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TECHNICAL PAPER

Effect of Flux Gap and Particle Size on the Depth of Penetration in FBTIG Welding of Aluminium

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Abstract Flux Bounded TIG welding is a variation of Activated TIG welding wherein a narrow strip of base metal is coated with activating flux and is exposed to the arc during welding. Bead on plate welds by FBTIG process on commercially pure aluminium plates were performed using silica as flux. This paper investigated the effect of flux gap and flux powder particle size on the weld penetration and depth to width ratio. Microstructural analysis was carried out to understand the changes in grain structure in the weld pool and adjacent zones. It was observed that the weld penetration and depth to width ratio increased with the decreasing flux gap. Also, results showed better penetration for activating flux with finer flux powder size. The mechanisms that supported these observations have been explained.

Keywords A TIG welding · Aerospace · Aluminium · Bead on plate · GTA welding · Silica · Particle size

1 Introduction

Aluminium and its alloys are widely used in strategic applications such as aerospace, defence and ship-building for its light weight and other attributed characteristics. Welding of aluminium and its alloys is inevitable and Gas Tungsten Arc Welding (GTAW) is the widely adopted process in all the industries. TIG welding is used because of the high quality welds obtained and the high levels of shielding achieved from atmospheric oxidation. When compared to the Shielded Metal Arc welding (SMAW) or Gas Metal Arc welding, TIG promises a better control over the welding process. However, one general problem associated with TIG welding of aluminium is the lack of penetration. This means that multiple passes for welding has to be done in order to weld thick plates involving larger heat input. However, multiple weld passes results in a larger Heat Affected Zone (HAZ) and its associated demerits. It is well known that increasing HAZ effectively reduces the strength of the weld [1]. In this scenario, it is important to avoid multiple passes during welding, which means that alternate methods for increasing penetration is to be obtained for welding thicker plates of aluminium.

One such novel idea in the field of welding is the use of activating fluxes to increase the penetration. Many associate this observation with a scientific phenomenon called Marangoni convection currents. Presence of large concentrations of fluorine and oxygen affects the surface tension of the weld pool to cause a reversal in the molten metal flow direction. This results in enhanced penetration and reduced bead width. However, another proposed mechanism attributes this observation to arc constriction phenomenon. According to this, constriction of arc is brought about by the presence of certain species like oxygen and fluorine (highly electro-negative) in the arc. This causes a reduction in the arc thickness, thus making the arc more concentrated and the overall process an energy intensive one [2].

Usually, the ratio of penetration (or depth of weld) and the width of the weld are used to compare the effectiveness of various welding techniques. Ruckert et al. [3] investigated the effect of activating fluxes in TIG and found an increase in the depth to width ratio. Experiments shows

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that penetration get almost doubled when activating fluxes are coated on the surface. This means that Active Flux TIG (ATIG) can be used as a substitute for multi-pass welding and thicker plates can be welded without creating large HAZ.

As an extension to this method, came the idea of Flux Bounded Tungsten Inert Gas welding (hereby referred to as FBTIG). In this process, the component that is to be welded is coated with an activating flux, leaving a narrow strip of exposed metal, where the weld bead will appear as shown in Fig. 1. Sire and Marya carried out an investigative study on enhancing the weld penetration by using the flux bounded technique of TIG welding and observed an increase in weld penetration and depth to width ratio [4]. Arc constriction is the mechanism that is used to explain the increase in weld penetration. The chemicals widely used as activating flux are silicon dioxide (silica—SiO_2), titanium dioxide (TiO_2) and aluminium oxide (alumina—Al_2O_3). This process only requires a coat of activating flux on the surface of the plate to be welded, but produces results of multi-pass welding without many of the disadvantages associated with it. This means that FBTIG can act as a cost effective solution to the problem of lack of penetration in TIG welding of aluminium and the negative impacts of HAZs caused by multiple weld passes.

