Optimization of Process Parameters of Tungsten Inert Gas Welding By Taguchi Methodology

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Abstract— Tungsten Inert Gas welding (TIG) is one of the most important joining technologies in welding-related fabrication. High quality weld joints without spattering and slags qualify this welding technology for the major part of metals. As the filler-metal supply is separated from the arc, the molten pool can be controlled in the best way possible an advantage which ensures the quality of the execution of the weld but entails a relatively low deposition rate and welding speed. When manufacturing consumer products where appearance is of importance; then the choice has to be TIG welding. Jobs that call for code requirements such as nuclear work, piping, and high profile consumer goods often require at least the first weld in the pipe joint to be TIG welding for an effective bond. In some cases all the passes on a multi-pass pipe weld may have to be TIG welding, if demand has high quality and code requirements.
Key words: TIG welding, Taguchi method, spattering, slag

I. Introduction

TIG welding is a thermal process depending on conducted heat through the weld joint materials to achieve the penetration. The melting temperature necessary to weld materials in the TIG welding is obtained by maintaining an arc between a tungsten alloy electrode and the work piece and the weld pool temperatures can approach 2500^{o}C [1]. In TIG welding, a non-consumable tungsten electrode of diameter between 0.5 to 6.5 mm is used with an envelope of inert gas shielding (argon) around it. Since the process uses a non-consumable electrode, extra filler material is usually added. The shielding gas protects both the tungsten electrode and the weld pool from the detrimental effects of surrounding atmosphere gases. Argon is commonly used in welding unalloyed, low alloyed and stainless steels. Both power supply sources (AC or DC) are used for this process. Generally, this process uses a direct current (DC) arc, where the tungsten electrode has a negative polarity thus the tungsten electrode becomes the cathode and the work piece becomes the anode and the polarity is called straight polarity or direct current electrode negative (DCEN). This process has all welding position capabilities while others are limited to one or a few welding positions. TIG welding process is well accepted for pressure vessels, aero, rocket, and missile, nuclear and marine industries.

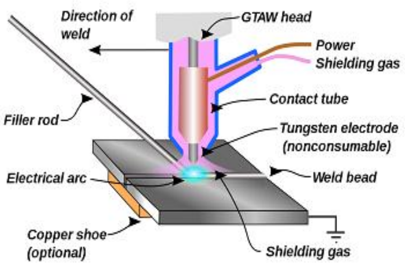

Fig. 1 Schematic Diagram of TIG welding process

The welding torch holds the tungsten electrode which conducts welding current to the arc and provides a means of conveying shielding gas to the arc zone. Torches are rated accordance with the maximum welding current that can be used without overheating. The function of the tungsten electrode is to serve as one of the electrical terminals of the arc which supply the heat required for welding. Its melting point is 3500°C. Depending on the weld preparation and the work-piece thickness, it is possible to work with or without a filler wire. The shield gas usually is chosen according to the material to be welded.

II. Process variables

A. Material

Base metal properties like material composition and material properties (like thermal conductivity, coefficient of thermal expansion, reaction with atmospheric oxygen, effect of flux residue, and crack sensitivity) are considered as the most influential parameter

B. Weld geometry

It is used for the selection of welding process. The joint type may be butt, lap, fillet or T-joint. Bevel may be single-V, double-V or U shape. Weld geometry is directly influential upon weld quality.

Welding positions can either be flat, horizontal, vertical, or overhead etc. Mainly vertical and horizontal welding position is used. Difficult welding position increases the problems in achieving the required weld quality. Weld bead geometry is affected by the position in which the work piece is held with respect to welding gun.

C. Shielding Gas (lit/min)

It is a protective gas used to prevent atmospheric contamination. TIG welding process is mostly conducted in shielding. It has been very promising in enhancing weld quality. Shielding gas flow rate has significant effect on weld bead shape which in turn effects the distortion, residual stresses, heat effected zone (HAZ) and mechanical properties of the material to be welded.

