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Evaluate Effect of Pulsed Current Gas Tungsten Arc Welding Process Parameter on Intergranular Corrosion of SS304L Weld

Sagarkumar I. Shah[a,b*], Hemantkumar R. Thakkar[c], Harmik Patel[d], Pratik T. Kikani[b] & G. D. Acharya[e]

[a]Gujarat Technological University, Gujarat, India.
[b]Mech. Engg. Dept., Atmiya University, Rajkot, Gujarat, India
[c]Mech. Engg. Dept., G. H. Patel College of Engineering & Technology, V.V.Nagar, Gujarat Technological University, Gujarat, India
[d]Atmiya Institute of Technology & Science, Rajkot, Gujarat Technological University, Gujarat, India
[e]Atmiya University, Rajkot, Gujarat, India

**Corresponding author: shahsagar.7@gmail.com*

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ABSTRACT

Austenitic stainless steel (ASS) is the most common type of stainless steel which offers excellent weldability and mechanical properties. ASS is being used for various applications i.e. automotive, oil and gas and chemical industries in which the welding process plays a prominent role. Welding process selection is the main factor that emphasizes mechanical and corrosion resistance properties in various aggressive environments. There are various corrosion occurs in ASS but intergranular corrosion (IGC) forms during welding at elevated temperatures. IGC mainly occurs at grain boundaries of structure and resulting chromium depletion due to precipitation of chromium carbide at the grain boundary. In present work pulsed current gas tungsten arc welding (PCGTAW) process was used to investigate intergranular corrosion by oxalic acid test as per ASTM A262 Practice A. Experiments performed based on Taguchi L9 using design of experiments and corrosion rates are evaluated at base metal, heat affected zone and weld zone. This work is aimed to optimize process parameters followed by regression analysis to IGC susceptibility in the weldment. In this investigation, it has been found from ANOVA and main effects plots that peak current and base current are the most significant parameters in the PCGTAW process. The results of the corrosion test revealed that heat affected zone is more susceptible to IGC. At the end, it has been observed that the optimum value of peak current, base current and frequency based on regression analysis are 100 A, 50 A and 6 Hz respectively.

Keywords: Pulsed current gas tungsten arc welding (PCGTAW); SS304L; intergranular corrosion; ASTM A262 PRACTICE A; Regression analysis

INTRODUCTION

Steel has been invented from the beginning of the twentieth century by adding a minimum of 12% chromium compared to carbon steel to achieve better corrosion resistance properties. Chromium tends to form an efficient protective layer of passive film on steel which minimizes the risk of surface dissolution. Vannan & Thangavel (1978) showed that due to development in metallurgical science furthermore, alloying elements i.e. molybdenum, sulfur, nickel, silicon, titanium, copper, etc. have been added in steel to create stainless steel and attain desired mechanical as well as corrosion resistance properties. Stainless steels are further categorized as austenitic, ferritic, duplex, martensitic and precipitation hardenable steel. Austenitic stainless steel is the most popular grade of stainless steel with excellent weldability but it is exposed to higher temperatures then arise problems like intermetallic phases formation, intergranular corrosion, embrittlement, etc. especially during welding and heat treatment.

There are various applications of austenitic stainless steel such as nuclear, oil and gas, petrochemical, marine and corrosive chemical environment where these types of issues are facing challenges to control intermetallic phase formation, intergranular corrosion, etc.(Malik, 1981). These are the major concern to carry out such investigations to overcome real-time issues in various industrial applications.