In this study, bead-on-plate weld runs have been carried out in commercially pure aluminium. Further, the plates have been sectioned and subjected to microstructural evaluation. Creating a weld with high penetration and low width will increase the productivity and decrease welding part distortion. Also, the effect of activating flux on weld geometry and mechanical properties have been studied.

Although certain industries practice the method of ATIG or FBTIG, there is no complete understanding behind the observations and the obtained experimental results. Although several hypotheses have been proposed for these welding processes, till date, none has been proved to be the actual mechanism. Since the process of welding is very important in the field of manufacturing technology and the methods of FBTIG has a significant and direct application in almost all fields where welding is carried out, it is necessary to have a complete understanding of the scientific reasons behind the observations. A complete knowledge of the mechanism behind FBTIG will also help in deciding and optimizing the process parameters. This study is aimed at providing an insight into the mechanisms causing increased weld penetration and higher depth to width ratio, thereby improving the understanding of the FBTIG process.

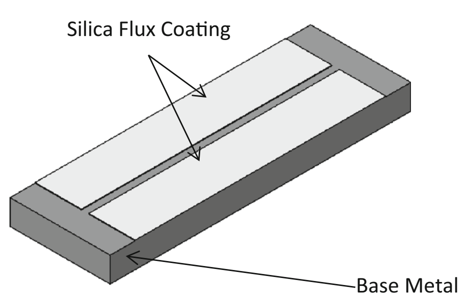

Fig. 1 A schematic diagram showing the configuration of the weld plates with the flux coat

2 Methodology

2.1 Welding

Specimens for the bead-on-plate welding trials were machined to dimensions of 100 cm × 4 cm × 12 mm and were prepared from commercially pure aluminium. Several oxides like TiO_2, Al_2O_3, Fe_2O_3, Cr_2O_3, SiO_2 etc. qualified as activating fluxes that caused increased weld penetration [5]. Among these, several oxides are highly toxic in nature and their usage have been limited [6]. However, SiO_2 and TiO_2 pose no such risk in terms of toxicity and thereby could be used as activating fluxes. Among silica and titanium dioxide, silica was proved to be a better flux, giving more penetration for the same quantity. A comparison of the stability of oxides showed that titanium dioxide was much more stable than silica, which could be observed from the respective position of SiO_2 and TiO_2 in the Ellingham Diagram [7]. This caused TiO_2 to melt at a much higher temperature than silica, which meant that more energy was required to melt TiO_2 than silica. Thus, the concentration of Oxygen in the weld pool would be higher for silica than titanium oxide, causing increased penetration and greater reduction in the weld depth. Also, the easily decomposed silica would cause more efficient arc constriction than TiO_2 [8].

Silica powder was mixed with a proper amount of acetone to form a flux paste that could be brushed over the surface of the plate. A small gap (hereby referred to as flux gap) was maintained in the middle of the plate and the flux was coated on either sides of this gap. The flux paste was applied manually, using a brush just before welding. Experiments were carried out with varying flux gaps of 3, 4 and 5 mm. The entire process was repeated using silica flux with different particle sizes to study the effect of particle size (0.6 and 2.5 μm) of the activating flux on the weld penetration. The results were compared with the weldments made through normal TIG process.

The bead-on-plate TIG welds were made using a Lincoln Electric welding unit (Invertec V405T PULSE). The images of the arc were captured using a high resolution camera. The captured images were enhanced, filtered and made free of disturbances and noises.

2.2 Characterization and Evaluation of Properties

Once the bead-on-plate welding was completed, the plates were sectioned and polished using emery papers of different grades. The samples were further polished to near mirror finish using diamond paste (Table 1).

These samples were then etched using Keller's Reagent (refer Table 2). The microstructures were captured at different magnifications in an optical microscope (Carl Zeiss Axioscope) and the fusion boundary was identified. The depth of penetration and width of the weld bead was measured using the microscope and the average values were reported. The entire process was then repeated for the weldments made with the varying flux gap (x = 3, 4, 5 mm) and powder particle size. The depth to width ratios were then compared with each other and also with that obtained for the normal TIG welded specimen.