D. Welding Speed (cm/min)

It is the parameter that varies the weld penetration and width of beads. Maximum weld penetration is at a specific welding speed and decreases as speed varies. The increased input heat per unit length due to reduced speed results increase in weld width and vice versa. Variations in travel speed at a set current and voltage also affect bead shape. As welding speed is decreased, heat input per length of joint increases, and the penetration and bead width increase. Excessively high travel speeds results a crowned bead as well as the tendency for undercut and porosity.

E. Wire Feed Rate (cm/min)

It is the parameter that controls the speed of welding filler wire. It is normally attributed to increase resistance heating which itself is increased with the increase in wire feed rate. The welding current varies with the change in wire feeding and the relationship is linear at lower feeding rate.

F. Material Thickness (mm)

Material thickness plays a vital role in process selection and parameters setting. Material thickness is used to decide the input heat required and to control the cooling rate. Higher thickness means higher cooling rate resulting increase in heat effected zone (HAZ) and hardness of weld metal.

G. Welding Current (Amp)

It is one of the most important parameter that directly affects the penetration and lack of fusion by affecting the speed of welding. Welding current is the current being used in the welding circuit during the making of a weld. If the current is too high at a given welding speed, the depth of fusion or penetration will be too great. For thinner plates, it tends to melt through the metal being joined. It also leads to excessive melting of filler wire resulting in excessive reinforcement. This means additional heat input to the plates being welded leading to increased weld induced distortions and if the welding current is too low, it may result in lack of fusion or inadequate penetration.

H. Welding Voltage (V)

This is the electrical potential difference between the tip of the welding wire and the surface of the molten weld pool. It determines the shape of the fusion zone and weld reinforcement. Depth of penetration obtain maximum at optimum arc voltage. It is the parameter that directly affects the bead width. It also influences the microstructure and even the success and failure of the operation. Like current, welding voltage affects the bead shape and the weld deposit composition. Increase in the arc voltage results a longer arc length and a correspondingly wider, flatter bead with less penetration. Slightly increase in the arc voltage results the weld to bridge gaps when welding in grooves. Excessively high voltage produces a hat shaped concave weld, which has low resistance to cracking and a tendency to undercut. Lower voltages reduce the arc length and increase penetration. Excessively low voltage produces an unstable arc and a crowned bead, which has an uneven contour where it meets the plate

III. Selection of Input Parameters and Their Effect on Welding

A. Welding Current

Welding current is the most influential variable in arc welding process which controls the electrode burn off rate, the depth of fusion and geometry of the weldments. The current to be used depends on many factors including electrode type, size, welding position, joint design. Fig. 3.1 shows as increase welding thickness, welding current changes.

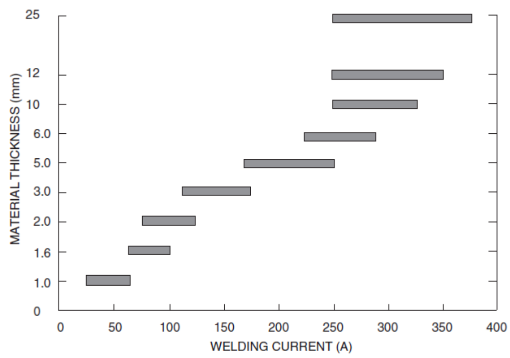

Fig. 2: Relation between material thicknesses and welding currents

B. Welding Speed

Increasing the speed of travel and maintaining constant arc voltage and current will reduce the width of bead and also increase penetration until an optimum speed is reached at which penetration will be maximum. Increasing the speed beyond this optimum will result in decreasing penetration.

In the arc welding process increase in welding speed causes:

- Decrease in the heat input per unit length of the weld.
- Decrease in the electrode burn off rate.
- Decrease in the weld reinforcement.

If the welding speed decreases beyond a certain point, the penetration also will decrease due to the pressure of the large amount of weld pool beneath the electrode, which will cushion the arc penetrating force.

