Cavitation erosion behavior of high strength steels

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SUMMARY

Cavitation erosion is still one of the most important degradation modes in hydraulic turbine runners. Part of researches in this field focuses on finding new materials or coatings which exhibit high resistance to this phenomenon. In terms of purely mechanical properties, quenched and tempered high strength steels turn out to be a good alternative to the commonly used martensitic stainless steels (13Cr-4Ni). In the present study, the cavitation erosion behavior of ASTM A514 high strength steels in a laminated form and in welded form is investigated. This paper states a two side approach which has been used to get an advanced understanding of this kind of steel behavior regarding cavitation phenomenon. First, the overall behavior is determined using a cavitating liquid jet facility according to a modified ASTM G134-95 standard to simulate aggressive flow conditions and determine the cavitation erosion resistance. Moreover, 20 kHz vibratory test according ASTM G32-10 standard has been performed to study as thoroughly as possible the incubation period to get evidence of the degradation mechanism during the incubation stage. In both cases, mass losses and erosion rate have been followed during the exposure time. Furthermore, a particular effort has been implemented to determine the evolution of surface damages in terms of pitting, surface cracking and material removal. For this, 3-D optical profilometry technique as well as scanning electron microscopy has been used to link the microstructure to the degradation mechanisms at each stage. The results showed that the cavitation erosion behavior is similar for base and welded materials in aggressive conditions whereas it is possible to observe a difference in smoother conditions. Actually a longer incubation time has been determined for welded form due to bainite structure. In both case the degradation mechanism suggests that the erosion was mainly controlled by ductile fracture.

INTRODUCTION

Cavitation erosion is a degradation phenomenon caused by the collapse of bubbles due to pressure fluctuations in turbulent flows. These collapses generate shock waves of the GPa order [1]. Consequently, severe damages can be observed in hydraulic components such as valves, ship propellers, pumps or turbine runners. To reduce erosion in such components, many studies have been conducted to develop and characterize materials behavior. In the past conventional carbon steels [2], austenitic and martensitic stainless steels [3, 4, 5] as well as stellite alloys [6, 7] have been extensively studied. However, quenched and tempered high strength steels (ASTM A514) have not been yet characterized regarding cavitation erosion. These steels are high performance carbon steels commonly used in oil industry for pipelines and in the civil construction field for bridges or building structures. This class of materials has the particularity to present noticeable high mechanical properties at a relatively low cost. For these reasons, the hydroelectric field is getting more and more interested in this material family as an alternative to martensitic stainless steel commonly used today to build hydraulic turbine runners [8]. The purpose of this investigation is to observe the cavitation erosion behavior and to determine the degradation mechanism during the incubation stage.

EXPERIMENTAL APPROACH

Materials

In the present study, two different forms of ASTM A514 [9] have been tested: one quenched and tempered high strength steels (S550QL) and one welded high strength steels (Carbofil). These kinds of materials have been chosen because they are or they will be used for hydraulic turbines runners. The chemical composition and the mechanical properties of the different tested materials are presented in Table 1 and Table 2.

<table>
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<tr>
<th>Material</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
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<td>S550QL</td>
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<td>Ti</td>
<td>Cu</td>
<td>Al</td>
<td>Nb</td>
<td>B</td>
<td>N</td>
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<td>0.001</td>
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<td>0.0018</td>
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<table>
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<tr>
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<tbody>
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<td>Carbofil</td>
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<td>1.39</td>
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<td>0.006</td>
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<td></td>
<td>-</td>
<td>0.21</td>
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Table 1: Chemical composition of tested materials
Table 2: Mechanical properties of tested materials

<table>
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<tr>
<th>Material</th>
<th>Yield strength (MPa)</th>
<th>Ultimate strength (MPa)</th>
<th>Elongation (%)</th>
<th>HV 300g</th>
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<tr>
<td>S550QL</td>
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<td>780</td>
<td>18</td>
<td>249</td>
</tr>
<tr>
<td>Carbofil</td>
<td>605</td>
<td>734</td>
<td>23</td>
<td>240</td>
</tr>
</tbody>
</table>

