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TAGUCHI APPROACH FOR MODELING THE EFFECT OF SENSITIZATION IN PULSED TIG WELDING OF 316L

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ABSTRACT

In the present work Taguchi based design has been used to study the effect of sensitization in pulsed mode of tungsten inert gas (PTIG) welding for austenitic stainless steel (316L). Further comparison of Taguchi design based model has been made with conventional skip mode of tungsten inert gas (TIG) welding. Taguchi design (L-9 orthogonal array) has been used for experimentation at three levels of current (90 Amp, 100 Amp and 110 Amp), frequency (4 Hz, 6 Hz and 8 Hz) and gas flow rate (10 L/min, 15 L/min and 20 L/min). The results of study suggests that better mechanical properties are attained at 100 Amp peak current, 8 Hz frequency and 10 L/min gas flow rate in PTIG welding. Experiment results have been counter verified with scanning electron microscopy (SEM) analysis, which shows least effect of sensitization at above mentioned levels of input parameters for PTIG welding. However as regards to sensitization is concerned skip mode of TIG welding results in to better option as compared to PTIG.

Keywords: *Taguchi Design, PTIG Welding, Sensitization, Skip Welding.*

1. Introduction

TIG welding has become a popular choice of welding processes when high quality, precision welding is required [1]. In TIG welding an arc is formed between a non consumable tungsten electrode and the metal being welded. Gas is fed through the torch to shield the electrode and molten weld pool. If filler wire is used, it is added to the weld pool separately, which is in the form of either bare rods or coiled wire for automatic welding. Stainless steels are always welded in the DCEN (Direct current electrode negative) or DCSP (Direct current straight polarity) mode [2]. In this condition the work piece is struck by electrons. The inert gas flow protects the zone from ambient air and enables a very stable arc to be maintained. Fig. 1 shows schematic of TIG welding.

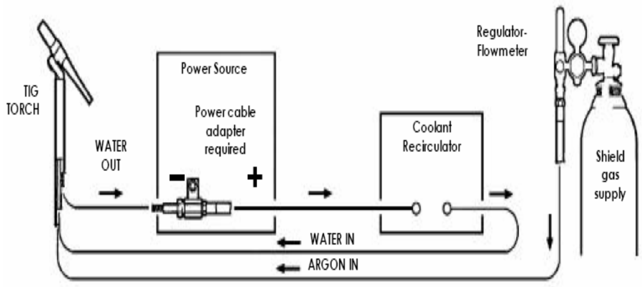

Fig. 1 Schematic of TIG Welding

Stainless steels are considered to have very good resistance to general and localized corrosion due to their chromium content [2-3]. The chromium content in stainless steel is around 13%. The property of corrosion resistance constitutes the main criterion for selecting austenitic grades of steels for service in the chemical, nuclear and aerospace industries although their mechanical properties are relatively modest. However, this resistance can degrade when structural components manufactured from these steels are used in a chemically aggressive environment especially when service involves exposure to high temperatures [4]. This exposure gives rise to precipitation of chromium carbides producing chromium depletion at grain boundaries that brings the inter-granular corrosion (IGC) or sensitization of these materials [3-5].

1.1 Austenitic stainless steel

Austenitic stainless steels have austenite as their primary phase (face centered cubic crystal). It contains a maximum of 0.15% carbon, a minimum of 16% chromium and sufficient nickel and/or manganese to maintain a stable austenite structure over the temperature range from 1100 degree C to room temperature without the formation of martensite. Austenite, or nonmagnetic stainless steels, are classified in the 200 and 300 series, with 16% to 30% chromium

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and 2% to 20% nickel for enhanced surface quality, formability and increased corrosion and wear resistance [6]. These steels are the most popular grades of stainless produced due to their excellent formability and corrosion resistance. All austenitic steels are nonmagnetic in the annealed condition (depending on the composition, mainly the nickel content, austenite does become slightly magnetic when cold worked). Austenitic stainless steel grades include: Type 201, 300, 301, 304, 305, 309S, 316, 316L, and 321. Austenite is used for automotive trim, cookware, food and beverage equipment, processing equipment, and a variety of industrial applications. Grade 316L contains <0.03% C, 16-18.5% Cr, 10-14% Ni, 2-3% Mo, <2% Mn, <1% Si, <0.045% P, <0.03% S, Fe. The 'L' Grades are used to provide extra corrosion resistance and indicates low carbon. The carbon is kept to 0.03% or under to avoid carbide precipitation. Carbon in steel, when heated to temperatures in what is called the critical range (i.e. 430°C to 880°C), precipitates out and combines with the chromium and gather on the grain boundaries. This deprives the steel of the chromium in solution and promotes corrosion adjacent to the grain boundaries [4]. By controlling the amount of carbon, this is minimized. The property of corrosion resistance constitutes the main criterion for selecting austenitic grades of steels for service in the chemical, nuclear and aerospace industries although their mechanical properties are relatively modest.

