Effect of post weld thermal aging (PWTA) sensitization on micro-hardness and corrosion behavior of AISI 304 weld joints

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Abstract. In present study, investigation has been carried out to determine the effect of different post welding thermal aging techniques on Micro-hardness and corrosion behavior of the SS-304 weld joints. The corrosion behavior is investigated in terms of the degree of sensitization. The linear weld joints are fabricated using gas tungsten arc welding using double V groove edges with an overall heat input of 5.496KJ/mm. The post weld thermal aging is carried out by heating to the 650°C temperature for 30 and 120 minutes of soaking duration and then normalizing it. The DLEPR technique is exploited to evaluate sensitization. The results revealed that Micro-hardness studies conclude that Micro-hardness values decrease due to sensitization conditions. The corrosion studies showed that thermally aged welds for shorter duration result into lesser DOS values than the thermally aged welds for longer duration which results into higher DOS value.

1. Introduction

Stainless steel is widely used for mechanical, automotive, and nuclear industries. The wider applications of the stainless steel have been reported by past researchers [1-6]. The chromium, nickel, and molybdenum enhance its corrosion resistance properties. Different grades of austenite steels have been used in the phosphoric acid industry. The worse conditions and impurities loaded chemical attack significantly affects the life-span of the steel [7].

The main problem related to the austenitic stainless steel is its ability to get sensitized when exposed to a temperature range of 450°C to 850°C [8]. Due to sensitization, its corrosion resistance at grain boundaries decreases. The process of formation of carbide precipitates and chromium depletion leads to the reduction in corrosion resistance and is termed as sensitization [9]. Hence, it becomes critically important to determine post weld thermal aging (PWTA) sensitization effect on the behavior of weld joints. Kumar and Shahi investigated the effect of sensitization with varying inputs of heat during welding on AISI 304 specimens [10]. The functional characteristics such as toughness and metallurgical traits were investigated. In another sensitization study, the effect of factors such as corrosion and metallurgical has been carried out on AISI 304 SS Welds [11]. The authors outlined that low degree of sensitization was achieved for low heat input
welds. Jones and Randle [12] studied the sensitization in the temperature range of 723-1173 ℃. It was reported that sensitization directly depends on the structure of grain boundary. The authors found that the degree of sensitization decreases with an increase in boundary length fraction. Atanda et al. [13] observed that SS 316L was found to be sensitized and desensitized at different time and temperature combination. Aydogdu et al. [14] used double loop electrochemical potentiokinetic reactivation (DLEPR) technique to evaluate the DOS in 316L type stainless steel welds.

In the present research work, an effort has been made to determine the effect of post weld thermal aging (PWTA) sensitization on micro-hardness and corrosion behavior of AISI 304 Weld Joints. The Micro-hardness studies have been carried using Micro-hardness tester while corrosion studies in terms of degree of sensitization have been performed with DLEPR technique.

2. Material and Methods

2.1. Experimentation

The workpiece used is AISI 304 stainless steel owing to its applications in fabrication and nuclear industry. The chemical composition of AISI 304 SS is presented in Table 1. The double V groove edges were prepared on the plates for welding. The edges were prepared with root face of 2 mm and groove angle of 60°. The filler wire used in present work was AISI 308L SS wire with a diameter of 2.4 mm. The cleaning was done just prior to welding by wire brushing to remove the oxide layer and then by wiping the surface with acetone to remove any traces of oil, grease, and dust etc. The machining conditions were selected on the basis of preliminary trials. Selected parameters in coded form as well as actual value i.e. first procedure coded as Plate 1 (I = 120A & S = 1.56mm/sec ) for root pass, (I = 140A-145A & S=1.45mm/sec ) for weld passes and second procedure coded as Plate 2 (I = 120 A & S =1.38mm/sec ) for root pass, (I= 140A-145A & S=1.45mm/sec ) for weld passes are presented in Table 1 and Table 2. The final welds were made using the selected parameters. Welds were made by joining two 400mm*50mm*10mm using multi-pass welding. The welding current was varied by giving input to the machine through the control panel. The welding voltage was varying from 13V-15V and welding speed was calculated by measuring the time taken during welding using a stopwatch. The welded joints are shown in Figure 1.