3 Results and Discussion

3.1 Effect of Flux Gap on Depth to Width Ratio

The flux gap has a significant impact on increasing the weld penetration and decreasing the weld bead width as shown in the Tables 3 and 4. As the flux gap decreases, the weld penetration increases resulting in larger depth to width ratio as compared to a normal TIG process. This observation can be supported by the fact that in TIG welding, the energy required for melting the base metal is obtained from the kinetic energy that is imparted to the charged species (electrons or positively charged ions). The resistance of silica flux coating is much higher when compared to the base metal (aluminium) and this causes the flow of electrons to be channelled only along the region without any flux coating, i.e. only within the flux gap [9]. This phenomenon is known as the Insulation effect.

The constriction of the arc is clearly visible from the image of the arc captured during the welding (Figs. 2, 3). Figures 2a and 3a correspond to the normal TIG welding process, whereas Figs. 2b and 3b shows the structure of the arc for flux gaps of 4 and 3 mm respectively. In both the figures, on the left side, the arc corresponds to that of the normal TIG weld and it can be observed that the shape of the arc resembles the shape of a bell, with the flame diameter increasing outwards from the tip of the torch. However, from the images of the arc corresponding to flux gap of 4 and 3 mm, it is clear that the arc initially expands outwards, just like the arc in TIG welds, but then converges sharply back inwards because of the constriction effect caused by the silica flux coating.

Also, during welding, the extremely high temperature in the fusion zone can cause the thermal breakdown of silica molecules. The vaporised flux can further constrict the arc by means of electron absorption. The heat energy induced during the welding process, thermally breaks down the flux into vapours. This flux cloud which consists of vapourised molecules and dissociated atoms envelops the arc. The flux cloud absorbs the electrons from the periphery of the arc, thereby constricting the effective diameter. This phenomenon cannot occur in the core of the arc due to the presence of strong electric field, high temperature and high energy electrons. However, in the outer regions, which are comparatively cooler, and have weaker electric fields,

Table 1 Welding parameters for the bead-on-plate weld

Parameter	Value
Material	Commercially pure aluminium
Plate dimensions	100 cm × 4 cm × 12 mm
Welding supply	3 Phase AC 60 Hz
Welding current	200 A
Welding speed	50 mm/s
Electrode diameter	2.4 mm
Electrode type	W + 2 % ThO_2
Torch angle	5°–15°
Shielding gas	Helium
Activating flux	Silica

Table 2 Chemical composition of Keller's reagent

Chemical reagent	Quantity (mL)
HNO_3	2.5
HCl	1
HF	1.5
Water (distilled)	95

Table 3 Depth to Width ratio for (1) TIG and (2)–(4) for varying flux gaps for silica flux with particle size = 0.6 µm

Sl. No	Flux gap (X) (mm)	Depth (mm)	Width (mm)	DWR = D/W
1	TIG	2.2	7.14	0.31
2	5	2.7	5.6	0.43
3	4	3	4.9	0.61
4	3	3.4	3.6	0.94

Table 4 Depth to Width ratio for varying flux gaps for silica flux with particle size = 2.5 µm

Sl. No	Flux gap (X) (mm)	Depth (mm)	Width (mm)	DWR
1	5	2.2	6.1	0.36
2	4	2.5	4.6	0.54
3	3	2.8	5	0.56

