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Scaling of cavitation erosion progression with cavitation intensity and cavitation source

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ABSTRACT

A simple mathematical expression is presented to describe cavitation mean depth of erosion versus time for cavitating jets and ultrasonic cavitation. Following normalization with a characteristic time, t^*, which occurs at 75% of the time of maximum rate of erosion, and a corresponding material characteristic mean erosion depth, h^*, the normalized erosion depth is related to the normalized time by $\bar{h} = 1 - e^{-\bar{t}^2} + e^{-1}\bar{t}^{1.2}$. This was obtained by conducting systematic erosion progression tests on several materials and varying erosion field intensities. Both a modified ASTM-G32 method and DYNAFLOW's cavitating jets techniques were used and the jet pressures were varied between 1000 and 7000 psi. The characteristic parameters were obtained for the different configurations and the correlation was found to be very good, exceeding an R^2 of 0.988 for all cases. Relationships between these parameters and the jet pressure were obtained and resemble familiar trends presented in the literature for mass loss. The study allowed a comparative evaluation and ranking of the various materials with the two accelerated erosion testing methods used. While several materials ranked the same way with the different erosion intensities and testing method, the relative ranking of erosion resistance of some materials was seen to be dependent on the cavitation intensity.

1. Introduction

Prediction of cavitation erosion performance of a new material is a very difficult endeavor as it involves good knowledge of both the material and the cavitation environment to which it will be subjected. This prediction is, however, commonly expected or required as one designs a new turbo machinery blade or propeller or addresses whether a new claimed 'advanced' material will provide the promised performance. To do so, the industries have to rely on laboratory testing, using accelerated erosion testing methods and comparative tests between the new material and previously used materials. This raises questions, such as: (a) How to transpose the accelerated test results to the operation at full scale of the new design? (b) How accurate is it to accept that ranking and quantitative erosion rate ratios remain the same between the accelerated method erosion tests and the full scale erosion, especially that previous studies indicate that the erosion resistance of materials sometimes depends on the intensity of the cavitation field [1–6]. There have been numerous recent studies to better understand the cavitation erosion and attempts to model the physical process involved [7–14].

With the continual desire to increase ship speeds and carrying capacity motivated by increased economic benefits of higher speed transportation or larger payload, the hydrodynamic loading on propellers has significantly increased over the past decades [15]. As a result, potential for cavitation erosion on various parts of the ship control and propulsion system, such as propeller blades, hub, rudders and nearby ship stern sections continues to increase along with the search for better erosion resistant materials.

Proper evaluation of new materials for their resistance to cavitation erosion requires a comprehensive effort contrasting the "*intensity*" of the cavitation field with the "*resistance*" of the material. In the absence of historical data on the performance of a proposed new material in the target cavitating flow fields, the designer and the decision maker have to rely on laboratory experimental studies. Field erosion studies have been conducted for hydraulic turbines and pumps (e.g. [15–19]), but for marine applications small scale laboratory tests are more common. The laboratory experimental studies aim at determining within required short time periods an evaluation of the new material, whereas in the real field cavitation erosion is expected to not occur but after a long duration of exposure. Such accelerated erosion test techniques include the utilization of ultrasonic vibration to generate the cavitation [20–22], cavitation flow loops with strong flow separation or venturi effects [23–26], and submerged cavitating jets [6,27–29] among other methods. There are also attempts to test the

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model propeller in the water tunnel [30]. Some of these techniques are standardized and follow the American Society for Testing and Materials (ASTM) Standards [31]. The ultrasonic technique and the liquid jet technique are the two most popular laboratory techniques for testing cavitation erosion characteristics of materials. In the present study, the ultrasonic cavitation and cavitating jets at different intensity were used.

In this paper, we follow the progression of erosion (i.e. time history of material loss) and represent the progression using a mathematical function. This is comparable to previous attempts to use Weibull functions to describe the mass loss curves [32]. This was not used here as is, since Weibull functions have the limitation that the terminal erosion rate (as time goes to infinity) has to be zero. In this paper, we propose an improved mathematical model to erosion progress, and show that it is useful to compare different erosion progressions for different materials under a large range of cavitation intensities for both cavitating jet and ultrasonic cavitation.

The aim of the current work is to understand the relative aggressivity of the cavitation fields generated by ultrasonic cavitation and jet cavitation of various driving pressures and to identify the relative erosion resistance ranking of the tested materials. The dependency of such ranking on the cavitation intensity is also addressed in this study.