| Type of pass | Current (I) | Voltage (V) | Average speed (S), (mm/s) | Heat input/length(H), (kJ/mm) |
|-------------|-------------|-------------|--------------------------|-------------------------------|
| Root pass   | 120         | 13          | 1.56                     | 0.700                         |
| Middle pass | 145         | 15          | 1.43                     | 1.064                         |
| Cover pass  | 145         | 13          | 1.39                     | 0.949                         |

| Type of pass | Current (I) | Voltage (V) | Average speed (S), (mm/s) | Heat input/length(H), (kJ/mm) |
|-------------|-------------|-------------|--------------------------|-------------------------------|
| Root pass   | 120         | 13          | 1.49                     | 0.732                         |
| Middle pass | 145         | 14          | 1.44                     | 0.986                         |
| Cover pass  | 140         | 15          | 1.38                     | 1.065                         |

Net input heat (kJ/mm) 5.496
Table 2. The control conditions used in plate 2.

| Type of pass   | Current (I) | Voltage (V) | Average speed (S), (mm/s) | Heat input/length (H) (kJ/mm) |
|---------------|-------------|-------------|---------------------------|-----------------------------|
| Root pass     | 120         | 13          | 1.38                      | 0.792                       |
| Middle pass   | 145         | 14          | 1.43                      | 1.022                       |
| Cover pass    | 145         | 14          | 1.39                      | 1.024                       |
| Root pass     | 120         | 13          | 1.48                      | 0.737                       |
| Middle pass 1 | 145         | 15          | 1.44                      | 1.057                       |
| Middle pass 2 | 145         | 14          | 1.38                      | 1.029                       |
| Cover pass    | 145         | 14          | 1.39                      | 1.024                       |

Net input heat (kJ/mm) 6.685

After the completion of gas tungsten arc welding (GTAW) process, heat affected zone (HAZ) and weld zone (WZ) suffered from the distinctive conditions of the material which are significantly affected by the amount of heat input provided to the work specimens. In order to assess the different PWTA treatments, the specimens have been sensitized forcibly in the weld specimen. Two treatments were given to the welded specimen i.e. $T_1$ and $T_2$ as heating to the 650°C temperature for 30 and 120 minutes followed by normalizing it.

Figure 1. Welded joints on plate 1 and plate 2.

In the present case, overall heat input control was never the intention, the only intention was to control the heat inputs from pass to pass. Table 3 shows the codification used for plate 1 and plate 2.

Table 3. Specimens codification used in present work.

| S.No | Artificial aging condition | Codification for plate 1 | Codification for plate 2 |
|------|----------------------------|--------------------------|--------------------------|
| 1    | As welded                  | $W_1$                    | $W_2$                    |
| 2    | PWTA for 30 mins ($T_1$)  | $W_1T_1$                 | $W_2T_1$                 |
| 3    | PWTA for 120 mins ($T_2$) | $W_1T_2$                 | $W_2T_2$                 |

2.2. Characterization

In order to find the Micro-hardness variations across and along the weldments of gas tungsten arc welded joints (with and without post weld thermal aging treatment), Micro-hardness studies were carried out on the samples prepared for this purpose. The specimens are further polished using emery paper and thereafter polished specimens were subjected to Micro-hardness testing with the help of a Micro-hardness tester with
a capacity of 1 kg load. For each specimen, the load used was 500 grams using the dwell time of 20 seconds. Consecutive indents were made from the left side to the right side of the weld. According to the ASTM G-108 standard the dimensional details of the specimen extracted from the welded plates for DLEPR test used for measuring the DOS values as shown in Figure 2.

![Potentiostat, Graphite electrode, Electrochemical cell, Standard calomel electrode, Workpiece, Floating ground](image)

**Figure 2.** Potentiostate and electrodes used for DOS studies.

3. Results and Discussion

3.1. Micro-hardness studies

Micro-hardness studies were carried out along and across the weld center line on different zones of the weldments corresponding to different heat input conditions with PWTA treatments. The data generated from this part of the study is given in Table 4.

