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Experimental Device for the Study of Erosion by Ultrasonic Cavitation

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Abstract: A device is implemented to reproduce the cavitation erosion process applying some guidelines of ASTM G32. The objective is to study the physics behind such complex phenomenon and to develop methodologies that help understand the dynamic processes of cavitation erosion in both hard and soft materials. We study the onset of cavitation at various experimental conditions that include liquid height, and % intensity.

Keywords: Acoustic cavitation; cavitation fields; ultrasonic reactor; erosion rate.

1. Introduction

The purpose of most cavitation-erosion laboratory tests is to predict the performance of bulk and protective materials under cavitation attack, either by continuous or pulsed cavitation fields. These tests are ran in a full-scale to improve the materials design, develop preventive and corrective maintenance procedures, and to evaluate to risk of the use of certain materials in advanced hydrodynamic machinery, structures and high-speed ships. Many efforts have been applied to raise the quality and practical significance of cavitation resistance assessments. The hydrodynamic tunnel, rotating disk, and vibratory device are the principal laboratory techniques used for erosion measurements. Generally speaking, the cavitation erosion resistance of materials is assessed by applying a cavitation intensity much higher than received in field [1-2]. The intensity of cavitation is controlled by modifying the flow system geometry and/or changing hydraulic circuit operating parameters, including flow obstacles as cavitators. In vibration rigs, cavitation clouds are generated by a high frequency horn immersed in the liquid, the pulsations being generated by a magnetostrictive or piezoelectric transducer, and excitation frequencies usually lie in the range of 20 to 60 kHz [3-4].

The above factors indicate that further progress, in this area, it is necessary involve four aspects: a) improving repeatability of test results (by upgrading existing standards or developing new ones); b) correlating cavitation load with erosion rate; c) reducing test durations; and d) economics and reliability of the evaluation test. Considering the excessive cost to materials evaluation in the traditional cavitation erosion facilities, we focus here only emulate in some aspects of the erosion of solid surfaces using ultrasonic excitation inspired in the ASTM G 32 test method (standard test method for eroding solid materials by cavitating liquid jet, 1998), with the purpose of studying the physics behind this phenomenon.

2. Experimental setup, materials and methods

Experimental setup. An ultrasonic processor with cylindrical sonotrode (136 mm long and 13 mm diameter) having a solid tip is used. The power amplitude is controlled in % from 10 to 100, with a maximum electrical power of 500 W at 20 kHz. The sample holder is made of a ½” thick acrylic circular-plate with a diameter of 120 mm. The samples are attached onto the upper face of the sample-holder and the latter is rotatee with the aid of a stepper motor (0-200 rpm), the driving torque being controlled by an Arduino platform and a personal computer. The square liquid-container dimensions are 45x45x22 cm^3 with open top and filled with

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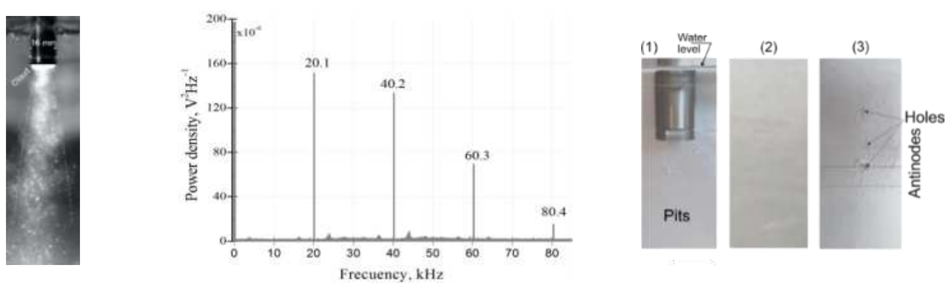
non-degassed water at room temperature. Piezoelectric sensors are placed on faces of the sample holder and, near the region of the liquid affected by the ultrasonic field. A digital camera (Fujifilm), a high speed Phantom camera (710 V1), 150 W halogen lamps, and a 1GHz LeCroy digital oscilloscope are also part of the setup. The device sketch and its photography are shown in Figure 1.
Materials. 6 µm and 50 µm aluminum foils, and a thick strontium ferrite ceramic Y35 corrosion resistant, were used to study the dynamics and the type of interaction with fluidic structures.
The experimental methodology consists of: a) the determination of the erosive cavitation intensity as a function of the distance between ultrasonic-processor tip and the sample (in static conditions). The damage is expected to occur in the vicinity of the pressure antinodes; b) tests with sample fixed at different distances *h* from the tip, increasing the ultrasonic irradiation power; c) tests with sample under rotation.
Antinodes characterization. The antinodes are formed within the volume of the liquid that is irradiated. In order to determine its vertical location with respect to the sonotrode tip, a thin aluminum foil is placed on one side of sonotrode, and turned on at 30 %, and its signal is acquired with a PVDF film sensor. The data is processed to obtain the power density spectrum of the cavitation field, see Figure 2.