2. Background: materials response to cavitation loads

Cavitation erosion, no matter where and how it is generated, results from the repeated impulsive loading of the material by high intensity short duration pressures loads, due to shock waves and bubble reentrant jet impacts [23,24,34–37]. These are difficult to measure but can be inferred from acoustic signals and pit measurements [7,27,29,33]. Statistical correlations can be obtained between these measurements and can be associated with the facility producing the erosion and with empirically accepted cavitation intensity indicators, such as flow speed, ambient pressure, amplitude and frequency of ultrasonic horn. While "weak" materials may fail rapidly under the repeated shock waves and jet impacts, a more "resistant" material will accumulate stain and experience over a long period the symptoms of fatigue. Initially the material surface gets deformed and is modified microscopically without any loss of material (*incubation period*). This is accompanied by work hardening of the surface. Cavitation peening techniques take advantage of this phase to render the material more resistant to stress. During this initial phase, permanent deformation may occur, sometimes accompanied with plastic flow and local displacement of material micro particles, as well as the development in the later stage of micro-cracks for brittle materials. On a weight loss versus time curve (Fig. 1) this is the initial very short period where little material loss is observed. This can be difficult to observe in some accelerated tests, but its duration is actually very important to the determination of the life extent of the cavitating device (e.g. propeller in the full scale application). Following this period, the erosion process accelerates.

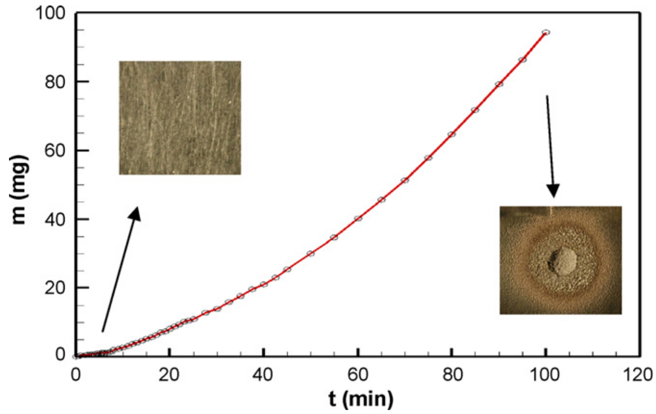

Fig. 1. Erosion progression curve for aluminum 1100-0 obtained in a cavitation jet erosion test. Inserts show a picture during the incubation period and another picture during the acceleration period.

It is known that the weight loss curve has an S shape, as illustrated in Fig. 2, which shows an erosion acceleration phase during which the erosion rate increases until attaining a maximum. This is called the *Accumulation* or *Acceleration Period*. In this phase, the material experiences increased fracture and weight loss following the end of hardening in the incubation period. The extent of this zone depends upon the strain-hardening properties of the material and involves microscopic chunks of material being removed following propagation of large cracks in between the grains of the material. The accumulation period ends once the surface properties of the material have changed so much that an interaction begins

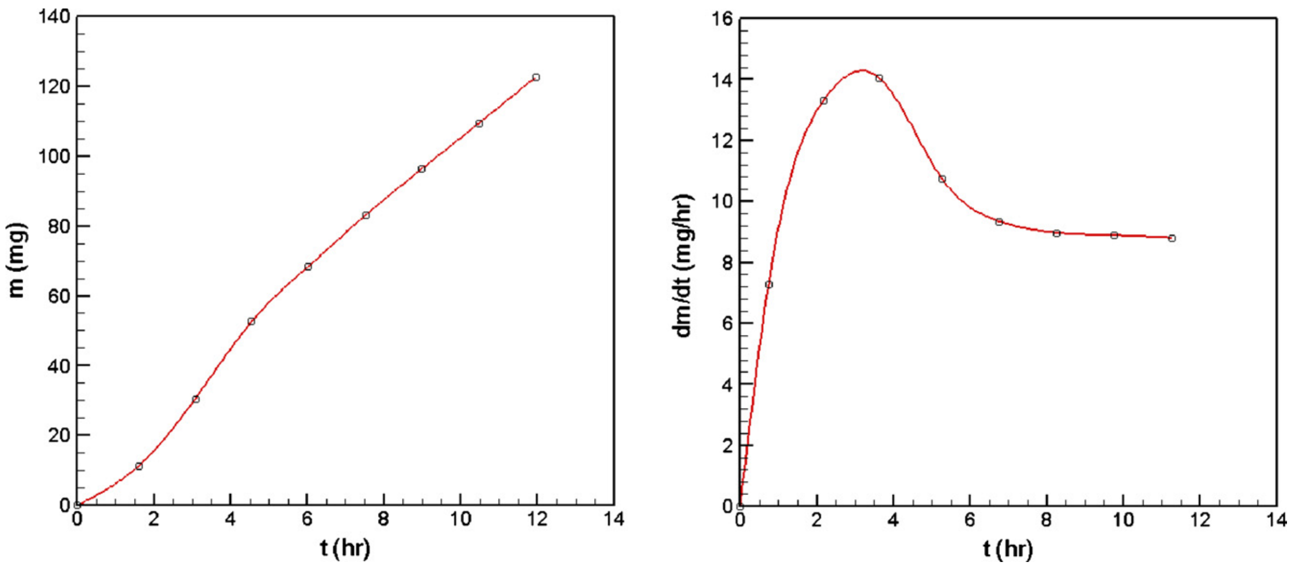

Fig. 2. Typical G32 test erosion curves: weight loss S-curve and erosion rate versus time curve.