Scientific Journal of Impact Factor (SJIF): 5.71
e-ISSN (O): 2348-4470
p-ISSN (P): 2348-6406
International Journal of Advance Engineering and Research Development
Volume 5, Issue 03, March -2018

EFFECT OF SIO2 IN A-GTAW MADE OF AISI SS304

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Abstract- *Gas Tungsten Arc Welding (GTAW) is the most important joining technique in almost all types of manufacturing sector. GTAW is suitable for welding thin work materials when good quality and surface finish are required. The presence of certain impurities in steel such as sulphur, oxygen etc in the weld pool can significantly change the change the welding penetration depth in GTAW. Several mechanisms have been proposed for producing a relatively deep and narrow weld. A novel variant of GTAW process called the A-GTAW process involves application of thin coating (10-15µm thick) of activated flux on the joint area prior to welding. Literature identifies that the penetration capability of the arc in GTAW can be significantly increased by the application of a flux coating containing active ingredients, onto the joint surface prior to welding.*
The present study investigated the performance of stainless steel (AISI SS304) using A-GTAW process using Design of Experiments (DOE) methodology. L18 orthogonal array design matrix was followed. Mechanical testing- Tensile testing, micro hardness testing and microstructures was performed to check the performance of the welded joints. Taguchi`s method was used to analyze the results. The results indicated that the performance of weldments was improved by welding with A-GTAW. Tensile strength and micro hardness was improved by A-GTAW.

Key words- *GTAW, A-GTAW, stainless Steel (AISI SS304), Design of Experiments, Taguchi Methodology, Performance, Measures, Optimization.*

1. INTRODUCTION

After the discovery of the electric arc in 1800 by Humphry Davy, arc welding developed slowly. C. L. Coffin had the idea of welding in an inert gas atmosphere in 1890, but even in the early 20th century, welding non-ferrous materials like aluminum and magnesium remained difficult, because these metals reacted rapidly with the air, resulting in porous and dross-filled welds. Processes using flux-covered electrodes did not satisfactorily protect the weld area from contamination. To solve the problem, bottled inert gases were used in the beginning of the 1930s. A few years later, a direct current, gas-shielded welding process emerged in the aircraft industry for welding magnesium.

Principle of Operation:

Gas tungsten arc welding (GTAW), also known as tungsten inert gas (TIG) welding, is an arc welding process that uses a non-consumable tungsten electrode to produce the weld (figure 1).

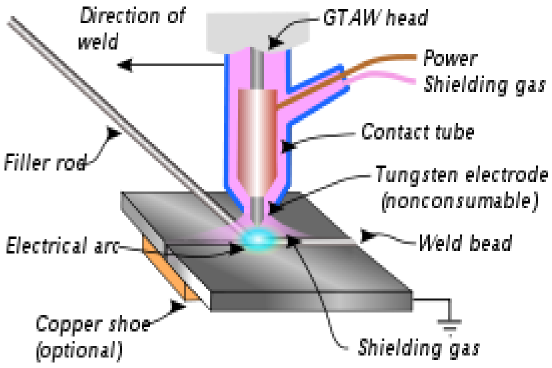

Figure 1: GTAW process

The weld area is protected from atmospheric contamination by an inert shielding gas (argon or helium), and a filler metal is normally used, though some welds, known as autogenous welds, do not require it. A constant-current welding power supply produces energy which is conducted across the arc through a column of highly ionized gas and metal vapors known as plasma. [2]

GTAW is most commonly used to weld thin sections of stainless steel and non-ferrous metals such as aluminum, magnesium, and copper alloys. The process permits the operator greater control over the weld than competing processes such as shielded metal arc welding and gas metal arc welding, allowing for stronger, higher quality welds. However, GTAW is comparatively more complex and significantly slower than most other welding techniques. A related process, plasma arc welding, uses a slightly different welding torch to create a more focused welding arc and is often automated. Manual gas tungsten arc welding is often considered the most difficult of all the welding processes commonly used in industry. Because the welder must maintain a short arc length, great care and skill are required to prevent contact between the electrode and the work piece. [2]

Activated Gas Tungsten Arc Welding:

