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Review Article

Development of Flux Bounded Tungsten Inert Gas Welding Process to Join Aluminum Alloys

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Abstract: Tungsten Inert Gas (TIG) welding process is normally used to join aluminum alloys because of its simplicity. However its penetration capability is limited. To improve penetration capability of TIG process to join aluminum alloys, Flux Bounded TIG (FBTIG) was developed. This paper consolidates the developments that took place in FBTIG process specifically in the selection of flux, flux gap, flux particle size, current polarity, weld bead depth enhancement achieved in the investigations and characterisation of the welds in terms of its tensile strength and corrosion resistance.

Keywords: FBTIG, Weld Penetration, Aluminium Alloy Weld

1. Introduction

Tungsten inert gas welding (TIG) is an arc based process between a tungsten electrode and a work piece. In view of its simplicity, good weld appearance and feasibility to join bigger structures, this process is commonly used to join reactive materials like stainless steel, magnesium alloys, aluminum alloys etc. However the limitation of this process is its lower penetration capability. Generally TIG welding process can be used to join material thickness up to 3 mm in single pass autogenously.

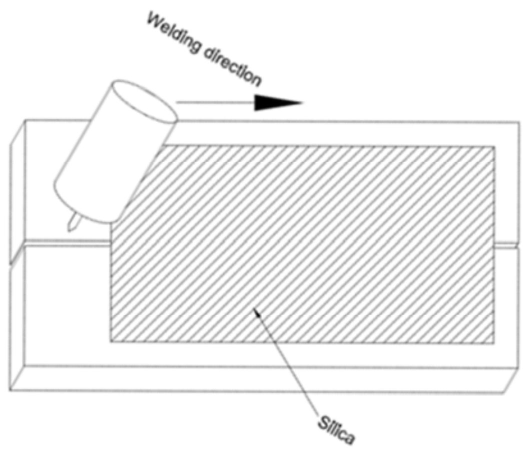

Figure 1. *Scheme of ATIG welding.*

In order to join higher thickness materials, multipass welding is used, which needs joint preparations and filler additions. For titanium alloys, in 1960s, Paton Electric Welding Institute developed a new flux assisted TIG welding process called Activated Flux TIG (ATIG) process, in which a thin layer of activating flux is applied on the surface of the material prior to welding. Subsequently this new process is used for experimental investigations in other materials viz. stainless steels, magnesium alloys and aluminum alloys [1]. The ATIG welding process is schematically shown in Figure 1. The flux powder is mixed in acetone and applied on the material surface by using a brush. On drying, a thin layer of flux coat is formed on the work surface. For aluminum alloy welds, Sire and Marya [2] observed that a silica application according to Figure 1 was not suitable. On detailed investigations by Santhana Babu et al [3], it was observed due to uneven electric resistance across the flux covered surface (because of the minor variation in the flux coat thickness), arc wandering happens in ATIG welds which may affect the weld joint strength. Hence, ATIG process was modified by applying two symmetric flux coatings closer to the weld joint by maintaining a small gap between them as shown in Figure 2.

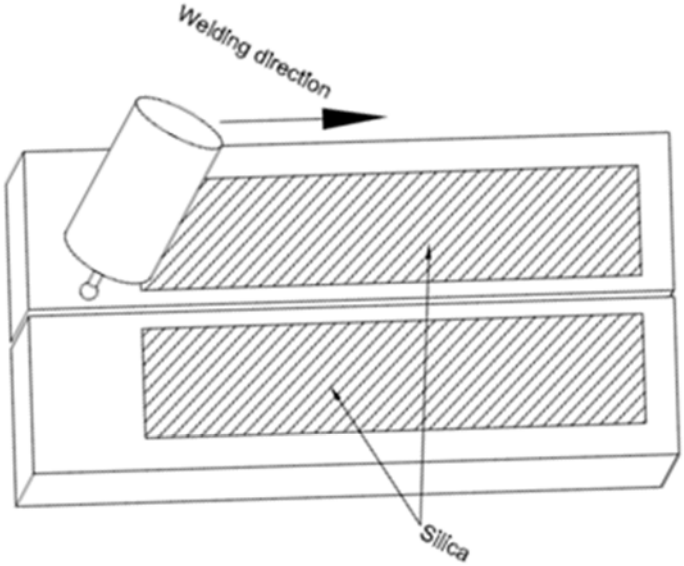

Figure 2. *Scheme of FBTIG welding.*

This process is named as Flux Bounded TIG (FBTIG). It was also observed that ATIG welds are prone to liquation cracks due to excessive grain boundary liquation. But FBTIG welds do not exhibit the cracking tendency because of the absence of continuous grain boundary liquation and due to the presence of finer grains [3]. In ATIG/FBTIG welding, constriction of the electric arc and reversal of Marangoni convection were found to be the mechanisms for deeper penetration [4, 5].