1.2 Sensitization

Sensitization is one of the corrosion mechanisms that cause widespread problems in austenitic stainless steels [4]. Fig. 2 shows the mechanism of sensitization. When austenitic stainless steels are extensively heated or slowly cooled in the temperature range of 850°C to 450°C, chromium rich carbides precipitate along the grain boundaries leading to subsequent chromium depletion in the vicinity of the grain boundaries. This phenomenon is called sensitization.

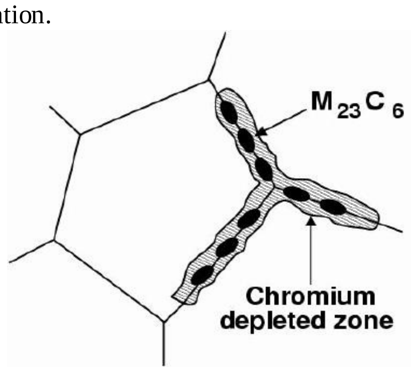

Fig. 2 Mechanism of Sensitization

The main carbide phase is $M_{23}C_6$, where the 'M' stands for a mixture of metal atoms including iron, molybdenum, chromium and manganese, depending on the steel composition and heat-treatment. These carbides require long-range diffusion in order to precipitate and hence can be avoided by rapid cooling from the solution-treatment temperature. When sensitized austenitic stainless steel is exposed to a corrosive environment, chromium depleted zones preferentially dissolve leading to IGC [5]. The solubility of carbon in austenite is about 0.006% at ambient temperature. However austenitic stainless steel generally contains about 0.05% carbon. Since chromium has high affinity for carbon, there is always a strong tendency for carbide formation. During the normal cooling rates encountered during fabrication of stainless steel, chromium carbides can be precipitated, making the steel susceptible to IGC and IGSCC (Intergranular stress corrosion cracking). Fig. 3 shows the sensitization of stainless steel during welding.

Sensitization is the formation of chromium carbides in the heat-affected zone (HAZ), the area directly adjacent to the weld [2]. The heat-affected zone has been heated to just below its melting temperature followed by rapid cooling. These metals are the iron, chromium, nickel, molybdenum and manganese atoms. The carbon atoms occupy the small spaces between the metal atoms called interstitial spaces. In the temperature range of 430˚C - 850˚C, the carbon atoms actually move through the metal matrix and combine with the chromium atoms to form chromium carbide ($Cr_{23}C_6$).

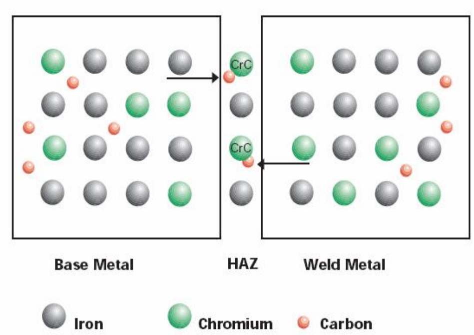

Fig. 3 Sensitization of Stainless Steel

The degree of sensitization can be greatly influenced by several parameters such as chemical composition, cold work, grain size, microstructure and heating/cooling rate [4-6]. The literature review reveals that many researchers have worked upon different aspects of sensitization, but very little work has been reported for reducing the sensitization while adopting different procedures in the TIG welding operation [5-9].

Austenitic stainless steel (316L) is used extensively as a corrosion resistance material, however when heated or cooled at elevated temperatures it shows predominant effects of sensitization resulting in failure of the material after some time [2, 4, 6]. During the welding of Austenitic Stainless Steel (316L) sensitization occurred in the welded material mainly due to the temperature and time of exposure within particular temperature ranges. Conventionally, ‘annealing methods’ are used to reduce sensitization. But, while welding at elevated heights it becomes difficult to anneal the welded material.

