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To cite this version:

Samir Chandra Roy, Marc C. Fivel, Jean-Pierre Franc, Christian Pellone. Cavitation induced damage: FEM inverse modeling of the flow aggressiveness. 11th International Conference on Flow Dynamics, Oct 2014, Sendai, Japan. hal-01134458

HAL Id: hal-01134458

https://hal.science/hal-01134458v1

Submitted on 5 May 2020

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Cavitation Induced Damage: FEM Inverse Modeling of the Flow Aggressiveness

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ABSTRACT

An inverse method is proposed to identify the pressure fields that could generate individual pits as observed experimentally in eroded samples made of three different materials. Assuming each pit was generated by a single bubble collapse, the pressure load is defined by two parameters, the peak pressure and its radial extent. An inverse method based on finite element modeling is proposed. The method gives access to the load distributions relevant to the aggressiveness of the cavitation test which is found to be consistent with the three materials responses.

1. Introduction

In order to predict erosion damage, it is essential to know the loading conditions generated by the bubble collapses. However, the determination of the loading conditions due to bubble collapses remains a major issue in cavitating flows. The pressure pulses may be directly measured experimentally inside the cavitation facilities for example by using pressure transducers flush mounted in the region of the bubble collapses [1-3]. However this method gives the impact loads in Newtons but the determination of the pressure field in term of stress amplitude (in MPa) is difficult because the loaded surface area is unknown and usually much smaller than the transducer sensitive surface.

Alternatively, CFD simulations could be used but generally these simulations assume that the impacted materials is a rigid surface which is a strong assumption leading to overestimations of the applied pressure.

In order to overcome these measurement difficulties, another option may be used based on an inverse modeling approach. The idea is that each pit is the signature of a single bubble collapse. Then, it can reasonably be expected that the loading conditions be derived from the geometry of the pit and the material properties.

In the present work, such a technique is proposed for deriving the loading conditions from pitting tests conducted during the incubation period. It is based on FEM (Finite Element Method) computations of the response of the material to a representative pressure pulse. An inverse procedure is then proposed to derive the distribution of the pressure profiles from the depth and diameter of pits observed experimentally.

2. Method

2.1 Material characterization

Prior to any simulation, the material behavior needs to be identified. This has been done using spherical nanoindentation tests performed on three tested materials: an Aluminum alloy Al 7075 (Al), a stainless steel A2205 (SS) and a Bronze (NAB). Using Tabor's equation, the tensile equivalent loading curves have been identified as the dashed curves plotted in Fig.1.

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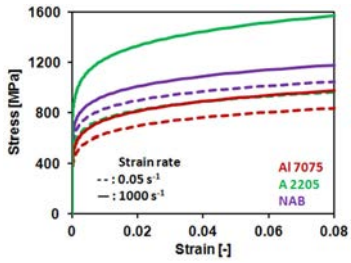

Fig. 1 Material characterization using nanoindentation data and Johnson-Cook extrapolations to high strain rate.

Since a bubble collapse takes place in a very short period of time (typically less than one microsecond), the stress-strain curve has been corrected in order to account for high strain rates. The stress is modified using the Johnson Cook model

$$\sigma_0(\dot{\varepsilon}) = \sigma_0\left(1 + C\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)$$

for which parameter C has been taken from literature (Al: C=0.017 ; SS: C=0.011; NAB: C=0.06). The strain rate effect on the stress-strain curve is shown in Fig.1.

2.1 Cavitation erosion data

Cavitation erosion tests have been performed on the same three materials using the device described in details in [4]. Pits produced at upstream pressure of 10 and 40 bars for exposure times up to 15 minutes have been considered for the current analysis. Sample surfaces after pitting test have been analyzed using a conventional contact profilometer with microprobe of radius 2 µm.

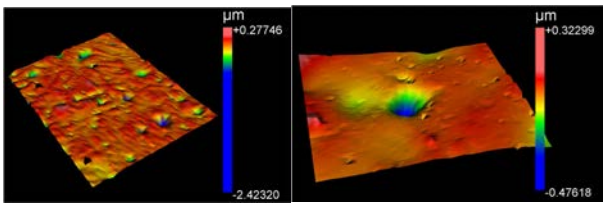

Fig. 2 Typical eroded surface of Al sample. (a) 2x3mm scan of the surface with multiple impacts (b) zoom on a 10x10µm zone surrounding a typical pit.