1.1. Constriction of Electric Arc

The current path in the case of conventional TIG welding process without flux expands widely over the whole weld pool surface area and hence the penetration is shallow and wide. However in the ATIG process, the flux particles at the central zone are melted and the unmelted flux particles in the surrounding outer zone offer resistance to the current flow. As a result, the current path is constricted at the centre. In FBTIG process, the absence of flux in central zone makes it more conducting than the outer regions which leads to arc constriction. The constricted arc delivers concentrated heat flux at the central zone which results in deeper penetration.

1.2. Reversal of Marangoni Convection

This convection arises due to shear stress induced by surface tension gradient in the weld pool. In the absence of a surface active agent, the surface tension of the liquid metal decreases with increasing temperature and hence negative correlation prevails between them as shown in Figure 3 (a). In view of this, the warmer liquid metal with a lower surface tension is pulled outward by the cooler liquid metal with a higher surface tension as shown in Figure 3 (b). This causes the liquid metal to flow from the center of the pool surface to the edge and return below the pool bottom along the pool boundary, as shown in Figure 3(c). As a result, a shallow and wider weld pool is developed. However by adding surface active agents, the surface tension gradient can be made positive as shown in Figure 3 (d). Due to this change, at weld pool surface, convective flow happens from outer edge towards the centre of the pool as shown in Figure 3 (e) and liquid metal reaches pool bottom along pool axis as shown in Figure 3 (f). This is called reversed Marangoni convection which aids deeper weld penetration [6]. In ATIG/FBTIG process, traces of dissolved flux into the molten weld pool act as surface active agents which reverse the direction of Marangoni convection.

2. Literature Review

2.1. Studies on Flux Selection

For FBTIG welds on aluminium alloy AA 5086, Stephane Sire and Surendar Marya [2, 7] used silica (SiO_2) as the flux to get defect free welds. Later, Huang Yong et al. [8] made a comparative study of the effect of fluxes SiO_2, TiO_2, CaF_2 and a multi element active flux AF305 (for which composition is not disclosed) on FBTIG welds and observed better results by using flux AF305. A further study by Huang Yong et al. [9] also confirmed better result with flux AF305 when compared with SiO_2. Yong Zhao et al. [10] investigated the effect of fluxes SiO_2, TiO_2, CaF_2, MgO, and NaCl on AA 5083 welds and found all of them as good candidates for flux. However in their investigations, SiO_2 gave superior results. Subsequently SiO_2 was used in investigations by other researchers.

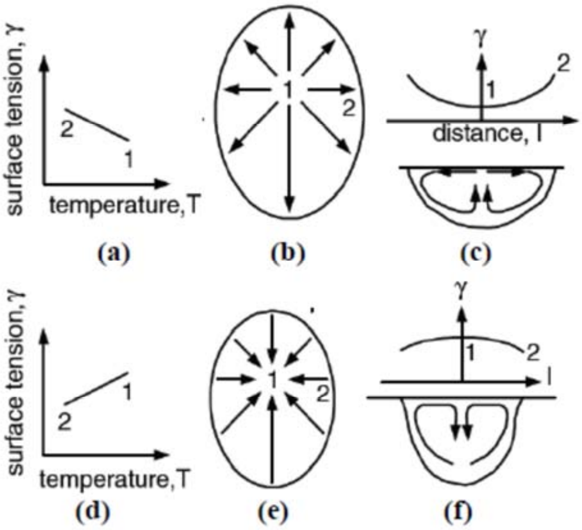

Figure 3. *Marangoni flow in weld pool (a-c) without surface activation elements (d-e) with surface activation elements.*

2.2. Studies on Flux Gap

Flux gap of 4 mm was found to be optimum to get maximum depth to width (D/W) ratio by Huang Yong et al. [8]. Yong Zhao et al. [10] also reported flux gap of 4 mm as the optimum in joining AA 5083 aluminum alloy. When the flux gap was increased beyond 4 mm, wider conductive path made available for the arc decreases the arc constriction effect due to which, decreasing tendency of weld penetration depth was observed. Also chances of mixing the traces of flux particle in weld pool is remote in the wider flux gap beyond 4 mm, which does not favour reversal of Marangoni convection in the weld pool. This is also confirmed in Reference [11]. These results guided other researchers to follow 4 mm of flux gap in their investigations.