A novel variant of GTAW process called the A-GTAW process involves application of thin coating of activated flux on the joint area prior to welding. Activated flux is a solution of acetone and metal-oxide. Metal oxides mainly used in A-GTAW are Cr_2O_3, TiO_2 and SiO_2. Activated flux is prepared by making a paste of acetone and metal oxide. Activated flux is applied to the joint area with a paint brush.
It has been observed that the A-GTAW improves the overall quality of GTAW welds. The main effect of A-GTAW is on the penetration. Penetration is increased by 300% in a single pass weld. The current theory on effect of A-GTAW on penetration is that the flux changes the surface tension in the weld pool so that the fluid flow is changed, and tends to increase the penetration. [4]
Published work identifies that the use of activated flux does not cause any change in chemical properties of the weld metals as compared to the base metal. Further, it has been found that there is no degradation in microstructure or mechanical properties. The procedure and apparatus or machine used in A-GTAW is same as used in GTAW; only difference being application of activated flux prior to welding.

Mechanism:

If the surface tension were to vary along an interface, there would be an imbalance of forces which in turn would cause flow. This flow is called the Marangoni effect since a liquid with a high surface tension pulls more strongly on the surrounding liquid than one with a low surface tension, the presence of a gradient in surface tension will naturally cause the liquid to flow away from regions of low surface tension. The surface tension gradient can be caused by concentration gradient or by a temperature gradient (surface tension is a function of temperature).

Mechanism in Weld pool:

In GTAW molten pools, there is always a temperature gradient on the molten pool surface, with high temperatures in the pool center under the arc and low temperatures at the pool edge. For GTAW welding without flux, the surface tension decreases as the temperature increases. In this condition, the surface tension is highest at the edge of the pool and lowest at the center of the pool. This surface tension gradient $d\sigma/dT$ produces an outward surface fluid flow, as Figure 2(a) indicates, and generates wide and shallow weld geometry.

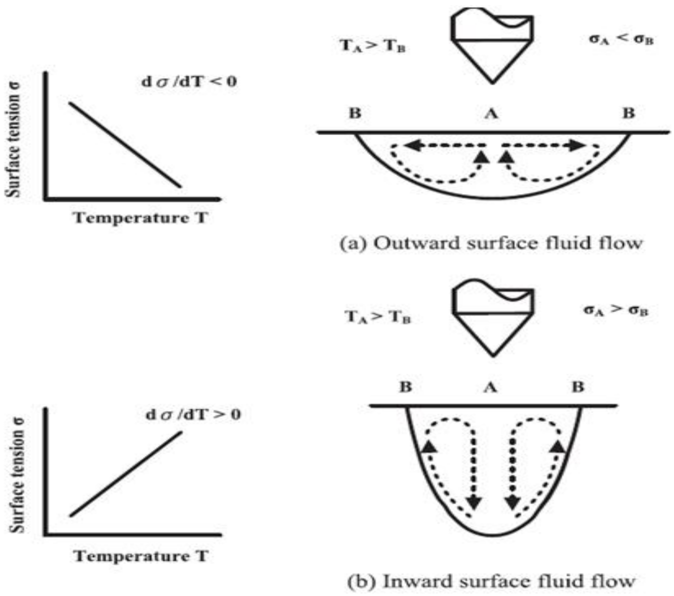

Figure 2: schematic diagram of surface fluid flow pattern

For GTAW welding with oxide fluxes, adding surface active element oxygen to the molten pool can drastically change the temperature dependence of surface tension. In this condition, the surface tension will be highest at the pool center, creating an inward surface fluid flow result, as Figure 2(b) shows that this surface fluid flow pattern produces narrow and deep weld geometry.

Work Material: Stainless Steel (AISI SS304)

Stainless Steel (AISI SS304) is a variation of the basic 18-8 grade, type 302, with higher chromium and lower carbon content. Its lower carbon content minimizes chromium carbide precipitation due to welding and its susceptibility to intergranular corrosion. In many instances, type 304 can be used in the “as-welded” condition, while type 302 must be annealed in order to retain adequate corrosion resistance. Type 304L is an extra low carbon variation of type 304 with 0.03% maximum carbon content that eliminates carbide precipitation due to welding. As a result, this alloy can be used in the “as welded” condition, even in severe corrosive condition. In many cases it eliminates the necessity of annealing weldments excepted for application specifying stress relief. Type 304L has slightly lower mechanical properties than type 304. [5]

Objectives of Present Study:

1. To perform GTAW and A-GTAW on stainless steel (AISI SS304) specimens.
2. To perform the following tests and compare them.
   - Tensile testing
   - Micro-hardness testing
   - Microstructure

To analyze the results using Design of Experiments methodology

2. LITERATURE SURVEYED

Chang-Pin Chou et al. (2011) studied the effect of Activated TIG flux on performance of dissimilar weld between mild steel and stainless steel and found the effect of CaO, Fe_2O_3, Cr_2O_3, and SiO_2 fluxes on surface appearance, weld morphology, angular distortion, and weld defect when using TIG process to weld 6 mm thick dissimilar metals between G3131 mild steel and 316L stainless steel. The SiO_2 powder can give the greatest improvement in joint penetration and also a satisfactory surface appearance of G3131 mild steel to 316L stainless steel dissimilar welds.