Stainless steel is chromium and nickel based alloy and austenitic stainless steel (ASS) is one of the most commercial types of stainless steel used in various applications. Usually, austenitic stainless steel having an average percentage ratio of chromium (Cr) and nickel (Ni) is 18:8. The 300 series is well-known in austenitic stainless steel and the most common grade is 304. Based on the weightage of carbon percentage 304 is further categorized by straight grades SS304, L-grades SS304L and H-grades SS304H. The carbon content of all three categories is straight grades 0.03 – 0.08%, L-grades ≤ 0.03% and H-grades 0.04-0.10% (Malik, 1981). The straight grades are normally used in various applications such as food processing equipment, heat exchangers, chemical containers, etc. which shows good integration of mechanical and corrosion resistance properties. The L-grades are particularly made with low carbon content to minimize the risk of corrosion susceptibility and enhance weldability in a different aggressive environment. The h-grades with higher carbon content are generally used in high-temperature applications where wear resistance and hardness are a concern. Moreover, higher carbon content creates an issue in heat affected zone (HAZ) of the weld and it tends to carbon diffusion at elevated temperature which causes cracks (Malik 1981).

Typically the austenitic stainless steel is welded by any arc welding process with excellent weld quality. Although welding of austenitic stainless steel is having some intrinsic issues with the arc welding process but still it is considered as the most suitable and appropriate process (Vannan & Thangavel, 1978). In general weld quality is affected by every arc welding process and facing issues of cold claps, micro-fissures, hot cracks and non-homogeneities of chemicals at weld joint (Malik, 1981). Austenitic stainless steel is not required any pre-heating or post-weld heat treatment if it is welded by arc welding because it becomes non-hardenable during cooling which offers superior toughness (Malik 1981).

During arc welding of austenitic stainless steel, there may be also a risk of cracks in heat affected zone and weld zone. As austenitic stainless-steel structure contains the major portion of austenite which leads to solidification cracking in the weld zone and it also weld zone becomes further susceptible to cracks (Malik, 1981). Ferrite presence in the structure plays a prominent role to minimize the occurrence of cracks in the weldment. The benefit of ferrite content in structure can reduce the risk of interdendritic cracks and segregation of harmful dissolve impurities at low temperatures. Ferrite content can be restrained in the microstructure of austenitic stainless steel by selecting appropriate filler wire with 5 – 10% ferrite content which is tremendously advantageous and defeats crack susceptibility using gas tungsten arc welding (Cornu & Weston 1988; Brooks & Thompson 1991).

Welding of thin austenitic stainless steel is often challenging due to variation weld penetration and this can be avoided by selecting appropriate filler wire and use of base metal with sulfur content less than 0.008 % (Cornu & Weston, 1988). SS304L is used for various applications for joining thick and thin sections where pulsed current gas tungsten arc welding (PCGTAW) technique is more adequate to attain good weld quality at minimal cost and maximum repeatability (Murugan et al. 1993). These kinds of qualities are fulfilled by using an appropriate statistical method such as taguchi method which is developed to optimize the product and process design (Kapur & Cho, 1994). The pulsed GTAW process has been studied very little for intergranular corrosion (IGC) using the design of experiments through Taguchi (Tarng & Yang, 1998). However, up till now, many researchers have investigated geometry of weld bead and PCGTAW process parameters optimization using fuzzy logic, artificial neural network and visual image analyzer (Chen et al. 2000; Chen et al. 2003; Chen et al. 2004; Zhao et al. 2004; Tsai et al. 2006).

It has been also noticed that welding of SS304L with other alloy leads to higher hardness in the weldment (Ahmad et al. 2007). Experimental results of past research on corrosion revealed that the modified taguchi method exhibits good corrosion resistance and base current, as well as peak current, are proved as significant parameters in PCGTAW (Balasubramanian et al. 2007). PCGTAW process has plenty of benefits like low heat input and accordingly reduce distortion as well as warpage in thin sheets. It also allows better control over welding speed, weld penetration in the weld pool with good quality of the weld. PCGTAW process has the facility to customize process parameters as per the required application in a meaningful way to carry out weld joint defect-free (Tsai et al. 2006). One of the major issues in the PCGTAW process is to weld thin sections with desired weld penetration and it is recommended to use stainless steel with less than 0.008% sulfur content (Giridharan & Murugan, 2009; Yousefieh et al. 2011).

