated at constant cavitation number, i.e. for the same cavitation extent in the loop.

This work is part of an ongoing effort between the laboratories of the authors and two US Navy laboratories (NSWCCD and NRL) to derive a procedure for estimating impact loads from pitting tests. The cavitation intensity, which can roughly be defined as the spectrum of impact loads, should obviously be independent of the material used for pitting tests, even though the use of soft materials probably makes it possible to extend the spectra towards loads of small amplitude. The analysis of pitting tests on different materials carried out in this paper is an important step in the development of a technique to assess the cavitation intensity from pitting tests.

2. Experimental facility and procedures

2.1. Test section

Experiments were conducted in a cavitation flow loop described in details in Ref. [25]. The test section, also described in [25], is axisymmetric and made of a straight nozzle 16 mm diameter which generates a high velocity flow. As illustrated in Fig. 1, the flow is deflected by the sample to be eroded which is set at a distance of 2.5 mm from the nozzle exit, and propagates in between two parallel circular plates formed by the plane of the sample and that of the nozzle exit orifice. Cavitation takes the form of a toroidal cavity attached to the nozzle orifice. Cavitation erosion is observed in the closure region of the cavity in the form of a circular ring whose mean diameter is of the order of 50 mm. The radius where maximum damage occurs can easily be determined from mass loss tests and the detection of the radius where the erosion depth is maximum. The flow remains confined in opposition to a cavitating submerged jet.

The maximum operating pressure of the tunnel is 40 bars, which corresponds to a maximum velocity of 90 m/s. Pitting tests were conducted at different velocities between 45 m/s (upstream pressure of 10 bar) and the maximum velocity of 90 m/s. For all tests, the ambient pressure was adjusted such that when the flow velocity was changed the cavitation number remained constant. This

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