Chou Chang-Pin et al. (2005) studied the evaluation of TIG flux welding on the characteristics of stainless steel and found that TIG flux welding can significantly reduce the angular distortion of stainless steel weldments and the 80% MnO_2, 20% ZnO mixture can give full weld penetration and also a satisfactory surface appearance with type 304 stainless steel TIG flux welds. TIG flux welding can increase the arc voltage, the amount of heat input per unit length in a weld is also increased, and therefore the retained ferrite content in austenitic stainless steel welds will be increased. As a result, the hot cracking susceptibility in as welded structures is reduced.

Dongjie Li et al. (2012) studied the law between the weld pool shape variations with the welding parameters under two TIG processes and concludes that the changes in the welding parameters directly change the heat input and the pattern of the Marangoni convection, thus controlling the shape of the molten pool. The double-shielded TIG process is an appropriate method for adding an active element, such as oxygen, into the weld pool so as to transform the outward flow of Marangoni convection into an inward flow.

Hidetoshi Fujii et al. (2008) presented the development of an advanced A-TIG welding method by control of Marangoni convection and found that the addition of oxygen to the molten pool can control the Marangoni convection from the outward to inward direction on the liquid pool surface. When the oxygen content in the liquid pool is over a critical value, around 70 ppm the weld shape suddenly changes from a wide shallow shape to a deep narrow shape due to the change in the direction of the Marangoni convection.

Kiyoshi Nogi et al. (2010) studied the weld shape variation and electrode oxidation behavior under Ar-(Ar-CO_2) Double Shielded GTAW and conclude that Double shielded GTAW using 15 the pure inert Argon gas as the inner layer shielding and the active CO_2 or Ar-CO_2 gas as the outer layer shielding can protect well the tungsten electrode from oxidation in the welding process. The active gas, carbon dioxide, in the out layer shielding is decomposed and the active element, oxygen, dissolves in the liquid pool during the welding process, which successfully adjusts the active element content in the weld pool and controls the Marangoni convection mode on the pool surface.

Kuang-Hung Tseng et al. (2010) studied the performance of activated TIG process in austenitic stainless steel welds and conclude that TIG welding with SiO_2 and MoO_3 fluxes achieves an increase in weld depth and a decrease in bead width, respectively. The SiO_2 flux can facilitate root pass joint penetration, but the Al_2O_3 flux led to a deterioration in the penetration compared to the conventional TIG process for Type 316L stainless steel welds. The interaction between the centripetal Marangoni convection and the constricted arc plasma as a mechanism in increasing activated TIG penetration. The addition of oxide flux does not significantly affect the hardness of Type 316L stainless steel activated TIG weld metal.

Kuang-Hung Tseng et al. (2011) studied the effect of activated TIG flux on performance of dissimilar welds between mild steel and stainless steel and conclude that the SiO2 powder can give the greatest improvement in joint penetration and also a satisfactory surface appearance of G3131 mild steel to 316L stainless steel dissimilar welds.TIG welding with SiO2 powder can increase weld depth to width ratio, which indicates a high degree of energy concentration during welding process, and tends to reduce angular distortion of the weldment. Furthermore, the defects susceptibility of the welds can also be reduced.

Lucas et al. (2000) studied an investigation into arc constriction by active fluxes for TIG (A-TIG) welding and found that the arc or plasma is constricted by the action of the A-TIG fluxes and that the associated increase in current density results in increased forces which alter the molten pool flow to give increased penetration. The most dominant mechanism for increased penetration is considered to be arc constriction rather than a change in the surface tension of the molten pool.

Marya et al. (2007) optimized the design of silica coating for productivity gains during the TIG welding of 304L stainless steel and found that optimized thickness in A-TIG is observed to vary between 40-70 micro meter depend upon welding current. Further increase in coating thickness overall performance in terms of weld penetration is reduced. The silica application generates higher inclusion density in weld metal with resulting decrease in the tensile strength. However, this reduction is comparatively weak when improvement in weld penetrations are considered in overall process analysis.

