# EFFECT OF WELDING PARAMETERS ON PITTING RESISTANCE EQUIVALENT NUMBER OF DUPLEX STAINLESS STEEL CLAD METALS

By
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**ABSTRACT**

Resistance to pitting corrosion is commonly expressed by Pitting Resistance Equivalent Number (PREN). During duplex stainless steel weld cladding, pitting resistance balance is disturbed by the formation of intermetallic precipitates, or by excessive precipitation of secondary austenite in surface regions. Redistribution of alloying elements as a result of such transformations may lead to local reductions in pitting resistance. Hence, control of PREN is very important to maintain the required pitting resistance. This paper highlights an experimental study and analysis of various welding parameters influencing PREN in duplex stainless steel cladding deposited by Flux Cored Arc Welding (FCAW). The experiments were conducted based on four-factor five level central composite rotatable design and a mathematical model was developed to predict PREN. The effects of welding parameters on PREN have been presented in graphical form, which helps in selecting appropriate welding parameters to obtain the desired PREN quickly.

## 1. INTRODUCTION

Corrosion is one of the main problems in the chemical industries. A huge quantity of metal is lost by corrosion, which affects the cost of products and the environment. The development of new chemical processes requiring storing facility for more corrosive substances, call for new materials for the fabrication of storage and pressure vessels. The fabrication of a vessel entirely from corrosion resistant material becomes an extremely uneconomical solution in many situations. The composite materials solved the problem, using a base material of carbon steel for the strength of the structure and a clad layer of corrosion resistant material in contact with the chemical corrosive atmosphere. The characteristics desirable in such a cladding alloy are reasonable strength, weldability to the steel, resistance to general and localized corrosion attack, and good corrosion fatigue properties [1]. A candidate material for cladding that has excellent corrosion resistance and weldability is duplex stainless steel [2].

The clad layer is generally obtained by rolling, explosive welding and fusion welding. In recent years, fusion weld cladding processes have been developed rapidly and are now applied in numerous industries such as chemical plants, nuclear power plants, food processing and petrochemical industries, etc. The biggest difference between welding a joint and cladding is dilution. The composition and properties of clad metals are strongly influenced by the dilution obtained. Control of dilution is very important in cladding, where low dilution is typically desirable.

It is well known that chromium, molybdenum, and nitrogen improve the resistance to pitting corrosion in Fe-Ni-Cr alloys. The effects of these elements can be quantified by an empirical parameter termed PREN, which is expressed [3] using the following equation (1).

$$PREN = (wt.\ \%\ Cr) + 3.3\ (wt.\ \%\ Mo) + 16\ (wt.\ \%\ N) \quad \text{----------} (1)$$

PREN of clad layer is mainly governed by its chemical composition. During cladding, pitting resistance balance is disturbed by the formation of intermetallic precipitates, or by excessive precipitation of secondary austenite in surface regions [3]. Redistribution of alloying elements as a result of such transformations may lead to local reductions in pitting resistance and associated corrosion attack, either in regions that are depleted with respect to crucial alloy elements, or in the precipitates themselves. This is due to dilution of filler metal and base metal. For this reason, a critical attention during cladding of these steels is required.

This paper highlights an experimental study carried out to analyze the effects of various FCAW process parameters on PREN in duplex stainless steel cladding of low carbon structural steel plates. The experiments were conducted based on four-factor five level central composite rotatable design with full replications technique and a mathematical model was developed using multiple regression method. The developed mathematical model has been checked for their adequacy and significance.

## 2. EXPERIMENTAL PROCEDURE

The experiments were conducted using UNIMACRO welding machine. Test pieces of size 200 mm × 150 mm × 20 mm were cut from low carbon structural steel (IS: 2062) plate and its surfaces were ground to remove oxide scale and dirt before cladding. Flux cored duplex stainless steel welding wire (E2209T1- 4/1) of 1.2 mm diameter was used for depositing the weld beads. Chemical composition of the substrate and welding wire is given in Table 1. $CO_2$ gas at a constant flow rate of 18 liters/min was used for shielding. The experimental setup used consisted of a traveling carriage with a table for supporting the specimens. The experiments were conducted by laying three beads using stringer bead technique with a constant overlap of 40%. An interpass temperature of 150° C was maintained during all the cladding experiments.

The chosen welding parameters affecting PREN were welding current, welding speed, contact tip-to-workpiece distance, and welding gun angle. In this study, forehand welding (push angle) technique was used. The chosen response was PREN.

