Optimization of Advanced Square Wave AC-GTAW Parameters to Improve Localized Corrosion Resistance of AA6082-T651 Aluminum Welds

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ABSTRACT

In this study, optimization of advanced square wave alternative current GTAW(ASW-AC-GTAW) parameters were conducted to improve localized corrosion resistance of AA6082-T651 aluminum alloy welds. To this objective, positive half cycle current(PHC), negative half cycle current(NHC), frequency(F) and positive half cycle current percentage(PHC%) were selected as main welding parameters and altered at three levels according to Taguchi method and L9(3^4) orthogonal array. To study the localized corrosion resistance of weld metals; potentiodynamic polarization test was performed on all samples and corresponding \( \Delta E_{pit} (E_{pit} - E_{corr}) \) (mV) were measured and considered as evaluation criter. Implementation of variance analysis(ANOVA) on measured data and S/N (Signal-to-Noise) ratios indicated that the optimum levels of PHC, NHC, F, and PHC% were 300A, 190A, 2Hz, 40%, respectively. According to ANOVA of S/N ratios, contribution of PHC, NHC, F, and PHC% to the results were 35.05%, 25.98%, 23.57%, and 15.27%, consecutively. Interval domain for average \( \Delta E_{pit} \) of optimum sample were 381.13 and 385.47 mV. Both of this measurement fallen in the Interval domain. Therefore, the experimental results were in excellent agreement with analytical predictions. The regression model for predicting \( \Delta E_{pit} \) values was obtained using multivariate nonlinear regression.

1-Introduction

Aluminum alloys have gathered a great deal of application in different industries due to their versatile properties. AA6082-T651 alloy is used extensively in different applications such as aerospace, marine, transportation industries, cryogenics and coastal conditions due to the properties such as high specific strength, good weldability, corrosion resistance, formability and low cost [1–5]. Strengthening of AA6082-T651 occurs through heat treatment and artificial aging that causes the formation of \( Mg_2Si \) precipitations in aluminum matrix [6–8]. This alloy is typically fusion welded with GTAW and GMAW processes[9,10]. 5000 aluminum filler metals such as ER5356 are used

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to reduce the solidification cracking sensitivity of AA6082-T651 joints [11]. Welding heat cycles cause many metallurgical changes in metals including dissolution of precipitates, grain growth, alteration of mechanical and corrosion properties[12]. The microstructure of ER5356 weld metal consists of columnar α-Al dendrites, discontinuous interdendritic network which is identified as Al-Mg₂Al₃ eutectic, and secondary phases distributed throughout the matrix. It has been revealed that the interdendritic region contains Al, Mg, Si, Mn and Fe elements, while the secondary phases are identified as Mg₂Al₃, Mg₅Al₈, and Al₁₂(Fe,Mn)₃Si [11,13,14]. Considering the chemical composition of base metal and filler metal, the formation of β” ß’ and Q precipitates in weld zone are possible [15]. Differences between the corrosion potential of the microstructural constituents, result in reduction of resistance to pitting and intergranular corrosion [16–18]. Resistance to localized corrosion will become a major priority when using AA6082-T651 in marine welded structures like ships and supporting structures of offshore oil platforms which are exposed to environments containing chloride ions(Cl⁻).

In ASW-AC-GTAW process, the welding current fluctuates instantaneously between positive and negative half cycles at a certain frequency (i.e. pulsing current). This changes the convection patterns and creates vibration in the weld pool, that results in improvement of joint microstructure and properties. The process includes positive half cycle current (PHC), Negative half cycle current (NHC), frequency (F) and positive half cycle percentage (PHC% or balance) as the main parameters. Bear in mind that the thermal efficiency of PHCs (0.5) are less than NHCs (0.75), thus NHCs melt the base metals and create the weld pool while PHCs maintain an stable arc and provides oxide removal [9,21–23]. Reported metallurgical advantages of welding with pulsing current include weld zone grain refinement, segregation control, reduced solidification cracking sensitivity, less residual stresses and distortion [24–26]. Extensive researches were done on pulse current effects on joint mechanical properties [24–28]. However, despite of using AA6082-T651 welded structures in marine corrosive media and the differences between weld metal and base metal corrosion resistant to pitting, less attention have been payed to weldments corrosion properties [16]. Moreover, the process parameters effect weld metal corrosion properties. Hence, The present research has been executed to comprehend the effects of ASW-AC-GTAW parameters on pitting corrosion of AA6082-T651 alloy welds.

