Effect of GTA Welding Parameters on Bead Geometry of SAF2507 Super Duplex Stainless Steel

C. B. Sekar, S. R. Boopathy, S. Vijayan, S. R. K. Rao

In this investigation the effect of GTA welding parameters on bead geometry of SAF 2507 Super Duplex Stainless Steel were studied. Single pass autogenous square butt joints were made on 6 mm thick plate. Taguchi L16 Orthogonal experimental design is used to optimize the process parameters. Arc Current, Welding Speed, Shielding Gas Flow Rate and Arc Gap are the input process parameters, while the aspect ratio and the depth of penetration are the responses considered. The micro structural image analysis is used to measure the bead geometry parameters such as aspect ratio and the depth of penetration. From this investigation it is found that the Arc current and Welding speed are the dominant and significant process parameter which affects the bead geometry of the joints. Regression equations have been derived to predict the depth of penetration and aspect ratio of GTA weld beads on 2507 Super Duplex Stainless Steel.

KEYWORDS: SUPER DUPLEX STAINLESS STEEL SAF (2507), GTA WELDING, ASPECT RATIO, TAGUCHI L_{16} OPTIMIZATION.

INTRODUCTION

Oil and gas industries operate offshore in hostile environments. Designing offshore structures is a major challenge as systems have to be designed to protect the structures from destructive atmospheric conditions leading to failure [1]. By optimizing the properties of materials and weldments, the structure can be protected from corrosion, erosion, fatigue, hydrogen related cracking, wear, stress corrosion cracking etc [2].

Structures made of austenitic stainless steel are being replaced by duplex stainless steels which have found extensive usage in construction of critical process equipments, where intergranular corrosion, pitting corrosion, crevice corrosion, stress corrosion cracking, strength, and weldability are of great concern [3]. Duplex stainless steels are characterised by the presence of equal proportions of ferrite and austenite phases in an iron based alloy matrix.

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Combining 50% austenitic and 50% ferritic stainless steel results in unique properties which cannot be achieved individually by them. [4]

The presence of 50% ferrite in duplex stainless steels makes them more ferromagnetic, have higher thermal conductivity, have low thermal expansion and higher corrosion resistance especially in pitting and stress corrosion cracking environments. [5] Refinement in the grain size of both austenite and ferrite was induced by the presence of ferrite in duplex stainless steels which leads to greater resistance to intergranular corrosion [6].During welding in duplex stainless steels the high carbon contents causes sensitization in Heat affected zones and weld regions, which results in the appearance of undesirable secondary phases such as **σ** (sigma) or ᵡ(chi) and intermetallic precipitates. [7]

Corrosion resistance is reduced and toughness lowered in the heat affected zone of the welds due to the presence of excessive ferrite content compared to the base metal [8].DSS are stronger, harder and more attractive where abrasion is a concern, as they have higher yield strength compared to austenitic steels [9].Using AOD (Argon –oxygen –decarburisation) modern duplex grades produced, had low carbon content, high nitrogen and carbon content and a balance between austenite and ferrite. 2205 was the first commercial duplex grade and its success lead steel producers to continue with lower alloyed duplex grades referred as Lean duplex grades and higher alloyed as super duplex grades.25% Cr and 7% Ni duplex stainless steel grade came in favour and developed into super duplex stainless steel (SAF 2507) as they can withstand higher aggressive environments such as chloride and sulphur environment. [10]

Alloying elements Cr, Mo, and nitrogen in stainless steels influence resistance to pitting which is quantified using the pitting resistance equivalent (PRE). PRE= %Cr+3.3 %(Mo+0.5W) +16%N. To have a balance between austenite and ferrite micro structure and to improve pitting corrosion resistance nitrogen is added to duplex stainless steels. Materials with PRE above 40 are resistant to both pitting and Hydrogen sulphide environments. However, the presence of higher content of alloying elements lead to precipitation of unfavourable phases when they are exposed to higher temperatures and to certain environments like chlorine and sulphur [11]. DSS with 25%Cr-7%Ni-4%-Mo and 0.27% N which is used in this study is referred to as Sandvic austenite ferrite (SAF2507) and is a super duplex SS (SDSS).

