The effect of shot peening on the stress corrosion cracking resistance of 304 AISI stainless steel immersed in NaCl solution

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Abstract:- Corrosion can deteriorate the material as a result of reaction with its environment. It is one of the major problems encountered in industry and it does cost the world billions of dollars every year. Substantial savings can be obtained in many types of plants through the use of corrosion-resistant materials of construction. Pitting, corrosion and stress corrosion cracking can lead to catastrophic unexpected failures to many engineering applications. Resistance to stress corrosion cracking and pitting can be greatly increased by a cold working process called shot peening. The present experimental work aimed to evaluate the effect of shot peening on retarding pitting and enhancing the stress corrosion cracking resistance of 304 AISI stainless steel in a 250000-ppm sodium chloride solution (NaCl) at 60°C. The results obtained indicated that shot peening is beneficial against corrosion fatigue. Also it is found from the results that increasing intensity and coverage of shot peening will lead to an increase in corrosion resistance.

Keywords: Corrosion; SCC; 304 AISI; Pitting; Stainless steel

1. Introduction

In the 1950s and 1960s martensitic stainless steels for aerospace applications were discovered to be vulnerable to stress-corrosion cracking, and even the very corrosion-resistant titanium alloys could be cracked in environments containing methanol. The problem seemed worse with every new application [1].

One of the most economic and effective preventives for Stress Corrosion Cracking SCC of metallic materials is surface working by shot peening. Using shot peening to control the corrosion of austenitic stainless steel was the topic of Friske's study [2]. It was suggested that shot peening could influence the SCC of these steels by replacing tensile stresses with compressive stresses.

SCC was found to occur in all engineering solids, in a wide range of environments, and in a wide range of compositions and solid-state structures within the materials classes. Since 1950, there was a major effort to find the mechanism of SCC and despite the researchers' huge work there is no definite single mechanism of SCC till now [3,4]. Stress corrosion cracking (SCC) is a progressive localized fracture mechanism in metals that is caused by the simultaneous interaction of a corrodent and a sustained tensile stress [2]. Resistance to stress corrosion cracking and pitting can be greatly increased by a cold working process called shot peening.

The main reason for using stainless steels is their corrosion resistance, but they suffer localized attack in specific environments. Austenitic stainless steels are the most widely used in process industries, but that is not always trouble free.

1.1 Theory of Pitting

Pitting corrosion is a localized accelerated local anodic dissolution where metal loss is exacerbated by the presence of a small anode and a large cathode. It is typified by the formation of holes or cavities on the metal surface called ‘pits’. Pits may be rather small and difficult to detect. In some cases they may be masked due to general corrosion. Pitting may take some time to initiate and develop to an easily viewable size [2,4]. Pitting is considered to be one of the most destructive and insidious forms of corrosion because it can cause failure due to perforation with only a small percent weight loss of the entire structure. The total corrosion, as measured by
weight loss, might be rather minimal. The rate of penetration by pitting may be 10 to 100 times that by general corrosion. Pitting is considered to be more dangerous than uniform corrosion damage because it is more difficult to detect, predict and design against. An extreme example of such catastrophic failure happened recently in Mexico, where a single pit in a gasoline line running over a sewer line was enough to create great havoc to a city, killing 215 people in Guadalajara [1]. Chloride is the most common agent for initiation of pitting. Once a pit is formed, it is effect becomes a crevice; the local chemical environment is substantially more aggressive than the bulk environment. This explains why very high flow rates over a stainless steel (SS) surface tend to reduce pitting corrosion; the high flow rate prevents the concentration of corrosive species in the pit [2, 3].

Grade 304 AISI has excellent corrosion resistance in a wide range of media. It resists ordinary rusting in most architectural applications. It is also resistant to most food processing environments, can be readily cleaned, and resists organic chemicals, dyestuffs and a wide variety of inorganic chemicals. In warm chloride environments, 304 AISI is subject to pitting and crevice corrosion and to stress corrosion cracking when subjected to tensile stresses beyond 50°C. However, it can be successful in warm chloride environments where exposure is intermittent and cleaning is a regular event (such as saucepans and some yacht fittings) [3,4]. The physical properties of grade 304 AISI are shown in Table 1, 2, and 3.

2. Experimental setup:

The objective of the present experimental work is to study the effect of shot peening on corrosion resistance of stainless steel 304 AISI in terms of coverage and intensity. The forms of corrosion taken into consideration here are pitting and stress corrosion cracking. The rolling direction effect was also studied.

Material

The material used is 304 AISI stainless steel sheets of 3.18 mm thickness. Mechanical properties and chemical composition are summarized in the Table 4.