Taguchi method as a systematic approach for experiment design and data analysis is used to control and improve product quality. Furthermore, the experiment design using Taguchi method reduces required tests, experiment cost and time. Optimization of ASW-AC-GTAW parameters using Taguchi method can result in weld quality improvement [16,29,30]. In this work, the experiment design carried out using L₉(3⁴) orthogonal array in accordance with Tguchi method.

2- Experimental Procedure

In this study, wrought AA6082-T651 alloy plates (150×100×6 mm) and ER5356 filler metal (2.4mm in diameter for root pass, 3.2mm in diameter for cap pass) were used. Nominal composition of AA6082-T651 alloy and ER5356 filler are presented in Table 1. Prior to welding procedure, cleaning and oxide removal of the specimens and filler metals were performed by HNO₃ and NaOH chemical solutions. Schematic of joint design is presented in Fig. 1. Welding carried out by Miller Syncrowave 350 LX TIG machine with 16.8 V voltage and advanced square wave AC current (Fig. 2). The Scheme of the polarization test and the results evaluation process are shown in Fig 2 as well. High purity argon gas(99.9%) with 12 lit/min flow rate were used as shielding gas. The main parameters of ASW-AC-GTAW process and their levels are presented in Table 2.

| Table 1. Chemical composition of base metal and filler metal (wt.%). |
|-----------------|---|---|---|---|---|---|---|---|---|
|                | Mg | Si | Cu | Mn | Fe | Ti | Cr | Zn | Al |
| AA6082 (base material) | 0.6-1.2 | 0.7-1.3 | 0.25 | 0.4-1 | 0.50 | 0.10 | 0.25 | 0.20 | Balance |
| ER5356 (filler metal)     | 4.5-5.5 | 0.25 | 0.1 | 0.05-0.20 | 0.40 | 0.06-0.20 | 0.05-0.20 | 0.10 | Balance |
Two specimens were cut off from each welded joint. The root of each weld was notched and a wire connection was fitted closely in the notched area. Specimens were mounted and sanded up to 3000 grid abrasive papers, then they were cleaned completely in an ultrasonic bath. Afterwards, the surface of each sample was masked with a nonconductive coating to obtain an exposure area about 25 mm$^2$. Each test was carried out in a cell containing 1 liter of 3.5 wt.% NaCl solution. The three electrode system was employed for conducting potentiodynamic polarization test with the test sample working as an anode, platinum rode as counter electrode and Ag/AgCl as a reference electrode. The Initial and final potential were consecutively -300 and +600 mV with respect to open circuit potential ($E_{OCP}$). Scanning rate was set to 0.5 mV/s, and due to the unstable nature of the $E_{OCP}$ of this alloy, the test samples were kept in the cell for 1 h before starting the polarization tests to obtain steady measurements. $\Delta E_{pit}(mV)$ was measured and considered as evaluation criteria.

$$\Delta E_{pit} = E_{pit} - E_{corr}$$  \hspace{1cm} (1)\hspace{1cm}

Where $\Delta E_{pit}(mV)$, $E_{pit}$ and $E_{corr}$ are the width of

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**Table 2.** ASW-AC-GTAW variable parameters and levels of each parameter.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Abbr.</th>
<th>Levels</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positive half cycle current (A)</td>
<td>PHC</td>
<td>300</td>
<td>280</td>
<td>260</td>
<td></td>
</tr>
<tr>
<td>Negative half cycle current (A)</td>
<td>NHC</td>
<td>170</td>
<td>190</td>
<td>210</td>
<td></td>
</tr>
<tr>
<td>Frequency (Hz)</td>
<td>F</td>
<td>2</td>
<td>6</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Positive half cycle %</td>
<td>PHC%</td>
<td>40</td>
<td>60</td>
<td>80</td>
<td></td>
</tr>
</tbody>
</table>
of the passive region, pitting potential and corrosion potential, respectively. Taguchi method and $L_9(3^4)$ orthogonal array (Table 3) were used to design the experiment. This array produces 9 welding combinations in which the four main welding parameters of ASW-AC-GTAW are varied in 3 levels. Compared to full factorial design which require 81 samples, using this method reduces the sample size, time and experimental costs. In order to decrease undesirable and uncontrollable variables (i.e. noise effects and bias data) workpieces were welded randomly according to the experiment design in the same day[16,31].