SDSS is preferred in aggressive environments as it has wide spread applications which include pipe lines, pressure vessel tanks, digesters, manifolds, rotors, impellers and shafts. Improper welding techniques and procedures of SDSS, forms unbalanced ferrite to austenite ratio, formation of intermetallic phases and high ferrite concentration in Heat affected zone which are detrimental to both corrosion resistance and mechanical properties. To make SDSS welds reliable and fit to serve different environments requires it to have higher toughness strength, greater resistance to corrosion, erosion and stress corrosion cracking. By integrating the welding process, technique, bead shape, preheat/interpass temperature and heat input, suitable SDSS welds can be produced, which can solve the above problems [13]. An attempt is made to study the effects of GTA welding process parameters on the aspect ratio and depth of penetration in GTA welded SAF2507 Super Duplex Stainless Steel.

GTA Welding Process Parameters and their levels.

The Current, Welding speed, Gas flow rate and the Arc gap are the significant process parameter of GTA welding as mentioned in many literatures [14 -17] is considered as the input processes parameter in this investigation. But choosing their level plays a vital role in GTA welding of Super Duplex Stainless Steel since the temperature cycles and the effect of cooling determines the formation of austenitic and ferrite phases, which in turn determinates the mechanical and corrosion properties of the weld. The melting point of super duplex steel is around 1350 °C. The heat input of the process is governed by the amount of current supplied, in order to fix the desired temperature range, the current is to be controlled between 220 to 250 amperes. In GTA welding of super duplex Stainless Steel the initial heat input will be equal or more than 1350 °C, during heating the austenite phases will dissolve into coarse grains of ferrite matrix. The formation of austenite precipitates around ferrite grain boundaries happens when the cooling rate is in between 1350 to 800 °C. The welding speed plays a major role in the cooling rate of the weld pool. In order to maintain the desired cooling rate the range of the welding speed is set at 100 to 130 mm/min. The gas flow rate and the air gap is controlled between 10 to 16 LPM and 1.4 to 2.8 mm respectively. The process parameters and their levels are listed in the table 1. The equal proportions of the austenite and ferrite phases depend upon the parameters of thermal cycles, peak temperature and cooling rate which provides the optimum characteristics of the material. The objective of the paper is to optimize GTA process parameters on the aspect ratio and depth of penetration of welded SAF2507 Super Duplex Stainless Steel.

Tab.1 - Process parameters of GTA welding and their levels

SI.NO	FACTORS	UNIT	LEVEL 1	LEVEL 2	LEVEL 3	LEVEL 4
1	Current	A	220	230	240	250
2	Welding speed	mm/min	100	110	120	130
3	Gas flow rate	L/min	10	12	14	16
4	Arc gap	mm	1.8	2	2.2	2.4

EXPERIMENTAL PROCEDURE

SAF2507 Super Duplex Stainless Steel of 200 X 100 X 6 mm plates was taken and the edges are prepared to conduct the flat butt joints. Autogenous GTA welding is done by changing the process parameters in concurrence with L16 orthogonal experimental design. The electrode material and the tip angle of the electrode are kept constant for all the 16 experiments. The middle portions of the weld are moulded, polished and etched with kalling's reagent no 2 for capturing the micro and macro structure of the weld. The dimensions of the weld penetration and the face width are obtained using the image analyzer and shown in the table 2.