Pitting and SCC Testing

The most common and easiest way to perform SCC test category is that which combines the initiation and propagation stages of SCC in a single test method. The most important factor is that the specimen must have a tensile stress, and it is desirable to know accurately the stress in the specimens. For applied loads on simply supported beams, the stresses can be readily calculated from simply supported deflection formulas, as in equations 1 to 4.

Source of Stress

In order to induce SCC, we need three elements: corrosive media such as a hot 20% w/w (250000 ppm) NaCl solution, susceptible alloy like 304 AISI in chloride solutions, and a sustained tensile stress. This stress is obtained here by means of a galvanized screw stressed against the specimen that is fixed on an aluminum holder. Figure 1-appendix 1 shows a simplified assembly.

Specimens were stressed at yield strength. This was accomplished by stressing a screw against the specimen. The deflection is measured in terms of the distance (X) between horizontal base line and the center of stressed specimen (Figure 2). This distance can be calculated according to the following equations:

\[ M/I = \sigma/y = E/R --- (1) \]

From (1):

\[ \sigma = (y.E)/R --- (2) \]

But \( y = 0.5 \ t \), then:

\[ \sigma = (0.5t.E)/R \]

\[ R^2 = (R-x)^2 + (0.5L)^2 \]

Rearrangement leads to:

\[ R = L \sqrt[2]{(8x)} --- (3) \]

Substitution of (3) in (2):

\[ \sigma = 4t \cdot E \cdot X / L^2 --- (4) \]

Where:

\( \sigma \): yield stress (Pa).

\( t \): thickness of specimen (m).

\( E \): modulus of elasticity (Pa).
X: deflection (m).
L: distance between supports (m).

![Figure 2 Specimen in deflection](image)

Using the information provided in Table 4, and substituting in Eq.4, then (X) can be calculated as follows:

\[
241 \times 10^6 = 4 \times 192.92 \times 10^9 \times 0.00318 \times X (0.121)^2
\]

\[
X = 0.00144 \text{ m.}
\]

In order to avoid errors, a micrometer was used to measure (X) accurately.

**Experimental procedure**

**Specimen Preparation**

Two sets of specimens were used. Both of specimens sets have length and breadth of 121mm and 25 mm respectively. First set was cut parallel to the rolling direction (Longitudinal (L)) and the second were cut at right angle to the rolling direction (Longitudinal transverse (LT)) (Figure 3).

![Figure 3 the two sets of specimen](image)

**Shot Peening coverage**

Specimens were peened at different intensities (i.e. 8A, 10A, and 12A) and coverage's of 100% and 200% were obtained. Peened specimens were cleaned with 20% nitric acid and then washed with distilled water in order to remove the residual shots.

**Immersion**

The specimens were fixed on the aluminum holders using a galvanized screw to prevent galvanic corrosion before they were immersed in the NaCl solution (Dead Sea Water). Figure 4 shows the specimens aquarium with the immersed specimen.

![Figure 4 Immersion aquarium and immersed specimen](image)

The specimens were first immersed on Thursday 4th of December, 2003 at 6:45 p.m and were removed from the solution on Sunday 18th of April, 2004 at 4:15 p.m. This means that the specimens were immersed for 3,237.5 hrs (19 weeks and 4 days approximately). During this period the specimens were checked every 24h and the solutions level was adjusted to the same level by adding distilled water. After leaving the aquarium, the specimens were cleaned with distilled water to remove corrosion products, but we were unable to remove completely the oxide layer formed.

**3. Results & Discussion**
Table 5 summarizes the results obtained. Time to fail was calculated on the basis of pitting formation.

Specimens were taken to Al-Salt College at Albalqa’ Applied University, to be inspected for failures using the Scanning Electron Microscope. They were cleaned with concentrated HCl solution to reduce the thickness of the oxide layer, but the layer was not completely removed (Figure 5).

**Figure 5** Cleaned specimen

The results of scanning were as follows: Specimen No. 1 showed extreme pitting (Figure 6). This is expected since it represents 10A coverage and 100% intensity. This specimen was cut parallel to the rolling direction (L). The specimen showed larger size pits (Figure 6), and intergranular cracks were detected on the surface (Fig. 6).

**Figure 6** Cracks on specimen 1

For specimen No.2 (L) the intensity kept as it is at 10A but this was compensated with increasing the coverage to 200%. The specimen showed better corrosion resistance than that for No.1. Pitting initiation in its early stages was detected after 2087 hour (Figure 7).

**Figure 7** results of specimen 2

The intensity was increased to 12A in the case of specimen No.3 and the coverage kept to 100%, leading to a pronounced increase in resistance (2351 h). Only two tiny pits were found. This was expected since increasing intensity increases residual compressive stresses on the surface (Fig.8).

**Figure 8**Pitting initiation on specimen 3

Specimen 4 was cut normal to rolling direction (LT), it was peened at 10A with 100% coverage, which are the same variables for specimen 1, but the (LT) specimen 4 showed better corrosion resistance than the (L) specimen 1 (Figure 9).