Here the pulsed current is a mode of metal transfer and in this mode welding current speedily changes between higher current level and lower current level. The lower current level and higher current level are termed as base current and peak current respectively. In this pulsed technique, weld area fused during higher or peak current due to heating and solidified during lower or base current due to cooling. This can be done by an operator using a manual operated gas tungsten arc welding machine and it permits an operator to set pulsed mode process parameters such as peak current, base current and frequency as per particular applications (Mohan, 2014; Prasad et al. 2014). Normally good mechanical and corrosion resistance properties are exhibited by the PCGTAW process for stainless steel weld (Cornu & Weston 1988). These process parameters of PCGAW are represented in Figure 1 in which Ib, Ip, Tb and Tp represent base current, pulse current, base current duration and pulse current duration respectively. Pulse frequency (F) can be formulated based on Tb and Tp which is given by

$$F(Hertz) = \frac{1}{Tp + Tb} \tag{1}$$

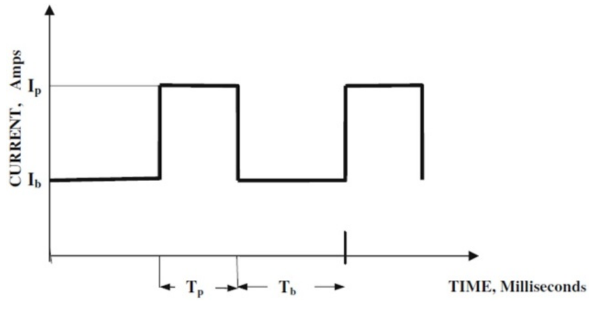

FIGURE 1. PCGTAW Process Parameters
(Yousefieh et al. 2011)

Intergranular corrosion is a relatively uncommon form of corrosion and occurs at elevated temperatures. In this corrosion mechanism chromium is reacting with carbon and it creates chromium carbide Cr23C6 at the temperature range from 450^0 C to 850^0 C. This phenomenon is known as sensitization and usually arises during the welding and heat-treatment process. Very few researches have been carried out in a thin section of SS304L using the PCGTAW process in the context of intergranular corrosion (Prasad et al. 2014). Chromium alloy in austenitic stainless steel plays a key role to improve corrosion resistance and act as a passive layer but due to sensitization chromium content is reduced functionally which leads to corrosion Prasad et al. 2014). ASTM A262 is a standard screening examination that helps to find the materials that are incorrectly processed (ASTM A262-15, 2015). In IGC, carbon content is affected by the temperature range of sensitization which accelerates the kinetics of corrosion (Iacoviello et al. 2017; Kamachimudali et al. 2017). Intergranular Corrosion is the result of the precipitation of carbides in the vicinity of the grain boundaries. For the carbides to precipitate along the grain boundaries it must obtain chromium from the surrounding metal and this causes chromium depleted zones at the grain boundaries. If materials with improper heat treatment are subjected to a corrosive environment in the higher temperature range they fail or crack much more rapidly than properly treated materials (Pichumani et al. 2018). In ASS sensitization occurs in the case of isothermal heating which leads to poor mechanical properties and precipitation of intermetallic phases (Hu et al. 2020; Shah et al. 2021; Shah et al. 2022).

An exhaustive study of literature shows that lots of research work have been carried out on SS304 using gas tungsten arc welding (GTAW) for process parameter optimization to predict weld bead geometry using various statistical methods. However, both GTAW and PCGTAW process have been used to check susceptibility of IGC on SS304 but less work has been reported on SS304L using PCGTAW. This work is emphasized on intergranular corrosion behavior of SS304L weldment using PCGTAW process as per ASTM A262 Practice A at weld zone (WZ), base metal (BM) and heat affected zone (HAZ).