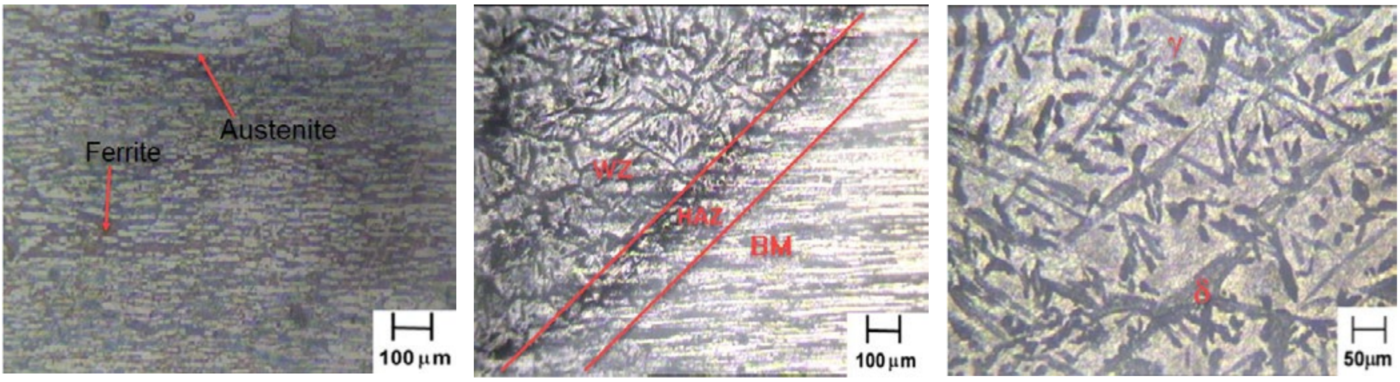
Tab.2 - Experimental Layout and its responses

Sl.No	Current (A)	Welding Speed mm/min	Gas Flow Rate L/min	Arc Gap mm	Area mm²	Width mm	Depth of penetration mm
1	220	100	10	1.8	44.7871	13.9382	5.6081
2	220	110	12	2.0	30.2972	12.7189	3.5785
3	220	120	14	2.2	23.6036	11.3133	3.3028
4	220	130	16	2.4	15.4972	10.4724	1.9266
5	230	100	12	2.2	46.8771	13.0662	5.4702
6	230	110	10	2.4	30.0661	11.9112	3.9565
7	230	120	16	1.8	27.7019	12.1567	3.6817
8	230	130	14	2.0	23.3273	11.5005	2.8901
9	240	100	14	2.4	43.7093	13.9691	5.1261
10	240	110	16	2.2	32.6469	12.4064	4.1286
11	240	120	10	2.0	28.1809	12.2200	3.6812
12	240	130	12	1.8	27.8621	12.8750	3.2689
13	250	100	16	2.0	45.0543	13.7507	5.3678
14	250	110	14	1.8	42.1698	13.0627	5.0918
15	250	120	12	2.4	41.7941	13.2209	5.2639
16	250	130	10	2.2	32.4937	12.0629	3.7156