3- Results and discussion
3-1- polarization test

The results of polarization test for 18 samples are presented in table 4 and are plotted in Fig.3. The sample 7 with $\Delta E_{pit} = 98.829 \, mV$ and sample 1 with $\Delta E_{pit} = 347.614 \, mV$ exhibited the lowest and the highest mean of passive region, respectively. Other samples had an intermediate mean width of $\Delta E_{pit}$ ranging from 157.508 to 276.158 mV.

Table 3. $L_9(3^4)$ Orthogonal array – parameter combinations used for welding each joint (coded).

<table>
<thead>
<tr>
<th>Joint no.</th>
<th>PHC level</th>
<th>NHC level</th>
<th>F level</th>
<th>PHC% level</th>
<th>Combinations (PHC,NHC,F,PHC%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>300</td>
<td>170</td>
<td>2</td>
<td>40</td>
<td>(1,1,1,1)</td>
</tr>
<tr>
<td>2</td>
<td>300</td>
<td>190</td>
<td>6</td>
<td>60</td>
<td>(1,2,2,2)</td>
</tr>
<tr>
<td>3</td>
<td>300</td>
<td>210</td>
<td>10</td>
<td>80</td>
<td>(1,3,3,3)</td>
</tr>
<tr>
<td>4</td>
<td>280</td>
<td>170</td>
<td>10</td>
<td>80</td>
<td>(2,1,3,3)</td>
</tr>
<tr>
<td>5</td>
<td>280</td>
<td>190</td>
<td>6</td>
<td>60</td>
<td>(2,2,2,2)</td>
</tr>
<tr>
<td>6</td>
<td>280</td>
<td>210</td>
<td>2</td>
<td>40</td>
<td>(2,3,1,1)</td>
</tr>
<tr>
<td>7</td>
<td>260</td>
<td>170</td>
<td>10</td>
<td>60</td>
<td>(3,1,3,2)</td>
</tr>
<tr>
<td>8</td>
<td>260</td>
<td>190</td>
<td>2</td>
<td>80</td>
<td>(3,2,1,3)</td>
</tr>
<tr>
<td>9</td>
<td>260</td>
<td>210</td>
<td>6</td>
<td>40</td>
<td>(3,3,2,1)</td>
</tr>
</tbody>
</table>

Table 4. Polarization test results (i.e. $\Delta E_{pit}(mV)$), MSD and $S/N$ ratios corresponding to each joint no.

