Methods to Avoid Material Sensitization During Welding for Developing Corrosion Resistant Exhaust System

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Abstract—Manufacturing technology, as a process, revolves around material and material management. The choice of material based on its applications and the necessity of the performance plays as the major clause for manufacturing technology. Material selection itself has many constraints of which corrosion resistance, weld ability are critical in choice of material to suit needs. There are many factors to be considered during choice of material for welding like base material service temperature, compatibility to filler material, shielding gas, weld parameter compatibility - voltage, current and temperature, after weld treatment and cooling methodology etc. These parameters when not chosen to optimum suit, will lead to corrosion or material fracture. One such corrosion to be avoided is inter-granular corrosion near weld zone commonly termed as sensitization.

Sensitization is the phenomenon during which carbides rich in chromium (M23C6 – 65% Cr) are formed along the grain boundaries during welding. Selection of base material, filler material, welding conditions and after weld treatment remains a prime clause to avoid this phenomenon. At conditions there will be restrictions to use materials that are prone to such corrosion and at such times after weld treatment are essential to avoid inter-granular corrosion (Sensitization). This paper explains the iterations carried out on 20 different welded samples prepared by result of DOE method. Experimentations are conducted to check the combinations that are susceptible to inter-granular corrosion near heat affected zones after welding. Paper also discusses about the after treatment methods that shall avoid sensitization.

I. Introduction

Sensitization is the loss of alloy integrity. It results from chromium depletion in the vicinity of carbides precipitated at grain boundaries. Sensitization occurs during welding or annealing after cold-working. Sensitization happens when SS Steel is heated at temperatures between 425°C – 815°C.

At this condition, carbides of chromium are formed near grain boundaries. The precipitation occurs because the carbides are insoluble at these temperatures. Sensitization promotes stress corrosion cracking failure in some stainless steels.

Sensitization often occurs in austenitic steels but however ferritic steels, Martensitic steels are also prone to this phenomenon. Any sensitized microstructure will undergo selective localized corrosion along grain boundaries leading to inter granular corrosion.

Figure 1: Intergranular Stress Corrosion
Figure 2: Stress cracking near HAZ

Figure 3: Stage wise propagation of granular corrosion
Stainless Steels

Stainless Steels (SS): Defined as Iron-base alloy containing \( >10.5\%\)Cr\&\(<1.5\%\)C.

Austenitic stainless steels typically have 16-26% chromium (Cr) and 8-22% nickel (Ni).

Ferritic stainless steels are iron-chromium alloys with body-centred cubic crystal structure having chromium content.

Martensitic stainless steels, which have chromium content between 12 and 18% with 0.15 – 0.30% carbon.

Ferritic – austenitic (Duplex) stainless steels, which contain 18-25% chromium, 3–5% nickel and up to 3% molybdenum.

Martensitic-austenitic steels, which have 13–16% chromium, 5–6% nickel and 1–2% molybdenum.

### Table 1

<table>
<thead>
<tr>
<th>Chemical Properties</th>
<th>Major families of Stainless Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe, &lt;0.12% C</td>
<td>Austenitic Stainless Steel</td>
</tr>
<tr>
<td>16-18% Cr</td>
<td>Ferritic Stainless Steel</td>
</tr>
<tr>
<td>&lt;0.75% Ni</td>
<td>Martensitic Stainless Steel</td>
</tr>
<tr>
<td>&lt;1.0% Mn</td>
<td>Precipitation-hardening Stainless Steel</td>
</tr>
<tr>
<td>&lt;1.0% Si</td>
<td>Duplex ferritic-austenitic Stainless Steel</td>
</tr>
<tr>
<td>&lt;0.040% P</td>
<td>Austenitic Stainless Steel</td>
</tr>
<tr>
<td>&lt;0.030% S</td>
<td>Ferritic Stainless Steel</td>
</tr>
</tbody>
</table>

### Effects of Sensitization

1. Sensitization causes inter granular corrosion
2. Carbide precipitation removes Cr to \(<12\%\) (Sometimes \(<5\%\)) – passive film is lost
3. M23C6 must not form, to prevent sensitization – use stabilized or L grades
4. N delays sensitization kinetics

### Figure 4: Intergranular corrosion observed @ temperatures between 400°C - 900°C

### Figure 5: Chromium depletion due to sensitization @ temperatures between 400°C - 900°C

### Austenitic Steel

- Austenitic stainless steels typically have 16-26% chromium (Cr) and 8-22% nickel (Ni).
- Type 304, which contains approximately 18%Cr and 10%Ni, is a commonly used alloy for welded fabrications and these alloys can be readily welded using any of the arc welding processes (TIG, MIG, MMA and SA).
They exhibit good toughness because they are non-hardenable on cooling, and there is no need for pre- or post-weld heat treatment.