RESULT AND DISCUSSION

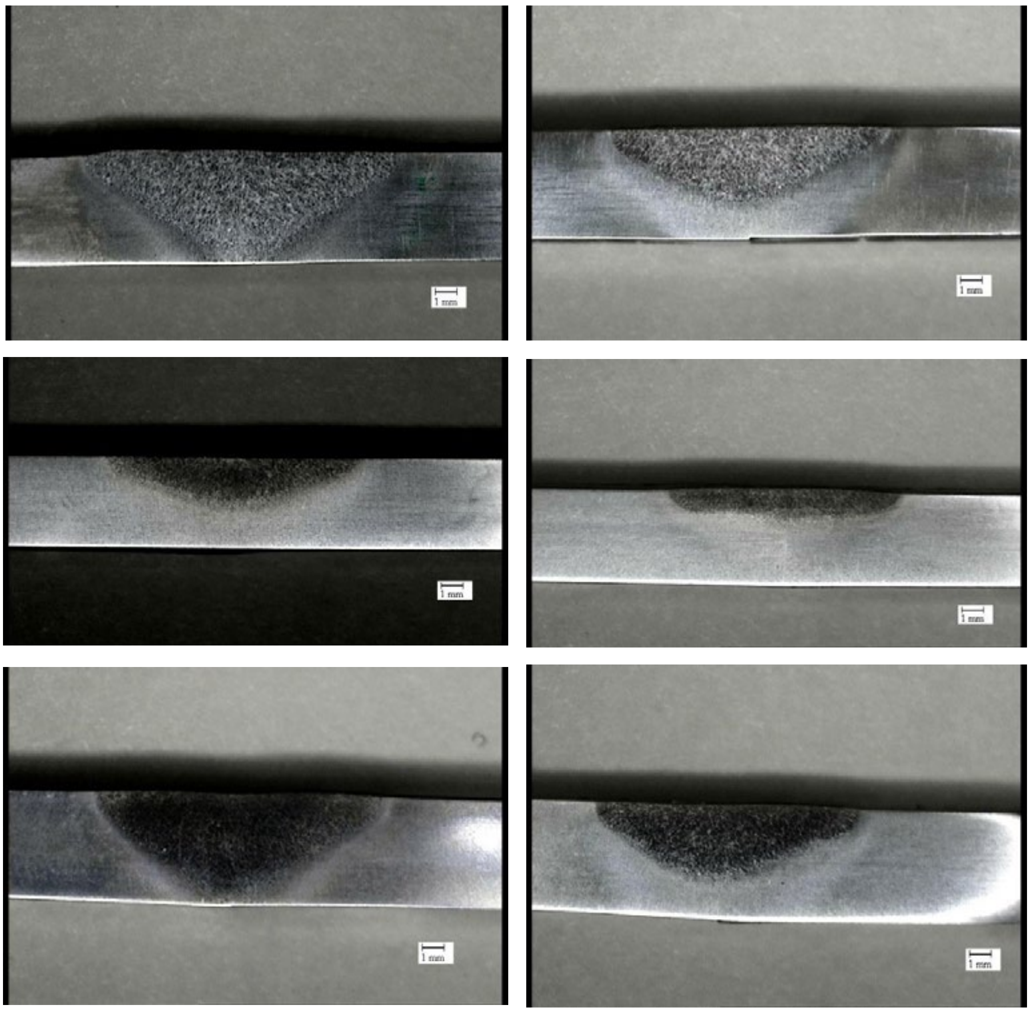
Micro Structure and Macrostructure

The base metal and the GTA samples are moulded polished with different grades 500 #, 800 #, 1200 # and 1500 # grit of SiC emery paper and cleaned dried in warm flowing air. The Super duplex stainless steel has the equal proportions of the austenite and ferrite phases, which enhances the greater mechanical strength ,pitting ,fatigue and high corrosion resistance than most type of steels .The optical micrograph of the base metal is shown in figure 1 (a) which clearly captures equal proportions of austenite and ferrite phases. The figure 1 (b) shows the three different zones, the base metal region, Heat affected zone and weld zone. Micro graph of autogenous GTA weld shows γ-Austenite δ-ferrite. The ferrite phase exhibit smaller grain size than austenite phase comparatively throughout the weld zone and shown in figure 1(c). The macrostructure of all the L16 experiments are shown in the figure 2.The macrostructure clearly shows the penetration of the weld and the aspect ratio of the different levels of the process parameters.