<table>
<thead>
<tr>
<th>Joint no.</th>
<th>Combinations (PHC,NHC,F,PHC%)</th>
<th>$\Delta E_{pit}(1), (mV)$</th>
<th>$\Delta E_{pit}(2), (mV)$</th>
<th>Mean $\Delta E_{pit}(mV)$</th>
<th>MSD</th>
<th>S/N ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(1,1,1,1)</td>
<td>345.69</td>
<td>349.53</td>
<td>347.61</td>
<td>8.28E-06</td>
<td>50.82</td>
</tr>
<tr>
<td>2</td>
<td>(1,2,2,2)</td>
<td>267.96</td>
<td>264.65</td>
<td>266.31</td>
<td>1.41E-05</td>
<td>48.51</td>
</tr>
<tr>
<td>3</td>
<td>(1,3,3,3)</td>
<td>156.48</td>
<td>158.55</td>
<td>157.52</td>
<td>4.03E-05</td>
<td>43.95</td>
</tr>
<tr>
<td>4</td>
<td>(2,1,3,3)</td>
<td>240.37</td>
<td>273.96</td>
<td>239.17</td>
<td>1.74E-05</td>
<td>47.57</td>
</tr>
<tr>
<td>5</td>
<td>(2,2,2,2)</td>
<td>248</td>
<td>250.86</td>
<td>249.43</td>
<td>1.60E-05</td>
<td>47.94</td>
</tr>
<tr>
<td>6</td>
<td>(2,3,1,1)</td>
<td>190.350</td>
<td>193.46</td>
<td>191.91</td>
<td>2.71E-05</td>
<td>45.66</td>
</tr>
<tr>
<td>7</td>
<td>(3,1,3,2)</td>
<td>96.39</td>
<td>101.26</td>
<td>98.83</td>
<td>1.03E-04</td>
<td>39.89</td>
</tr>
<tr>
<td>8</td>
<td>(3,2,1,3)</td>
<td>277.66</td>
<td>276.65</td>
<td>276.16</td>
<td>1.31E-05</td>
<td>48.82</td>
</tr>
<tr>
<td>9</td>
<td>(3,3,2,1)</td>
<td>157.76</td>
<td>159.53</td>
<td>158.65</td>
<td>3.97E-05</td>
<td>44.01</td>
</tr>
</tbody>
</table>
3-2- Finding the optimum condition
The highest width of passive region is desirable, and an increase in $\Delta E_{\text{pit}}$ means higher pitting corrosion resistance [32]. Therefore, in order to find out the optimum condition, analysis of data using Taguchi method on the average of $\Delta E_{\text{pit}}$ were carried out. For Taguchi method, the “Larger The Better (LTB)” were used as quality control criterion. Comparing the mean values is the usual method for data comparison, but it is not well suited when the objective is the performance consistency. Taguchi defines quality as the performance consistency, so a quantity called mean square deviation (MSD) were presented in order to measure it [16, 31]. MSD depends on quality control criterion and for the LTB, it is defined by the following equation [33]:

$$MSD = \frac{1}{n} \times \sum_{i=1}^{n} \left( \frac{1}{y_i^2} \right)$$  \hspace{1cm} (2)

Where $y_i$ is the result of ith sample (in present study $\Delta E_{\text{pit}}$ value of ith sample) and n is the number of test repetitions or replications (i.e. 2 in this case). Logarithmic transformation of the MSD called signal-to-noise ($S/N$) recommended by Taguchi for results evaluation [31,33]:

$$S/N = -10 \log(MSD)$$  \hspace{1cm} (3)

The average of $\Delta E_{\text{pit}}$ for 2 replications and corresponding MSDs and $S/N$ ratios are given in Table 4. Average value of $\Delta E_{\text{pit}}$ corresponding to each level of the parameters are given in Table 5 and Fig 4. The average value of $S/N$ ratios corresponding to each level of the parameters are given in Table 6 and Fig 5. Also, the quantity called $\Delta = \text{Max} - \text{Min}$ is presented in Tables 6, which ranks the parameters according to their influence on the obtained results. Considering the $\Delta$ of Taguchi analysis, welding parameters ranked as following: F (1st), NHC (2nd), PHC (3rd), PHC% (4th). Analysis of means declare that, if samples are welded in optimal condition (i.e. (PHC, NHC, F, PHC %) = (1,2,1,1)), so the average of $\Delta E_{\text{pit}}$ for such samples would be maximum. Meanwhile, analysis of $S/N$ ratios declare that, if samples are welded in optimal condition, so the steadiest performance could be expected. Noted that optimal combination did not exist in prior 9 welded samples that is not unusual because only 9 of 81 possible combinations were welded according to DOE.

**Fig. 3.** Plot of Tafel polarization test results for 9 welded samples.
Table 5. Mean analysis results.

<table>
<thead>
<tr>
<th>parameters</th>
<th>$\Delta E_{\text{pit}}, \text{level 1}$</th>
<th>$\Delta E_{\text{pit}}, \text{level 2}$</th>
<th>$\Delta E_{\text{pit}}, \text{level 3}$</th>
<th>optimum level (coded)</th>
<th>Optimum level (value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHC</td>
<td>257.15</td>
<td>226.84</td>
<td>177.88</td>
<td>1</td>
<td>300</td>
</tr>
<tr>
<td>NHC</td>
<td>228.54</td>
<td>263.97</td>
<td>169.36</td>
<td>2</td>
<td>190</td>
</tr>
<tr>
<td>F</td>
<td>271.89</td>
<td>221.38</td>
<td>168.59</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>PHC%</td>
<td>251.89</td>
<td>185.68</td>
<td>224.28</td>
<td>1</td>
<td>40%</td>
</tr>
</tbody>
</table>

Fig. 4. Plot of Mean $\Delta E_{\text{pit}}(mV)$ of each parameter at three levels (i.e. Main effects plot for means).

