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Effect of Activating Flux on Penetration in ATIG Welding of 316 Stainless Steel

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ABSTRACT

Tungsten inert gas welding is popular in some industries due to the possibility of obtaining good weld bead surface and high-quality joint without any weld defect. However, compared to many welding processes, shallow penetration of TIG welding hinders its applicability to weld thick components in one pass, thus the productivity is relatively low. An increased depth of penetration can be achieved by Activated TIG (ATIG) welding leading to overall reduction in number of welding passes, and thus increasing productivity. In the present work, attempts were made to find out the optimum flux mixture of SiO_2 and TiO_2 from various ratio of mixtures by carrying out bead-on-plate welding on AISI 316 Stainless Steel specimens. From the obtained experimental data, suitable flux ratio was tried to find out giving the highest depth of penetration.

Keywords: Welding; GTAW; ATIG welding; Activating flux; Bead-on-plate welding; Bead geometry; Penetration.

1.0 INTRODUCTION

Austenitic stainless steels contain a maximum of 0.15% carbon and a minimum of 16% chromium to have enough corrosion resistance. Nickel is added to it to retain austenitic phase at room temperature. It can also include elements like molybdenum, titanium, niobium, copper, etc. [1]. These steels offer high corrosion and impact resistance at a low temperature. Because of these properties, they are employed in marine components, chemical plants, etc. Welding is done to fabricate different structures in these applications [1,2].

Tungsten inert gas (TIG) welding, or Gas tungsten arc welding (GTAW), uses [3,4] a non-consumable tungsten electrode and an inert shielding gas, generally argon, is applied to protect the weld from atmospheric contamination. TIG is usually employed to weld thin stainless steel and non-ferrous components with high-quality [5]. However, due to the low depth of penetration, its productivity is low [6]. If current is increased, weld bead becomes too wide to give good penetration [7]. Activated TIG (ATIG) welding may be practiced to gain higher penetration than TIG welding [6-8]. By employing ATIG, it is possible to weld 8-10 mm thick stainless steel plate in only one pass without any edge preparation [9,10]. This is done by coating the faying surface by a thin layer of activating flux before welding [11,12]. Some oxides, chlorides and fluorides are used as the activating flux. Acetone, ethanol or similar solvent is used to produce a slurry of these. The flux tries to constrict the arc thereby making hike in current density and arc force on the weld pool [8,13]. The favourable effect of activating flux in TIG welding was first reported by EO Paton Institute of Electric Welding, former Soviet Union, way back in 1960s. About three times enhancement in penetration was demonstrated with the use of a thin layer of flux [14-17]. Activating fluxes by now are commercially used in different applications for welding Mn steels, Cr-Mo steels, nickel-based alloys, etc. [3].

Thus, ATIG welding is not very new, but there is lacking of well-accepted theoretical explanation behind this process of activation. In this paragraph, some models are reviewed to explain the ATIG welding as thought of by some researchers in the past. Simonik proposed a model while experimenting on titanium with flux made up of calcium and aluminium fluorides that considered major role of vaporized ions of flux generated by arc heating for this activation. He assumed ions at the arc periphery to have lower mobility than that at the central region, and this might lead to a hike in current density at the centre of the arc. On the other hand, Heiple and Roper assumed occurrence of reversed Marangoni flow for this activation. In this model, the flux is assumed to revert the sign of temperature coefficient of surface tension from negative to positive, and it changes the direction of surface Marangoni flow from outward to inward direction. This inward flow is transformed into a downward direction at the hot centre of the weld, thereby increasing heat transfer due to convection and melting of the metal in a downward direction. Savitskii and Leskov postulated a model based on surface tension reducing effect of the flux that causes high arc pressure creating deep depression inside weld pool and resulting in high depth of penetration. Arc constriction model considered [18-20] electrical insulating effect of the flux. Flux covered surface offers high electrical resistance, reduces size of arc spot, and leads to deep penetration.

ATIG process mainly focuses on increasing depth of penetration of weld bead. Again, reduction in weld bead has a significant role in good welding because large size of bead width results in a wide heat affected zone (HAZ). Therefore, analysis of both depth of penetration and bead width is having remarkable significance [21, 22]. In another work, effect of different oxide flux materials on the depth of penetration was investigated [23] during A-TIG Welding of austenitic stainless steels. The authors also studied the microstructure and corrosion behaviour of austenitic stainless steel in A-TIG Welding using those flux materials, and concluded that increased content of oxide flux resulted in more corrosion resistance.