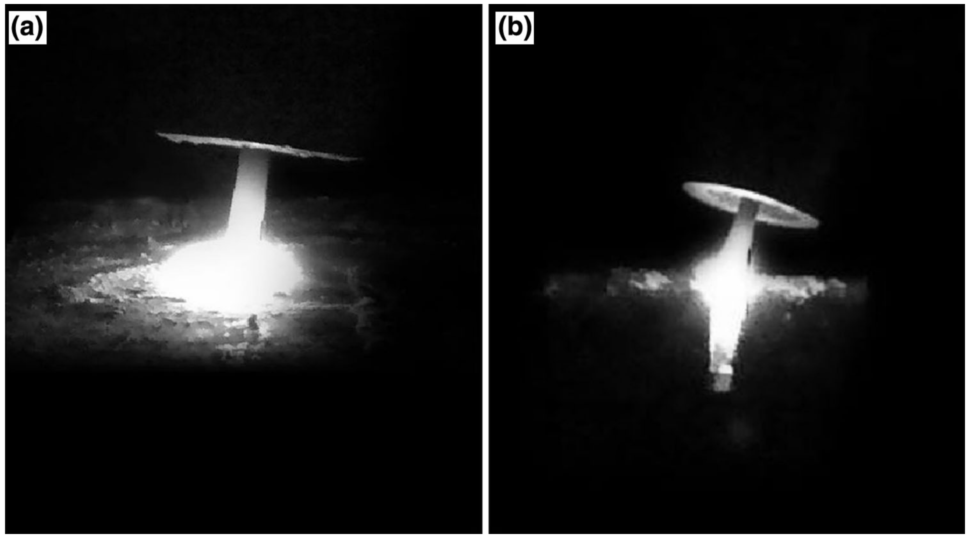

Fig. 2 Constriction of the arc root for **a** TIG and **b** FBTIG ($x = 4$)

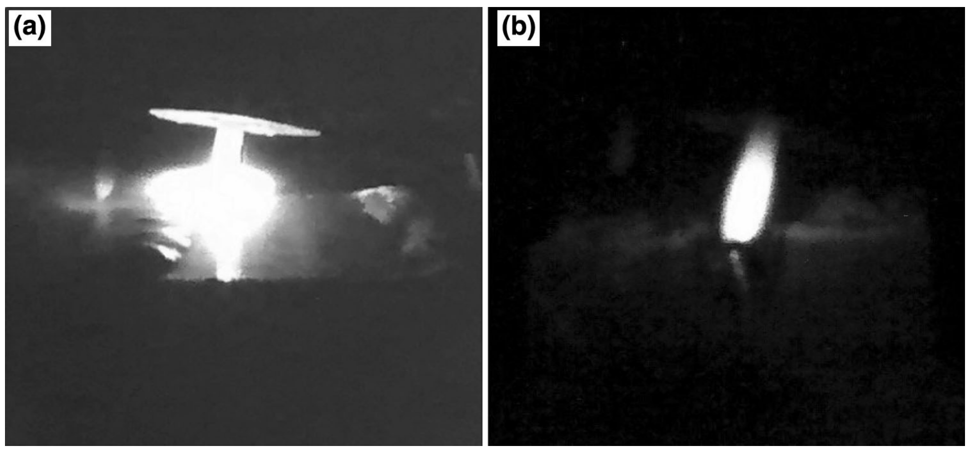

Fig. 3 Constriction of the arc root for **a** TIG and **b** FBTIG ($x = 3$)

electrons tend to attach to the flux cloud. This results in the current flow to be restricted to the central portions of the arc, which increases the current density, thereby reducing the diameter of the arc. With an increase in the current density, the arc becomes more energy intensive, forming a tight anode spot, resulting in deeper weld penetration and lesser weld pool width [2, 10, 11].

The depth and shape of the weld bead is significantly affected by the molten metal flow patterns and the mode of fluid flow in the weld zone. Generally, for pure metals and alloys, the surface tension (σ) decreases with increasing temperature (T). This means that the centre of the weld pool, which experiences maximum heat from the weld torch, will have minimum surface tension when compared to the outer edges of the weld bead.