MATERIALS AND METHODS

WELDING PROCESS

In the present investigation, a 5 mm thick plate of SS304L was welded by using the PCGTAW process with ER304 filler wire of 1.5 mm diameter and pure argon as a shielding gas. A schematic diagram of the PCGTAW process is shown in Figure 2 (Mohan, 2014). The root gap, root face and included angle were kept 2 mm, 1.5 mm and 60^0 respectively as shown in Figure 3 through weld joint design. During welding pulse on time was kept constant as 40%. The chemical composition in wt % of SS304L is shown in Table 1. The levels of selected process parameters for the PCGTAW process are given in Table 2 based on essential process parameters and size of filler wire as per ASME section IX.

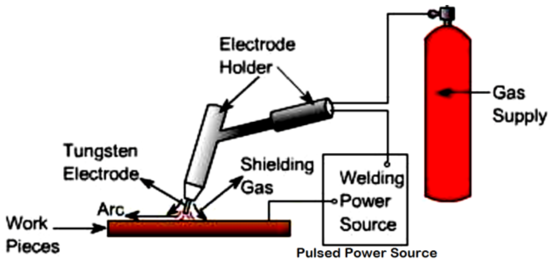

FIGURE 2. Schematic Diagram of PCGTAW Process (Mohan, 2014)

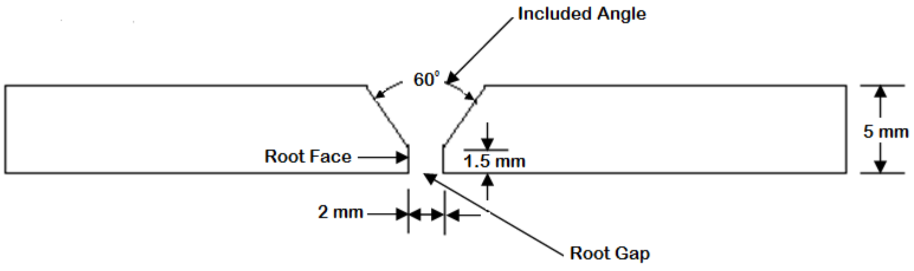

FIGURE 3. Weld Joint Design

TABLE 1. Chemical Composition of SS304L in wt %

Element	C	Mn	S	P	Si	Cr	Ni	Mo	Cu
wt %	0.017	1.420	0.004	0.027	0.369	18.406	8.346	0.010	0.031

TABLE 2. Levels of Process Parameters

Parameters	Levels		
	Low	Medium	High
Peak Current (I_p) Amp	100	130	160
Base Current (I_b) Amp	50	60	70
Frequency (f) Hz	6	8	10

DESIGN OF EXPERIMENTS

In this experiment three parameters i.e. base current, peak current and frequency were selected and performed for three levels. Experiments were designed by Taguchi L9 orthogonal array method using MINITAB 17 and it is shown in Table 3. The reason for chosen three levels in design was the non-linear behavior of the selected process parameters. Taguchi method is acquiring data very effectively with less number of experiments which saves time, cost, and discovering significant factors quickly (Kapur & Cho 1994).

TABLE 3. Design of experiments as per Taguchi L9

Sample	Peak load (Ip)	Base load (Ib)	Frequency (f)
1	100	50	6
2	100	60	8
3	100	70	10
4	130	50	8
5	130	60	10
6	130	70	6
7	160	50	10
8	160	60	6
9	160	70	8

INTERGRANULAR CORROSION TEST

Intergranular corrosion was evaluated by using ASTM 262A Practice-A oxalic acid etch test (ASTM A262-15, 2015). First specimen prepared by cutting the weldment from weld zone, base metal and heat affected zone according to ASTM standards. For solution preparation 100gm of Oxalic acid crystals ($H_2C_2O_4{\bullet}2H_2O$) and 900mL distilled water were mixed and then stirring the solution till all crystals dissolve. Then specimens were clean using acetone and weight each before immersion in solution. Specimens were immersed in the solution for 48 hours to accelerate corrosion. After 48 hours specimens were taken out from the solution and rinsing it in hot water as well as clean with acetone to avoid crystallization of oxalic acid on the etched surface during drying. Last each specimen were weighted for weight loss due to corrosion and based on that corrosion rate was formulated using the given equation

$$\text{millimeter per month} = \frac{7305 \times W}{A \times t \times d} \tag{2}$$