2.3. Studies on Flux Particle Size

When the silica flux particle size was reduced from 2.5 microns to 0.6 microns, improvement in weld bead depth to width ratio was observed from 0.56 to 0.94 [11]. This is attributed to the increase in the effective surface area of the flux particles due to the decrease in its size. Further, flux particles of finer size undergo thermal decomposition much easily when compared to coarser flux particles. This means that finer flux can cause more efficient electron absorption to improve the electric arc constriction than coarser flux, which results in higher depth to width ratio.

2.4. Studies on Current Polarity

Good results were demonstrated by Stephane Sire and Surendar Marya [2, 7] and Yong Zhao et al. [10] by using AC mode current in their investigations. The effect of current polarities namely Alternating Current (AC), Direct Current Electrode Positive (DCEP) and Direct Current Electrode Negative (DCEN) which is also called as Direct Current Straight Polarity (DCSP) on weld penetration was studied by Huang Yong et al. [9] by using multi component activating flux AF305 (for which composition is not disclosed) in aluminum alloy 3003 welds. The duration of AC TIG welding can be sub divided into DCEP duration and DCEN duration. Cathode cleaning action is associated with DCEP and deep penetration is associated with DCEN polarity. Since AC TIG welding consists of both DCEP and DCEN, a clean weld with penetration over two times more than that of conventional TIG welds could be obtained in AC polarity. In DCEN TIG welding, weld penetration has improved but, an oxide film existed on the weld surface in the region without flux because, cathode cleaning action does not happen. In the region with flux, the entire weld surface was found covered with black flux layer. In DCEP ATIG welding, the weld surface without flux had metal luster. In the region with flux, black slag distribution was observed on the surface. However the improvement in weld penetration was very little. Hence for FBTIG welding, AC polarity is considered as best among the three options.

3. Experimental Results on Weld Bead Depth Enhancement and Weld Characterization

By using SiO_2 as flux with a flux gap of 4 mm, Sire and Marya [2, 7], Yong Zaho et al. [10] and Santhana Babu et al. [12] reported weld bead depth enhancement in their investigations by using AC current polarity, which is reflected in Table 1. In these investigations, bead depth of 6 mm and depth to width ratio of 0.75 are reported by Sire and Marya [2, 7]

3.1. Mathematical Model Development

Bead on plate welding is carried out on AA2219 T87 material of 100 x 40 x 7 mm size specimens to predict and control the FBTIG weld bead geometry by varying the following controllable process parameters, by maintaining the base current of 100 A, to generate the data on bead geometry viz. bead depth to width ratio (D/W) and bead depth (D).

- Peak current (Ip): 160-240 A
- Speed (v): 160 to 200 mm-min^{-1}
- Pulse duration (t): 20 to 80 %
- Pulse frequency (f): 2 to 10 Hz

The pulse duration is calculated as the ratio of peak current duration to the total cycle duration and expressed in %. For the experiments, welding is done in AC polarity by using silica as flux with a flux gap of 4 mm. With the use of the experimental data, mathematical models shown in Equation 1 and 2 are developed to correlate controllable FBTIG process variables with bead geometry by using Design of Experiments based on four factors five level central composite rotatable design [12]. The model accuracy is found better than 95% of the prediction in the confirmatory tests.

$$D/W\ ratio = 0.33 + 0.0212\ Ip - 0.0113\ v + 0.0612\ t + 0.0021\ f - 0.0128\ Ip^2 + 0.0009\ v^2 + 0.0197\ t^2 + 0.0022\ f^2 - 0.0006\ Ip*v + 0.0044\ Ip*t - 0.0144\ Ip*f - 0.0206\ v*t + 0.0031\ v*f - 0.0069\ t*f \quad (1)$$

$$D = 2.1743 + 0.5017\ Ip - 0.2125\ v + 0.8808\ t + 0.0192\ f - 0.0334\ Ip^2 - 0.0246\ v^2 + 0.2879\ t^2 + 0.0254\ f^2 - 0.03\ Ip*v + 0.2775\ Ip*t - 0.0375\ Ip*f - 0.2975\ v*t + 0.1200\ v*f - 0.0675\ t*f \quad (2)$$

Based on the above mathematical models, the main (direct) effects and interaction effects of different process variables on weld bead parameters and the possible causes for them were analyzed [12]. Main effect is the effect of varying a single welding process variable on bead geometry when the remaining variables are held constant at their mean level. Interaction effect is the effect of varying two welding process variables simultaneously on the bead geometry when the remaining variables are held at their mean level. In this analysis, the process variables peak welding current (Ip), welding speed (v) and pulse current duration (t) are found to have significant effect on the bead shape.