There will be a significant surface tension gradient when the centre and the edges of the weld pool are considered. This results in the molten metal flowing from the region of lower surface tension (centre of the weld pool) to the region with higher surface tension (periphery of the weld pool) [12]. As the flux gap progressively decreases, the concentration of surface active element (oxygen) in the molten weld pool will increase as the silica particles adjacent to the weld pool will melt due to the intense heat during the weld. As the concentration of oxygen in the weld pool increases, the temperature co-efficient of surface tension undergoes a change from negative to positive. This causes the surface tension forces, σ to increase with increase in temperature. This results in higher surface tension in the middle of the molten pool since maximum temperature will be experienced by this region. Because of this, the molten metal flow directions will be reversed (generally called Reverse Marangoni Currents or Reverse Marangoni Convection) causing more penetration of the weld bead with a reduction in the weld bead width [10, 11]. Thus, the weld pool becomes deep and narrow rather than being wide and shallow [13]. Another constraint to this mechanism is the concentration of oxygen that needs to be present in the weld pool so that Marangoni Currents reverses. The reversal of Marangoni Convection requires the temperature co-efficient of surface tension to undergo a change from negative to positive. This happens when active elements (in this case Oxygen) achieves a particular concentration in the weld pool (100–300 ppm). The concentration of Oxygen in the weld pool increases due to the thermal breakdown of the silica molecules. Thus, this mechanism becomes active only when the flux gap is significantly small to allow the silica particles to melt and thermally break down [14].

From Table 3, it is quite evident that there is a significant increase in the DWR, especially between flux gaps of 3 and 4 mm. The increase in DWR from 0.61 for 4 mm flux gap to 0.94 for 3 mm flux gap can be attributed to the combined influence of all the three mechanisms, in addition to the particle size effects. With a decrease in flux gap from 4 to 3 mm, the effective concentration of silica flux particles in the weld pool increases, which makes the Reverse Marangoni Convection currents more pronounced. This phenomenon significantly contributes to the increased depth of the penetration.

This means that at the point where the arc meets the aluminium plate (called root of the arc), the energy density of the arc is high, resulting in a tight anode spot, which makes the process highly energy intensive. These results in smaller weld bead width and smaller HAZ with increased penetration.

3.2 Effect of the Activating Flux Powder Size on Depth and DWR of the Weld

It has been observed that the depth to width ratio of the weld increases when silica flux of fine particle size is used. From Tables 3 and 4, it is noticed that the DWR increases from 0.56 for a flux powder size = 2.5 µm to 0.94 for a flux powder size = 0.6 µm having flux gap of x = 3 mm. Melting Point is defined as the temperature at which both the solid and liquid phases of the substance coexist. As the particle size of the powder decreases, the effective surface area of the powder increases. However, the atoms and molecules present on the surface will have dangling bonds or unsatisfied valencies (since the atoms and molecules on the periphery are not equally surrounded by other atoms when compared to the bulk of the substance), resulting in higher surface energy of the molecule. This makes the atoms and molecules more reactive in an attempt to attain a low energy equilibrium state. Thus, as the particle size of the silica flux decreases, the melting point of the flux comes down. This phenomenon is generally known as Melting Point Depression [15, 16]. This causes the flux to melt at a much lower temperature, causing an increased concentration of surface active elements in the weld pools when compared to the silica flux of higher particle size. Thus, the Reversal of Marangoni Currents will be more pronounced in case of silica flux of finer particle size. Also, finer silica flux particles undergo thermal decomposition much easily when compared to coarser silica flux particles. This means that finer silica particles can cause more efficient electron absorption than coarser silica flux. The combined effect of these two phenomena result in the increased DWR for fine particle size. As the flux gap increases beyond 3 mm, the increase in the DWR is observed to be less significant, when compared to increase in DWR for flux gap of 3 mm (Fig. 4). This can be attributed to the decreasing role of Reverse Marangoni convection currents in increasing the weld penetration.