1.3 Skip welding technique

A skip weld (sometimes called an intermittent weld) is often used instead of one continuous weld [6]. When using a skip weld, a short weld is made at the beginning of the joint. Next, skip to the center of the seam and weld a few inches. Then, weld at the other end of the joint. Finally, return to the end of the first weld and repeat the cycle until the weld is finished. This welding technique is designed to control heat input and increase cooling rate. This is mainly used to control distortion between the plates. Fig. 4 shows the skip welding procedure.

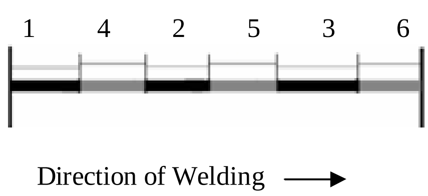

Fig. 4 Skip Welding Procedure

Earlier studies have highlighted the effect of sensitization in conventional mode of TIG welding [2, 4] and PTIG welding of stainless steel [5]. Whereas in the present research work efforts have been made to compare conventional TIG with Pulsed TIG welding for minimum sensitization of 316L, So that judicious decision can be made for selection of particular welding technique/ parametric settings for industrial applications, (like at elevated heights by controlling the temperature and time of exposure in welding). The work has been limited to Austenitic Stainless Steel (316L) material of 5 mm thickness, while welding in the flat position. Two different welding modes namely, pulsed and skip welding has been used to compare the sensitization based upon physical and mechanical properties (like micro hardness, tensile strength and yield strength) during welding. The main objectives of this study are:

1. To investigate the effect of welding procedures/modes (PTIG and skip TIG welding) on mechanical properties of Austenite Stainless Steel (316L).
2. To find the best settings of input parameters for controlling sensitization in the PTIG/TIG welding of Austenite Stainless Steel (316L).

Table 1 shows list of input and output parameters in the present research work.

2. Experimentation

Welded specimens were prepared at different values of current (that is 80, 100,120,140 and 160 Amp). After this mechanical tests were performed on the specimens. Table 2 shows the effect of current on mechanical properties of the specimen.

Table 1: List of Parameters

Input Parameters	Output Parameters
1. Welding Procedure	Sensitization based upon microstructure and mechanical properties like:
I. Skip Welding	✓ Tensile Strength
II. Pulsed Welding	✓ Percentage elongation
a) Peak Welding Current	✓ Micro hardness
• 90 amp	
• 100 amp	
• 110 amp	
b) Pulse Frequency	
• 4 Hz	
• 6 Hz	
• 8 Hz	
c) Shielding Gas Flow	
• 10 Lit/min	
• 15 Lit/min.	
• 20 Lit/min.	
2. Welding Current	
• 80 Amp	
• 100 Amp	
• 120 Amp	
• 140 Amp	
• 160 Amp	

Welding current controls the rate at which the electrode is melted, the depth of fusion and the amount of base metal melted. If the current is too high for a given travel speed of electrode and filler wire then the depth of fusion or penetration will be too high, the weld may melt through the joint and the weld heat affected zone will be larger. So as the welding current increases, the heat input rate is also increased which further raises the ultimate tensile strength and hardness of the joints. After achieving the peak value of the ultimate tensile strength and hardness, it starts decreasing on further increase in current (Ref. Table 2). This is due to excessive heat input, which resulted in a loss of mechanical properties. Since cooling rate is a function of heat input, so if heat input increases, the rate of cooling decreases for a given base metal thickness. This cooling rate affects the properties of the material.

Table 2: Effect of Current on Mechanical Properties

S. No.	Current Amp	Yield Strength N/mm^2	Tensile Strength N/mm^2	% age Elongation	Hard-ness No (VHN)
1	80	345	597.57	44.00	197
2	100	443	686.75	45.08	239
3	120	415	683.79	41.23	232
4	140	452	671.93	42.63	206
5	160	412	666.00	45.08	202

Rapid cooling rates produce stronger and harder steels; whereas slow cooling rates produce the opposite properties. As observed from Table 2, the best mechanical properties have been obtained at a 100 Amp current level. The microstructure of the specimens was examined through a microscope at 200x magnification, which shows the detail of the weld metal, HAZ and base metal. Fig. 5 show microstructure with fine grains at 100 Amp current. Since current effects the heat input rate, which affects the microstructure of the specimen. In other words current affects the grain size and further mechanical properties are attained with fine grains.