Here, W = Loss of weight (gm), A = Surface area (cm^2), t = Time of exposure (hours) and d = Material density (gm/cm^3)

REGRESSION ANALYSIS

In regression analysis, the regression equation is developed through mathematical and statistical techniques. The regression method is used to evaluate the effect of process parameters and also to predict corrosion rate by developing the regression model in the form of an imperial equation (Kamachimudali et al. 2017). In regression equation base current, peak current and pulsed frequency are raw parameters which are functions of corrosion rate as a response. There were three models predicted such as for BM, HAZ and WZ. In the present work, main effect plots for means and SN ratios were analyzed based on a linear regression model to evaluate the significance of process parameters.

RESULTS AND DISCUSSION

INTERGRANULAR CORROSION BEHAVIOR

Intergranular corrosion (IGC) was performed as per ASTM 262A Practice A and accelerated by using oxalic acid for 48 hours. There were three zones from weldment selected such as BM, HAZ and WZ for the test and weldments are shown in Figure 4. All samples were evaluated for IGC and corrosion rate calculated based on weight loss due to corrosion. The results of corrosion rate for all samples with three different zones are given in Table 4 based on weight loss due to chromium carbide precipitated at grain boundaries. Chromium carbide reduces the chromium content at grain boundaries which leads to intergranular corrosion and deterioration of material. The ill effect of this intergranular corrosion causes reduction in weight of material. It indicated that HAZ is more prone to IGC compare to WZ and BM. However, all the weldments are meeting the requirements as per ASTM 262A in terms of corrosion rate.