The working ranges of all selected welding parameters were fixed by conducting trial runs. The working range of each process parameters was decided upon by inspecting the cladded plate for a smooth appearance without any visible defects such as surface porosity, undercut, etc [4]. The upper limit of the parameters was coded as +2 and the lower limit was coded as -2. The decided limits and levels of the selected process parameters with their units and notations are given in Table 2.

The design matrix chosen to conduct the experiment was a central composite rotatable design [5]. In this work, thirty-one deposits were made using cladding condition corresponding to each treatment combination of parameters as shown in Table 3 at random. At the end of each run, settings for all four parameters were disturbed and reset for the next deposit. This is essential to introduce variability caused by errors in experimental settings [6].

The cladded plates were cross-sectioned at their midpoints to obtain test specimens of 20 mm wide. The top surface of the specimens was ground flat and three test burns were taken to find out chemical composition using an optical emission spectrometer. The average values of the three readings were presented in Table 3. PREN was calculated using equation (1). The calculated values are given in Table 3.

## 3 DEVELOPMENT OF A MATHEMATICAL MODEL

The response function representing PREN can be expressed using the equation (2)

$$Y = f(X_1, X_2, X_3, X_4) \text{ ------------- } (2)$$

Where $Y$ = PREN
$X_1$ = Welding current, A
$X_2$ = Welding speed, cm/min
$X_3$ = Contact tip-to-workpiece distance, mm and
$X_4$ = Welding gun angle, degree

The second order response surface model [7] for the four selected parameters is given by the equation (4)

$$Y = \beta_o + \sum_{i=1}^{4}\beta_i X_i + \sum_{i=1}^{4}\beta_{ii} X_i^2 + \sum_{\substack{i=1\\ i<j}}^{4}\beta_{ij} X_i X_j \text{ ------- } (3)$$

The second order response surface model [equation (3)] could be expressed as follows

$$Y = {}_{0} + {}_{1}I + {}_{2}S + {}_{3}N + {}_{4}T + {}_{11}I^2 + {}_{22}S^2 + {}_{33}N^2 + {}_{44}T^2 + {}_{12}IS + {}_{12}IN + {}_{13}IN + {}_{14}IT + {}_{23}SN + {}_{24}ST + {}_{34}NT \text{ ---------------- } (4)$$

Where $â_0$ is the free term of the regression equation, the coefficients $â_1$, $â_2$, $â_3$ and $â_4$ are linear terms, the coefficients $â_{11}$, $â_{22}$, $â_{33}$, and $â_{44}$ are the quadratic terms, and the coefficients $â_{12}$, $â_{13}$, $â_{14}$, $â_{23}$, $â_{24}$, and $â_{34}$ are the interaction terms. The coefficients were calculated using QA six-sigma software. After determining the coefficients, the mathematical model was developed as follows

**PREN** = $32.496 - 0.662I - 1.001S + 0.334N - 0.493T + 0.221I^2 + 0.071S^2 + 0.077N^2 - 0.222T^2 - 0.174IS - 0.093IN + 0.121IT + 0.041SN - 0.526ST + 0.083NT$

The insignificant coefficients were eliminated without affecting the accuracy of the developed model by using t-test. This is done by back elimination technique, which is available in QA six-sigma software. The final mathematical model was constructed by using only these coefficients. The developed final model with welding parameters in coded form was given below.

**PREN** = $32.632 - 0.662I - 1.001S + 0.334N - 0.493T + 0.207I^2 - 0.236T^2 - 0.174IS - 0.526ST$

The adequacy of the developed model was tested using the analysis of variance (ANOVA) technique [8]. As per this technique, if the calculated F-ratio value for the developed model does not exceed the standard tabulated value of F-ratio for a desired level of confidence (95%) and the calculated R- ratio value of the developed model exceeds the standard tabulated value of R-ratio for a desired level of confidence (95%), then the model is said to be adequate within the confidence limit. These conditions were satisfied for the developed model, which is given in Table 4. The validity of this model was again tested by drawing scatter diagram as shown in Fig. 1.

Conformation tests were conducted in the same experimental setup to confirm the results of the experiments. The results of the conformity tests show the accuracy of the model developed, which is above 97%. This is shown in Table 5.

## 4.RESULTS AND DISCUSSIONS

The above developed model can be used to predict PREN by substituting the coded values of the respective welding parameters. The PREN calculated from this model for each set of coded welding parameters are represented in graphical form in Figs. 2 to 5. Effects of welding parameters on PREN are given below.

### 4.1 Effect of welding current on PREN

Fig 2 shows PREN decreases with increase in welding current. This may be due to increase in dilution with increase in welding current. Increase in dilution enhances the carbon content and reduces the chromium and nickel content of the claddings. The base metal had no chromium and nickel and higher carbon with respect to the chemical composition of the duplex stainless steel welding wire. Hence, the change in dilution affects chromium and nickel content [9]. The decrease of chromium and nickel with increase in dilution results in decreased PREN in the clad metals.