Modenesi et al. (2000) studied the TIG welding with single-component fluxes and found simple fluxes of only one component present an adequate performance for A-TIG welding, resulting in a great increase of penetration in comparison to TIG welding, without any important deterioration of the welding conditions or of the microstructure of the welds.

Parameswaran et al. (2011) studied the comparison of creep rupture behavior of type 316L(N) austenitic stainless steel joints welded by TIG and activated TIG welding processes and found that weld joints of 316L(N) austenitic stainless steel possessed lower creep rupture life than the base metal. Joining of 316L(N) austenitic stainless steel adopting single pass Activated TIG (A-TIG) welding process increased the creep rupture life of the steel weld joint over that multi-pass TIG (MP-TIG) weld joint. Progressive localization of creep deformation and cavitations in the weld metal led to the premature failure of the joints in the weld metal.

Qing ming et al. (2007) studied the effect of activating flux on arc shape and arc voltage in tungsten inert gas welding and found that SiO2 flux increase the arc voltage while TiO2 has no effect on arc voltage. Arc shape changed in A-TIG with SiO2. Weld penetrations are both increased greatly when using SiO2 and TiO2, however, their reasons are not the same. When using SiO2, arc shrinkage is the main aspect to increase the weld penetration. When using TiO2, arc shrinkage plays a secondary role in weld penetration, change of flow direction of molten metal in molten pool may be the main effect.

Present Work
The present study will investigate the performance of stainless steel (AISI SS304) welds by GTAW and A-GTAW process using Design of Experiments (DOE) methodology. A comparison of mechanical properties of the welds made by GTAW and A-GTAW of stainless steel (AISI SS304) will be done for the industrial benefits. Mechanical testing such as tensile testing, micro-hardness testing and microstructures will be performed to check the performance of welded joints.

3. DESIGN OF EXPERIMENTS (DOE)

Design of Experiments (DOE) is a commonly used technique in analyzing experimental data resulting in the optimization of processes parameters. It is an empirical statistical modeling technique employed for multiple regression analysis using quantitative data obtained from properly designed experiments to solve multivariate equations simultaneously. It is a formal structured technique for studying any situation that involves a response that varies as a function of one or more independent variables and commonly used to address complex problems where more than one variable may affect a response and two or more variables may interact with each other. It can provide the answers to specific questions about the behavior of a system, using the optimum number of experimental observations. The design of experiment is a procedure of selecting number of trials and conditions running them, essential and sufficient for solving a problem that has been set with the required precision. The advantages of designs of experiments are summarized as follows:

- Numbers of trials are significantly reduced.
- Identification of important decision variables, which control and improve the performance of the product or process.
- Optimal setting of the parameters can be found out.
- Determination of experimental error can be made.
- Inference regarding the effect of parameters on the characteristics of the process can be made.

Experimental design is a strategy to gather empirical knowledge, i.e. knowledge based on the analysis of experimental data. Building a design means, carefully choosing a small number of experiments that are to be performed under controlled conditions. There are four interrelated steps in building a design:

1. Design an objective, i.e. effect of process variables or find optimal parameters.
2. Define the process variables that will be controlled during experimentation and their working range.
3. Define the variables that will be measured to describe the outcomes of the experimental runs i.e. response variables.
4. Among the available standard designs, choose the one that is compatible with the objective, number of design variables and precision of measurements and has a reasonable cost.

Taguchi's Methodology:

The traditional full factorial designs require experimental data for the possible combinations of the factors involved in the study, consequently a very large number of trials need to be performed. Therefore, in case of the experiments involving relatively more number of factors, only a small fraction of combinations of factors are selected that produces most of the information to reduce experimental efforts. This approach is called fractional-factorial design of experiment. The analysis of results in this approach is complex due to non Taguchi method gives a solution to this problem. Taguchi method simplifies and standardizes the fractional factorial design by introducing orthogonal array (OA) for constructing or laying out the design of experiments. It also suggests a standard method for the analysis of results. Orthogonal arrays are two dimensional arrays of numbers which possess the interesting quality that by choosing any two columns in the array you receive an even distribution of all the pair –wise combination of values in the array.