Table 6. Mean $S/N$ ratio analysis.

<table>
<thead>
<tr>
<th>parameters</th>
<th>$(S/N)_{\text{level 1}}$</th>
<th>$(S/N)_{\text{level 2}}$</th>
<th>$(S/N)_{\text{level 3}}$</th>
<th>optimum level (coded)</th>
<th>Optimum level (value)</th>
<th>$\Delta$</th>
<th>rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHC</td>
<td>47.76</td>
<td>47.05</td>
<td>44.24</td>
<td>1</td>
<td>300</td>
<td>3.52</td>
<td>3</td>
</tr>
<tr>
<td>NHC</td>
<td>46.09</td>
<td>48.42</td>
<td>44.54</td>
<td>2</td>
<td>190</td>
<td>3.88</td>
<td>2</td>
</tr>
<tr>
<td>F</td>
<td>48.43</td>
<td>46.69</td>
<td>43.92</td>
<td>1</td>
<td>2</td>
<td>4.51</td>
<td>1</td>
</tr>
<tr>
<td>PHC%</td>
<td>47.59</td>
<td>44.68</td>
<td>46.78</td>
<td>1</td>
<td>40%</td>
<td>2.91</td>
<td>4</td>
</tr>
</tbody>
</table>

Fig. 5. Plot of Mean $S/N$ ratios of each parameter at three levels (i.e. Main effects plot for $S/N$ ratios).

3-3- Analysis of variance (ANOVA)

The $\Delta$ quantity ranked main parameters from the most influential parameter (F) to the least influential parameter (PHC %). But contribution of each parameter to the results should be determined. Hence, ANOVA was performed on $\Delta E_{\text{pit}}$s (Standard ANOVA) and $S/N$ ratios (ANOVA of $S/N$ ratios). Both analyses are quite similar and terms of ANOVA were calculated through equations 5 to 9.
\[ SS_T = \sum_{i=1}^{m} \eta_i^2 \times (1/m) \times [\sum_{i=1}^{m} \eta_i]^2 \tag{5} \]

Where \( SS_T \) represents total sum of squares, \( m \) is total number of tests (in this case 18), \( \eta_i \) is \( S/N \) ratio (for ANOVA of \( S/N \) ratios) or \( \Delta E_{pit} \) (for Standard ANOVA) of the \( i \)th test.

\[ SS_p = \sum_{j=1}^{t} \left( S_{\eta j}^2 / t \right) \times \left[ \sum_{i=1}^{m} \eta_i \right]^2 \tag{6} \]

Where \( SS_p \) is the sum of squares from the tested parameters, \( p \) one of the tested parameters, \( j \) the level number of the \( p \) parameter, \( t \) the repetition of each level of the \( p \) parameter, and \( S_{\eta j} \) the sum of \( S/N \) ratios (for ANOVA of \( S/N \) ratios) or \( \Delta E_{pit} \)'s (for Standard ANOVA) involving this parameter and level \( j \).

\[ V_p(\%) = (SS_p / D_p) \times 100 \tag{7} \]

Here \( V_p \) represents the variance of a tested parameter and \( D_p \) is the degree of freedom (DOF) of \( p \) parameter.

\[ SS_p' = SS_p - D_p V_e \tag{8} \]

Where \( SS_p' \) is the corrected sum of squares for \( p \) parameter, and \( V_e \) represents the error variance.

\[ P_p(\%) = (SS_p' / SS_T) \times 100 \tag{9} \]

Where \( P_p \) is the contribution percentage of \( p \) parameter to the obtained results.