Cavitation liquid jet

Cavitation liquid jet erosion tests were carried out according to a modified ASTM G134-95 [10] in a test chamber filled with tap water at a constant upstream pressure of 23.8 MPa (the corresponding velocity was 218 m/s), at a liquid temperature of 22 ± 1°C, and at a cavitation number $\sigma = 0.013$ (the downstream pressure was 0.21 MPa). It must be noted that these parameters were optimized to get a 1000 mg/h weigh loss rate on Al6061T6 reference sample. The stand-off distance between the nozzle outlet and the test specimen was 15 mm. The experimental apparatus is shown in Figure 1.

![Figure 1: Schematic representation of the cavitating liquid jet setup](image)

Each test was performed for a total of 150 minutes exposure time (5 periods of 30 min). After each cavitation period, the sample is cleaned in a methanol ultrasonic bath, dried and weighted. The topography of the surface is determined by optical profilometry technique. A series of 3 tests for each sample is done. The mean values are calculated.

Cavitation erosion using vibratory apparatus

Cavitation erosion tests were carried out in ultrasonic equipment according to ASTM G32 standard [11]. The test samples were held stationary 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 50um, respectively and the test liquid was distilled water maintained at 20 ± 1°C. The experimental apparatus is shown in Figure 2.

![Figure 2: Schematic representation of the cavitation erosion vibratory apparatus](image)

RESULTS AND DISCUSSION

Microstructure

Figure 3(a) presents the micrographs S550QL (base materials), low alloyed steels quenched and tempered at 550°C for 1h. Grain size is quite fine and the microstructure consists mainly of tempered martensite with a small amount of lower bainite (labeled $\alpha_{lb}$) and upper bainite plates in prior austenite grain (labeled $\alpha_b$). We can observe the microstructure of Carbofil (welded materials) in Figure 3(b), a copper coated solid wire electrode. Its composition is near the S550QL but with a lower amount of carbon to improve weldability and higher amount of nickel to improve the mechanical properties. The microstructure consists in martensite with a sizeable amount of bainite (labeled $\alpha_{lb}$) and acicular ferrite (labeled $\alpha_a$).

![Figure 3: Optical micrograph (500x) of tested materials](image)
**Erosion resistance**

Figure 4 presents the cumulative weight loss as a function of cavitation erosion time for S550QL and Carbofil. It was evidenced that the welded material presents a slightly better cavitation erosion resistance than the base material in the case of the vibratory test whereas it exhibits an equivalent resistance to Carbofil in more aggressive conditions in the cavitating liquid jet experiment. Both materials pass through a 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 for S550QL and Carbofil are of 80 and 90 min for vibrating apparatus tests and 14 min in more aggressive conditions. These results indicate that Carbofil can build up a higher amount of plastic deformation before initiating cracks than base material. This property can be attributed to the sizeable amount of bainite. Actually, that structure is known to improve the toughness of materials [12, 13, 14]. After the incubation periods the erosion rate increases rapidly (Figure 5), demarcating the acceleration period until reaching the maximum erosion rate of 120 mg/h in aggressive condition whereas the maximum is not reached after 270 min in smoother conditions.

After being eroded for 270 min in the vibratory apparatus, the weight loss was 14 mg and 22 mg respectively. Figure 6 shows the micrographs of the worn surfaces for both materials after 270 min. We can observe that the effect of the impacts induced by bubbles collapse took the form of crater and hollows on grains. This characteristic suggests that the erosion was mainly controlled by ductile fracture. We also see the presence of deep cracks between the grains. The depth of these cracks is more pronounced on S550QL. Moreover on Figure 6 (a) and (c) it seems that cracks propagate along prior austenite grains whereas the fracture mechanism presents transgranular evidences in Figure 6 (b) and (d) for Carbofil.