For each material, image analysis of the measures gave 200 characterizations of isolated pits as the one shown in Fig.2b. Each pit is characterized by its diameter and depth.

2.2 Finite Element Modeling

For sake of simplicity, the modeling is restricted to a 2D axisymmetric investigation. The applied load consists of a pressure distribution with a Gaussian shape applied on the top surface defined by the hydrodynamic pressure σ_H and its extent radius r_H.

$$\sigma = \sigma_H \exp\left(-\left(\frac{r}{r_H}\right)^2\right)$$

The mesh is locally refined in the vicinity of the maximum loaded zone. Finite Element simulations are conducted using software ABAQUS© and 8100 CAX4R elements surrounded by a layer of CINAX4 infinite elements in the bottom-right sides of the simulation cell.

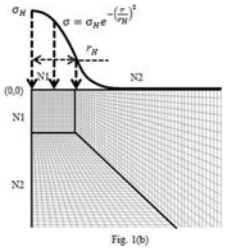

Fig. 3 Typical FEM mesh used in the simulations (N1=20 N2=30 elements). The figure only shows a magnified view of the loaded zone.

The material behavior is taken as elastic-plastic with the reference curves defined at the strain rate of $1000s^{-1}$ (continuous curves in Fig.1).

3. Results and Discussion

An inverse method is conducted in a view to find the best set of parameters (σ_H,r_H) that generates a given experimental pit profile. Results are reported in Fig.4. As expected the higher upstream pressure leads to higher hydrodynamic stresses.

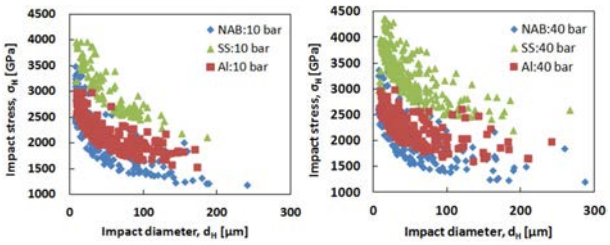

Fig. 4 Results of the inverse method for the two test conditions (10 and 40 bars).

In order to quantify the flow aggressiveness, we chose to plot the number of impacts per area and per unit of time. It appears that the points calculated from the three materials do not fall on a given master curve. This indicates that such a plot is not relevant of the flow characteristics. One way to solve this problem is to plot the impact frequency for a given range of r_H or σ_H. This better addresses the bubble distribution in term of pressures and sizes. This has been done in Fig.5 where the impact frequency is now plotted as a function of the impact stress σ_H, but for a given range of applied pressure radius r_H. One can clearly see that the three materials get aligned on a given unique curve.

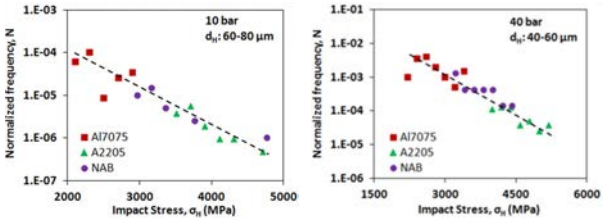

Fig. 5 Impact frequency as a function of the pressure stress σ_H for a given range of pressure extent r_H=d_H/2.

Figure 6 gives the 2D distribution of the impact frequency.

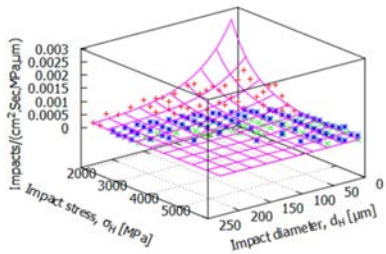

Fig. 6 2D distribution of impact frequency. Data obtained for the upstream pressure of 40bars.

A 3D fit of the surface passing through all the data points give the following analytical expression of the frequency of impacts in function of σ_H and d_H.

$$N = N^* \exp\left(-\left(\frac{\sigma_H}{\sigma_H^*}\right)\right)\exp\left(-\left(\frac{d_H}{d_H^*}\right)\right)$$

This expression is the signature of the flow aggressiveness.

4. Concluding Remarks

The inverse FEM approach presented here gives an analytical expression of the impact frequency for a given cavitation condition. This expression is material independent and quantifies the flow aggressiveness. Since each material reacts differently to a pressure pulse, they filter the impacts left at the surface so that the material can be viewed as a sensor of the cavitation conditions.

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