**Figure 9**Some pitting found on specimen 4

The best results were those obtained for specimen 5, which is (LT) with 8A and 200% coverage. The metal surface was found intact and no failures were detected (see Figure 10).
In all the previous cases, shot peening with different intensities and coverages was effective in minimizing corrosion, this was confirmed by scanning specimen 6, which is an ‘as machined’ sample (no peening), the thing that led to its premature failure (only in 319 hours failed). Intergranular cracks and pits were detected all over its surface (see Figure 11).

Some differences can be found between ‘Times to Failure’ listed in Table 5 and scanning results. The reason for this is that pitting was naked eye detected, and some pits are so tiny that they must be magnified thousands of times in order to be detected. Corrosion products on the specimens make the detection even more difficult. Generally, increasing intensity and coverage increased pitting and SCC resistance, and better results were obtained for (LT) specimens. This suggests that corrosion resistance decreases when cutting parallel to rolling direction (L).

4. Conclusions

The 304AISI SS can be considered in certain environments and applications, including marine conditions. The resistance to stress corrosion cracking and pitting can be greatly increased by a cold working process called shot peening, because compressive stresses suppress pit growth. Also shot peening can prevent or at least retard cracking, leading to economic savings as a result of longer equipment life. Also, increasing intensity and coverage increases corrosion resistance, because more compressive stresses are stored in the surface to overcome tensile stresses that lead to cracking.

It can be concluded from the results that specimens cut parallel to rolling direction are more dangerous than those cut normal to rolling direction because they are more susceptible to pitting and stress corrosion cracking.

References

### Table 1: Physical Properties of Grade 304 AISI (Typical Values in Annealed Condition)

<table>
<thead>
<tr>
<th>Physical Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>8.000 kg/m³</td>
</tr>
<tr>
<td>Elastic modulus</td>
<td>193 GPa</td>
</tr>
<tr>
<td>Mean coefficient of thermal expansion</td>
<td>17.3 μm/m°C</td>
</tr>
<tr>
<td>0-100°C</td>
<td>16.8 μm/m°C</td>
</tr>
<tr>
<td>0-315°C</td>
<td>18.4 μm/m°C</td>
</tr>
<tr>
<td>0-535°C</td>
<td>16.2 W/m·K</td>
</tr>
<tr>
<td>Thermal conductivity at 100°C</td>
<td>21.5 W/m·K</td>
</tr>
<tr>
<td>Specific heat 0-100°C</td>
<td>500 J/kg·K</td>
</tr>
<tr>
<td>Electrical conductivity</td>
<td>7200 mΩ</td>
</tr>
</tbody>
</table>

### Table 2: Mechanical Properties of Grade 304 AISI (Typical Values in Annealed Condition)

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength</td>
<td>515 MPa min</td>
</tr>
<tr>
<td>0.2% proof stress</td>
<td>205 MPa min</td>
</tr>
<tr>
<td>Elongation</td>
<td>40% min</td>
</tr>
<tr>
<td>Brinell hardness</td>
<td>201 HB max</td>
</tr>
<tr>
<td>Rockwell hardness</td>
<td>92 HRB max</td>
</tr>
<tr>
<td>Vickers hardness</td>
<td>210 HV max</td>
</tr>
</tbody>
</table>

Note: Slightly different properties are given in other specifications.

### Table 3: Composition of 304 AISI

<table>
<thead>
<tr>
<th>Grade</th>
<th>C (%)</th>
<th>Cr (%)</th>
<th>Mn (%)</th>
<th>Ni (%)</th>
<th>Si (%)</th>
<th>P (%)</th>
<th>S (%)</th>
</tr>
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<tbody>
<tr>
<td>UNS S30400</td>
<td>0.08</td>
<td>18.0-20.0</td>
<td>2.0</td>
<td>8.0-10.5</td>
<td>1.00</td>
<td>0.045</td>
<td>0.03</td>
</tr>
</tbody>
</table>

### Table 5 Results

<table>
<thead>
<tr>
<th>Specimen</th>
<th>N°</th>
<th>Intensity</th>
<th>Percentage Coverage</th>
<th>Time to fall (hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal (L)</td>
<td>1</td>
<td>10</td>
<td>100%</td>
<td>1087</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>10</td>
<td>100%</td>
<td>2087</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>12</td>
<td>100%</td>
<td>2351</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>10</td>
<td>100%</td>
<td>2087</td>
</tr>
<tr>
<td>Longitudinal transverse (LT)</td>
<td>5</td>
<td>8</td>
<td>200%</td>
<td>Not Failed yet</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>As machined</td>
<td></td>
<td>319</td>
</tr>
</tbody>
</table>

Figure 1: Specimen and holder assembly