Chromium nickel alloys this is high temperature oxidation

**Resistance**

- High temperate strength: Carbon, nitrogen, niobium and molybdenum.
- The Carbon levels of austenitic stainless steels are always relatively low, so strain-induced martensite is self-tempering and not brittle.

**Material Chemical Composition**

- The chemical composition of the base metal and weld wires are compared.
- The 430LNb weld wire compositions compared with the SUS409, SUS441 and 308.

**Ferritic Stainless Steel**

- Ferritic stainless steels are iron-chromium alloys with body-centred cubic crystal structure having chromium content.
- Ferritic stainless steels have a Cr content of 11-28% with a carbon content below 0.1%.
- These steel exhibit good ductility, formability and moderately better yield strength, but the high temperature strength is somewhat poor.

**Conventional Availability of Steel**

**Choice of shielding gas:**

Should use “Ar+O₂” instead of “Ar+CO₂”

**Surface cleansing and prevention from oil & Dirt**

Washing base metal before welding and cleanse it dirt & oil free before welding

<table>
<thead>
<tr>
<th>PARAMETERS</th>
<th>CONDITION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal thickness (mm)</td>
<td>1.5</td>
</tr>
<tr>
<td>Filler wire diameter (mm)</td>
<td>1</td>
</tr>
<tr>
<td>Voltage (V)</td>
<td>30</td>
</tr>
<tr>
<td>Current (A)</td>
<td>225</td>
</tr>
<tr>
<td>Welding speed (cm/min)</td>
<td>208</td>
</tr>
<tr>
<td>Wire speed (cm/min)</td>
<td>965</td>
</tr>
<tr>
<td>Heat input (kJ/cm)</td>
<td>1.95</td>
</tr>
<tr>
<td>Shielding gas</td>
<td>EN 439-M3 (Ar+2% O2)</td>
</tr>
<tr>
<td>Back protection</td>
<td>EN 439-11 (Pure argon)</td>
</tr>
<tr>
<td>Gas flow (L/min)</td>
<td>8</td>
</tr>
</tbody>
</table>

**Root Cause - Precipitation of carbides and nitrides**

Carbon is normally considered as an undesirable impurity in austenitic stainless steel. While it stabilizes the austenitic structure, it has a great thermodynamic affinity for chromium. Because of this affinity, chromium carbides, M23 C6, Form whenever carbon reaches levels of super saturation in austenite, and diffusion rates are sufficient for carbon and chromium to segregate into precipitates. The solubility of carbon in austenite is over 0.4% at solidification but decreases greatly with decreasing temperature. The solubility is given by:

\[
\log (C \text{ ppm }) = 7771 - \frac{6272}{T \text{ (°K)}}
\]
At room temperature, very little carbon is soluble in austenite; even the 0.03% of L grade is mostly in a supersaturated solution. The absence of carbides in austenitic stainless is due to the slow diffusion of carbon and the even slower diffusion of chromium in austenite. At a carbon level of 0.06%, which is found in most 304, super saturation increases exponentially, while diffusion decreases exponentially. These results in precipitation rates vary with temperatures. Grain boundary diffusion is much more rapid than bulk diffusion and grain boundaries provide excellent nucleation sites. This phenomenon induces precipitation along grain boundaries. Carbon diffuses several orders of magnitude more rapidly than Chromium essentially in situ, depleting the grain boundaries of chromium in solution.

It is understood that Sensitization is a phenomena which occurs mainly in austenitic stainless steel during fabrication which include welding.

Heat Affected Zone - HAZ can lose corrosion properties in ferritic steels and reason for that need not be sensitization. SMIL used mainly ferritic steels for its applications till now. However as a pro-active approach, SMIL has devised its experimentation to avoid sensitization.