The Results of standard ANOVA are given in Tables 7, Fig.6. The Results of ANOVA of \( S/N \) ratios are given in Tables 8, Fig.7 In accordance with ANOVA of \( S/N \) ratios, the contribution of F, NHC, PHC and PHC\% to the results were 35.05%, 25.98%, 23.57%, and 15.27%, consecutively. According to standard ANOVA, the contribution of F, NHC, PHC and PHC\% to the results were 34.81%, 29.80%, 20.87%, and 14.43%, respectively.

<table>
<thead>
<tr>
<th>parameters</th>
<th>Degree of freedom (f)</th>
<th>Sum of squares (( SS_p ))</th>
<th>Variance (V)</th>
<th>F-ratio</th>
<th>pure sum of squares (( SS_p' ))</th>
<th>Influence percentage (p)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHC</td>
<td>2</td>
<td>19197.9</td>
<td>9598.95</td>
<td>1927.94</td>
<td>19187.94</td>
<td>20.87</td>
</tr>
<tr>
<td>NHC</td>
<td>2</td>
<td>27415.4</td>
<td>13707.7</td>
<td>2753.18</td>
<td>27405.44</td>
<td>29.80</td>
</tr>
<tr>
<td>F</td>
<td>2</td>
<td>32018.2</td>
<td>16009.1</td>
<td>3215.41</td>
<td>32008.24</td>
<td>34.81</td>
</tr>
<tr>
<td>PHC%</td>
<td>2</td>
<td>13274.3</td>
<td>6637.15</td>
<td>1333.06</td>
<td>13264.34</td>
<td>14.43</td>
</tr>
<tr>
<td>Error</td>
<td>9</td>
<td>44.8</td>
<td>4.98</td>
<td></td>
<td></td>
<td>0.09</td>
</tr>
<tr>
<td>Total</td>
<td>17</td>
<td>91950.6</td>
<td></td>
<td></td>
<td></td>
<td>100</td>
</tr>
</tbody>
</table>

Fig. 6. Contribution diagram of main welding parameters to the results according to ANOVA of \( S/N \) ratios.
3-4- F-Test (test of significance)
Identifying the significant parameters was accomplished by performing significance test on ANOVA data. In this regard, the F-ratio ($V_p/V_e$) calculated from experimental results is compared with the F-value obtained from the standard F-table for the desired confidence level (C.L.), risk and the degree of freedom of error ($f_e$). If the experimentally calculated F-ratio exceeds F-value extracted from the F-table, then the parameter is significant [31]. From table 8, PHC% has the least value of $SS_p$, which means the least contribution to the results. Experimentally calculated F-ratio for this parameter is 1333.6 while F-value extracted from the F-table for 95% confidence level, risk ($\alpha$) = (1-C.L.)/100 = 0.05 and $f_e = 9$ is $F_{0.05}(1,9)95\% = 5.1174$ [31]. Therefore, this parameter passed the test of significance. Since the parameter with the least contribution to the result is significant then the rest of the parameters are significant too. For ANOVA of $S/N$ ratios it can be seen that $f_e$ is zero, therefore the F-ratio cannot be calculated and F-test is not applicable. Since the confidence level is 95%, so any parameters which contributed more than 5% to the results can be considered as a significant parameter [31].

3-5- Estimation of $\Delta E_{pit}$ of optimal sample
The Following Taguchi model based on results average was used to estimate mean $\Delta E_{pit}$ for the optimum sample [16]:

$$\Delta E_{pit, estimated} = M\beta(M) + (\Delta E_{pit,F1,M})\beta(F) + (\Delta E_{pit,NHC1,M})\beta(NHC) + (\Delta E_{pit,PHC1,M})\beta(PHC) + (\Delta E_{pit,PHC9,M})\beta(PHC\%)$$  \hspace{1cm} (10)

