CONCERNING THE DAMAGE OF STAINLESS STEELS BY CAVITATION EROSION

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This paper presents the experimental results of cavitation erosion behavior of some stainless steels. The experimental investigations were performed in magnetostrictive vibrating apparatus at Cavitation Laboratory of Polytechnic University of Timisoara (LMHT) in accordance with ASTM G32-2006. Several investigations were done on macro structural analysis and electron microscopy where determined many structural features, such as affected area destroyed by cavitation, ratio between affected and nonaffected cavitation areas through diameter measurements. Also, the samples was analysed through X-ray diffraction where there phases were identified.

Keywords: cavitation, erosion, depth, chemical composition, stainless steel

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1. Introduction

The search for the origin of erosion by cavitation bubbles is nearly one hundred years old: it was initiated by the finding of severe destructive effects on the propellers of the great ocean liners Lusitania and Mauretania, reported first by Silberrad (1912). This was the beginning of investigations of bubble dynamics by numerous researchers all over the world [1].

While the history of cavitation has been traced back to the middle of the eighteenth century, little reference to cavitation pertaining directly to the marine industry has been found until the mid-nineteenth century [2].

Cavitation erosion is a common cause of failure in machinery such as hydro-turbines, ship propellers, pumps, valves, diesel engines and is an important factor in many areas of science, engineering, including acoustics, chemistry and metallurgical [3, 4,5,6,7].

Cavitation is a general fluid mechanics phenomenon that can occur whenever a liquid is used in a machine which induces pressure and velocity fluctuations in the fluid [8]. Pressure differentials in the fluid generate gas or vapor bubbles in the fluid. When these bubbles encounter a high-pressure zone, they collapse and cause explosive shocks to the surface. These surface shocks cause localized deformation and pitting. Cavitation pits eventually link up and cause a general roughening of the surface and material removal. Cavitation is similar to particle erosion in its damage [9].

Cavitation can take different forms as it develops from inception. Some authors revealed correlation between structure and properties of different metallic materials in connection with cavitation erosion resistance [10]. The aim of present paper is to put in evidence the erosion- cavitation damage of different stainless steels through structural characterization.

2. Materials and Methods of Investigations

Different stainless steels were investigated in order to reveal erosion-cavitation behaviour. The chemical composition of the experimental stainless steels made by spectrometry is given in table 1. In according with Schaeffler diagram, after determining equivalents in chromium and in nickel we consider two types of stainless steels, austenitic stainless steel ( steels C and D) and austenitic – ferritic stainless steels ( steels A, B, E, F, G and H) with different percents of constituents.

The cavitation erosion tests were carried out in a magnetostrictive facility, in according with Standard Test Method for Cavitation Erosion Using Vibratory Apparatus (ASTM G32), using as cavitant liquid drink water at 20 ±1°C [11,12,13].
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Table 1