(a) Base Metal (b) Weld Metal,HAZ and Base metal (c) Weld Metal

Fig.1 - Micrograph of the base metal and the welded joints



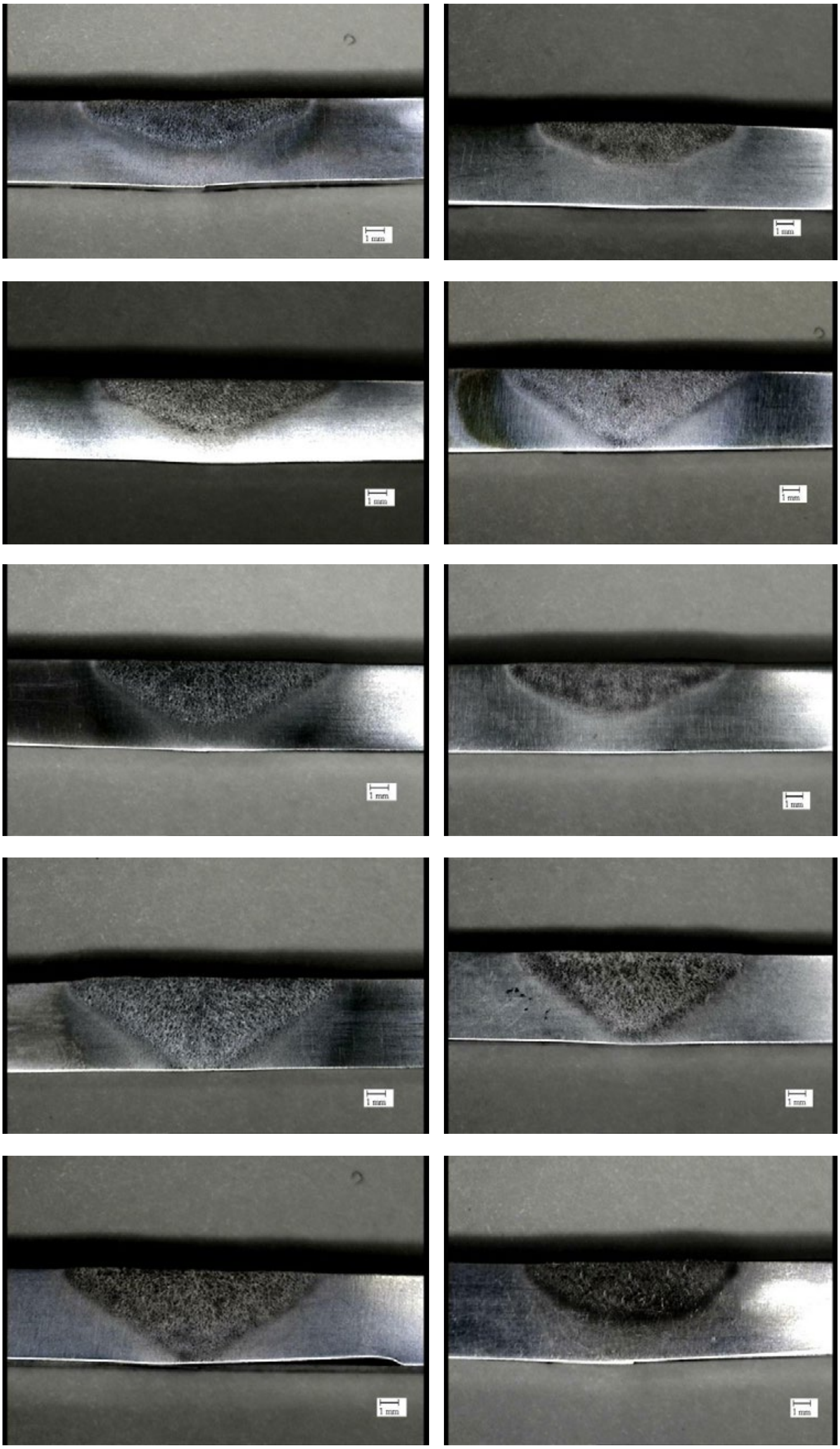


Fig.2 - Macrographs showing the weld bead shape and size. Corresponding welding parameters are given in Table 2.

