Cavitation erosion – corrosion behavior of some hydraulic turbine runner steels

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Abstract. Cavitation erosion is still a phenomenon which causes severe damages to hydraulic turbine runners. A lot of effort has been deployed in the scientific community to understand the materials response to this kind of solicitation. Part of researches which are conducted at Research Institute of Hydro-Quebec are focused on determining the materials behavior laws. For this, the classical ASTM G32 standard is used. Mass losses are followed during the exposure time. Also degradation parameters i.e mean depth of erosion and erosion rate are determined. Furthermore, a lot of effort has gone into the determination of the evolution of surface damages in terms of pitting, surface cracking and material removal. For this, microscopy techniques have been used to link the microstructure to the material removal mechanisms. Furthermore, another part of the researches is focused on enlightening and quantifying the deleterious effect of the environment. In some cases, a synergistic effect can establish between cavitation erosion mechanisms and corrosion kinetics and increase the material degradation. In the present study the ultrasonic cavitation rig has been coupled with electrochemical techniques to determine the contribution of corrosion to this phenomenon in natural river freshwater. The electrochemical behavior of three commonly used materials in hydraulic turbine runners, ASTM A27, E309L and UNS S41500 are studied in condition of quiescence and also in cavitation conditions.

1. Introduction

Cavitation erosion is still a phenomenon which causes severe damages in fluid systems such as hydraulic turbines, pump impellers, ship propellers or high-speed hydrofoils. The formation and the subsequent collapse of cavitation small vapor bubbles could generate shock-waves and/or micro-jets of the GPa order [1]. These mechanical solicitations can lead to very high surface stresses leading to material removal. The degradation of the best protective materials and coatings can occur by this mechanism. A variety of materials, [2-6] protective coatings [7, 8] and surface treatments [9, 10] have been studied and developed to raise their cavitation resistances in order to mitigate this phenomenon effect. However, usually in these studies, the electrochemical contribution of the environment is neglected whereas it has been demonstrated that the medium can act synergistically with erosion phenomenon to enhance the degradation mechanisms [11-13]. Actually the corrosion processes can enhance cavitation phenomenon and the reciprocity is valid. In the context of hydroelectric industry, it is proposed here to characterise three materials commonly used in hydro-turbines in presence of natural river freshwater to understand the contribution of each parameter.
2. Experimental methodology

2.1. Materials and medium

In the present study, ASTM A27, E309L and UNS S41500 have been tested. These kinds of material have been chosen because of their wide use in hydraulic turbines runners. ASTM A27 has been extensively used to build runners in the 1950’s. For ASTM A27 the samples have been extracted from a blade casting. Then, UNS S41500 is the preferred steel for the more recent equipment. The samples have been extracted from a laminated plate. Finally, E309L is nowadays most commonly used welding material to repair fatigue cracks or cavitation damages in hydraulic turbines. The samples have been extracted from a bulk sample made of welding bead.

For pure cavitation tests the samples have been prepared from 25mm diameter cylinder by 20mm inch height. For cavitation/corrosion experiments they have been prepared from 15mm diameter cylinder by 10mm height. The reduced size of sample for cavitation/corrosion experiment was chosen to fit under the 15.6mm vibrating horn. By this, it was assured that the entire sample surface was exposed to cavitation. This also avoids any galvanic coupling phenomenon between cavitation affected and non-affected zones.

The chemical compositions and the mechanical properties of these different materials are presented in Table 1 and Table 2.

Table 1. Chemical composition of tested materials.

|          | Fe  | C   | Si  | Mn  | P  | S   | Cr  | Ni  | Mo  | Cu  | Al  | Sn  |
|----------|-----|-----|-----|-----|----|-----|-----|-----|-----|-----|-----|-----|
| ASTM A27 | 97.7| 0.28| 0.36| 0.81| 0.02| 0.025| 0.34| 0.12| 0.05| 0.14| 0.073| 0.024|
| UNS S41500 | 81.5| 0.034| 0.44| 0.68| 0.018| 0.001| 12.7| 4.0 | 0.57| -   | -   | -   |
| E309L    | 58.6| 0.03| 0.72| 2.12| 0.006| 0.001| 24.5| 13.7| 0.3 | -   | -   | -   |

Table 2. Mechanical properties of tested materials.

|          | Yield strength (MPa) | Ultimate strength (MPa) | All (%) | Hardness (HV) |
|----------|----------------------|-------------------------|---------|---------------|
| ASTM A27 | 330                  | 548                     | 30      | 150           |
| UNS S41500 | -                    | -                       | -       | 250           |
| E309L    | 353                  | 646                     | 42      | 180           |

Figure 1 presents the micrographs of the three steels. In the case of ASTM A27 mean grain size is about 80 μm and the microstructure consists mainly in ferrite, acicular ferrite and pearlite. The UNS S415 microstructure is composed of martensite phase with a small amount of reformed austenite. And for the E309L, the dendritic microstructure is typical of a solidification process after the weld bead deposition. The predominant phase is reformed austenite.
Figure 1. Micrographs of the studied steels.