(a) (b)

Figure 1. a) Sketch of the experimental setup showing the liquid container, instrumentation and equipment; and b) Photograph of the emerging platform of ultrasonic cavitation system.



(a) (b) (c)

Figure 2. a) Acoustic field generated by the transducer at 100% power and immersed 23 mm in water. A cloud attached to the sonotrode tip and an inhomogeneous axisymmetric field can be observed; b) Power density vs. frequency at 70%, showing fundamental, harmonic and subharmonic peaks; c) Images of the aluminum foils before and after exposure to ultrasonic cavitation, showing antinodes and pits on its surface.

3. Results

To test the device, two experimental runs are performed: i) under static conditions where the distance *h* between the sample and horn tip is fixed, and the acoustic intensity is increased, and ii) tests in which the sample develops a boundary layer (laminar) on its surface by rotation, ω, before passing beneath the sonotrode tip; controlled by Arduino device. In this case, the sample develops a boundary layer (laminar) before passing below of sonotrode tip.

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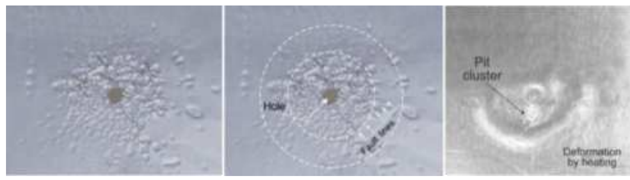
3.1. Static conditions

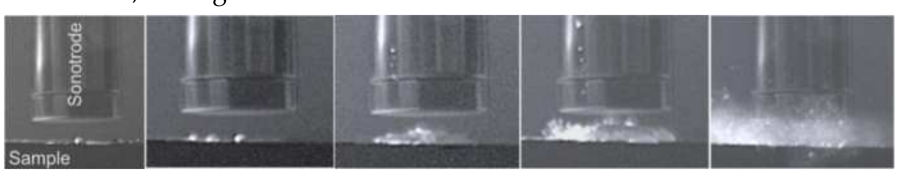
A. ***Ultrasonic irradiation on soft metallic samples***. A 6 μm thick aluminum foil is fixed with silicone paste on a sample holder at 3 mm below the sonotrode tip. Ultrasonic irradiation is applied for 10 s at 50% power. Damage is immediately detected as shown in Figure 3a. Figure 3b shows three typical erosion characteristics: pitting that increases in size as it approaches the principal attack center, loss material at the attack center, and parallel fault lines. When the sample thickness is increased by one order of magnitude (to 50 μm) and under the same experimental conditions, the sample does not show visible damage. However, increasing the irradiation for 60 s at 70% power, the damage looks as shown in image 3c, where a cluster of pits and large protrusions (plastic deformation) are generated, the latter being due to the heat evolved during the interaction.



(a) (b) (c)

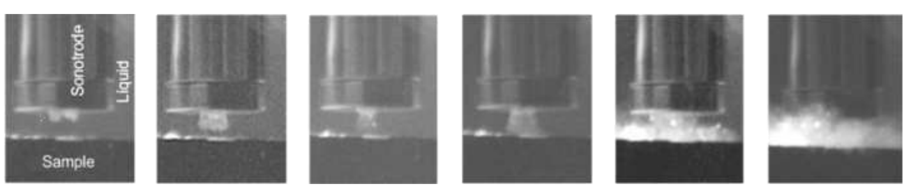
Figure 3. Cavitation erosion on aluminum. Image (a) and (b) are, respectively, original and digitally-processed images of the 6 μm aluminum foil eroded during 10 s at 50 %; (c) 50 μm aluminum foil irradiated by 60 s.