The occurrence of sensitization is mostly due to the following combinations

- Material composition used for exhaust assembly
- Welding process used
- Filler wire/electrode used
- Thickness of the job
- Multi layer or single layer weld
- Cooling time(if any) between welding passes
II. CONTROL MEASURES

Three primary ways to combat sensitization

1. Use a low carbon base and filler metal to reduce or eliminate carbon in the welding application. However, is not always practical as carbon is a vital alloying ingredient in some applications.

2. Minimize the time the weld and heat affected zone spend at temperatures conducive to sensitization. General consensus puts that range between 500°C - and 800°C.

3. Use filler metals with special alloying ingredients to prevent the formation of chromium carbides. For instance, titanium and niobium can be alloyed into the filler metal and help prevent reactions between chromium and carbon.

Manipulation of available options

The choice of base metal and Weld wire

Aim of ingredient: \( \frac{Ti+Nb}{C+N} \geq 8 \)

- Ti – Titanium (22)
- Nb – Niobium (41)
- C - Carbon (6)
- N – Nitrogen (7)

Note: Numbers identify the Atomic Number

Base Material and Weld Wire (Filler) point of view

Addition of stabilizers such as niobium or titanium in base material and in filler material prevents sensitization

| Aim of ingredient: | \( \frac{Ti+Nb}{C+N} \geq 8 \) |

Process point of view

Carbon and Nitrogen presence induces and catalyses sensitization phenomenon. The surface of the base material should be cleansed before welding to remove carbon and nitrogen.

Parameter point of view

Usage of Ar+O\(_2\) instead of Ar+CO\(_2\) helps reduce granular corrosion

Figure 8: Weld process optimization

Sensitization can be prevented

Add strong carbide former (stabilizers) Ti, Nb to prevent M23C6 from forming.

Reheat steel to 950 - 1100°C to dissolve Cr23C6 & rapidly cool.

Reduction of carbon content : <0.03wt% or L grade steels

- Modern steel –making methods involving oxygen lancing
- @ 0.02% C complete immunity from inter granular corrosion in 18/8 steels.
- Reducing the time of exposure to the critical temperature range

Control of M23C6 kinetics

- Mo addition lengthens sensitization time
- Ni addition has an adverse effect
- Increasing Cr has beneficial effect

Use of strong carbide – forming elements

- Nb , Ti addition form trans granular carbides & scavenge C
- Less chances of Cr23C6.

Table 4: Optimum Weld Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Trail 1</th>
<th>Trail 2</th>
<th>Trail 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage (V)</td>
<td>18 - 20</td>
<td>18 - 20</td>
<td>18 - 20</td>
</tr>
<tr>
<td>Current (A)</td>
<td>100 - 120</td>
<td>100 - 120</td>
<td>100 - 120</td>
</tr>
<tr>
<td>Shielding Gas</td>
<td>(Ar+5% O(_2))</td>
<td>(Ar+2 % O(_2))</td>
<td>(Ar+20 % O(_2))</td>
</tr>
<tr>
<td>Gas Flow (L/min)</td>
<td>10 - 15</td>
<td>10 - 15</td>
<td>10 - 15</td>
</tr>
</tbody>
</table>
Oxalic Etch Test

Oxalic acid etch test is a rapid method of screening specimens of certain stainless steel grades which are essentially free of susceptibility to inter angular attack associated with chromium carbide participates. The test is used for acceptance but not for rejection of material.

This test may be used in conjunction with other tests to provide a quick method for identifying specimens that are certain to be free of susceptibility to rapid intergranular attack. These specimens are identified by means of their etch structures.

In an environment of 10% oxalic acid (H₂C₂O₄) an anodic current of 1A/cm² is applied for 1.5 minutes at room temperature to a polished sample. By microscopic analysis it is determined if the specimen needs to undergo further testing or if it is not sensitized. If the grain boundaries appear as ditches in the micrograph, it indicates that the sample needs further testing.