3.2. Tensile Strength Evaluation

To characterize the tensile strength of the FBTIG welds, 7 mm thickness AA 2219 T87 specimens were welded with the parameters of 100 A base current, 220 A peak current, 120 mm-min^{-1} welding speed and 65% pulse duration with silica as the flux. Pulse frequency is maintained as 2 Hz except for FBTIG at Experiment No 4 of Table 2, for which 8 Hz is maintained. In this study, tensile properties of FBTIG welded joints are found better than conventional TIG welded joints [13].

Table 1. *Weld bead depth enhancement reported in investigations.*

Material	Welding Current in A	Welding Speed in mm/min	Bead depth in mm	Depth to width ratio	Investigator
AA 5086	175	150	6	0.75	Sire and Marya [2, 7]
AA 5083	140	125	5	0.59	Yong Zhao et al. [10]
AA 2219	220 (pulsed mode)	170	4.61	0.5	Santhana Babu et al. [12]

The stress – strain plot obtained from tensile tests is shown in Figure 4. In this investigation, yield strength has improved from the order of 41% in conventional TIG welds to about 50-54% in FBTIG welds as reflected in Table 2. The improvement of UTS and elongation in FBTIG welds is not remarkable but still better than normal TIG welds without flux. Based on the microstructure investigation, the improved strength in FBTIG welds is attributed to the presence of fine grain structure in the welds.

3.3. Stress Corrosion Cracking Resistance of FBTIG Welds

By using the same material of aluminum alloy AA 2219 T87 used for tensile tests, stress corrosion cracking (SCC) behavior of FBTIG welds was evaluated in 3.5 weight percent NaCl solution using Slow Strain Rate Test technique (SSRT) as per ASTM G129 [14]. The weld process parameters were kept as same as used for tensile test study. Pulse frequency is maintained as 2 Hz and 8 Hz for Experiment No 2 and 3 respectively. Stress-strain curves obtained for the base metal and FBTIG welds are compared in Figure 5 [14]. Stress-strain graph shows similarity in the behavior of base metal in both NaCl and air with negligible loss in elongation due to the exposure to corrosive environment. SCC index which is defined as the ratio of the elongation of tensile tested specimen in NaCl to that of air is taken as a measure of the susceptibility to cracking.