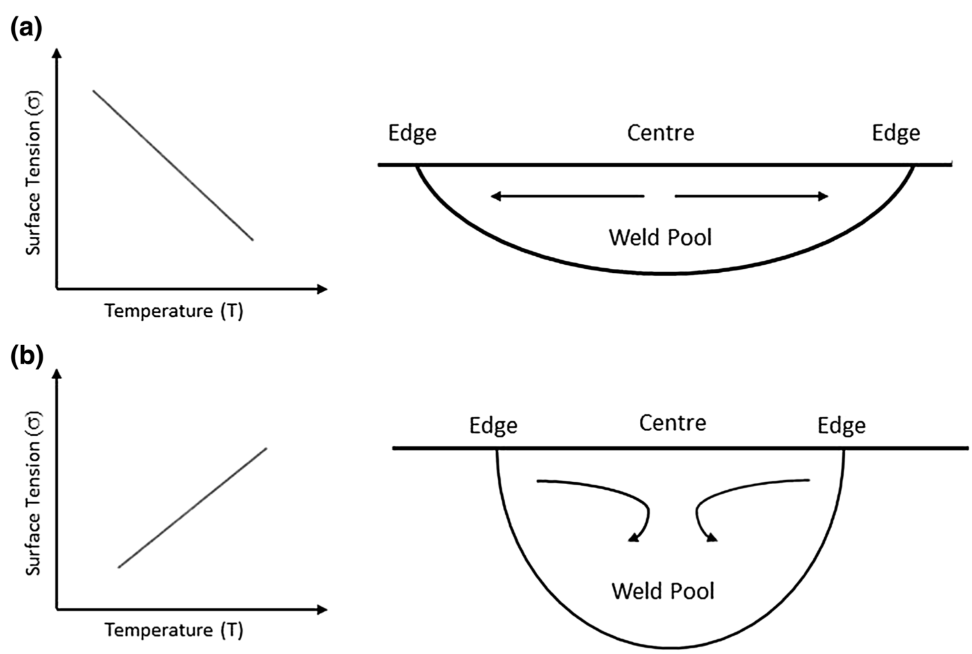

Fig. 4 Marangoni Convection in the weld pool for **a** $\frac{\partial \sigma}{\partial T} < 0$ and **b** $\frac{\partial \sigma}{\partial T} > 0$

3.3 Microstructure

Figure 5 depicts the microstructure of the base metal which reveals the grains to be elongated and oriented in the same direction which is typically a rolled structure.

There is a significant difference observed between the grains found in the base metal and fusion zone. The grains in the fusion zone are fine when compared to the grains present in the base metal as shown in Figs. 6 and 7. It is also observed that the columnar grains are formed along the fusion boundary and structure get transformed to finer equi-axed grains towards the centre of the fusion zone. It is also very evident that the microstructure does not contain any silica particle inclusion in the weld bead.

Reverse Marangoni Convection plays a vital role in increasing the DWR, and in this process, there is every probability that these silica particles can get trapped in the weld pool and become a part of the weld bead. This may affect the quality and life of the weld marginally. Almost all the plates welded with different parameters does not reveal any such inclusions. In the case A TIG process, the arc directly melts the activating flux present on the surface of the weld component resulting in higher concentrations of molten silica flux in the weld pool, which can affect the quality and life of the weld adversely [17]. However, in the FBTIG process, since the flux coating is only present along the edges of the arc, the amount of molten silica flux entering the weld pool will be relatively less. Thus, FBTIG process ensures cleaner weld pools with minimum amount of silica inclusions, and thus produces high quality weld joints [18]. Also, the reduction in mechanical properties due to higher inclusion density is negligible when compared to the improvement in the weld properties [19].

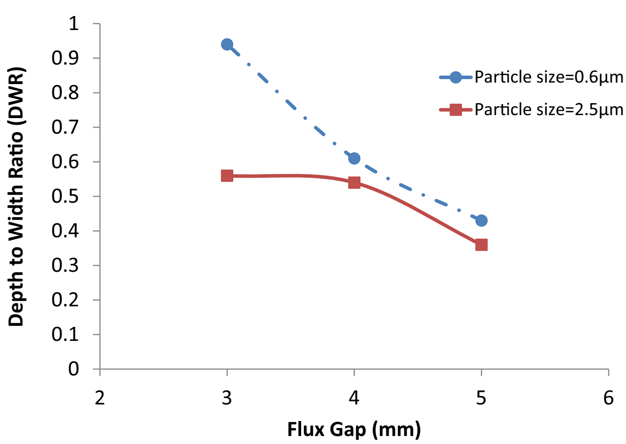

Fig. 5 Graph showing the variation of the DWR with different activating flux powder sizes