Extra low-carbon grades and stabilized grades are tested after sensitizing heat treatments at 1200 to 1250°F(650°C - 675°C), which is the range of maximum carbide precipitation. These sensitizing treatments must be applied prior to submitting the specimens to the oxalic acid etch test. The most commonly used sensitizing treatment is 1 hour at 1250°F (675°C)

Each practice specification contains a table showing which classifications of etch structures on a given stainless steel grade are equal to acceptable or non acceptable performance in that particular test. Specimens having acceptable etch structures need not be subjected to the hot acid test. Specimens having non acceptable etch structures must be tested in the specified hot acid solution.

The etch test is applicable only to those grades listed in the individual hot acid tests and classifies the specimens either as acceptable or as suspect.

Aim

To classify the Etch structures of Austenitic stainless steels using Oxalic acid Etch Test.

Apparatus Required

- Source of Direct Current- capable of supplying about 15 V and 20 A.
- Multimeter(to measure the flow of current)
- Variable Resistance (Note 1).
- Cathode- A cylindrical piece of stainless steel
- Large Clamp - To hold specimen to be etched.
- Metallurgical Microscope-For examination of etched microstructures at 250 to 500 diameters.
- Electrodes of the Etching Cell -The specimen to be etched is made the anode, and a stainless steel hollow rod as large as the specimen to be etched is made the cathode.
- Electrolyte - Oxalic acid, (H2C2O4-2H2O), reagent grade, 10 weight % solution.

Note 1-The variable resistance and the ammeter are placed in the circuit to measure and control the current on the specimen to be etched.
Principle: The experiment works on the principle of Ohm’s Law.

Ohm's Law deals with the relationship between voltage and current in an ideal conductor. This relationship states that:

The potential difference (voltage) across an ideal conductor is proportional to the current through it. The constant of proportionality is called the "resistance", R. Ohm's Law is given by:

\[ V = I R \]

Where; \( V \) is the potential difference between two points which include a resistance \( R \) and \( I \) is the current flowing through the resistance.

Test Practice

<table>
<thead>
<tr>
<th>Sample Description</th>
<th>Type of Welding</th>
<th>Filler Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.3 x 1.3 mm, SUS 304</td>
<td>MIG Welding</td>
<td>SUS 309</td>
</tr>
</tbody>
</table>

Table 6: Test Specimen Preparation

Observations

As per the Specification yellow-green film is should be formed on the cathode side. But here Yellow green film is obtained from Anode side.

Tested as per specification:

Table 7: Polishing

<table>
<thead>
<tr>
<th>Sample Description</th>
<th>Polishing Time</th>
<th>Machines Used</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.3 x 1.3 mm, SUS 304</td>
<td>1 minute (Buff Polish) + 4 minute (220 Emery Paper)</td>
<td>Cutting &amp; Polishing Machine</td>
</tr>
</tbody>
</table>

Table 8: Rinsing

<table>
<thead>
<tr>
<th>Sample Description</th>
<th>Rinsing Liquids</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.3 x 1.3 mm, SUS 304</td>
<td>Hot Water</td>
</tr>
<tr>
<td></td>
<td>Acetone</td>
</tr>
<tr>
<td></td>
<td>Nitric Acid</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sample Description</th>
<th>Rinsing Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.3 x 1.3 mm, SUS 304</td>
<td>3 min</td>
</tr>
<tr>
<td></td>
<td>3 min</td>
</tr>
<tr>
<td></td>
<td>Just dip &amp; take the specimen</td>
</tr>
</tbody>
</table>
Microscopic Analysis - Defect Definition

- The oxalic acid etch test is used to identify intergranular corrosion
- Any sensitized microstructure will undergo selective localized corrosion along grain boundaries leading to intergranular corrosion

The occurrence of sensitization is mostly due to the following combinations;

- Material composition used for exhaust assembly
- Welding process, Filler wire/electrode used
- Thickness of the job, Multi layer or single layer weld
- Cooling time (if any) between welding passes
- After weld cooling time and methodology

Experiment Definition

20 samples were tested upon on defined conditions. Iterated samples were checked with Etch structures Classification (ASTM A 262 – 02ae3) standard reference for sensitization to conclude on granular corrosion.