Chemical composition of the experimental stainless steels

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Element, wt.%</th>
<th>Si</th>
<th>Mn</th>
<th>Mo</th>
<th>Cr</th>
<th>Ni</th>
<th>Al</th>
<th>Ti</th>
<th>P</th>
<th>S</th>
<th>Cu</th>
<th>Fe</th>
<th>E_Cr</th>
<th>E_Ni</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td></td>
<td>3.59</td>
<td>3.16</td>
<td>-</td>
<td>18.54</td>
<td>7.59</td>
<td>1.83</td>
<td>0.77</td>
<td>0.03</td>
<td>0.012</td>
<td>-</td>
<td>ball</td>
<td>23.925</td>
<td>11.57</td>
</tr>
<tr>
<td>B</td>
<td></td>
<td>1.91</td>
<td>3.45</td>
<td>-</td>
<td>21.18</td>
<td>8.59</td>
<td>2.72</td>
<td>1.13</td>
<td>0.04</td>
<td>0.013</td>
<td>-</td>
<td>ball</td>
<td>24.045</td>
<td>11.215</td>
</tr>
<tr>
<td>C</td>
<td></td>
<td>1.38</td>
<td>2.69</td>
<td>2.86</td>
<td>21.37</td>
<td>23.4</td>
<td>2.17</td>
<td>-</td>
<td>0.04</td>
<td>0.015</td>
<td>2.82</td>
<td>ball</td>
<td>26.30</td>
<td>24.34</td>
</tr>
<tr>
<td>D</td>
<td></td>
<td>1.81</td>
<td>2.56</td>
<td>2.64</td>
<td>21.30</td>
<td>22.19</td>
<td>-</td>
<td>-</td>
<td>0.04</td>
<td>0.013</td>
<td>3.48</td>
<td>ball</td>
<td>26.655</td>
<td>23.47</td>
</tr>
<tr>
<td>E</td>
<td></td>
<td>1.73</td>
<td>2.48</td>
<td>2.66</td>
<td>20.88</td>
<td>8.00</td>
<td>-</td>
<td>-</td>
<td>0.04</td>
<td>0.015</td>
<td>-</td>
<td>ball</td>
<td>26.135</td>
<td>10.74</td>
</tr>
<tr>
<td>F</td>
<td></td>
<td>2.18</td>
<td>2.10</td>
<td>2.47</td>
<td>19.31</td>
<td>8.17</td>
<td>-</td>
<td>-</td>
<td>0.04</td>
<td>0.015</td>
<td>0.86</td>
<td>ball</td>
<td>25.05</td>
<td>10.72</td>
</tr>
<tr>
<td>G</td>
<td></td>
<td>0.99</td>
<td>2.50</td>
<td>-</td>
<td>20.62</td>
<td>8.71</td>
<td>0.83</td>
<td>0.03</td>
<td>0.03</td>
<td>0.012</td>
<td>-</td>
<td>ball</td>
<td>22.105</td>
<td>11.46</td>
</tr>
<tr>
<td>H</td>
<td></td>
<td>3.87</td>
<td>5.38</td>
<td>-</td>
<td>19.99</td>
<td>11.73</td>
<td>1.87</td>
<td>-</td>
<td>0.04</td>
<td>0.012</td>
<td>-</td>
<td>ball</td>
<td>25.795</td>
<td>15.02</td>
</tr>
</tbody>
</table>

Cavitation erosion behaviour after 165 minutes was appreciated considering macrostructural analysis made at stereomicroscope type OLYMPUS equipped with QuickMicrophoto 2.2 software.

Also, the samples of stainless steels were cut for microscopic analysis (SEM/EDS) and for X-ray diffraction analysis. For SEM samples were examined in a scanning electron microscope type Philips XL 30 ESEM TMP equipped with secondary electron detector in low-vacuum and solid state backscattered electrons signals (BSE) detector with two diodes [14]. The XRD were made on D8 ADVANCE diffractometer with molybdenum K_α radiation because the sample has iron composition and the samples were measured in average from 10° to 90° with a step size of 0.040°, the scan step time was 1 second.

3. Results and interpretations

Results concerning structural investigation of cavitation behaviour of the investigated stainless steel are given in next figures.

Stereomacrostructural aspects of the experimental test samples are given in Fig. 1.

In steel A and steel B the surface attacked by cavitation is found approximately in a concentric circle (Fig. 1a, 1b), on may observe that macroscopic interconnected cavitations with radial disposal so this aspect gives best behavior from a macroscopic point of view.
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Fig. 1 Stereomacroscopic aspect of experimental samples, x8:

a- steel A ; b- steel B ; c- steel C ; d- steel D ; e- steel E ; f- steel F ; g- steel G ; h- steel H

Steels C, E, F, with the behavior given in figures 1c, 1e, respectively fig. 1f, has also concentric circle aspects of the affected surfaces by cavitation. The difference from previous images consists a highly degraded surface with many interconnected cavitations and radial disposal.

In the steel D from figure 1d, with 100% austenite, the surface degraded through cavitation is well delimitated and it has huge interconnected cavitations with radial disposal.

On steel G, with 60% austenite and 40% ferrite, the surface degraded through cavitation is well delimitated and it presents many cavitations with uniform disposal (Fig. 1g). At, steel H from figure 1h, with 80% austenite and 20% ferrite, the cavitation attack is also found approximately in a concentric circle, many cavitations with non-uniform disposal and the right side is more affected by corrosion than the left.