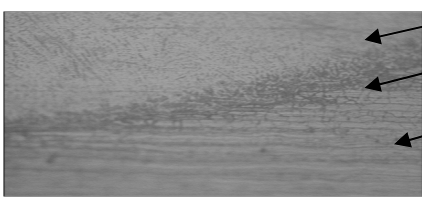

Fig. 5 Microstructure of Sample Prepared at 100 Amp Current

3. Results and Discussion

Two welding procedures (conventional skip mode of TIG and PTIG welding) have been used to study the effect of sensitization on mechanical properties (such as tensile strength, percentage elongation and hardness). Table 3 shows the effect of skip welding procedures at 100 Amp current on mechanical properties.

Table 3: Effect of Skip Welding Procedures on Mechanical Properties

Welding Procedure	Tensile Strength N/mm^2	%age Elongation	Hardness No. (VHN)
Skip Welding	689.00	47.02	247

Also specimens have been prepared at different values of peak current; gas flow rate and pulse frequency based upon control log of experimentation (Ref. Table 4) and corresponding tests were performed on specimens to check their properties. Here L9 orthogonal array of Taguchi design has been used because there were 3 levels of peak current, pulse frequency and gas flow rate. Based upon test data summary (Ref. Table 4), S/N ratio (for ideal function: Nominal the best) and ANOVA test was conducted.
The objective function to be maximized here is:

$$Ŋ = 10 \log_{10} (\mu^2/\sigma^2)$$

Where

$$\mu = 1/n. \sum_{i=1}^{n} y_i^2$$

$$\sigma^2 = 1/ (n-1). \sum_{i=1}^{n} (y_i - \mu)^2$$

Table 4: Control Log for Experimentation

S. No.	Peak current (Amp)	Pulse Frequency (Hz)	Gas Flow Rate (Lit/min.)	Tensile strength (MPa)	%age Elongation	Hardness No. (VHN)
1	90	4	10	524.25	15.4	166
2	90	6	15	597.44	29.2	182
3	90	8	20	592.34	40	193
4	100	4	15	576.32	39	180
5	100	6	20	573.33	32.4	174
6	100	8	10	616.17	41.2	216
7	110	4	20	593.33	30.6	180
8	110	6	10	582.12	37.8	183
9	110	8	15	602.55	34.8	197

Table 5: S/N Ratio for Output Parameters

S. No.	Tensile strength S/N ratio		Hardness S/N ratio		Percentage elongation S/N ratio	
1	524.25	-41.99	166	-36.77	15.4	-28.49
2	597.44	-39.41	182.5	-34.4	29.2	-22.14
3	592.34	-35.21	193.5	-32.36	40	-6.02
4	576.32	-37.34	180	-34.8	39	-9.54
5	573.33	-37.69	174	-35.7	32.4	-19.64
6	616.17	-30.58	216.5	-25.34	41.2	1.93
7	593.33	-35.06	180.5	-34.72	30.6	-21.13
8	582.12	-36.63	183.5	-34.23	37.8	-12.46
9	602.55	-33.52	197.5	-31.48	34.8	-17.14
Total Sum	5257.85	-327.43	1674	-299.8	300.4	-134.63
Mean	584.2	-36.38	186	-33.31	33.37	-14.95

Table 6: ANOVA for Output Parameters

Input parameters	Output parameters											
	Tensile strength				Hardness				Percentage elongation			
	Sum of Squares	V	F	Percentage contribution	Sum of Squares	V	F	Percentage contribution	Sum of Squares	V	F	Percentage contribution
Current	808.65	404.325	0.44	14.69	141.5	70.75	0.48	8.09	135.37	67.78	0.69	26.71
Frequency	2327.25	1163.625	1.27	42.3	1255.5	627.75	4.26	71.84	160.44	80.22	0.82	31.61
Gas flow	541.71	270.85	0.29	9.84	56	28	0.19	3.2	16.44	8.22	0.08	3.23
Error	1824.11	912.05		33.15	294.5	147.25		16.85	195.11	97.55		38.44

Table 5-6 shows S/N ratio and ANOVA test for output parameters. As observed from Table 5and 6 better mechanical properties are attained at 100 Amp current, 10L/min of gas flow rate and 8 Hz pulse frequency. This means that at these input parametric settings there are less chances of sensitization. These results are valid at 95% confidence limit.