![Etch structures Classification (ASTMA 262 – 02ae3)](image)

**Legends**

1. Base Metal Welding
2. Polishing
3. Etching Solution Preparation
4. Electrical Adjustment
5. Electrolytic Etching
6. Rinsing
7. Drying
8. Microscopic Analysis
9. Etch Surface Classification
10. Result and Summary

![Figure 11: Experimentation step by step process](image)

![Figure 12: ASTM A 262 – 02ae3 standard reference for sensitization to conclude on granular corrosion](image)

The etch structures obtained after conducting oxalic acid test on the 20 samples, are compared to the ASTM A 262 – 02ae3 etch structure to conclude on occurrence of sensitization. If the structures observed match with any 1 of the 6 samples, then it can be concluded that sensitization has occurred. If the observation does not match the structures of the ASTM standards, then we conclude that the sample is free from sensitization.
Test Samples

Table 9: 20 sample base materials and filler materials with their respective after weld treatment followed for experimentation

<table>
<thead>
<tr>
<th>S.No</th>
<th>Base 1</th>
<th>Base 2</th>
<th>Filler</th>
<th>Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SUS 409L</td>
<td>SUS 409L</td>
<td>SUS 409</td>
<td>Atmospheric air cooled</td>
</tr>
<tr>
<td>2</td>
<td>SUS 409L</td>
<td>SUS 304</td>
<td>SUS 409</td>
<td>Atmospheric air cooled</td>
</tr>
<tr>
<td>3</td>
<td>SUS 304</td>
<td>SUS 409L</td>
<td>SUS 309</td>
<td>Atmospheric air cooled</td>
</tr>
<tr>
<td>4</td>
<td>SUS 304</td>
<td>SUS 304</td>
<td>SUS 309</td>
<td>Atmospheric air cooled</td>
</tr>
<tr>
<td>5</td>
<td>SUS 409L</td>
<td>SUS 409L</td>
<td>SUS 409</td>
<td>Hot air blown @ 141.6°C</td>
</tr>
<tr>
<td>6</td>
<td>SUS 409L</td>
<td>SUS 304</td>
<td>SUS 409</td>
<td>Hot air blown @ 141.6°C</td>
</tr>
<tr>
<td>7</td>
<td>SUS 304</td>
<td>SUS 409L</td>
<td>SUS 309</td>
<td>Hot air blown @ 141.6°C</td>
</tr>
<tr>
<td>8</td>
<td>SUS 304</td>
<td>SUS 304</td>
<td>SUS 309</td>
<td>Hot air blown @ 141.6°C</td>
</tr>
<tr>
<td>9</td>
<td>SUS 409L</td>
<td>SUS 409L</td>
<td>SUS 409</td>
<td>Water quenching</td>
</tr>
<tr>
<td>10</td>
<td>SUS 409L</td>
<td>SUS 304</td>
<td>SUS 409</td>
<td>Water quenching</td>
</tr>
<tr>
<td>11</td>
<td>SUS 304</td>
<td>SUS 409L</td>
<td>SUS 309</td>
<td>Water quenching</td>
</tr>
<tr>
<td>12</td>
<td>SUS 304</td>
<td>SUS 304</td>
<td>SUS 309</td>
<td>Water quenching</td>
</tr>
<tr>
<td>13</td>
<td>SUS 409L</td>
<td>SUS 409L</td>
<td>SUS 409</td>
<td>Oil dipped</td>
</tr>
<tr>
<td>14</td>
<td>SUS 409L</td>
<td>SUS 304</td>
<td>SUS 409</td>
<td>Oil dipped</td>
</tr>
<tr>
<td>15</td>
<td>SUS 304</td>
<td>SUS 409L</td>
<td>SUS 309</td>
<td>Oil dipped</td>
</tr>
<tr>
<td>16</td>
<td>SUS 304</td>
<td>SUS 304</td>
<td>SUS 309</td>
<td>Oil dipped</td>
</tr>
<tr>
<td>17</td>
<td>SUS 409L</td>
<td>SUS 409L</td>
<td>SUS 409</td>
<td>Heated to 1000°C</td>
</tr>
<tr>
<td>18</td>
<td>SUS 409L</td>
<td>SUS 304</td>
<td>SUS 409</td>
<td>Heated to 1000°C</td>
</tr>
<tr>
<td>19</td>
<td>SUS 304</td>
<td>SUS 409L</td>
<td>SUS 309</td>
<td>Heated to 1000°C</td>
</tr>
<tr>
<td>20</td>
<td>SUS 304</td>
<td>SUS 304</td>
<td>SUS 309</td>
<td>Heated to 1000°C</td>
</tr>
</tbody>
</table>

The experiment was conducted on all 20 samples and the after treatment as in above table was carried out. The samples were then studied under microscope and the grains were compared to ASTM reference to confirm sensitization. Of all the samples sample no 12, 13, 15, 16, 17, 19 and 20 showed sensitization occurrence; marked in red in above table.