C. Gas Flow Rate

The increase in gas flow results in change in bead geometry of the welded joint which dominates the weld characteristics such as weld height, weld bead.

IV. Taguchi Methodology

Taguchi's methodology is an efficient tool for the design of high quality manufacturing system. Dr. Genichi Taguchi, a Japanese quality management consultant, has developed a method based on orthogonal array experiments [2], which provide much reduced process variance with an optimum setting of process control parameters. Optimization of process parameters is the key step in the Taguchi method to achieving high quality without increasing cost.

Taguchi has suggested that the product process must be applied at optimum levels with minimum variation in its functional characteristics. Functional characteristics of a manufacturing process are also affected by controllable factors and uncontrollable factors or noise factors. Selection of the orthogonal array is based on the calculation of the maximum degree of freedom of all the factors, and the number of rows of an orthogonal array selected should be greater than or equal to the maximum degree of freedom of a process (3). Orthogonal arrays are a special matrix in which entries are at various levels of input parameters, and each row represents individual treatment condition.

The total degree of freedom (DOF) =(Number of levels - 1) for each factor + (Number of levels - 1) (Number of levels - 1) for each interaction + 1 ...... (4.1)

Maximum degree of freedom (DOF) = $(\text{level})^{\text{factor}}$. (4.2)

In general, the signal-to-noise (S/N) ratio (η, dB) represents quality characteristics for the observed data in the Taguchi methodology. Taguchi's signal to noise ratio (S/N ratio) which is logarithm functions of required output serve as intended functions for optimization. This technique has been continuously used by researchers to analyses data to get an optimal solution. In order to finding out the optimum solution in a manufacturing design, Taguchi method utilizes signal to noise ratio(4). The advantage of taking S/N ratio is that it takes into account both mean and variance. It may be defined as the ratio of mean value (signal) to that of standard deviation (Noise). The standard S/N ratios generally used are as follows: Nominal is best (NB), lower the better (LB) and higher the better (HB)[5]. The optimal setting is the parameter combination, which has the highest S/N ratio.

Depending upon the objective function of the quality characteristic there can be various types of S/N ratios. The S/N ratio (η) is mathematically represented as:

$$\eta = -10\log_{10}(MSD \quad \text{(4.3)}$$

Where, MSD = mean square deviation from the desired value and commonly known as *quality loss function* [29].

The MSD is differently for different type of problems. Smaller the better (SB) type:

$$MSD = \frac{1}{n}\sum_{i=1}^{n} y_i^2 \quad \text{(4.4)}$$

Higher the better (HB) type:

$$MSD = \frac{1}{n}\sum_{i=1}^{n} \frac{1}{y_i^2} \quad \text{(4.5)}$$

Where, $y_i$are the observed data (or quality characteristics) at the i^{th} trial, and n is the number of trials at the same level.

The aim is always kept to maximise the S/N ratio whatever may be the nature of quality characteristics. The average value of all S/N ratios when a parameter is at same distinct level is used to describe the effect of a parameter or factor on quality characteristics at that level. A parameter level corresponding to the maximum average S/N ratio is called the optimum level for that parameter. The predicted value of S/N ratio (η_{opt}) at optimum parameter levels is calculated by using the following formula:

$$\eta_{opt} = \bar{\eta} + \sum_{i=1}^{k}(\eta_{mi} - \bar{\eta}) \quad \text{(4.6)}$$

Where, $\bar{\eta}$ is the mean S/N ratio of all experimental runs, k is the number of control factors, and $\eta_{mi}$is the average S/N ratio for i^{th} control factor corresponding to optimum parameter level.

Some verification experiments are conducted at suggested optimum parameter levels to confirm the predicted response. A better feel for the relative effect of the different parameters/ factors can be obtained by the decomposition of the variance, which is commonly called analysis of variance (ANOVA). It is a computational technique to estimate quantitatively the relative contribution that each control factor or parameter makes on the overall measured response. The relative significance of factors is often represented in terms of F-ratio or in percentage contribution. The greater the F ratio, the more significant the parameter will be. The following are the major steps of implementing the Taguchi methodology.