In this experimental investigation, ATIG welding is done on austenitic stainless steel specimens using different fluxes. The extent of penetration is observed for all the experimental runs to evaluate the condition to achieve the highest penetration within the domain of this investigation.

2.0 DETAIL OF THE EXPERIMENTAL WORK

AISI 316 stainless steel is used as the base material. It is a molybdenum-alloy steel, and is a common austenite stainless steel grade. It is often preferred for the use in marine environment because of its greater resistance to corrosion than other grades of steels without molybdenum. The composition of the base plate is shown in **Table 1**. Stainless steel plates are cut into samples having the size of 382mm x 317mm x 5mm with the help of an abrasive cutter. Edges of the plates are machined, and before welding, surfaces of the specimen are thoroughly cleaned with wire brush and acetone to ensure cleanliness.

It is known from previous research works that some metallic and non-metallic oxides, etc. work as a good activating flux in GTAW process. SiO_2 and TiO_2 are reported to be some of such activating fluxes. However, to explore the activation effect of some flux mixtures, in the present work, three different proportions of SiO_2 and TiO_2 are considered. Detail of flux used in this work is given in **Table 2**. First set of experiments is done without using any flux. Subsequent 2nd, 3rd and 4th sets of experiments are performed using different flux mixtures. According to the selected flux composition, SiO_2 and TiO_2 are taken to the required proportion, and the slurry is made by mixing the flux material in acetone. A thin layer of activating flux is applied with a brush on the surface, on which the bead is to be made.

Table 1: Chemical composition of base metal (wt %)

Material	C	Mn	Si	S	P	Cr	Ni	Mo	N	Fe
AISI 316	0.027	1.11	0.434	0.0045	0.017	16.77	10.03	2.03	0.044	Balance

Table 2 : Detail of Flux used

Sl. No.	Proportion of Flux (SiO_2:TiO_2) Used
1	No flux used
2	1:1
3	4:1
4	1:4

Bead-on-plate welding without any filler material, that is, autogenous welding, is performed with the flux as mentioned in **Table 2**. The welding passes were made with an automatic feeding vehicle on which the weld torch is mounted and moved at a constant speed. Welding parameters employed in this project are given in **Table 3**.

The base plate with bead deposit is cut along its cross section using an abrasive cutter. The cut surface was ground with the help of a belt grinder / polisher, disc grinder / polisher. It is polished using fine grade emery papers of rough to finer ones (180 to 1200 grade). The specimens are then polished on velvet cloth polisher with the help of alumina paste. The etchant solution is prepared by mixing 0.5 gm $CuCl_2$ and 10 ml C_2H_5OH (99%) in 10 ml HCL (40% v/v) and is applied on the polished surface of the specimen. After etching, specimens are observed under microscope for determining the bead geometry. Depth of penetration, bead width and cross-sectional area of weld bead are found out using a software programme. Bead cross sectional area corresponds to melting efficiency of welding.

Table 3 : Welding Parameters used

Welding speed	120mm/min
Current used	Pulsed DCSP, 40% duty cycle
Welding current	90A, 105A, 120A
DC pulse frequency	60Hz, 140Hz, 240Hz
Shielding gas	100% argon, flow rate: 15 litre/min
Electrode	3 mm diameter, thoriated tungsten
Electrode tip distance	5 mm

3.0 RESULTS AND DISCUSSION

Results of common TIG welding without using a flux to make bead-on-plate welds are shown in **Table 4**. In these tests, a maximum penetration of 2.174mm is found at experimental run No. 4. A low penetration of 1.284mm is obtained in the experimental run No.6. At a low pulse frequency of 60Hz corresponding to experimental run No.7, no measurable penetration is reported.