TAGUCHI METHODOLOGY

As the input parameters and their levels of the experimentation is finalised as four factors with four levels. Totally 256 experiments has to be conducted to explore completely. Its waste of time, materials and resource and it is not an engineering approach. Taguchi uses the special orthogonal design of experiments to analyse with limited number of experiments.L16 is the Taguchi experimental design is used in our investigation to find the effects of GTA parameters on aspect ratio and penetration in welding Super duplex stainless steel SAF (2507).The L16 experimental design is shown in table 1. Arc Current, Welding Speed, Shielding Gas Flow Rate and Arc Gap are the input process parameters, while the aspect ratio and the depth of penetration are the responses considered. The penetration of the weld characterised as maximum function the higher the best quality loss function is considered while the aspect ratio falls under the minimum quality function, lower the best quality loss function is computed. The formula for computing the quality loss function is given the equation 1 and 2. The commercial available software for Taguchi optimization is used to compute the SN values, ANOVA by using the response obtained and it is shown in the table 3.

Larger the Best

$$\text{S/N Ratio } (\eta) = -10 \log_{10} \frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_i^2} \quad 1)$$

Smaller the Best

$$\text{S/N Ratio } (\eta) = -10 \log_{10} \frac{1}{n} \sum_{i=1}^{n} y_{ij}^2 \quad 2)$$

Where n - number of replications

y_i - observed response value

Tab.3 - Tab. 3 - S/N ratio of the responses.

Experiment No.	Width [mm]	Depth [mm]	S/N ratio for D	Aspect ratio for W/D	S/N ratio for W/D
1	13.9382	5.6081	14.97631	2.485369	-7.9078
2	12.7189	3.5785	11.07402	3.554255	-11.0150
3	11.3133	3.3028	10.37765	3.425366	-10.6941
4	10.4724	1.9266	5.695831	5.435690	-14.7051
5	13.0662	5.4702	14.76006	2.388615	-7.5629
6	11.9112	3.9565	11.94622	3.010540	-9.5729
7	12.1567	3.6817	11.32097	3.301926	-10.3753
8	11.5005	2.8901	9.218257	3.979274	-11.9961
9	13.9691	5.1261	14.19574	2.725093	-8.7076
10	12.4064	4.1286	12.31606	3.004990	-9.5569
11	12.2200	3.6812	11.31979	3.319570	-10.4216
12	12.8750	3.2689	10.28803	3.938634	-11.9069
13	13.7507	5.3678	14.59593	2.561701	-8.1706
14	13.0627	5.0918	14.13743	2.565439	-8.1832
15	13.2209	5.2639	14.42615	2.511617	-7.9991
16	12.0629	3.7156	11.40058	3.246555	-10.2285

The optimum levels of the process parameters are obtained based on the highest S/N ratio computed, irrespective of the quality function. The average values of the levels are computed for both the responses considered and displayed in table 4 & 5. The analysis of variance (ANOVA) is computed to find the contribution of the process parameter towards the response as well as the show that the considered process parameters are statistically significant and shown in table 6 & 7. The optimum combination of the levels of the process parameters can be predicted based on the average values of S/N ratio at particular levels. The confirmation experimentation is conducted by setting the predicted level setting of the process parameters and compared with the results obtained with the theoretical calculation.

Tab.4 - Average S/N ratio Values for Depth of Penetration

Welding process	symbol	A	B	C	D
	Levels	Current (Ampere)	Welding speed (mm × min-1)	Gas flow rate (Liter per Minute)	Arc gap (mm)
TIG	1	10.53	14.632	12.41	12.68
	2	11.81	12.37	12.64	11.55
	3	12.03	11.86	11.98	12.21
	4	13.64	9.15	10.98	11.57

The optimum level of setting is $\mathbf{A_4B_1C_2D_1}$

Tab.5 - Average S/N ratio Values for Aspect ratio

Welding process	symbol	A	B	C	D
	Levels	Current (Ampere)	Welding speed (mm × min-1)	Gas flow rate (Liter per Minute)	Arc gap (mm)
TIG	1	-11.081	[-8.087]	[-9.593]	-9.593
	2	-9.877	-9.582	-9.621	-10.401
	3	-10.148	-9.873	-9.895	[-9.511]
	4	[-8.645]	-12.207	-10.702	-10.246