**Table 4.** Micro-hardness (VHN0.5) values across the weld: plate 1 (low heat input) and plate 2 (high heat input).

| S. No. | Distance across the weld from center (mm) | Plate 1 | Plate 2 |
|--------|------------------------------------------|---------|---------|
|        | VHN (As welded) W1 | VHN (PWHT for 30 mins) W1T1 | VHN (PWHT for 120 mins) W1T2 | VHN (As welded) W2 | VHN (PWHT for 30 mins) W2T1 | VHN (PWHT for 120 mins) W2T2 |
| 1 | -5 | 265.1 | 240 | 230 | 262.4 | 241.2 | 229.3 |
| 2 | -4 | 267.8 | 243.7 | 233.6 | 266.8 | 242.5 | 233.1 |
| 3 | -3 | 249.1 | 231.8 | 221.7 | 240.3 | 211.6 | 200.3 |
| 4 | -2 | 282.3 | 260.4 | 248.3 | 272.3 | 250.5 | 240.6 |
| 5 | -1 | 234.2 | 223.5 | 213.6 | 230.5 | 206.5 | 194.6 |
| 6 |  0 | 230.1 | 220.2 | 210.5 | 227.8 | 203.3 | 191.6 |
| 7 |  1 | 234.3 | 223.4 | 213.6 | 231.7 | 206.7 | 195.4 |
| 8 |  2 | 281.2 | 258.3 | 248.3 | 272.5 | 248.7 | 241.8 |
| 9 |  3 | 248.9 | 231.7 | 221.6 | 240.2 | 211.5 | 201.3 |
|10 |  4 | 267.3 | 243.7 | 232.6 | 264.2 | 242.7 | 231.7 |
|11 |  5 | 265.2 | 240.8 | 230.8 | 262.6 | 240.4 | 230.1 |
Micro-hardness testing has been carried out across and along the weld centerline (i.e. in the parallel direction to the welds) show that the VHN values were higher in case of low heat input welds and lower in case of high heat input both in as welded and thermally aged conditions. This may be due to the low cooling rates in the high heat input welds which result into coarse grain structure of the weld metal due to which VHN values got decreased. The VHN values while going across the welds were taken in such a way that it covered the base metal, HAZ region, fusion zone and the weld zone (root region). Here, from Figure 3, it was observed that when the indenter moves in a longitudinal direction from weld center to the fusion zone Micro-hardness increases 230.1 to 282.3 for low heat input welds and 227.8 to 272.3 for high heat input welds.

![Figure 3. VHN values across the weld for (plate 1 & plate 2) in as-welded & PWTA conditions.](image)

High VHN values indicate the un-melted (partially) grains in the vicinity of the fusion boundary. During the solidification stage, new precipitating phase consumes these grins as nuclei. After going towards base metal from the fusion zone VHN values show a decreasing trend of HAZ. This may be due to grain coarsening of the HAZ. Figure 3 indicates that after PWTA treatments the VHN values obtained were less than that of as-welded conditions. This may be due to the fact that softening induced in the weld metal due to PWTA treatments given to the weld metal.

### 3.2. Corrosion studies (degree of sensitization) of the weldments

The DOS has been evaluated using DLEPR technique and results have been compiled with related DLEPR curves as shown in Figure 4. The values of DOS come out to be 2.31 % and 3.37% for low and high input heat respectively. Table 5 and Table 6 show that the low heat input welds show lower DOS values than the high heat input welds which show higher DOS values.

**Table 5. DOS values of the as-welded and PWTA treated specimens for plate 1 (low heat input).**

| S.No. | Sample | Temperature (°C) | Time (min.) | $I_r$ (A/cm²) | $I_a$ (A/cm²) | DOS = $I_r/I_a \times 100$ (%age) |
|-------|--------|-----------------|-------------|---------------|---------------|---------------------------------|
| 1     | $W_1$  |     |              | 754.6×10⁻⁶   | 32.59×10⁻³   | 2.31                           |
| 2     | $W_1T_1$ | 650 | 30           | 2.051×10⁻³   | 33.11×10⁻³   | 6.19                           |
| 3     | $W_1T_2$ | 650 | 120          | 4.141×10⁻³   | 38.27×10⁻³   | 10.67                          |
| 4     | HAZ, $W_1$ | 650 |              | 4.026×10⁻³   | 38.25×10⁻³   | 10.54                          |
| 5     | HAZ, $W_1$ |     |              | 3.955×10⁻³   | 38.78×10⁻³   | 10.19                          |
6  HAZ₁ W₁T₁  650  30  8.767×10⁻³  36.33×10⁻³  22.30
7  HAZ₂ W₁T₁  650  30  8.209×10⁻³  37.52×10⁻³  21.87
8  HAZ₁ W₁T₂  650  120  1.076×10⁻³  38.08×10⁻³  28.27
9  HAZ₂ W₁T₂  650  120  1.180×10⁻³  37.53×10⁻³  31.45