### 4.2 Effect of welding speed on PREN

From Fig. 3, it is evident that PREN decreases with increase in welding speed. At higher speeds, the arc digs the base metal in front of the weld pool increasing dilution resulting in decreased PREN in clad metals [9].

### 4.3 Effect of contact tip-to-workpiece distance on PREN

It is evident from Fig.4 that PREN increases slightly with increase in contact tip-to-workpiece distance. Increase in contact tip-to-workpiece distance increases the circuit resistance, which reduces the welding current. This decrease of welding current reduces the penetration of arc and hence reduces the dilution [10]. The decrease in dilution significantly increases chromium and moderately increases nickel content of the claddings which results in increased PREN in the clad metals [9].

### 4.1.4 Effect of welding gun angle on PREN

From Fig. 5, it is evident that PREN increases with increase in welding gun angle. The reason is when the angle is increased in forehand welding the arc force pushes the weld metal forward i.e. towards the cold metal, which reduces penetration and dilution resulting in increased PREN in the clad metals [11].

**Table 1 Chemical composition of substrate and welding wire**

| Material | Elements, % (Wt.) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | C | Si | Mn | P | S | Al | Cr | Mo | Ni | $N_2$ | Cu |
| IS: 2062 | 0.150 | 0.160 | 0.870 | 0.015 | 0.016 | 0.031 | --- | --- | --- | --- | --- |
| E2209 T1-1/4 | 0.023 | 0.760 | 1.030 | 0.024 | 0.002 | --- | 23.14 | 3.05 | 9.22 | 0.130 | 0.09 |

**Table 2 Welding parameters and their levels**

| Parameter | Unit | Notation | Levels | | | | |
|---|---|---|---|---|---|---|---|
| | | | -2 | -1 | 0 | +1 | +2 |
| Welding Current | A | I | 200 | 225 | 250 | 275 | 300 |
| Welding Speed | cm/min | S | 20 | 30 | 40 | 50 | 60 |
| Contact tip-to-workpiece distance | mm | N | 22 | 24 | 26 | 28 | 30 |
| Welding gun (push) angle | degree | T | 20 | 15 | 10 | 05 | 00 |