The optimum level of setting is $\mathbf{A_4B_1C_1D_3}$

Tab.6 - ANOVA for Depth of Penetration

Process Parameter	Degrees of Freedom	Seq SS	Adj SS	Adj MS	F value	% contribution
Current	3	19.537	19.537	6.512	5.74	21
Welding speed	3	60.805	60.805	20.268	17.87	65
Gas flow rate	3	6.443	6.443	2.148	1.89	7
Arc gap	3	3.592	3.592	1.197	1.06	4
Error	3	3.402	3.402	1.134		4
Total	15	93.778				100

Tab.7 - ANOVA for Aspect Ratio

Process Parameter	Degrees of Freedom	Seq SS	Adj SS	Adj MS	F value	% contribution
Current	3	12.097	12.097	4.0324	6.73	22
Welding speed	3	34.858	34.858	11.6192	19.39	64
Gas flow rate	3	3.401	3.401	1.1337	1.89	6
Arc gap	3	2.443	2.443	0.8142	1.36	4
Error	3	1.798	1.798	0.5993		3
Total	15	54.596				100

PREDICTED VALUES OF DEPTH OF PENETRATION AND ASPECT RATIO

The predicted value for Depth of penetration and aspect ratio are calculated based on the additive model available in the literatures .

$$\eta_{predicted} = \eta_m + \sum_{i=1}^{q}(\bar{\eta}_i - \eta_m) \quad 3)$$

η_m= Average SN ratio
ηi = Average SN ratio corresponding to the i^{th} significant factor of the j^{th} level
q = Number of significant factors

Depth of Penetration (predicted) $=A_4+B_1+C_2+D_1-3\eta_m$
$=4.86+5.393+4.395+4.413 - 3*4.1285$
$=6.675313$ mm

Where
A 3: Average mean value of current at 4^{th} level.
B 1: Average mean value of welding speed at 1^{st} level.
C 2: Average mean value of Gas flow rate at 2^{nd} level.
D 1: Average mean value of Air Gap at 1^{st} level
η_m : Overall Mean
The linear equation for depth of Penetration = 5.67 + 0.382 A - 0.753 B - 0.169 C - 0.076 D

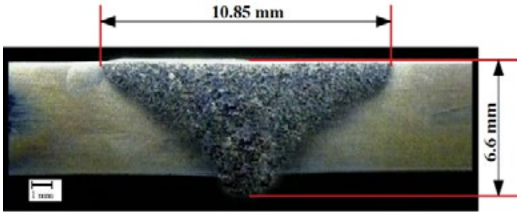
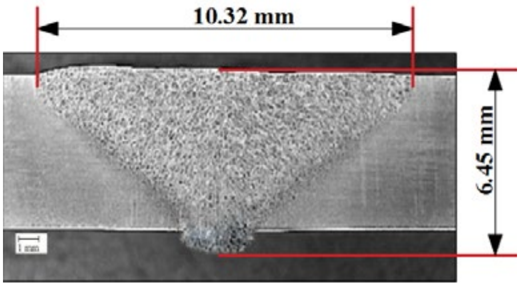
Aspect ratio (predicted) $=A_4+B_1+C_1+D_3-3\eta_m$
$=2.721+2.54+3.016+3.016 - 3*3.2159$
$=1.645$

Where
A4: Average mean value of current at 4^{th} level.
B 1: Average mean value of welding speed at 1^{st} level.
C 1: Average mean value of Gas flow rate at 1^{st} level.
D 3: Average mean value of Air Gap at 3^{rd} level
η_m : Overall Mean
The linear equation for Aspect ratio = 2.10 - 0.293 A + 0.494 B + 0.176 C + 0.0706 D

CONFIRMATION RUN

The confirmation run were conducted on setting the optimum levels of the process parameter from Taguchi L16 optimization to find out the depth of penetration and aspect ratio. The responses of the predicted values, the confirmation run and the micrograph were shown in the table 8.