Now by comparing the Tables 3, 4, 5 and 6 the variations in mechanical properties of the welded specimens using two different welding procedures can be observed. This variation may be because the amount of heat input was the same for all specimens, but the cooling rate was varying in two welding procedure. Now as mechanical properties are depending upon the heat input and cooling rate of the material, the specimens with high cooling rate results into high strength and hardness. It has also been observed that a non-uniform microstructure was formed in the HAZ, which is an indication of sensitization (Ref Figs. 6-7). In other words, sensitization resulted in the decrease in mechanical properties of the material. The best mechanical properties were obtained using a 100 Amp current and a 10 l/min-gas flow rate by the skip welding procedure.

Chromium Carbide

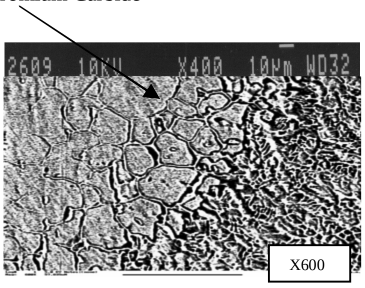

Fig. 6 SEM of Skip TIG Welding Sample

SEM results showed that sensitization occurred in all samples in the HAZ (Ref. Figs. 6-7). As observed from the SEM analysis, chromium has been displaced in all samples. Chromium has a high affinity to combine with carbon to form chromium carbide, which appeared as a network structure in the grain boundaries of the HAZ. In the SEM photographs, white lines in the HAZ along the grain boundaries show the formation of chromium carbide.

Chromium Carbide

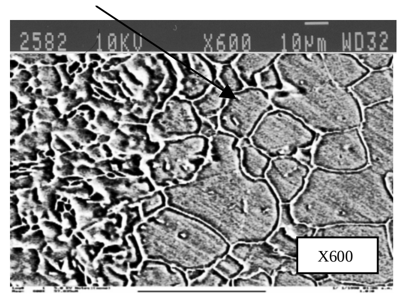

Fig. 7 SEM of PTIG Welding Sample

The SEM results showed that ferrite was also formed in the welded zone in all samples. The presence of ferrite affects the mechanical properties of steel. Ferrite appeared as a continuous network structure in the welded zone, which decreases the corrosion resistance of material. The amount of ferrite depends upon the chemical composition of the base metal, variations in the welding parameters, type of welding used, welding procedure and the type of joint of work-piece being welded. Based upon the comparison of all two welding procedures it was observed that skip welding resulted in the minimum formation of chromium carbide at the grain boundaries of the HAZ and ferrite in the welded zone (Ref. Figs. 6-7). PTIG welding resulted in highest presence of chromium carbide at grain boundaries of HAZ and maximum formation of ferrite in the welded zone. As heating and cooling takes place during welding and time is required for the transmission of heat from the welded specimen; time is also a factor affecting sensitization. In general it is desirable to finish the weld quickly, before a large volume of surrounding metal heats up and expands. The cooling rate depends on the thickness of the work-piece, geometry of the parts to be joined and the heat input during welding. The presence of carbide along the grain boundaries can lead to inter-granular corrosion, which will deteriorate the material. All these conditions have been better maintained during the skip welding procedure.

4. Conclusions

Based upon the present experimental study, the following conclusions have been drawn:

1. To reduce the extent of sensitization of austenitic stainless steel (316L) during welding, the skip-welding procedure is better over PTIG welding. Further better mechanical properties are obtained using a 100 Amp current and 10 l/min of gas flow rate with skip welding technique.

2. The results are in line with the observations made by other investigators [2, 4-5].

3. For PTIG welding better mechanical properties are attained at 100 Amp current, 10L/min of gas flow rate and 8 Hz pulse frequency. As regards to tensile strength is concerned current, frequency and gas flow contribute 15%, 42% and 10% respectively. For hardness current, frequency and gas flow contribute 8%, 71% and 3% respectively and for percentage elongation current, frequency and gas flow contribute 26, 31 and 3% respectively.

6. References

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