The medium that has been used in this work is a naturel river freshwater (NRW). This water is representative of the ones we can find in the south of Quebec. The electrochemical parameters are shown below in Table 3. In this table we can observe that conductivity is relatively high for a river water and pH is a little bit alkaline (>7). We can notice the presence of chloride, sulfate and calcium ions in reasonable but non negligible proportions.

Table 3. Natural river water parameters.

| pH   | Conductivity | Cl⁻ | SO₄²⁻ | Na⁺ | Ca²⁺ | Mg²⁺ | Alcalinity   |
|------|--------------|-----|-------|-----|------|------|--------------|
| 7.7  | 277 μS/cm    | 21 ppm | 21 ppm | 13 ppm | 33 ppm | 8 ppm | 86 mg CaCO₃/L |

2.2. Cavitation erosion testing using vibratory apparatus

In this study, cavitation erosion experiments have been performed in ultrasonic equipment according to ASTM G32 standard. The specimens were held stationary in liquid media just below a vibrating horn at a distance of 0.5± 0.02 mm (indirect method). The frequency of vibration and the peak to peak displacement amplitude of the horn were 20 kHz and 50μm. Cavitation bubbles are created below the horn and when they collapse, the generated micro-jets or shockwaves hit the sample surface and stress the materials. The experimental apparatus is shown in Figure 2.

After each cavitation erosion and/or corrosion experiment, the surface of the specimen was observed by a scanning electron microscopy (SEM) Hitachi S-3700-N to characterize the evolution with time.

Figure 2. Schematic representation of the cavitation erosion vibratory apparatus.
2.3. Electrochemical experiment

The electrochemical setup was a three-electrode system composed of the working electrode (studied steel), Ag/AgCl reference electrode and platinum mesh as a counter electrode. The water bath was a pyrex double walled beaker to prevent any electrochemical reaction and a thermostatic bath has been linked to the beaker in order to maintain temperature water at 20±2°C. The setup was connected to a potentiostat/galvanostat BioLogic SP-300 to monitor the electrochemical parameters.

The experiment started with a 5min cavitating condition to remove any surface oxides formed during the sample preparation. This step was followed by a quiescence period until the free corrosion potential reached a steady-state. Potentiodynamic polarisation curves were started at the free corrosion potential and swept in the cathodic direction at a rate of 0.5 mV/s until -1200mV. Following another rest period to stabilize the free corrosion potential, an anodic potential swept was applied at the same rate until +1300mV. An identical procedure was followed under cavitation conditions.

3. Results and discussion

3.1. Cavitation erosion behaviour law

Figure 3 presents the cumulative weight loss as a function of cavitation erosion time for the three studied steels in distilled water (DW) and for a minimum period of 570 min. We can notice that both curves exhibit an incubation period where the weight losses are low, followed by an increase of the cumulative weight losses. The incubation period has been defined as the value obtained from the intersection of a straight extension line of the maximum slope with the time axis. These periods are evaluated at 90min, 110min and 150min respectively for ASTM A27, UNS S41500 and E309L.

After the incubation period the erosion rate (Figure 4) increases drastically, demarcating the acceleration period until reaching the maximum erosion rate of 16mg/h for ASTM A27, around 6mg/h for UNS S41500 and around 5mg/h for E309L.
3.2. Surface evolution

To get a more advanced understanding of the cavitation erosion mechanism of ASTM A27 steel, it is relevant to observe degradation during cavitation erosion tests. Figure 5 presents SEM images of the evolution of worn surface during the test in distilled water.

After 30 min of exposure, ASTM A27 sample surface presents some plastic deformation. This deformation is quite important insofar as some voids already start to appear. The deformation saturation is reached at different place on the surface and some cracks are initiated along the weakest spots on grain boundaries. In the case of UNS S415 the deformation is less advanced, there are no voids but martensite blocks are drawn and the martensitic microstructure becomes clearly visible. In the case of E309L, the surface seems smoother and the austenite phase accommodates deformation by creating slip lines at the surface.

After 90 min, for ASTM A27 surface cracks join each other and metal particles are getting free. We can observe that some grains (around 50μm diameters) are removed. The material removal is occurring and the incubation period is finished. The erosion rate starts increasing rapidly. For UNS S41500, the surface presents advanced deformation stage. We can observe that a small amount of particles is removed. The deformation pattern let think that the degradation occurs at the scale of martensite blocks. Concerning the E309L, there is no particle loss, but the deformation is very visible. Also there are no visible cracks on the surface.