Tab.8 - The responses of the Predicted and the confirmation run

<table>
<tr><th>Process</th><th>Responses</th><th>Predicted Value</th><th>Confirmation Run</th><th>Macrograph</th></tr>
<tr><td rowspan="2">GTA Welding</td><td>Depth of Penetration (mm)</td><td>6.675313</td><td>6.6</td><td>
</td></tr>
<tr><td>Aspect Ratio</td><td>1.645</td><td>1.6</td><td>
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INPUT PARAMETER AND RESPONSES

The current is the one among the statically significant process parameter for GTA welding of Super duplex stainless steel SAF (2507) which contributes 21 percent to the depth of penetration and 22 percent to the aspect ratio. In GTA welding process the heat source is directly proportional to the current supplied i.e. the temperature increases as current increases and decreases as current decreases. In order to get the full penetration and good aspect ratio the current should be set at highest level. The optimum level of the process parameter current predicated is found to be at level 4 based on the Taguchi optimisation also confirming the same in order to get an optimum response. The current should be set at 250 A in GTA welding of Super duplex stainless steel.

The welding speed plays a major role in GTA welding of Super duplex stainless steel SAF (2507) which contributes 65 percent to the depth of penetration and 64 percent to the aspect ratio. The welding speed is indirectly proportional to the responses considered. The austenite phases will dissolve into coarse grains of ferrite matrix when the temperature is more than 13500 C and the formation of austenite precipitates around ferrite grain boundaries happens when the cooling rate is in between 1350 to 800 °C. The sudden fall in cooling rate is not advisable and in order to maintain the slow cooling rate the welding speed is to set at low level. The optimum level obtained from the Taguchi L16 also confirms that the welding speed is to be set at level 1 i.e. 100 mm/min.

The Gas flow rate and the Air Gap are also statically significant process parameter for GTA welding of Super duplex stainless steel SAF (2507). The contribution of these process parameters are not significant in affecting the response in the level considered. The Gas flow rate and the Air Gap is should be set at 12 L/min and 1.8 mm respectively in order to get the optimum response. The main effects at different levels for data means are plotted to the process parameter and shown in figure 3

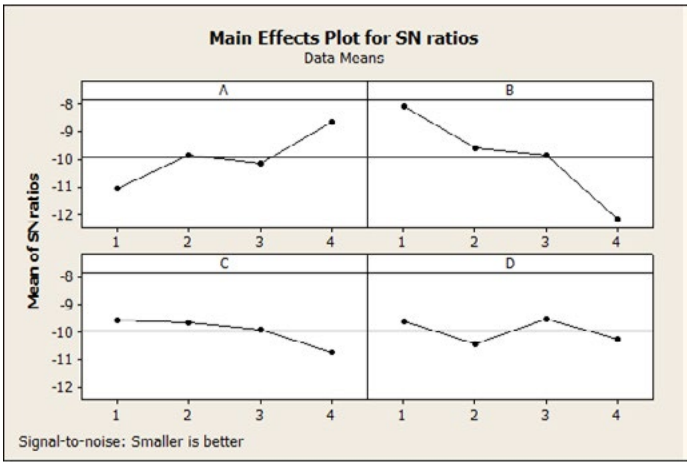

Fig.3 - Main Effects Plot for the Data mean

CONCLUSIONS

All the considered four process parameters i.e welding current, welding speed arc gap and shielding gas flow rate is statistically significant process parameters for GTA welding of Super Duplex Stainless Steel SAF (2507).

The welding speed followed by the welding current are the predominant factors that affect the depth of penetration and aspect ratio in GTA welding of Super Duplex Stainless Steel.

The optimum levels of the process parameters in order to get the full penetration and a good aspect ratio of 1.6 are: current = 250 A, welding speed = 100 mm /min, gas flow rate = 12 L / min, arc gap = 1.8 mm.

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