The extension of cavitation phenomenon is given in figure 2 and table 2, which may give the possibility of making a comparison concerning cavitations behaviour.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Sample diameter, μm</th>
<th>Extension of cavitation, μm</th>
<th>Surface affected by cavitation, %</th>
<th>Depth of cavitation, μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>13736</td>
<td>8780</td>
<td>41</td>
<td>305</td>
</tr>
<tr>
<td>B</td>
<td>13749</td>
<td>8733</td>
<td>40</td>
<td>275</td>
</tr>
<tr>
<td>C</td>
<td>13836</td>
<td>9162</td>
<td>44</td>
<td>540</td>
</tr>
<tr>
<td>D</td>
<td>13654</td>
<td>8866</td>
<td>42</td>
<td>325</td>
</tr>
<tr>
<td>E</td>
<td>13718</td>
<td>8456</td>
<td>38</td>
<td>515</td>
</tr>
<tr>
<td>F</td>
<td>13738</td>
<td>8554</td>
<td>39</td>
<td>326</td>
</tr>
<tr>
<td>G</td>
<td>13560</td>
<td>8374</td>
<td>38</td>
<td>335</td>
</tr>
<tr>
<td>H</td>
<td>13765</td>
<td>8762</td>
<td>41</td>
<td>400</td>
</tr>
</tbody>
</table>
So at steel A only 40.86% surface is affected by cavitation (Fig. 2a), about 40.35% of surface is affected by cavitation in steel B (Fig. 2b). The highest affected surface by cavitation is met at austenite stainless steel C, where 43.85 % of surface is affected by cavitation (Fig. 2c) and well defined cavitations are about 300-400µm diameters.

In steel D a surface about 42.16 % of is affected by cavitation (Fig. 2 d), about 38 % of surface is affected by cavitation in steel E (Fig. 2e), and, respectively about 38.77 % of surface is affected by cavitation in steel F (Fig. 2f) but the real affected cavitation surface can be smaller, due to very deep frame cavitations. At steel G only 38.14 % surface is affected by cavitation (Fig. 2g) where all the cavitations are uniform distributed inside the affected surface, and at steel H a surface about 40.52% is affected by cavitations (figure 2h), where one may remark also a general corrosion of surface. The best cavitation behaviour is for stainless steel with 20% austenite and 80% ferrite (steel E).
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Fig. 2 Stereomacrostructural aspect of samples after measuring cavitation affected zone, x8

a- steel A ; b- steel B ; c- steel C ; d- steel D ; e- steel E ; f- steel F ; g- steel G ; h- steel H

Fig. 3 indicates the depths of the erosion cavity in the investigated samples. The depth of erosion cavity is in the range of 300-540μm for the investigated stainless steels. The highest value of depth is met in case of steel C, with about 540μm (Fig. 3c), followed by steel E with about 515μm (Fig. 3e), in comparison with the other, where the depth is 305μm for steel A (Fig. 3a), 275μm for steel B (Fig. 3b), 325μm for steel D (Fig. 3d), 326μm for steel F (Fig. 3f), 335μm for steel G (Fig. 3g) and, respectively 400μm for steel H (Fig. 3h).
Fig. 4 reveals the structural analysis at scanning electron microscope of the experimental stainless steels. So, at steel A is observed surface with very fine cavitations; aspect mixed of cavitations; fragile character breaking with propagation intergranular and cracks cleavage planes (Fig. 4a). At steel B, is observed surface with fine cavitations and many cavity uniform degradation with fine and intergranulation very fine cracks and dimensions of cavitations about 10-15µm; fragile breaking with aspect intergranular with highlight a cavity of 5 µm and sliding paths (Fig. 4b). At steel C (Fig. 4c) one may reveal equal proportions of fine and big cavitations; the surface with deep secondary intergranular cracks; fragile character breaking with intergranular propagation and sliding paths. At steel D, reveals that aspect mixed of cavitations, with fine and big cavitations, surfaces with deep secondary intergranular cracks and many cavity uniform disposal; fragile breaking aspect with intergranular propagation and plane of cleavage (Fig. 4d).

In steel E, (Fig. 4e) the eroded surface presents a mixed aspect of cavitations, surface with very fine cavity initiated by nonmetallic inclusions; brittle fracture with very fine intergranular cracks, cleavage planes and propagation of wave breaking front. At steel F, the surface is with very fine cavitations and fine intergranular cracks; aspect mixed of cavitations with cleavage planes, propagation of the front by very fine intergranular cracks and cleavage planes (Fig. 4f).