**Table 3 Design matrix with chemical composition of the claddings and PREN**

| Trial | Design Matrix | | | | Elements, % (Wt.) | | | | | | | PREN |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | I | S | N | T | Cr | Mo | Nb | Ni | C | N | Cu | |
| 1 | -1 | -1 | -1 | -1 | 21.640 | 3.054 | 0.018 | 8.862 | 0.037 | 0.132 | 0.058 | 33.82 |
| 2 | +1 | -1 | -1 | -1 | 21.104 | 3.078 | 0.018 | 8.555 | 0.041 | 0.140 | 0.056 | 33.50 |
| 3 | -1 | +1 | -1 | -1 | 21.242 | 3.059 | 0.018 | 8.758 | 0.035 | 0.137 | 0.055 | 33.53 |
| 4 | +1 | +1 | -1 | -1 | 19.964 | 2.874 | 0.017 | 8.076 | 0.053 | 0.119 | 0.052 | 31.34 |
| 5 | -1 | -1 | +1 | -1 | 21.881 | 3.198 | 0.018 | 9.120 | 0.036 | 0.134 | 0.056 | 34.58 |
| 6 | +1 | -1 | +1 | -1 | 21.219 | 2.996 | 0.017 | 8.379 | 0.037 | 0.134 | 0.053 | 33.26 |
| 7 | -1 | +1 | +1 | -1 | 21.284 | 3.129 | 0.018 | 8.730 | 0.038 | 0.155 | 0.056 | 34.10 |
| 8 | +1 | +1 | +1 | -1 | 20.504 | 2.800 | 0.017 | 8.000 | 0.041 | 0.138 | 0.054 | 31.95 |
| 9 | -1 | -1 | -1 | +1 | 21.589 | 3.023 | 0.018 | 8.989 | 0.029 | 0.142 | 0.057 | 33.83 |
| 10 | +1 | -1 | -1 | +1 | 20.779 | 3.033 | 0.017 | 8.412 | 0.041 | 0.113 | 0.052 | 32.59 |
| 11 | -1 | +1 | -1 | +1 | 19.164 | 2.857 | 0.017 | 7.718 | 0.053 | 0.107 | 0.049 | 30.31 |
| 12 | +1 | +1 | -1 | +1 | 19.021 | 2.725 | 0.017 | 7.704 | 0.052 | 0.110 | 0.049 | 29.79 |
| 13 | -1 | -1 | +1 | +1 | 21.851 | 3.098 | 0.019 | 8.880 | 0.029 | 0.141 | 0.059 | 34.34 |
| 14 | +1 | -1 | +1 | +1 | 21.030 | 3.161 | 0.018 | 8.674 | 0.039 | 0.134 | 0.056 | 33.60 |
| 15 | -1 | +1 | +1 | +1 | 20.212 | 2.943 | 0.017 | 7.853 | 0.047 | 0.104 | 0.051 | 31.58 |
| 16 | +1 | +1 | +1 | +1 | 19.212 | 2.705 | 0.017 | 8.236 | 0.047 | 0.117 | 0.050 | 30.03 |
| 17 | -2 | 0 | 0 | 0 | 21.942 | 3.275 | 0.019 | 9.026 | 0.055 | 0.131 | 0.060 | 34.86 |
| 18 | +2 | 0 | 0 | 0 | 19.975 | 2.978 | 0.017 | 8.153 | 0.049 | 0.132 | 0.052 | 31.91 |
| 19 | 0 | -2 | 0 | 0 | 21.478 | 3.265 | 0.018 | 8.833 | 0.030 | 0.144 | 0.057 | 34.58 |
| 20 | 0 | +2 | 0 | 0 | 19.267 | 2.795 | 0.016 | 7.840 | 0.043 | 0.156 | 0.048 | 31.01 |
| 21 | 0 | 0 | -2 | 0 | 20.321 | 2.911 | 0.017 | 8.399 | 0.041 | 0.116 | 0.052 | 32.00 |
| 22 | 0 | 0 | +2 | 0 | 21.369 | 3.150 | 0.018 | 8.707 | 0.036 | 0.117 | 0.053 | 33.64 |
| 23 | 0 | 0 | 0 | -2 | 20.310 | 2.992 | 0.017 | 8.314 | 0.050 | 0.119 | 0.053 | 32.08 |
| 24 | 0 | 0 | 0 | +2 | 19.805 | 2.899 | 0.017 | 8.089 | 0.045 | 0.112 | 0.053 | 31.17 |
| 25 | 0 | 0 | 0 | 0 | 20.761 | 2.980 | 0.018 | 8.630 | 0.033 | 0.124 | 0.055 | 32.58 |
| 26 | 0 | 0 | 0 | 0 | 19.608 | 2.880 | 0.018 | 8.078 | 0.055 | 0.139 | 0.050 | 33.00 |
| 27 | 0 | 0 | 0 | 0 | 21.051 | 3.107 | 0.018 | 8.630 | 0.033 | 0.124 | 0.055 | 33.30 |
| 28 | 0 | 0 | 0 | 0 | 20.606 | 3.117 | 0.018 | 8.443 | 0.041 | 0.114 | 0.053 | 32.73 |
| 29 | 0 | 0 | 0 | 0 | 20.114 | 2.949 | 0.018 | 8.630 | 0.033 | 0.124 | 0.055 | 32.13 |
| 30 | 0 | 0 | 0 | 0 | 20.134 | 2.949 | 0.018 | 8.274 | 0.034 | 0.123 | 0.052 | 31.83 |
| 31 | 0 | 0 | 0 | 0 | 20.180 | 2.950 | 0.018 | 8.630 | 0.033 | 0.124 | 0.055 | 31.90 |

**Table 4 Analysis of variance for testing adequacy of the model**

| Response parameter | 1st order terms | | 2nd order terms | | Lack of fit | | Error terms | | F ratio | R ratio | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | SS | DF | SS | DF | SS | DF | SS | DF | | | |
| PREN | 43.09 | 4 | 8.84 | 10 | 2.01 | 10 | 1.9 | 6 | 0.64 | 11.74 | Adequate |

F-ratio (10, 6, 0.05) = 4.09, R-ratio (14, 6, 0.05) = 3.96, SS - Sum of squares, DF - Degrees of freedom

**Table 5 Comparison of predicted and actual values of PREN**

| Process parameters in Coded form | | | | Predicted PREN | Actual PREN | % Error |
|---|---|---|---|---|---|---|
| I | S | N | T | | | |
| - 0.11 | - 0.22 | 0.09 | - 0.3 | 33.05 | 33.80 | 2.27 |
| - 0.79 | - 0.35 | 0.94 | 1.02 | 33.34 | 32.66 | - 2.04 |
| - 0.66 | 0.03 | 0.90 | 1.03 | 32.66 | 33.62 | 2.94 |

$$\%\,\text{Error} = \frac{\text{Actual value} - \text{Predicted value}}{\text{Predicted value}} \, X\,100$$