Sample preparation remains the initial step where 2 base metals are welded using a filler material (per table) and the sample near weld zone is cut to desired dimension. Area of the sample is calculated to regulate appropriate current to the sample while testing.

Table 10: General settings and input parameters followed for all 20 samples

<table>
<thead>
<tr>
<th>SAMPLE PREPARATION - APPLIES TO ALL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polishing</td>
</tr>
<tr>
<td>Buffing (1 min)</td>
</tr>
<tr>
<td>220 grit size emery paper (4 min)</td>
</tr>
<tr>
<td>Anode</td>
</tr>
<tr>
<td>Sample to be etched (Welded)</td>
</tr>
<tr>
<td>Cathode</td>
</tr>
<tr>
<td>Austenitic Steel Hollow rod</td>
</tr>
<tr>
<td>Microscopic Analysis</td>
</tr>
<tr>
<td>500 X Observation</td>
</tr>
<tr>
<td>Voltage</td>
</tr>
<tr>
<td>15V DC Supply</td>
</tr>
<tr>
<td>Etching solution</td>
</tr>
<tr>
<td>100g Oxalic acid + 900ml Distilled water</td>
</tr>
<tr>
<td>Yellow fumes found</td>
</tr>
<tr>
<td>Sample dipped in 30% HNO₃</td>
</tr>
<tr>
<td>Air Dryer</td>
</tr>
<tr>
<td>Tilt the sample gets dried</td>
</tr>
<tr>
<td>Hot Water</td>
</tr>
<tr>
<td>3 Minutes</td>
</tr>
<tr>
<td>Acetone</td>
</tr>
<tr>
<td>3 Minutes</td>
</tr>
</tbody>
</table>

The above said settings are common to all sample preparation and there are certain parameters that differ to suit the sample dimensions. Such settings are mentioned in tables above observations in the following samples.

Sample 12:

Table 11: Input parameters for sample 12

<table>
<thead>
<tr>
<th>SAMPLE 12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base 1</td>
</tr>
<tr>
<td>SUS 304</td>
</tr>
<tr>
<td>Treatment</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>OXALIC ACID ETCHING</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area</td>
</tr>
<tr>
<td>1.60cm²</td>
</tr>
<tr>
<td>Current</td>
</tr>
<tr>
<td>1.75 A</td>
</tr>
</tbody>
</table>

Figure 13: Sample 12 showing characteristics of sensitization
The Etch structure obtained from the sample matches with the ASTM A 262 – 02a\(^3\) etch structure (6). Hence the heat affected zone was found to be sensitized.

**Sample 13:**

Table 12: Input parameters for sample 13

<table>
<thead>
<tr>
<th>SAMPLE 13</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Base 1</td>
<td>Base 2</td>
<td>Filler</td>
</tr>
<tr>
<td>SUS 309L</td>
<td>SUS 409L</td>
<td>SUS 409</td>
</tr>
<tr>
<td>Treatment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oxalic Acid Etching</td>
<td>Area</td>
<td>2.73cm(^2) Current</td>
</tr>
</tbody>
</table>

Figure 14: Sample 13 showing characteristics of sensitization

The Etch structure obtained from the sample matches with the ASTM A 262 – 02a\(^3\) etch structure (6). Hence the heat affected zone was found to be sensitized.