On steel G, there are put in evidence (Fig. 4g) surface with equal proportions of fine and big cavitations, the surface with secondary intergranular cracks, propagations through cleavage with accentuate sliding plane; fragile character breaking with intergranular propagation. At steel H, the eroded surface presents a mixed surface; intergranular and transcrystalline propagation; fragile
character breaking with intergranular aspect and cavitations with intergranular cracks (Fig. 4h).
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Fig. 4. Structural analysis at scanning electron microscope (SEM), after 165 minutes of cavitation loading (x2000):
- a- steel A, b- steel B, c- steel C, d- steel D,
- e- steel E, f- steel F, g- steel G, h- steel H

The spectrometer of each stainless steel XRD (Fig. 5) was compared with the ICDD records and it was found that they correspond.

Also, the X-ray diffraction analysis shows the evolution of the X-ray beam intensity, depending on the diffraction angle of each stainless steel investigated. For stainless steel A was identified austenite ($\gamma$) alloyed with chromium and nickel and ferrite ($\alpha$) alloyed with 36% nickel, with faced-centered cubic structure (Fig. 5a). At steel B was identified ferrite ($\alpha$) alloyed with nickel and silicon and austenite ($\gamma$) alloyed with chromium and nickel, with indicating the diffraction planes (Fig. 5b). Also, in Fig. 5c, which is from steel C is presented austenite ($\gamma$) alloyed with nickel and silicon who have crystal system faced-centered cubic and hexagonal. At, steel D from Fig. 5d, was identified the existing of austenite ($\gamma$) highlighting the alloying elements and the structure of this is faced-centered cubic and monoclinic.

In stainless steel E was identified ferrite ($\alpha$) alloyed with nickel and austenite ($\gamma$) alloyed with type chromium and nickel with the primitive cubic structure and faced-centered cubic (Fig. 5e). On Fig. 5f, XRD stainless steel F, containing ferrite ($\alpha$) alloyed complex with highlighting the alloying elements and austenite ($\gamma$) alloyed with chromium and nickel, where the structure are faced – centered cubic.

In XRD of stainless steel G one may remark ferrite ($\alpha$) alloyed with chromium and austenite ($\gamma$) alloyed with chromium and nickel, in comparison with steel H, which contains austenite ($\gamma$) alloyed with nickel and chromium and ferrite ($\alpha$) with nickel and ferrite ($\delta$) alloyed with aluminum and nickel.
In the analyzed stainless steels, for the stainless steel H beside the presence of ferrite ($\alpha$) and austenite ($\gamma$), that is found in the other stainless steels, one can notice the presence of ferrite ($\delta$).

![XRD of experimental stainless steel](image)

**Fig. 5 XRD of experimental stainless steel:**
a- steel A, b- steel B, c- steel C, d-steel D, e- steel E, f-steel F, g-steel G, h- steel H

### 4. Conclusions

The experiments of cavitation phenomena made on different stainless steels may reveal the following conclusions:

- The SEM analysis reveals different aspects of the affected surface through corrosion were found: very fine cavitations; many cavity uniform degradation with fine and intergranulation very fine cracks and dimensions of cavitations about 10-15µm; surface with equal proportions of fine and big cavitations, with secondary intergranular cracks and cleavage planes.

- The quantitative aspects of cavitation may decrease the cavitation resistance so, in samples of austenite stainless steels C the maximum depth of cavitation is 540µm higher than austenite-ferrite stainless steels B where the depth is only 275 µm. Also, the best cavitation behaviour (between our investigated stainless steels) is for austenite – ferrite stainless steel E, with about 38% surface affected by cavitation in comparison with
austenite stainless steel C where is the highest surface affected by cavitation about 43.85%. Thus, the best ferrous material that can be used in corrosive medium, from the ones presented in this paper, is austenite-ferrite stainless steel E.

- The stainless steels analyzed have 100% austenitic structures and austenite-ferrite with different percentages and precipitates of austenite and ferrite, and in stainless steel H on may observe the delta phase.
- The results confirmed the observations made with SEM method and macro structural analysis.

Future research plans, based on our results help for either the development of new materials with increased erosion cavity resistance, or in knowing the mechanism of cavitation evolution during erosion.

Acknowledgements

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