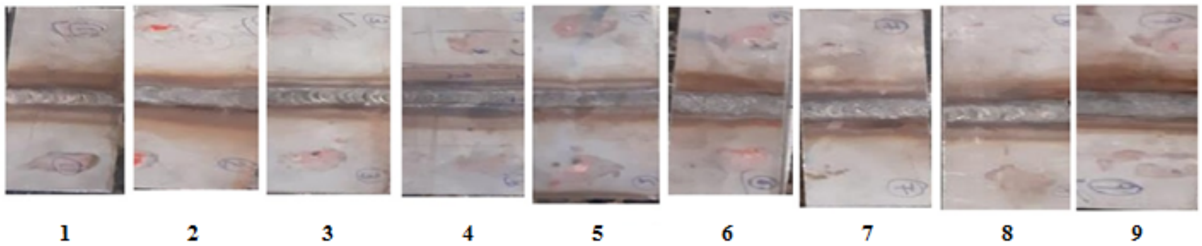

FIGURE 4. Welded Samples

TABLE 4. Corrosion Rate of weldments

Sample	Zone	Area (cm^2)	Weight (gm)		Weight Loss (gm)	Corrosion Rate (millimeter per month)
			Before	After		
1	BM	26.04	44.09	44.07	0.02	0.015
	HAZ	9.24	10.47	10.44	0.03	0.052
	WZ	9.48	11.22	11.20	0.02	0.04
2	BM	27.52	46.33	46.30	0.03	0.019
	HAZ	9.92	12.39	12.36	0.03	0.059
	WZ	11.04	14.51	14.49	0.02	0.039
3	BM	26.58	44.94	44.91	0.03	0.022
	HAZ	8.82	10.72	10.69	0.03	0.061
	WZ	11.18	14.05	14.03	0.02	0.042
4	BM	26.52	45.19	45.14	0.05	0.033
	HAZ	11.96	14.47	14.42	0.05	0.078
	WZ	12.86	17.91	17.86	0.05	0.067
5	BM	31.26	54.01	53.95	0.06	0.039
	HAZ	9.02	11.48	11.44	0.04	0.081
	WZ	10.04	13.90	13.86	0.04	0.071
6	BM	24.48	40.09	40.03	0.06	0.044
	HAZ	10.18	13.29	13.24	0.05	0.089
	WZ	9.78	12.57	12.53	0.04	0.069
7	BM	27.36	45.79	45.71	0.08	0.057
	HAZ	9.6	13.79	13.73	0.06	0.124
	WZ	8.8	11.46	11.41	0.05	0.116
8	BM	31.08	54.36	54.25	0.11	0.066
	HAZ	8.82	10.06	10.00	0.06	0.132
	WZ	9.44	11.85	11.80	0.05	0.108
9	BM	25.42	44.20	44.10	0.10	0.072
	HAZ	9.72	12.29	12.22	0.07	0.141
	WZ	10.6	16.49	16.43	0.06	0.114

REGRESSION ANALYSIS

The applied base current, peak current and frequency were examined in the development of the mathematical model of intergranular corrosion rate. The correlation between these factors and corrosion rate on the SS304L by PCGTAW process were obtained by multiple linear regression analysis with a confidence level of 95%. Table 5 and 6 shows the results of analysis of variance (ANOVA) for means and signal to noise (SN) ratios respectively with the response of corrosion rate at BM, HAZ and WZ. The prime objective of ANOVA is to investigate the most influence process parameter on corrosion rate.

Table 5 revealed that P-value for means implies that values 0.001 and 0.047 are significant because it has a value less than 0.05. It can be concluded that peak current and base current are significant parameters while frequency is a non-significant parameter for corrosion rate. The main effect plot for means is illustrated in Figure 5. It indicated that an increase in peak current corrosion rate increases drastically while an increase in a base current slight increase in corrosion rate. On the other end graph shows that there is no significant effect of frequency on corrosion rate.

Table 6 showcased that P-value for SN ratio implies that values 0.005 and 0.037 are significant because it contains P-value than 0.05. It can be summarized that peak current and base current are significant parameters while frequency is a non-significant parameter for corrosion rate. The main effect plot for the SN ratio is illustrated in Figure 6. It revealed that an increase in peak current corrosion rate increases significantly while an increase in a base current minor increase in corrosion rate. On the other end graph shows that there is no significant effect of frequency on corrosion rate.

TABLE 5. ANNOVA Results for Means

Source	DOF	Sum of Squares (SS)	Mean Squares (MS)	F - Value	P - Value
Peak Current , I_p (Amp)	2	0.006367	0.003183	1336.08	0.001
Base Current , I_b (Amp)	2	0.000096	0.000048	20.23	0.047
Frequency, f (Hz)	2	0.000002	0.000001	0.35	0.742
Error	2	0.000005	0.000002		
Total	8	0.006470			

TABLE 6. ANOVA Results for SN Ratios

Source	DOF	Sum of Squares (SS)	Mean Squares (MS)	F - Value	P - Value
Peak Current, I_p (Amp)	2	20.9108	10.4554	219.25	0.005
Base Current, I_b (Amp)	2	2.4807	1.2403	26.01	0.037
Frequency, f (Hz)	2	0.1600	0.0800	1.68	0.373
Error	2	0.0954	0.0477		
Total	8	23.6468			