Table 4 : Results of TIG welding without using a flux

Sl. No.	Weld Current (A)	DC Pulse frequency (Hz)	Weld Voltage (V)	Heat Input (kJ/mm)	Depth of penetration (mm)	Width of weld bead (mm)	Aspect Ratio	Area of Weld bead cross Section (mm^2)
1	90	60	17	0.57	2.046	6.75	0.303	8.807
2	90	140	15	0.57	1.875	7.43	0.25	8.062
3	90	240	12	0.405	1.701	5.80	0.29	7.25
4	105	60	13	0.51	2.174	8.30	0.26	13.69
5	105	140	15	0.59	1.404	8.05	0.17	7.002
6	105	240	16	0.63	1.284	9.63	0.13	4.574
7	120	60	14.5	0.65	----	----	----	----
8	120	140	15.2	0.68	1.477	8.47	0.17	9.484
9	120	240	14.8	0.66	1.701	8.51	0.10	----

Table 5 : Results of ATIG welding using a flux of SiO_2 and TiO_2 mixture in 1:1 ratio

Sl. No.	Weld Current (A)	Weld Voltage (V)	DC Pulse frequency (Hz)	Heat Input (kJ/mm)	Depth of penetration (mm)	Width of weld bead (mm)	Aspect Ratio	Area of Weld bead cross Section (mm^2)
1	90	17.5	60	0.59	2.695	4.50	0.598	10.75
2	90	17.2	140	0.58	2.182	5.853	0.372	9.899
3	90	17.0	240	0.57	2.423	6.050	0.40	10.801
4	105	18.1	60	0.71	3.955	7.18	0.55	21.853
5	105	17.8	140	0.70	4.204	6.61	0.636	21.367
6	105	17.6	240	0.69	3.875	7.22	0.537	18.297
7	120	18.5	60	0.83	2.752	9.15	0.30	21.177
8	120	17.9	140	0.80	Full	7.77	0.64	25.556
9	120	19.8	240	0.89	3.24	13.60	0.23	22.933

Results of ATIG Welding with a flux of SiO_2 and TiO_2 mixture in 1:1 ratio are presented in **Table 5**. Compared to common TIG welding without using a flux, this flux mixture of SiO_2 and TiO_2 gives remarkably higher penetration. While the maximum penetration reported in TIG welding is 2.174mm, in this ATIG welding with equal proportion mixture of silica and titania, the minimum penetration is seen to be 2.182mm at a low weld current with a low heat input of 0.58 kJ/mm (experiment Sl. No. 2) and in experimental run No.8 with high weld current and medium pulse frequency with the corresponding high heat input of 0.80 kJ/mm, full penetration of 5mm is noticed. Therefore, clear indication of large-scale effectiveness of the activating flux is observed.

Results of ATIG Welding with a flux of SiO_2 and TiO_2 mixture in 4:1 ratio are presented in **Table 6**. Compared to common TIG welding without using a flux, this flux mixture gives higher penetration on the whole. While the maximum penetration reported in TIG welding is 2.174mm, in this ATIG welding with 4:1 ratio of silica and titania mixture, the maximum penetration is seen to be as high as 4.137mm corresponding to experimental run No. 9 with 120A weld current, high pulse frequency of 240Hz and heat input of 0.58. This flux mixture indicates its effectiveness over common TIG welding; however, penetration obtained in this experiment is on the whole lesser than that obtained in ATIG welding using equal proportion of the two flux materials used.

Results of ATIG Welding with a flux of SiO_2 and TiO_2 mixture in 1:4 ratio are presented in **Table 7**. Compared to common TIG welding without using a flux, this flux of SiO_2 and TiO_2 mixture in 1:4 ratio gives lesser penetration in some cases and shows slightly higher penetration mainly at the high weld current of 120A with 0.63kJ/mm heat input. Maximum penetration seen in this ATIG welding is only 2.884mm. Thus, this flux mixture does not give much effect to raise weld bead penetration.

Variation of depth of penetration with welding current is shown in **Fig.1** through **Fig.3**. From these figures, it can be observed that the overall change in penetration with current is very low for common TIG welding. On the other hand, with the increase in current, penetration of ATIG welding using 1:1 and 4:1 (SiO_2:TiO_2) flux increases sharply. In case of ATIG welding using 1:1 flux mixture of silica and titania, best result is observed at medium frequency of 140Hz (**Fig.2**). For welding with 4:1 flux mixture, the penetration increases consistently with current at all frequencies and at high current deep penetration of about 4mm is observed. In case of ATIG welding using 1:4 flux mixture of silica and titania, penetration is poor at low and medium frequency (**Fig.1** and **Fig.2**). Only when current is changed to high value, increase in penetration is observed.