- To identify the factor affecting output variables.
- Identify the levels of each factor.
- Select an appropriate orthogonal array.
- Assign the factors/interactions to columns of the orthogonal array.
- Perform the experiments and minimize the systematic error.
- Analyse the data and determine optimal levels.
- Conduct the confirmation experiment.

V. PROPOSED DESIGN OF EXPERIMENTS

Dr. Genichi Taguchi, a Japanese quality management consultant, has developed a method based on orthogonal array experiments, which provide much reduced process variance with an optimum setting of process control parameters (6).

The design of experiments (DOE) is a technique that is used for the planning, conducting and analyzing the experiments to have the efficient and economical conclusions. The orthogonal array (OA) provides a set of well balanced (minimum experimental runs) experiments plan. Welding process input parameters play a very significant role in determining the quality of a weld joint. The joint quality can be defined in terms of tensile strength. Selection of experimental design is based on the following relationship [7].

$(\text{level} - 1)\times\text{factor} + 1 \le \text{Orthogonal Array} \le (\text{level})^{\text{factor}}$

In the present case

$(4-1)\times 3+1 \le \text{Orthogonal Array} \le 4^3$

or, $10 \le \text{Orthogonal Array} \le 64$

So, the L_{16} orthogonal array has been selected.

Experiment no.	**Factors level** A Welding speed	B Welding current	C Gas flow Rate
1	1	1	1
2	1	2	2
3	1	3	3
4	1	4	4
5	2	1	2
6	2	2	1
7	2	3	4
8	2	4	3
9	3	1	3
10	3	2	4
11	3	3	1
12	3	4	2
13	4	1	4
14	4	2	3
15	4	3	2
16	4	4	1

Table 1: Experimental layout using L_{16} orthogonal array

VI. EXPERIMENTAL STEPS

In the present study 16 pairs of V shaped butt joint specimens of dimensions 150mm× 100mm× 6 mm has been prepared. The plate's edges were cleaned and grinded along the weld line to ensure full contact.

S No.	Variables	Unit	Minimum Value	Maximum Value
1	Welding Speed	mm/sec	2.6	3.2
2	Welding Current	Ampere	150	225
3	Gas flow Rate	Lt/min	9	12

Table 2: Range of input variables for welding

In the Taguchi method, welding current, welding speed, gas flow rate were used as input variables. The combination of these variables have been used to predict weld tensile strength in a form of S/N ratio (larger is better) as output.

S No	Factors	Unit	Level 1	Level 2	level 3	Level 4
1	Welding speed	mm/sec	2.6	2.8	3.0	3.2
2	Welding current	Ampere	150	175	200	225
3	Gas flow rate	Lt/min	9	10	11	12

Table 3: Control factors and their level used in the experiments

VII. EXPERIMENTAL RESULTS

A. *Orthogonal Array Experiment and the S/N Ratio*

Experiment no.	Factors level			Tensile Strength Mpa
	A Welding speed	**B Welding current**	**C Gas flow Rate**	
1	2.6	150	9	300
2	2.6	175	10	330
3	2.6	200	11	306
4	2.6	225	12	350
5	2.8	150	10	353
6	2.8	175	9	366
7	2.8	200	12	333
8	2.8	225	11	343
9	3.0	150	11	263
10	3.0	175	12	350
11	3.0	200	9	360
12	3.0	225	10	363
13	3.2	150	12	266
14	3.2	175	11	253
15	3.2	200	10	260
16	3.2	225	9	316

Table 4: Experimental results for the tensile strength

B.

Furthermore, a statistical analysis of variance (ANOVA) has been also performed to indicate which process parameters are statistically significant; then the optimal combination of the process parameters has been predicted. The experimental result for the tensile strength has been shown in Table 4. Maximum value of tensile strength is 366MPa and minimum value of tensile strength is 253MPa.