**Sample 15:**

Table 13: Input parameters for sample 15

<table>
<thead>
<tr>
<th>SAMPLE 15</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Base 1</td>
<td>Base 2</td>
<td>Filler</td>
</tr>
<tr>
<td>SUS 304</td>
<td>SUS 409L</td>
<td>SUS 309</td>
</tr>
<tr>
<td>Treatment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oxalic Acid Etching</td>
<td>Area</td>
<td>2.16cm(^2) Current</td>
</tr>
</tbody>
</table>

Figure 15: Sample 15 showing characteristics of sensitization

The Etch structure obtained from the sample matches with the ASTM A 262 – 02a\(^3\) etch structure (6). Hence the heat affected zone was found to be sensitized.

**Sample 16:**

Table 14: Input parameters for sample 16

<table>
<thead>
<tr>
<th>SAMPLE 16</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Base 1</td>
<td>Base 2</td>
<td>Filler</td>
</tr>
<tr>
<td>SUS 304</td>
<td>SUS 404</td>
<td>SUS 309</td>
</tr>
<tr>
<td>Treatment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oxalic Acid Etching</td>
<td>Area</td>
<td>1.75cm(^2) Current</td>
</tr>
</tbody>
</table>

Figure 16: Sample 16 showing characteristics of sensitization
The Etch structure obtained from the sample matches with the ASTM A 262 – 02a^3 etch structure (6). Hence the heat affected zone was found to be sensitized.

**Sample 17:**

Table 15

<table>
<thead>
<tr>
<th>SAMPLE 17</th>
<th>Base 1</th>
<th>Base 2</th>
<th>Filler</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUS 309L</td>
<td>SUS 409L</td>
<td>SUS 409</td>
<td></td>
</tr>
</tbody>
</table>

**Treatment**

Heated to 1000°C using muffle furnace

<table>
<thead>
<tr>
<th>OXALIC ACID ETCHING</th>
<th>Area</th>
<th>Current</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.57cm^2</td>
<td>2.31 A</td>
</tr>
</tbody>
</table>

Figure 17: Sample 17 showing characteristics of sensitization

The Etch structure obtained from the sample matches with the ASTM A 262 – 02a^3 etch structure (6). Hence the heat affected zone was found to be sensitized.

**Sample 19:**

Table 16

<table>
<thead>
<tr>
<th>SAMPLE 19</th>
<th>Base 1</th>
<th>Base 2</th>
<th>Filler</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUS 304</td>
<td>SUS 409L</td>
<td>SUS 309</td>
<td></td>
</tr>
</tbody>
</table>

**Treatment**

Heated to 1000°C using muffle furnace

<table>
<thead>
<tr>
<th>OXALIC ACID ETCHING</th>
<th>Area</th>
<th>Current</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.34cm^2</td>
<td>2.87 A</td>
</tr>
</tbody>
</table>

Figure 18: Sample 19 showing characteristics of sensitization

The Etch structure obtained from the sample matches with the ASTM A 262 – 02a^3 etch structure (6). Hence the heat affected zone was found to be sensitized.

**Sample 20:**

Table 17

<table>
<thead>
<tr>
<th>SAMPLE 20</th>
<th>Base 1</th>
<th>Base 2</th>
<th>Filler</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUS 304</td>
<td>SUS 304</td>
<td>SUS 309</td>
<td></td>
</tr>
</tbody>
</table>

**Treatment**

Heated to 1000°C using muffle furnace

<table>
<thead>
<tr>
<th>OXALIC ACID ETCHING</th>
<th>Area</th>
<th>Current</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.97cm^2</td>
<td>3.01 A</td>
</tr>
</tbody>
</table>

Figure 19: Sample 20 showing characteristics of sensitization
The Etch structure obtained from the sample matches with the ASTM A 262 – 02a^3 etch structure (6). Hence the heat affected zone was found to be sensitized.

III. CONCLUSION

After clearly studying the behavior of the 20 samples treated in different conditions, the followings conclusions are made:

- Sensitization will be avoided if the base material and the filler material’s (Ti+ Nb)/(C+N) is > 8
- Sensitization can be avoided if the samples after welding are air dried
- Sensitization can be avoided if the samples are water quenched
- If the samples are dipped in oil after welding, sensitization phenomenon is most likely to happen
- If the samples are heated between 800F to 1650F, the austenitic steel undergoes changes and makes the sample susceptible to intergranular corrosion. In this temperature range chromium carbides precipitates near the grain boundaries and sensitization phenomenon is most likely to happen

Listed are some lessons that were learnt during the course of the experimentation:

- Sample to be etched must be as small as possible since sample size is very important for etching (1 sqinch – as per ASTM A 262 – 02a^3).
- Sample should be slightly polished up to emery papers 220.
- Yellow green formation indicates that resistance flows in the etching solution, there by chemical reactions take place.
- If no yellow green formation is observed, check the rheostat connection and vary for resistance flow.
- The weld area must free from spatters, burr & oil.