Figure 4. DLEPR curves in as-welded conditions and PWTA (T₁ and T₂) treatments of welds. (a) for plate 1 and (b) for plate 2.
From these results, it is clearly shown that the welding heat input has a remarkable effect on the weldments. It is noted that when heat input (either low or highs) welds are given PWTA treatments then the DOS values corresponding to each welded joint show an escalating trend of precipitation. Maximum DOS values are observed when the welds were given PWTA treatment T2 and measured values for low heat input and high heat input welds are 10.67% and 11.58%. These values show that after PWTA treatment the DOS of welded joints increases which indicates that the carbide formation occurred in these welds.

3.3 Heat affected zone (HAZ)

Table 6 shows the DOS values in the heat affected zone and corresponding DLEPR curves have been demonstrated in Figure 5 for different PWTA treatments.

| S.No. | Sample | Temperature (°C) | Time (min.) | \( I_r \) (A/cm²) | \( I_a \) (A/cm²) | DOS = \( I_r/I_a \times 100 \) %
|-------|--------|------------------|-------------|-----------------|-----------------|-----------------------------|
| 1     | W₂     | ---              | ---         | 1.096×10⁻³    | 32.47×10⁻³      | 3.37                        |
| 2     | W₂T₁   | 650              | 30          | 2.592×10⁻³    | 35.65×10⁻³      | 7.27                        |
| 3     | W₂T₂   | 650              | 120         | 4.446×10⁻³    | 38.37×10⁻³      | 11.58                       |
| 4     | HAZ₁ W₂| ---              | ---         | 3.336×10⁻³    | 30.20×10⁻³      | 11.24                       |
| 5     | HAZ₂ W₂| ---              | ---         | 3.655×10⁻³    | 30.80×10⁻³      | 11.86                       |
| 6     | HAZ₁ W₂T₁| 650           | 30          | 9.869×10⁻³    | 39.03×10⁻³      | 25.28                       |
| 7     | HAZ₂ W₂T₁| 650           | 30          | 20.19×10⁻³    | 81.59×10⁻³      | 25.41                       |
| 8     | HAZ₁ W₂T₂| 650           | 120         | 10.88×10⁻³    | 32.08×10⁻³      | 33.91                       |
| 9     | HAZ₂ W₂T₂| 650           | 120         | 12.26×10⁻³    | 40.87×10⁻³      | 30.01                       |

The values of DOS in HAZ come out to be 10.54% and 11.86% for low heat input and high heat input. These results show that DOS in the HAZ of these joints also depend upon the welding heat input used. From the Table 6 and 7, it is observed that after PWTA treatments (T₁ and T₂), DOS performance of the HAZ of these joints shows an increasing trend and the difference in values of PWTA (T₁ and T₂) treated clearly indicates that there is an increment in the DOS values.
Figure 5. DLEPR curves in as-welded conditions and PWTA (T₁ and T₂) treatments of the HAZ region. (a) for plate 1 and (b) for plate 2.
In the HAZ zone, the higher DOS value represents no carbide precipitation during welding process due to intergranular nucleation of carbides which may subsequently grow upon aging. It is also seen from this part of a study that the DOS values of the HAZ of these joints are more as compared to the DOS of the welded joints, which means the phenomenon of precipitation kinetics is more dominating in case of HAZ as compared to the weld metal.

4. Conclusion
The conclusion has been drawn as:

- Micro-hardness studies conclude that micro-hardness values decrease due to sensitization conditions. Corrosion studies which are carried out using DLEPR technique, where DOS measurements are taken across the WZ and HAZ of each joint resulted into higher values of the DOS in HAZ as compared to weld metal.
- The study shows that thermally aged welds for shorter duration result into lesser DOS values than the thermally aged welds for longer duration which results into higher DOS.
- It is indicated that corresponding to low heat input welds DOS values obtained was less as compared to high heat input welds. It indicates that higher heat input promotes greater tendency of carbide formation as compared to lower heat input welds.

Declaration of conflicting interests
The author(s) declares no conflict of interests among all authors.

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