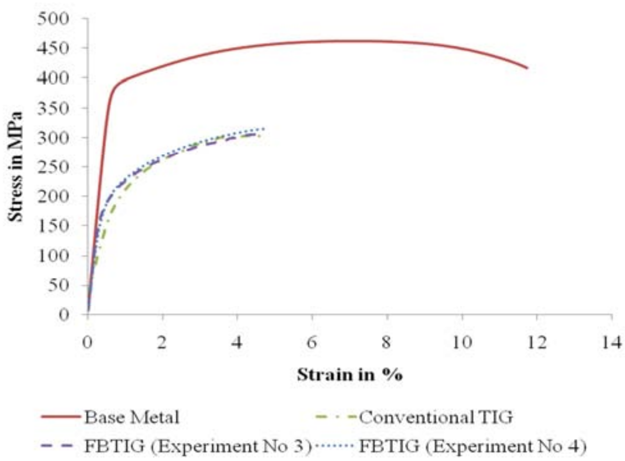

Figure 4. *Stress – strain plots of tensile tests.*

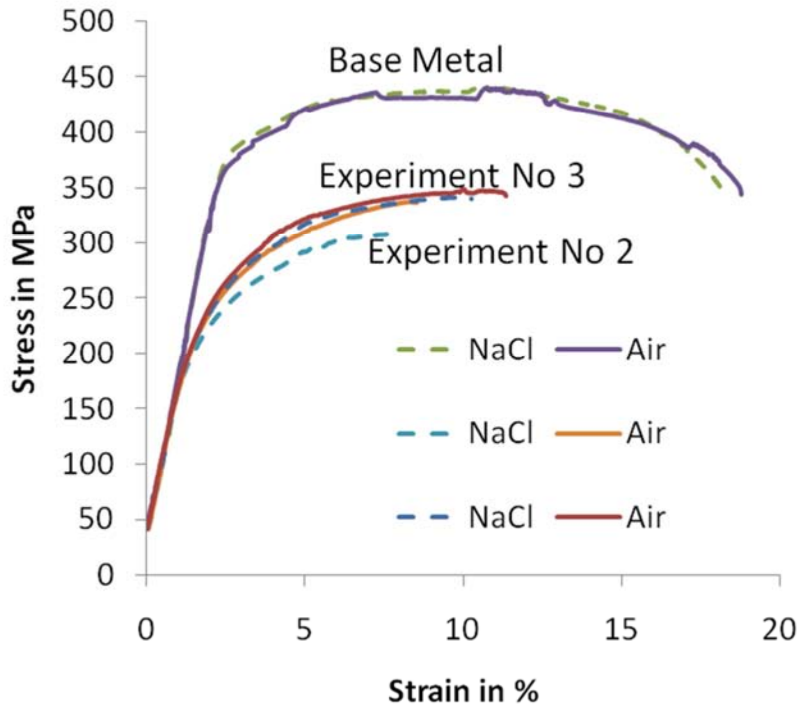

Figure 5. *Stress-strain plots of SSRT tests.*

Table 2. *Mechanical properties of tensile tested specimens.*

Experiment No	Specimen Identification	YS in MPa [0.2% offset]	UTS in MPa	Elongation in %
1	Base Metal	386	462	11.67
2	Conventional TIG	157	300	4.61
3	FBTIG	194	304	4.66
4	FBTIG	208	313	4.77

Table 3. *Mechanical parameters obtained from SSRT tests at the strain rate of 5.7 x 10^{-7}/s.*

Sample	Medium	UTS [MPa]	Elongation [%]	SCC Index
Experiment No 1 Base Metal (AA 2219-T-87)	Air	426	18.44	0.99 (Present study [14])
	NaCl	443	18.41	
Base Metal (AA 2219-T-87)	Air	389	15.8	0.97 (Reported by Venugopal et al. [15])
	NaCl	392	15.4	
Single pass (AA 2219-T-87)	Air	260	6.2	0.90 (Reported by Venugopal et al.[15])
	NaCl	256	5.6	
Multi-pass (AA 2219-T-87)	Air	280	7.9	0.96 (Reported by Venugopal et al.[15])
	NaCl	286	7.6	
Repair welded (AA 2219-T-87)	Air	256	8.1	0.77 (Reported by Venugopal et al.[16])
	NaCl	256	6.3	
Experiment No 2 (FBTIG welded)	Air	338	8.52	0.93 (Present study [14])
	NaCl	301	7.93	
Experiment No 3 (FBTIG welded)	Air	347	11.30	0.91 (Present study [14])
	NaCl	341	10.25	

Based on the SCC index, it was observed that the SCC resistance of FBTIG joints is good and comparable to that of conventional TIG welds. The SSRT results shown in Table 3 reveal that SCC index for base metal is high (0.99) demonstrating high stress corrosion cracking resistance of AA2219 T87 material [14]. In FBTIG welds both in Experiment No 2 and 3, decrease in the UTS and elongation are observed in NaCl environment which reduces the SCC index to 0.93 and 0.91 respectively. Stress corrosion characteristics of aluminum alloy AA 2219 T87 TIG welded joints in 3.5% NaCl solution is studied by Venugopal et al. [15, 16] extensively and test data in as welded (both single and multi-pass welds) and after repair welding are generated by them using SSRT. They observed that the alloy in as welded condition (both single and multi-pass) exhibited better SCC resistance in NaCl solution based on SCC index which was closer to one [15]. On the other hand, SSRT on repair welded specimens exhibited better ductility than those in as welded condition [16]. The SCC index of FBTIG welds observed by Santhana Babu et al. [14] is comparable with the data for conventional TIG welds published by Venugopal et.al. [15, 16]. Fractographic studies on the failed specimen revealed ductile failure in FBTIG welds in spite of exposure to corrosive environment.

4. Conclusions

a. FBTIG welding can improve the weld bead depth in aluminum alloy welds.
b. Silica (SiO_2) is the preferred flux for FBTIG process.
c. Flux gap of 4 mm is the optimum gap for FBTIG process
d. Alternating Current (AC) is the suitable polarity for FBTIG process
e. Process variables peak welding current (Ip), welding speed (v) and pulse current duration (t) are found to have significant effect on the bead shape.
f. Tensile properties of FBTIG welded joints are better than conventional TIG welded joints. Yield strength has improved from about 41% in conventional TIG welds to the order of 50-54% in FBTIG welds.
g. Stress corrosion cracking resistance of FBTIG joints is good and comparable to that of conventional TIG welds.
h. These studies will pave way for potential application of FBTIG process for aluminum welding in place of conventional TIG welding to improve the productivity.

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