B. ***Ultrasonic irradiation on a hard sample***. The 48 x 22 x 9.5 mm anisotropic ceramic is set at different *h* and processed at different % power. At *h* = 3 mm, the material surface does not show any damage. A 100% power test is only able to clean its surface. The ultrasonic cavitation process occurs according to the following steps: i) formation of a single pulsating gas bubble, emerging from the sample surface, which expands and collapses twice around 300 μs, having a maximum diameter of ϕ = 1.47 mm, see Figure 4a; ii) more bubbles emerge and align themselves circumferentially with a hydrophilic wetting pattern (contact > 90°) without contacting each other and having almost the same size, see Figure 4b; iii) coalescence occurs forming a large drop-shaped surface, see 4c; iv) tiny air-vapor bubbles are ejected (splashing) ; v) the phases form an emulsion or foam, see Figure 4e.



(a) 485 (b) 516 (c) 916 (d) 1381 (e) 2913 fps

Figure 4. Ultrasonic cavitation process generated on a simple hard surface. Ultrasonic irradiation at 100% on unpolished ceramic Y 35 for 285 ms. Fast video is acquired at 49000 fps with resolution of 512x384.



(a) (b) (c) (d) (e) (f)

Figure 5 (a-f). Cavitation on a clean surface. Formation of a vaporous layer on both surfaces, on the upper surface the vaporous flow is centered, with ϕ = 4 mm and on the lower surface it is expanded reaching 30 mm in diameter. File: Test 9-100%, 34000 fps, 640x480 resolution.

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After several experimental runs, where both *h* (mm) and % are varied, we observe (using high speed video) different initial regimes. Such regimes depend on the irradiation history that the sample has undergone. Thus, at the start of the experiment, the ultrasonic irradiation on the sample produces a gas cloud that is sucked from its surface, as in Figure 4, but after a certain period of rest, applying irradiation again, the cavitation begins this time at the sonotrode-tip surface. By increasing the power to 100%, the cavitation starts on both surfaces, there are pulls and sucks, and tiny vapor bubbles appear. An emulsion is again formed but it is more concentrated and expands concentrically, see Figure 5.

3.2. Dynamic conditions. For this set of experiments, a fluid circulates between two neighboring walls at relative low speed (< 100 Hz), i.e. there is a boundary layer on sample surface. Many tests are carried out at different angular velocities, ω, and fixed *h*, these are recorded in high speed video. The irradiation is confined between two surfaces generating a pulsation bubble cluster that ejects fluidic structures at a speed of 2m/s, see image sequence in Figure 6. The cloud at the tip has a uniform thickness of 1.64 ±0.12 mm, rate 10 000 fps, exposure 20 μs, . The mechanism of this process will be explained in a future work.

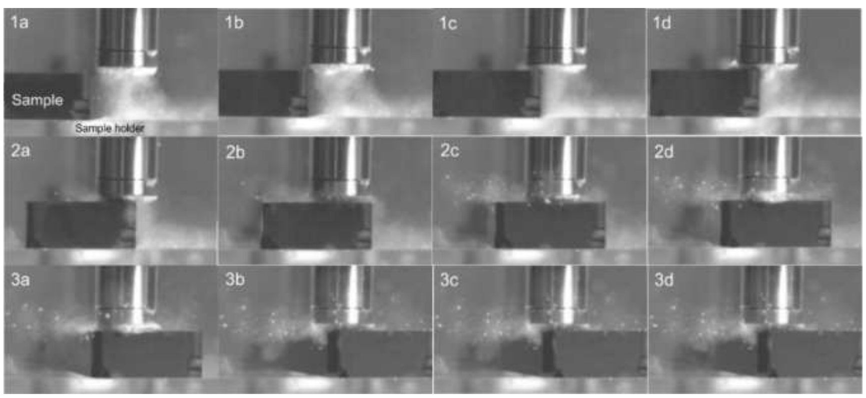

Figure 6. The sample rotates at 48 Hz, the intensity is set at 100%, h = 1.16 ± 0.14 mm, the tip is submerged 23.5 mm. (1a) - (1d) Pulsating cavitation cloud begins its sweep over the sample surface; (2a) - (2d), expansion and compression of the confined cloud; and (3a) - (3d) ejection of fluidic structures at a speed of 2ms^{-1} at the exit of the sample surface. Resolution 256x256.

4. Conclusions

In this paper, an experimental platform of ultrasonic cavitation erosion was implemented and instrumented to carry out studies under both static and dynamic conditions, varying experimental parameters such as liquid height, and % power. The differences are contrasting on both hard and soft surfaces.

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