Table 6 : Results of ATIG welding using a flux of SiO_2 and TiO_2 mixture in 4:1 ratio

Sl. No.	Weld Current (A)	Weld Voltage (V)	DC Pulse frequency (Hz)	Heat Input (kJ/mm)	Depth of penetration (mm)	Width of weld bead (mm)	Aspect Ratio	Area of Weld bead cross Section (mm^2)
1	90	12.2	60	0.41	0.723	5.089	0.14	2.509
2	90	12.1	140	0.408	1.035	5.077	0.20	4.204
3	90	11.5	240	0.38	1.838	5.306	0.34	6.607
4	105	12.5	60	0.49	1.773	5.820	0.30	7.557
5	105	12.6	140	0.49	1.685	6.23	0.27	8.814
6	105	11.8	240	0.46	1.934	8.37	0.23	13.69
7	120	12.3	60	0.55	3.683	7.62	0.48	19.041
8	120	12.5	140	0.56	3.979	7.11	0.55	19.116
9	120	13	240	0.58	4.137	8.12	0.50	22.091

Table 7 : Results of ATIG welding using a flux of SiO_2 and TiO_2 mixture in 1:4 ratio

Sl. No.	Weld Current (A)	Weld Voltage (V)	DC Pulse frequency (Hz)	Heat Input (kJ/mm)	Depth of penetration (mm)	Width of weld bead (mm)	Aspect Ratio	Area of Weld bead cross Section (mm^2)
1	90	11.4	60	0.38	0.906	6.05	0.149	4.448
2	90	12	140	0.40	0.818	4.894	0.167	3.350
3	90	13.1	240	0.44	0.971	5.804	0.167	4.467
4	105	11.8	60	0.46	1.243	6.492	0.191	5.546
5	105	13	140	0.51	0.818	5.787	0.141	3.298
6	105	13.7	240	0.53	1.067	6.439	0.167	5.199
7	120	13	60	0.58	1.620	7.76	0.209	10.619
8	120	13.5	140	0.60	1.388	7.19	0.193	17.550
9	120	14.1	240	0.63	2.884	6.411	0.449	18.629

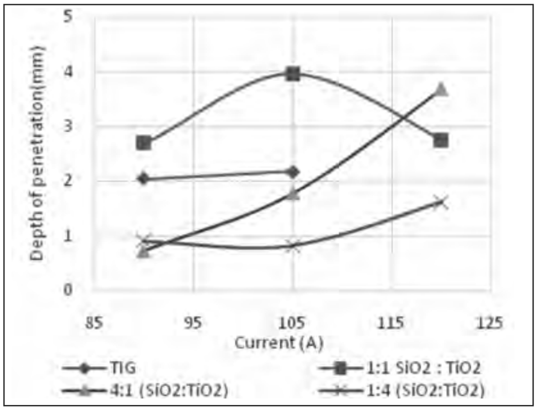

Fig.1 : Plot of variation of depth of penetration with welding current at 60Hz pulse frequency in TIG and ATIG welding processes

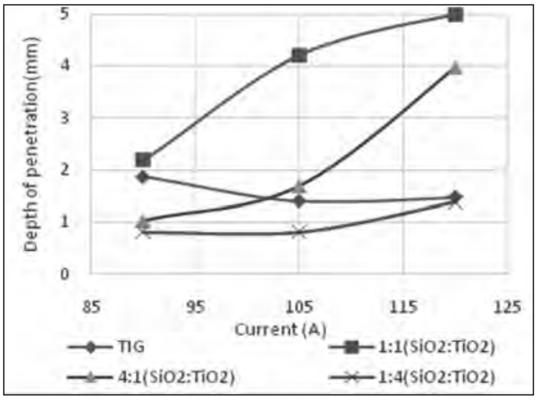

Fig.2 : Plot of variation of depth of penetration with welding current at 140Hz pulse frequency in TIG and ATIG welding processes