REFERENCES


AUTHOR’S PROFILE

1Dr. S Rajadurai, born in Mylaudy, Kanyakumari District, Tamil Nadu, India, received his Ph.D. in Chemistry from IIT Chennai in 1979. He has devoted nearly 36 years to scientific innovation, pioneering theory and application through the 20th century, and expanding strides of advancement into the 21st century. By authoring hundreds of published papers and reports and creating several patents, his research on solid oxide solutions, free radicals, catalyst structure sensitivity and catalytic converter and exhaust system design has revolutionized the field of chemistry and automobile industry.

As a corporate executive in the United States and India for over three decades, Dr. Rajadurai managed strategy on power train development and emission control for low, ultra low, super ultra low and partial zero-emission systems. From 1990-1996, he was the Director of Research at Cummins Engine Company. He was the Director of Advanced Development at Tenneco Automotive between 1996 and 2002 and subsequently Emission Strategist and Director of Emissions at ArvinMeritor until 2004. From 2004-2009, he was Vice-President of ACS Industries and since 2009 as Head of R&D Sharda Motor Industries Ltd. Dr. Rajadurai has held leadership positions on the Board of Directors for the U.S. Fuel Cell Council, Manufacturers of Emission Control Association (MECA), Chairman of MECA Committee on Advanced Technologies and Alternate Fuels and Walker Exhaust India. He is an active participant in Clean and Green Earth Day demonstrations since 1997 and US Clean Diesel School Bus Summit (2003). He was a panelist of the Scientists and Technologists of Indian Origin, New Delhi 2004. He is a Fellow of the Society of Automotive Engineers. He was the UNESCO representative of India on low-cost analytical studies (1983-85). He is a Life Member of the North American Catalysis Society, North American Photo Chemical Society, Catalysis Society of India, Instrumental Society of India, Bangladesh Chemical Society and Indian Chemical Society.

2Naveen, S, born in Coimbatore District, Tamil Nadu, India, completed his Mechanical Engineering in Amrita University in 2010. He is working as a Senior Engineer in Sharda Motor Industries limited, R&D, Chennai. He is a research and target oriented engineer with skill and global exposure to automobile exhaust product development. He has rich understanding and diversified exposure in the field of product lifecycle management. Having completed his Masters in Automotive Engineering from Staffordshire University, UK (2013), he has strong knowledge in DMAIC methodology to handle projects from concept definition, to manufacturing. He has an eye for intricate details to optimize vehicle emissions, CO₂ control and fuel efficient vehicle design.

3M. Af纳斯 is a senior engineer in Materials Division of Sharda Motor Industries Limited (Research and Development Center). He has completed his M.Tech in Automotive Mechatronics. He was an active student member of the ASME from 2007 – 2008. He has completed Non-destructive testing level-II Course. He is currently working on standardizing the weld procedure for Sharda Motor Industries Limited.

4T. Arun is a senior engineer in the Flow division of Sharda Motor Industries Limited (Research and Development Center). He has completed his B.Tech in Electrical & Electronics Engineering. He has also completed his M.B.A in General. He has done so many testing’s and he has actively involved in the benchmarking of various projects.

5P. Nirmal Kumar is a senior engineer in the Maintenance Division of Sharda Motor Industries Limited (Research and Development Center). He has completed his B.Tech in Mechanical engineering. He is doing his B.E in Electrical and Electronics Engineering. He has actively involved in the performing the preventive maintenance of all the machines. He has actively involved in the breakdown maintenance of all the machines. He is the in-charge of all the electrical works.

6S. Surendhar is an engineer in Materials Division of Sharda Motor Industries Limited (Research and Development Center). He has completed his Diploma in Automobile Engineering. He is currently working on standardizing the weld procedure for Sharda Motor Industries Limited.