Where $\Delta E_{pit,estimated}$ is mean $\Delta E_{pit}$ estimated by Taguchi model, $M$ is the total average of $\Delta E_{pit}$ of 18 tested samples and $\beta(M), \beta(F), \beta(NHC), \beta(PHC)$ and $\beta(PHC\%)$ are the coefficients corresponding to each parameter which can be calculated by the following equations [16]:

$$\beta(A) = \frac{1}{1/F_p}$$  \hspace{1cm} (11)

$$\beta(M) = \frac{1}{V_e/\sum_i^m \eta_i^2}$$  \hspace{1cm} (12)
Where \( F_p \) is experimentally calculated F-ratio of \( p \) parameter, \( \sum_{i}^{m} \eta_i^2 \) is the sum square of results. By replacing \( \sum_{i}^{m} \eta_i^2 = 968.074 \) and \( V_e = 4.98 \) in equation (12) gives \( \beta(M) = 0.99995 \). Using equation (10) and replacing the values from table 5 gives \( \Delta E_{pit, estimated} \) of optimal sample equal to 382.97 mV.

Prediction of the \( S/N \) ratio for the optimal condition was done by using equation (13) [30]:
\[
(S/N)_{\text{prediction}} = (S/N)_m + \sum_{i=1}^{n} ((S/N)_i - (S/N)_m)
\]
(13)

Where \( (S/N)_m \) is the average of \( S/N \) ratios, \( (S/N)_i \) is the mean \( S/N \) ratio at the optimal level, and \( n \) is the number of the significant parameters. Using equation (13) and replacing the values presented in Table 6 in equation (13) gives \( (S/N)_{\text{prediction}} \) of optimal sample equal to 53.14. According to predicted \( S/N \), \( \Delta E_{pit} \) of optimal sample is \( \Delta E_{pit, prediction} = 454.26 \text{ mV} \). Hence, a wide range estimation of \( \Delta E_{pit} \) of optimal sample is obtained. Since the predicted values are mean \( \Delta E_{pit} \) of optimal sample, then there is a 50/50 chance that the results of testing the optimal sample fall below or above the predicted value.

### 3-6 Finding Confidence Interval (C.I.)

The confidence interval (C.I.) is calculated as follows[31]:
\[
C.I. = \pm \sqrt{\frac{F_a(1,f_e) \times V}{N_{eff}}} \quad (14)
\]

Where \( N_{eff} \) is the effective sample size or effective number of replications and calculated by the following expression:
\[
N_{eff} = \frac{N}{(1 + \sum_{p} (f_p \times \beta(p))))} \quad (15)
\]

Where \( \beta(p) \) is the \( \beta \)-factor of \( p \) factor. \( C.I. \) represents the boundaries of the expected performance in the optimum condition at a confidence level used for the \( F \) value from the standard F-table. For 95% C.I., \( F \)-value extracted from the standard F-table is \( F_{0.05}(1,9)95\% = 5.1174 \). By replacing \( N_{eff} = 2 \) and \( V_e = 4.98 \) the confidence interval can be calculated as \( C.I. = \pm 3.57 \text{ mV} \). Therefore, the interval domain for average \( \Delta E_{pit} \) of optimum sample calculated with 95% confidence level is expected to be (379.4, 386.54) (mV). This domain means for a population of samples welded at the optimum condition, it can be expected that the \( \Delta E_{pit} \) of such set would be in the range between 379.4 and 386.54 mV. As the C.I. is calculated at 95% confidence level, then if many sets were welded at optimum condition and C.I. for each set were calculated, it can be expected that about 95% of these C.I.s would finally contain the mean \( \Delta E_{pit} \) of such sets. As \( f_e \) is zero in ANOVA of \( S/N \) ratios, then \( V_e \) cannot be calculated and therefore, C.I. cannot be calculated either.

In order to confirm the results obtained from Taguchi and ANOVA, a sample was welded at the optimum condition (PHC, NHC, F, PHC%) = (1,2,1,1). Polarization test was performed two times for the optimum sample. The \( \Delta E_{pit} \) values of the optimum sample were 381.13 and 385.47 mV. Both of these measurements were in the C.I. domain. Therefore, the experimental results were in excellent agreement with analytical predictions.