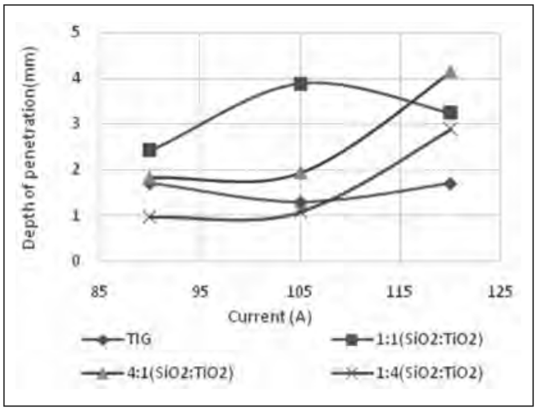

Fig.3 : Plot of variation of depth of penetration with welding current at 240Hz pulse frequency in TIG and ATIG welding processes

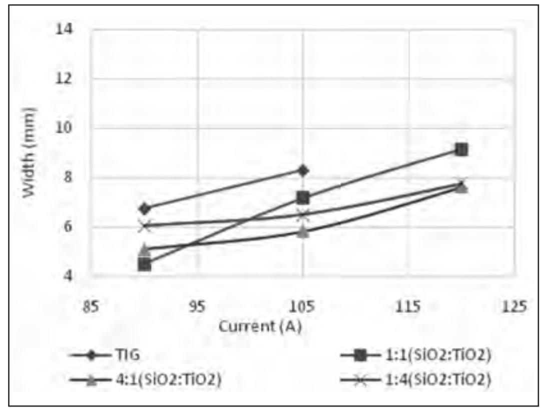

Fig.4 : Plot of variation of width of weld bead with welding current at 60Hz pulse frequency in TIG and ATIG welding processes

Variation of weld bead width with current is shown from **Fig. 4** to **Fig. 6**. From these plots, it is evident that ATIG welding with flux generally produces a narrow weld bead compared to common TIG welding without flux. Among the used flux mixtures, ATIG welding with 1:1 silica and titania mixture has produced wider weld bead compared to flux mixture with 4:1 and 1:4 of silica and titania. Overall, both 4:1 and 1:4 flux mixtures have shown quite narrow weld bead. For ATIG welding using 1:4 flux mixture, at high frequency, bead width almost remains constant with the increase in current (**Fig.6**).

Variation of aspect ratio with current is shown from **Fig. 7** to **Fig. 9**. A high aspect ratio is desirable as it is a characteristic of an increased energy density of the heat source in welding. With an increase in the density of heat input, overall heat requirement per unit length of welding decreases. From **Fig. 7** to **Fig. 9**, it is seen that for common TIG welding aspect ratio is generally low. As current is increased, aspect ratio generally falls to a low value ($\leqslant 0.2$ at high current). ATIG welding with 1:1 SiO_2 and TiO_2 flux mixture has shown high value of aspect ratio at low and medium current. For ATIG welding employing a flux of 4:1 mixture of silica and titania, the aspect ratio at low current becomes low, but as current is increased, the value of aspect ratio increases rapidly and reaches a high value of about 0.5 at high current. This indicates that with increasing current, the rate of increase in penetration is more compared to the rate of increase in bead width. The aspect ratio for ATIG welding with 1:4 flux mixture is, on the whole, quite low compared to the other welding processes tested in this work.

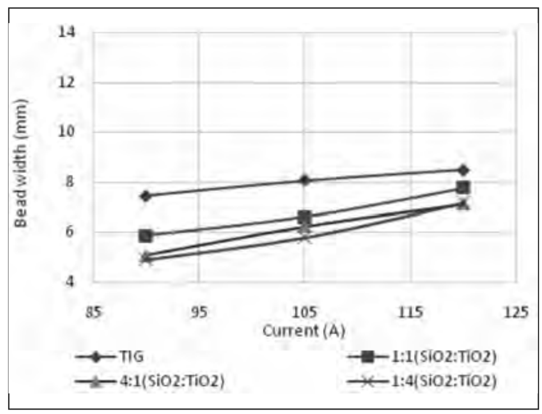

Fig.5 : Plot of variation of width of weld bead with welding current at 140Hz pulse frequency in TIG and ATIG welding processes