After 300 min, all the three samples show surfaces with missing materials. In the case of ASTM A27 the holes are equivalent to the grain size, with fracture surface giving evidence of grain decohesion enlightening an intergranular degradation mechanism. We can also notice that the fracture facies present evidence of both brittle and ductile fracture. We can attribute this two behaviors to the two different phases ferrite (hardness of around 80HV) and perlite (hardness of around 220HV) for which the hardness are in accordance with the above observations. In the case of UNS S41500 the fracture surface is related with the microstructure thinness. The size and the pattern of holes enlighten that the degradation occurs by removal mechanism of martensite blocks. Finally for E309L, the fracture surface exhibit a ductile behavior with hollows and craters typical of the austenitic stainless steels [2].
3.3. Cavitation- corrosion experiments

Metallic corrosion resistant materials are protected against corrosion through the formation of a surface oxide film. This passive oxide film may be altered via different mechanisms such as mechanical erosion-cavitation and electrochemical corrosion processes [12]. Figure 6 shows the cathodic followed by the anodic polarization curves of ASTM A27, UNS41500 and E309L under quiescence and cavitation conditions. Tafel extrapolation method was used to obtain corrosion current density ($i_{\text{corr}}$) value. Between each polarization curve, the free corrosion potentials were recorded versus time until a steady-state was observed. Free corrosion potential ($E_{\text{corr}}$) value and corrosion current density under quiescence and cavitation conditions are listed in Table 4.
For ASTM A27, it was observed that the polarization curve under cavitation condition was shifted towards more positive values by approximately 360mV. The anodic shift of free corrosion potential can be attributed to an increase of mass transport of oxygen supply under the generation of cavitation bubbles and to the increase of the anodic slope. This result is in accordance with a previous study [14] for which the potential shift was about 300mV. The slight difference can be attributed to the sample preparation. In the present study the 15mm metallic sample was mold in epoxy in order to expose a surface that was completely cavitated, the value of the corrosion potential was not influence by any non-cavitated part aside. Moreover for this material the corrosion current density increases by around 30% under cavitating condition denoting the influence of cavitation on this parameter.

Figure 6. Polarization curves of the different steels in NRW.
Table 4. Corrosion potential (E_{corr}) and corrosion current density (i_{corr}) for the different steel in NRW under quiescence and cavitation conditions.

| Material     | Corrosion potential (mV vs Ag/AgCl) | Corrosion current density (µA/cm²) |
|--------------|-------------------------------------|-----------------------------------|
|              | Quiescence | Cavitation | Potential shift under cavitation | Quiescence | Cavitation |
| ASTM A27     | -600       | -240       | 360 mV anodic                    | 7          | 10         |
| E309L        | +32        | -138       | 170 mV cathodic                  | 0.03       | 4          |
| UNS S41500   | 0          | -173       | 173 mV cathodic                  | 0.06       | 5          |

For the two stainless steel UNS 41500 and E309L, the free corrosion potential shift in more cathodic direction and reach a value of 170mV for both. This shift is in accordance with two previous studies performed on duplex stainless steel in seawater [15] and on stellite impinged by 3.5% NaCl solution containing solid particle [16]. Moreover, potentiodynamic polarization measurement shows that anodic current for UNS S41500 and E309L increases without exhibiting an active-to-passive transition under both quiescence and cavitation condition. These results can be interpreted by the fact that cavitation removes the passive film on the surface of stainless steel inducing bare metal surface exposition. This exposition gives rise to a large increase of the anodic current density due to active electrochemical dissolution of the free surface. Finally, it has been enlightened that under cavitation, the corrosion current density increases by two orders of magnitude.

4. Conclusion

The cavitation erosion behaviour of a carbon steel, a martensitic and an austenitic stainless steel which are widely used in the hydroelectric industry have been studied. Pure cavitation erosion and cavitation erosion/corrosion experiments have been performed in distilled water and natural river fresh water respectively.

(1) The ranking of tested materials in term of erosion resistance is E309L > UNS S41500 > ASTM A27. The incubation period lengths are in accordance with these results.

(2) SEM study shows that for all these materials, the degradation is mainly controlled by a ductile fracture mechanism. Some evidence of formation of cracks during cavitation erosion tests has been enlightened. These cracks propagate along grains/substructure boundaries.

(3) For the carbon steel potentiodynamic curves under cavitation show a free corrosion potential shift in more anodic values whereas it is the opposite effect (more cathodic values) for tested stainless steels. In the cases of E309L and UNS S41500 it can be explained by the removal of oxide films or passive layer and in the case of ASTM A27 by the increase of mass transport of oxygen supply under the generation of cavitation bubbles.

(4) For all the tested materials corrosion current densities have been increased by the cavitation phenomenon: a current increase of 30% for the carbon steel and of two orders of magnitude for both stainless steels.
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