### 3-7 Finding regression model

Finding an empirical relation between the ASW-AC-GTAW parameters and the data obtained from polarization test (i.e. \( \Delta E_{pit} \) values) was carried out using a multivariate nonlinear regression model. The simplest relation between the ASW-AC-GTAW parameters and \( \Delta E_{pit} \) values can be described by the following equation:
\[
y = \Delta E_{pit} = f(PHC,NHC,F,PHC%) = f(x_1,x_2,x_3,x_4) \quad (16)
\]

Where \( y \) is a substitute for \( \Delta E_{pit} \) and \( x_1, x_2, x_3 \) and \( x_4 \) are substituted for PHC, NHC, F and PHC%, consecutively. To describe the more detailed relation between the main parameters of the process (i.e. independent variables) and \( \Delta E_{pit} \) values (i.e. dependent variable) the following multivariate nonlinear equation was used:
\[
y = y_0 + a \times x_1 + b \times x_1^2 + c \times x_2 + d \times x_3^2 + m \times x_3 + n \times x_4^2 + r \times x_4 + t \times x_4^2 \quad (17)
\]

Where \( y_0 \) is the free term of regression eq. (17), the coefficients (a, c, m and r) are coefficients of linear terms and the coefficients (b, d, n and t) are coefficients of quadratic terms. The Coefficients of the regression model were calculated using SigmaPlot software. The following complete regression model has been obtained by replacing the values of each coefficient in the regression eq. (17):
\[
y = -9445.1236 + 14.7939 \times x_1 -0.0229 \times x_1^2 + 90.5012 \times x_2 -0.2460 \times x_2^2 + 20.0566 \times x_3 -2.1319 \times x_3^2 -33.2839 \times x_4 + 0.2717 \times x_4^2 \quad (18)
\]
Fitting of the regression model was evaluated by ANOVA. ANOVA results of the regression model were presented in Table 9. The comparison between experimental data and predicted values obtained using regression model are presented in Fig. 8.

If in ANOVA of the regression model, the value of F statistic is a large number it can be concluded that the independent variables contribute to the prediction of the dependent variable, and if the F ratio is around 1, it can be concluded that there is no association between the variables. The P value is the probability of being wrong in concluding that there is an association between the dependent and independent variables[36]. For the presented regression model R, $R^2$ and $R^2_{adj}$ values near 1 indicate that the equation is a good description of the relation between the independent and dependent variables[36]. For the presented regression model R, $R^2$ and $R^2_{adj}$ values were 0.9989, 0.9977 and 0.9960 respectively, and the standard error of estimation was 5.40. Therefore, it can be concluded that the regression model estimations are in excellent agreement with empirical data.

### 4- Conclusion

This study was conducted to optimize ASW-AC-GTAW parameters to improve localized corrosion resistance of AA6082-T651 Aluminum welds made by ER5356 filler metal. Experiment design was carried out using Taguchi method and L$_0$(3$^4$) orthogonal array. The following conclusion can be drawn:

All parameters concluded in the experimental
design passed the F-test and proved to be significant parameters. Optimum condition obtained in accordance with Taguchi and mean analysis was (PHC, NHC, F, PHC%) = (1,2,1,1) (i.e. 300A, 190A, 2Hz and 40% respectively). According to ANOVA of $S/N$, F with 35.05% had the predominant contribution to the result, and NHC and PHC with 25.98%, 23.57% consecutively had an intermediate contribution to the result, and PHC% with 15.27% had the least contribution. The experiment error due to uncontrollable factors was about 0.09%. The confidence interval at 95% confidence level was between 379.4 and 386.54 mV. $\Delta E_{pit}$ values of the optimum sample were 381.13 and 385.47 mV which is in excellent agreement with analytical predictions. For the presented multivariate nonlinear regression model $R$, $R^2$ and $R^2_{adj}$ values were 0.9989, 0.9977 and 0.9960 respectively, and the standard error of estimation was 5.40. Therefore, it could be concluded that Taguchi method, ANOVA and nonlinear regression are useful tools for optimization of ASW-AC-GTAW process and prediction of results.

References


[8] Abbas Bahrami, Modeling of Precipitation Sequence and Ageing Kinetics in Al-Mg-Si Alloys, This research was performed in the department of Materials Science and Engineering of Technical University of Delft., 2012. doi:10.1007/s13398-014-0173-7.2.