***Figure 4:** Cumulative weight losses with exposure time***

***Figure 5:** Erosion rate with exposure time***

**Figure 6:** SEM images of worn surfaces and cross section near the surface of S550QL (a,c) and Carbofil (b,d)

The samples surface profiles were determined at several time periods of the test. The measures were made with an optical profilometer with a lateral resolution of 2 μm and a Z-resolution of 280 nm. Figure 7 presents the surface evolution of both materials during the erosion periods. The surface study confirms the behavior observed on cumulative weight loss and erosion rate curves, in so far as welded material is more resistant to cavitation than base material. After 30 min, both surfaces present a roughness with deformation pits up to 15 μm whereas the samples are still in the incubation stage. The pits surface coverage is more important in S550QL. At this stage the mass loss is not significant; the surface accommodates the stress induced by the impact of bubbles collapse without loosing particles, this step is know as work hardening process [15]. After 90 and 150 min the weight losses rate increases and the difference in depth between surface roughness increases as well. After 210 min the difference is noticeable. The max depth of erosion (i.e. max roughness) is 45 μm for base material whereas 27 μm for welded material, as seen on Figure 8. We can also notice that for Carbofil the erosion is more advanced along interpass boundaries (yellow lines) which are the weak zones of the weld.
Degradation mechanisms during incubation period

To get a more advanced understanding of the cavitation erosion mechanism of high strength steels, it seems interesting to look at the deformation stages during incubation period. Figure 9 presents SEM images of the evolution of affected surfaces during this period for S550QL. At the beginning, after 6 min of exposure, the surface starts presenting deformation around martensite needles resulting from plastic deformation which begins to build up. After 12 and 18 min, the plastic deformation becomes more severe and prior austenite grains are drawn due to intense formation of slip lines at the grain boundaries. At 30 min, pits start appearing, deformation saturation is reached at different place on the surface. The intensity of plastic deformation is different for each grain due to difference of lattices spatial orientations. After 45 min, deformation saturation is reached on the overall surface and some cracks are initiated along the weakest spots on prior austenite grain boundaries. At 60 min surface cracks join each other and metal particles are getting free. This step indicates the end of incubation period. On Figure 10 for welded material, the degradation pattern is a bit different. At the beginning, the first step of deformation consists in planar deformation, such as base material. Slip lines are starting to appear and reveal the martensite laths microstructure. After 18 min, it is possible to distinguish that the deformation is oriented according to preferential crystallographic planes. Moreover, after 45 min a geometrical pattern is obvious. The martensite laths are forming triangular martensite packets. At 60 min there is no more available slip plane resulting in opening of new surfaces leading to crack propagation and failure of surface.

CONCLUSION

The cavitation erosion resistance of a quenched and tempered high strength steel (ASTM A514) and a welded high strength steel has been determined in a cavitating liquid jet tests and in vibratory apparatus.

The behavior of both materials is comparable in aggressive conditions whereas welded materials exhibit a higher resistance to cavitation erosion than the base materials in smoother conditions. This improved property was attributed to intrinsic mechanical properties of bainite.

For both materials, the degradation is mainly controlled by a ductile fracture mechanism. Some evidence of formation of wider and deeper cracks during cavitation erosion tests has been enlightened for S550QL. The cracks initiated from the surface propagate along the prior austenite grain boundaries in base material. In welded material, the cracks propagate according a transgranular mechanism.

Both materials observe an incubation period during which they build up plastic deformation before starting to form pits and cracks, along prior austenite grain boundaries in the case of S550QL and along preferentially oriented crystallographic planes in the case of welded material.
Figure 9: SEM micrograph of S550QL surface during the incubation stage

Figure 10: SEM micrograph of Carbofil surface during the incubation stage
ACKNOWLEDGMENTS

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REFERENCES