Orthogonal Array:

In the present study we has used L_{18} Orthogonal array as shown in Table 1. In this Table 1, A is noise factor and B, C, D are control factors. Noise factors are difficult to change during the process, it is nearly impossible to change the noise factor during the process, but control factors can be very easily varied or changed during our experiment or process.

Table 1 L_{18} Orthogonal array design

Runs	Factors			
	A	B	C	D
1	1	1	1	1
2	1	1	2	2
3	1	1	3	3
4	1	2	1	1
5	1	2	2	2
6	1	2	3	3
7	1	3	1	2
8	1	3	2	3
9	1	3	3	1
10	2	1	1	3
11	2	1	2	1
12	2	1	3	2
13	2	2	1	2
14	2	2	2	3
15	2	2	3	1
16	2	3	1	3
17	2	3	2	1
18	2	3	3	2

Runs: The number of rows in the array. This directly translates to the number of test cases that will be generated the OATS technique.

Factors: The number of columns in an array. This directly translates to the maximum number of variables that can be handled by this array.

Levels: The maximum number of values that can be taken on by any single factor. An orthogonal array will contain values from 0 to levels 1.

Signal to Noise Ratio

There are many S/N ratio, the important S/N ratios are

- Nominal the better
- Smaller the better
- Larger the better

Nominal the better: This case arises when a specified value is most desired, meaning that neither a smaller nor a larger value desirable.

$$\left(S/N\right)_{NB} = -\log\left(MSD_{NB}\right)$$

$$MSD_{NB} = \frac{1}{R}\sum_{j=1}^{R}\left(y_j - y_o\right)^2$$

R = Number of repetitions

Smaller the better: This is actually the chosen S/N ratio for all undesirable characteristics like defects etc for which the ideal value is zero

$$\left(S/N\right)_{LB} = -10\log\left(MSD_{LB}\right)$$

Where $MSD_{LB} = \frac{1}{R}\sum_{j=1}^{R}\left(y_j^2\right)$

Larger the better: This case has been converted to smaller the better by taking the reciprocals of measured data and then taking the S/N ratio as in the smaller the better case

$$\left(S/N\right)_{HB} = -10\log\left(MSD_{HB}\right)$$

$$MSD_{HB} = \frac{1}{R}\sum_{j=1}^{R}\left(1/y_j^2\right)$$

4. EXPERIMENTAL WORK

The materials were taken from Bombay steels, Ludhiana, Punjab, India. The chemical composition of the steels shown in table 2

Table 2: Composition of stainless steel 304 (wt %)

Alloy element	C	Si	Mn	Ni	Cr	P	S	Ti	Mo	Fe
Content (wt %)	0.037	0.36	1.33	8.73	18.83	0.0353	0.009	0.0	0.095	70.36

Grade AISI 304 stainless steel plate was selected as the test specimen. Table 4.1 lists the chemical compositions of this steel. Plates measuring 6 mm thick were cut into 100 × 150 mm strips with V-groove (1.2 mm root face, 1 mm root gap and included groove angle is 60°) using 1.6 mm diameter matching filler wire and roughly polished with 400 grit silicon carbide paper to remove surface contamination, and then cleaned with acetone.

GTAW Welding Machine:

GTAW welding was performed on an advanced square wave GTAW welding machine. The specifications of the GTAW welding machine are given in table 3. Shielding gas used in this study was industrially pure argon gas.

Table 3: GTAW machine specifications

Model	WSE-200 IGBT AC/DC GTAW WELDER
Input power voltage, frequency (V, Hz)	Single-phase, 220±10%, 50Hz
Rated input power (KW)	5.0
Power factor	0.98
Adjustment range of start current	AC, 5-200
Adjustment range of down slope time	0-10 (s)
Adjustment range of post-gas time	3-10 (s)
Clearance effect	-5 to +5

Design of Experiments:

The basic parameters selected for the current experimental study are type of welding (GTAW and Activated-GTAW welding), welding current (A), shielding gas flow rate (l/min).

1. Noise factors: Type of welding (GTAW and A-GTAW welding).
2. Control factors: welding current (A), shielding gas flow rate (l/min).

In the present experimental study each control factor is given three levels as shown in Table 4

Table 4: Experimental parameters and their levels

Factors	Units	Level 1	Level 2	Level 3
Type of Welding	---	A-TIG (Designated as`1`)	TIG (Designated as `2)	---
Current	A	120	140	160
Shielding gas flow rate	l/min	6	8	10

Taguchi's Orthogonal Array:

In the current study, L_{18} (2^1x3^2) orthogonal array has been used in the present study as shown in Table 5. Accordingly 18 runs were performed on the basis of orthogonal array. The noise factor (type of welding) has been assigned outer array, where as the control factors have been assigned inner arrays. The interaction between noise factor and control factor will also be studied.