Fig. 6 Grain structure of the base metal

Fig. 7 Grain structure in the fusion zone for x = 3 mm with flux powder size = 0.6 µm

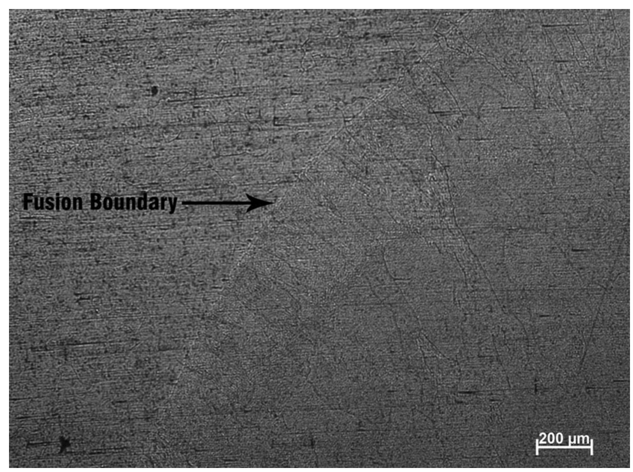

Fig. 8 Grain structure along the fusion wall

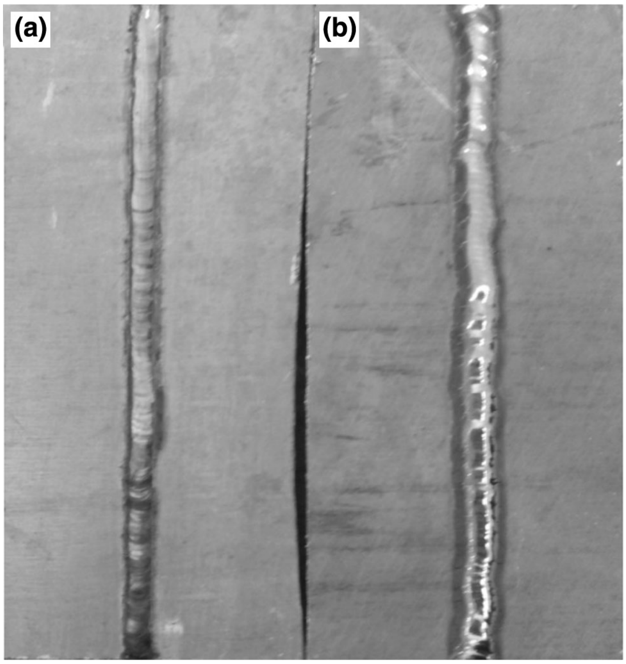

Fig. 9 Comparison of the weld bead aesthetics of **a** FBTIG and **b** TIG

3.4 Weld Bead Aesthetics

The process also increases the weld bead aesthetics. When compared to the normal TIG welded specimen, the FBTIG specimens have better weld aesthetics.

The presence of silica flux on either sides of the flux gap prevents the arc from wandering around, and hence concentrates the arc energy exactly at the gap. This results in better weld aesthetics as shown in Fig. 8 and counters the problems of arc wandering. However, too small flux gaps can result in the arc becoming unstable (Fig. 9).

4 Conclusion

The effect of flux gap and the flux powder particle size on the depth of penetration was analysed. The depth of penetration increased for a smaller powder particle size and this was attributed to easier decomposition of the flux, resulting in a larger flux cloud along with significant proportion of it in the molten weld pool. It was observed that with decreasing flux gap, the depth of penetration increased and this was attributed to three major mechanisms which were Insulation effect, Arc root constriction theory and Reverse Marangoni Effect. All these three mechanisms were discussed in detail. The microstructures also revealed no presence of inclusions resulting in a cleaner weld.

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