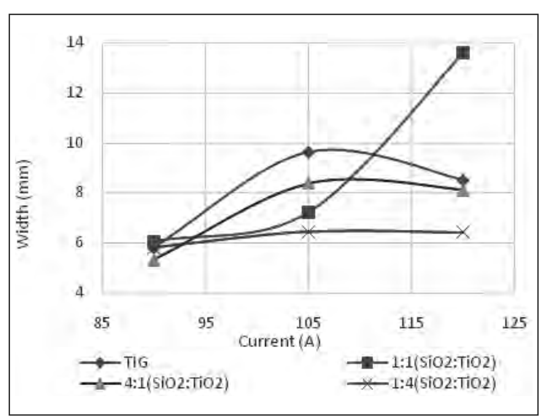

Fig.6 : Plot of variation of width of weld bead with welding current at 240Hz pulse frequency in TIG and ATIG welding processes

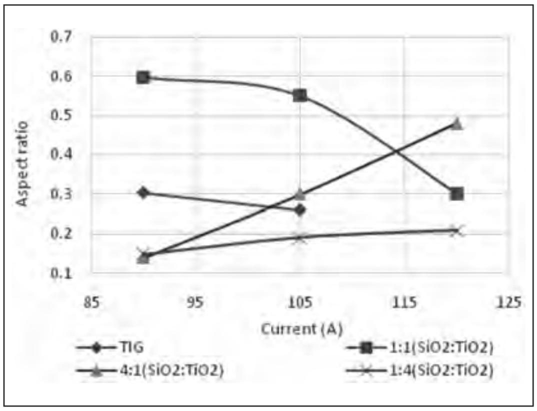

Fig.7 : Plot of variation of aspect ratio with welding current at 60Hz pulse frequency in TIG and ATIG welding processes

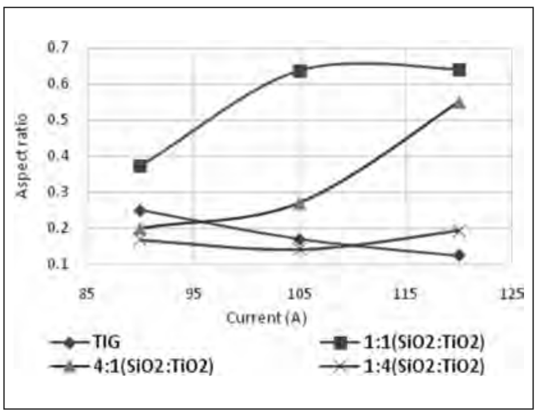

Fig.8 : Plot of variation of aspect ratio with welding current at 140Hz pulse frequency in TIG and ATIG welding processes

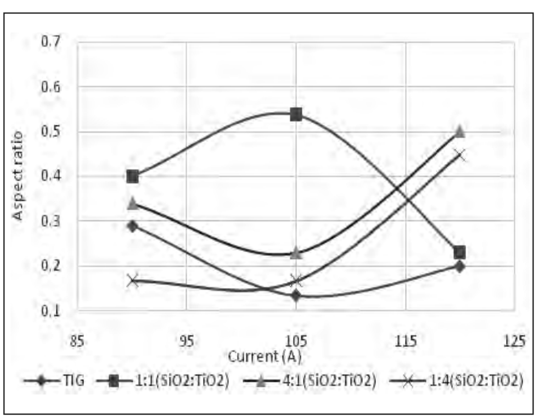

Fig.9 : Plot of variation of aspect ratio with welding current at 240Hz pulse frequency in TIG and ATIG welding processes

From the above discussion, it can be concluded that common TIG welding without a flux produced a sallow and wide weld bead. In TIG welding, the surface Marangoni flow of molten metal is from inward to outward direction. The arc is also spread over a wider region. Thus the arc force on the molten metal pool is low. Introduction of flux can change the direction of temperature coefficient of surface tension from negative to positive, which, in turn, changes the direction of surface Marangoni flow from outwards to inwards. It also constricts the arc thereby increasing arc force on the pool of molten metal. Thus a deep and narrow weld bead is obtained in ATIG welding using fluxes.