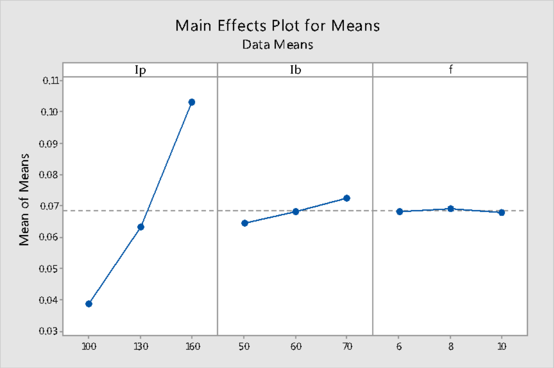

FIGURE 5. Main Effects Plot for Means

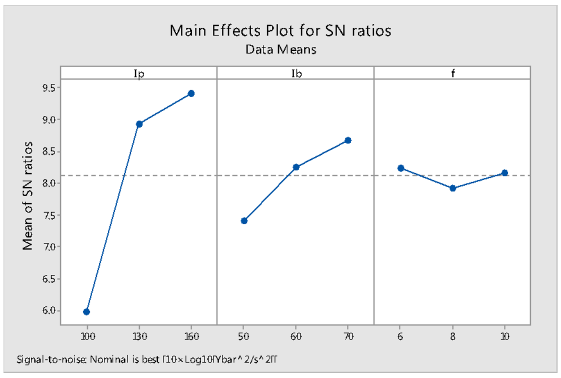

FIGURE 6. Main Effects Plot for SN Ratios

Development of Regression Model

In this study, a mathematical regression model is generated using linear regression and correlation analysis. This model was developed for optimum corrosion rate of BM, HAZ and WZ due to the PCTGAW process. However, the corrosion rate is a function of multiple independent variables and their relationship among the variables. Here coefficient of correlation (R^2) is also formulated to confirm experimental value with the predicted value. The regression model with a coefficient of correlation is given in Table 7.

TABLE 7. Regression Equation and Coefficient of Correlation

Response	Regression Equation (R)	Coefficient of Correlation (R^2)
Corrosion rate at BM	$R = -0.1668 + 0.001800\ I_p + 0.001010\ I_b + 0.01265\ f + 0.000008\ I_p{*}I_b - 0.000046\ I_p{*}f - 0.000107\ I_b{*}f$	99.98 %
Corrosion rate at HAZ	$R = -65.52 + 0.2168\ I_p + 0.3580\ I_b + 4.041\ f + 0.000312\ I_p{*}I_b - 0.01049\ I_p{*}f - 0.04252\ I_b{*}f$	99.94 %
Corrosion rate at WZ	$R = 0.2090 + 0.002304\ I_p + 0.000206\ I_b - 0.03353\ f - 0.000015\ I_p{*}I_b + 0.000131\ I_p{*}f + 0.000286\ I_b{*}f$	99.99 %

CONCLUSIONS

In the current work, pulsed current gas tungsten gas welding (PCGTAW) process parameters effect was evaluated for intergranular corrosion on SS304L weld. Based on experiments and regression analysis following are the concluding remarks:

1. The regression analysis by taguchi L9 orthogonal array a statistical method proved to be adequate to predict regression model and coefficient of correlation. The obtained coefficient of correlation is 99.98 %, 99.94 % and 99.99 % for base metal (BM), heat affected zone (HAZ) and weld zone (WZ) respectively.
2. The ANOVA and main effect plot results of means and SN ratios showcased that peak current and base current are the most significant parameters since both are having P - values less than 0.05. It also indicated an increase in peak and base current increases corrosion rate and a change in frequency does not affect corrosion rate. So, frequency is a non-significant parameter.
3. The corrosion test results inferred that HAZ is more susceptible to intergranular corrosion (IGC) compared to WZ and BM. The reason for HAZ susceptibility is due to heat produced in WZ produce chromium carbide which precipitates across the grain boundary of HAZ. This leads to loosing of chromium content in HAZ and causes IGC. Moreover, the corrosion rate formulated meets the requirements of ASTM 262A.
4. The overall results of experiments and regression analysis indicate the optimum value of PCGTAW process parameters peak current, base current and frequency are 100 A, 50 A and 6 Hz respectively.

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DECLARATION OF COMPETING INTEREST

None

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