Table 5: Design matrix using L_{18} orthogonal array

Runs	Welding type	Welding current	SGFR
1	1	120	6
2	1	120	8
3	1	120	10
4	1	140	6
5	1	140	8
6	1	140	10
7	1	160	6
8	1	160	8
9	1	160	10
10	2	120	6
11	2	120	8
12	2	120	10
13	2	140	6
14	2	140	8
15	2	140	10
16	2	160	6
17	2	160	8
18	2	160	10

Experimental Results:

The results of the experimentation and mechanical testing of different welded specimens are given in Table 5.1.

Table 6: Experimental results

Welding Type*	Welding Current (A)	SGFR (l/min)	Depth Width ratio	Mean Micro hardness (VHN)	Tensile Strength (KN/mm^2)	S/N Ratio Depth Width ratio	S/N Ratio Mean Micro-hardness	S/N Ratio Tensile Strength
1	120	6	0.58	225	110.0	-4.7314	47.0437	40.8279
1	120	8	0.62	209	118.5	-4.1522	46.4029	41.4744
1	120	10	0.59	220	112.6	-4.5830	46.8485	41.0308
1	140	6	0.62	201	119.1	-4.1522	46.0639	41.5182
1	140	8	0.64	190	121.0	-3.8764	45.5751	41.6557
1	140	10	0.60	206	116.0	-4.4370	46.2773	41.2892
1	160	6	0.45	248	92.2	-6.9357	47.8890	39.2946
1	160	8	0.60	228	101.1	-4.4370	47.1587	40.0950
1	160	10	0.46	260	94.0	-6.7448	48.2995	39.4626

2	120	6	0.47	237	98.2	-6.5580	47.4950	39.8422
2	120	8	0.55	233	100.4	-5.1927	47.3471	40.0347
2	120	10	0.44	250	91.4	-7.1309	47.9588	39.2189
2	140	6	0.33	270	82.3	-9.6297	48.6273	38.3080
2	140	8	0.35	261	85.5	-9.1186	48.3328	38.6393
2	140	10	0.48	264	84.2	-6.3752	48.4321	38.5062
2	160	6	0.29	266	87.2	-10.7520	48.4976	38.8103
2	160	8	0.39	252	91.2	-8.1787	48.0280	39.1999
2	160	10	0.43	260	90.4	-7.3306	48.2995	39.1234

(Note: * 1=A-TIG, 2=TIG)

Conclusion:

Based on the present work a few important conclusions could be drawn. These conclusions are specific to the GTAW and Activated-GTAW welding used in the present work besides the different welding parametric combination used.

1. The surface of GTAW welds produced with flux formed residual slag and spatters. Using GTAW welding with flux produced a small amount of fume.
2. Using SiO_2, flux not only significantly increased penetration capability, but also improved mechanical strength of the grade 304 stainless steel welds compared with conventional GTAW welds.
3. A-GTAW welding can increase the weld depth/width ratio and reduce the HAZ range, which are characteristics of a high degree of energy concentration during the GTAW flux welding process.
4. Depth Width Ratio has directly effect on mechanical properties of welded joint. Thus tensile strength of welded joint increase as the depth width ratio increased.
5. In GTA welding on SUS304 stainless steel, the heat transfer and fluid flow in weld pool occurs mainly by convection mode. Marangoni convection patterns on the pool surface are controlled by the combination of the oxygen content and the temperature distribution on pool surface, which depends to large extent on the welding parameters.
6. Changes in the welding current directly change the heat input and the pattern of the Marangoni convection, thus controlling the shape of the molten pool. For the GTA welding process as the welding current increase there is formation of outward marangoni convection and thus decrease in depth width ratio. In A- GTAW process as the welding current increase inward marangoni convection formed and thus increases in depth width ratio.
7. Mode of heat transfer in weld pool is find out using peclet number and increase in peclet number in A-GTAW signifies that heat transfer in liquid pool in this study is dominated by convection mode.
8. Welding parameters for best quality weld are
   - Welding type: Activated-TIG welding
   - Current: 120A
   - Shielding gas flow rate: 6 L/min

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