Experiment no.	Factors level			S/N Ratio(db) Tensile Strength
	A Welding speed	**B Welding current**	**C Gas flow Rate**	
1	2.6	150	9	49.5424
2	2.6	175	10	50.3703
3	2.6	200	11	49.7144
4	2.6	225	12	50.8814
5	2.8	150	10	50.9555
6	2.8	175	9	51.2696
7	2.8	200	12	50.4489
8	2.8	225	11	50.7059
9	3.0	150	11	48.3991
10	3.0	175	12	50.8814
11	3.0	200	9	51.1261
12	3.0	225	10	51.1981
13	3.2	150	12	48.4976
14	3.2	175	11	48.0624
15	3.2	200	10	48.2995
16	3.2	225	9	49.9937

Table 5: S/N ratios for tensile strength

The calculated S/N ratio corresponding to each experimental run has been given in Table 5. S/N ratio of tensile strength has been calculated through MATLAB program. Maximum S/N value of tensile strength is 51.2696 and minimum S/N value of tensile strength is 48.0624. The response S/N ratio of tensile strength is shown in Table 5.3. The maximum average S/N ratio for tensile strength is obtained at level 2 of welding speed, level 4 of welding current and level 1 of gas flow rate i.e. the optimum parameter setting for maximum tensile strength is $A_2B_4C_1$.Also, the graphical representation of factors effect is shown in Fig. 3

S No	Factors	Mean S/N Ratio db			
		Level 1	**Level 2**	**level 3**	**Level 4**
1	Welding speed	50.1271	50.8450*	50.4012	48.7133
2	Welding current	49.3487	50.1459	49.8972	50.6948*
3	Gas flow rate	50.4030*	50.2058	49.2205	50.1773

Table 6: S/N responses for tensile strength

Optimum level

Result of response S/N ratio for tensile strength has been calculated in MATLAB program.

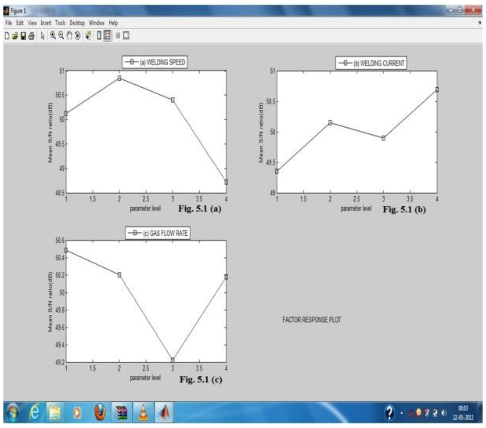

Fig 3: Factor response plot for tensile strength

Figure 3.1(a) shows the welding speed variation of mean S/N ratios (dB) and their levels. In this Fig. level 1 show 50.1271 mean S/N ratio, level 2 show 50.8450 mean S/N ratio, level 3 show 50.4012 mean S/N ratio, level 4 show 48.7133 mean S/N ratio. Level 2 has maximum mean value so it is the optimal value of welding speed.

Figure 3.1 (b) shows the welding current variation of mean S/N ratios (dB) and their levels. In the Fig. level 1 show 49.3487 mean S/N ratio, level 2 shows 50.1459 mean S/N ratio, level 3 show 49.8972 mean S/N ratio, level 4 show 50.6948 mean S/N ratio. Level 4 has maximum mean value so it is the optimal value of welding current.

Figure 3.1 (c) shows the gas flow rate variation of mean S/N ratios (dB) and their levels. In the Fig. level 1 show50.4030 mean S/N ratio, level 2 shows 50.2058 mean S/N ratio, level 3 shows 49.2205 mean S/N ratio, level 4 shows 50.1773 mean S/N ratio. Level 1 has maximum mean value so it is the optimal value of gas flow rate.

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