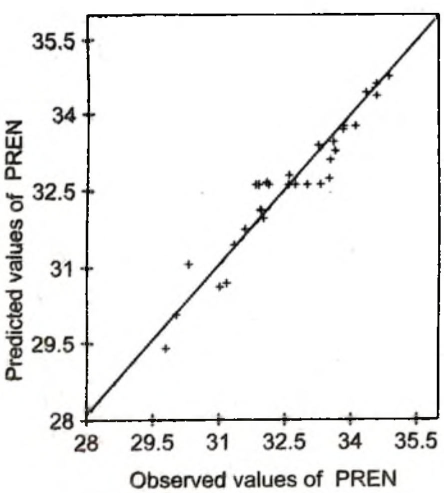


Fig.1 Scatter diagram of PREN model

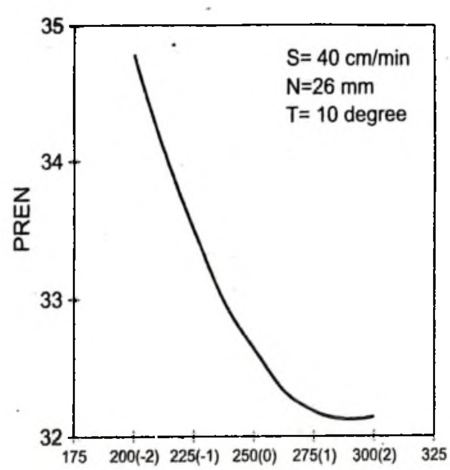


Fig.2 Effect of welding current on PREN

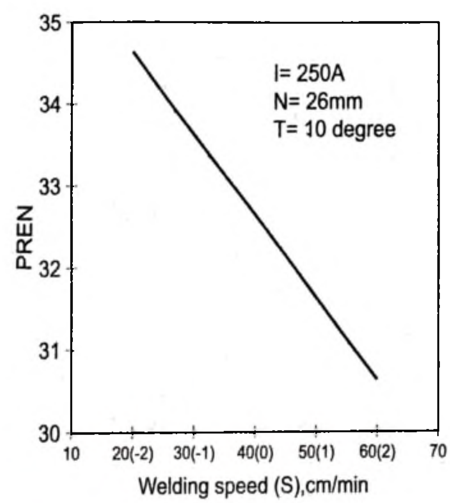


Fig.3 Effect of welding speed on PREN

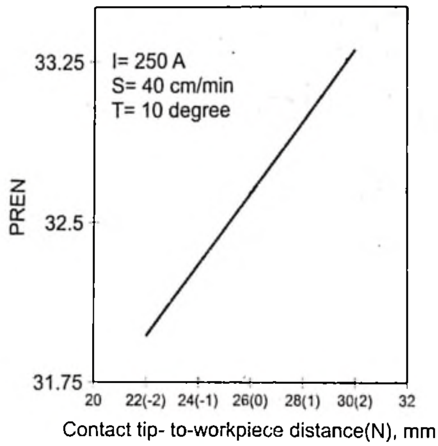


Fig.4 Effect of contact tip-to-workpiece distance on PREN

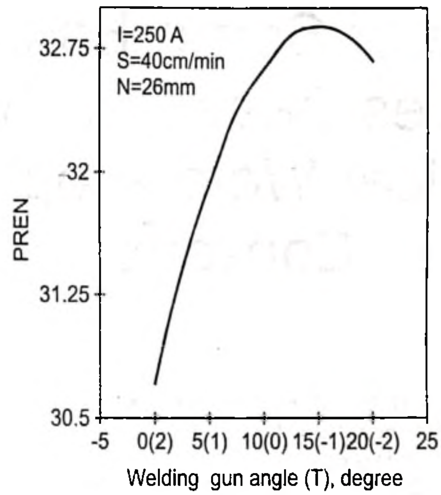


Fig.5 Effect of welding gun angle on PREN

## 5. CONCLUSIONS

The effects of welding current, welding speed, contact tip-to-workpiece distance and welding gun angle on PREN in duplex stainless steel clad deposits was investigated. The following are the conclusions derived from the above investigation.

- A five level four factor full factorial design matrix based on the central composite rotatable design technique can be used for the development of mathematical model to predict PREN of duplex stainless steel cladding deposited by FCAW.
- PREN decreases with rise in welding current and welding speed.
- PREN increases with rise in welding gun angle and contact tip-to-workpiece distance.
- PREN can be maximized by appropriate selection of welding process parameters.

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