In this experiment, the effect of different fluxes on penetration is found to vary largely. It can be observed that SiO_2 flux causes deeper penetration compared to TiO_2 flux. This can be explained by comparing the properties of these two oxides. For SiO_2 flux, the dominating factor in increasing the penetration seems to be constriction of arc. Silica has a lower boiling point (2230°C) compared to titania (2972°C). Under intense heat of the arc, silica easily vaporizes and causes redistribution of charge career in the arc column. Silicon being more electro-negative compared to titanium, can absorb electrons in the periphery region of the arc easily. In this region, the temperature is sufficiently low to form negative ion. The ions in the periphery region are less mobile compared to the high energy electrons of the central region of the arc. Thus, the arc gets constricted and a higher arc force is exerted on the molten metal pool. This effectively increases the depth of penetration of welding using SiO_2 flux. Additionally, SiO_2 has more resistance value compared to TiO_2. So the arc is more restricted at the anode root for ATIG welding using SiO_2 flux. This also causes SiO_2 flux welding to achieve greater penetration compared to TiO_2 flux welding.

Application of flux mostly produces a narrow, deep weld bead compared to that at conventional TIG welding. Typical bead profiles for TIG and ATIG with different flux mixtures are shown in **Fig.10** and **Fig.11** corresponding to weld current of 105A and 120A under 140Hz DC pulse frequency.

An inferior weld bead appearance is produced by the use of flux compared to that seen in conventional TIG welding. The surface slag residue is left out after welding that needs be removed after welding. Increased percentage of SiO_2 in the flux mixture improves overall bead appearance compared to that using TiO_2.

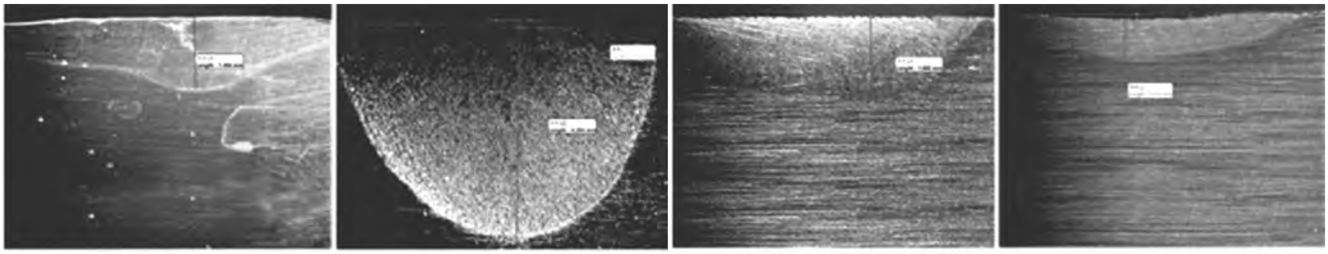

Fig.10 : Typical view of weld beads at 105A current and 140Hzpulse frequency [Left to right: TIG welding, ATIG welding with SiO_2:TiO_2 flux mixture of 1:1, 4:1 and 1:4]

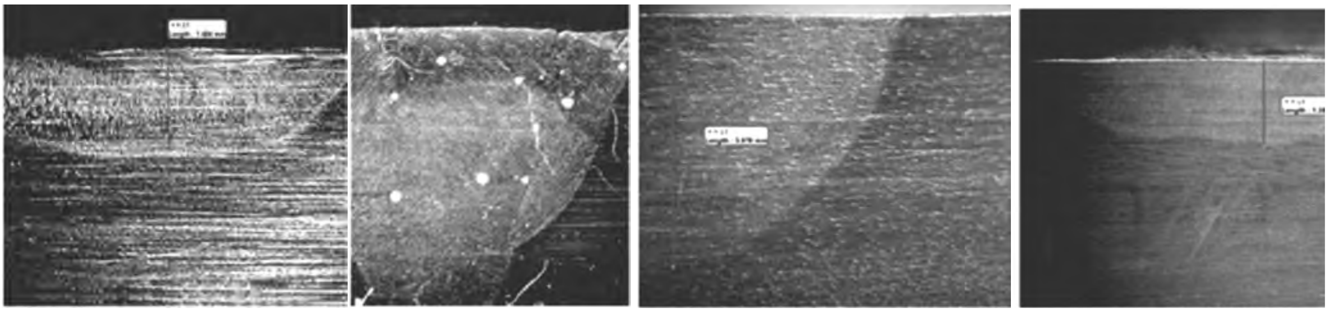

Fig.11 : Typical view of weld beads at 120A current and 140Hz pulse frequency [Left to right: TIG welding, ATIG welding with SiO_2:TiO_2 flux mixture of 1:1, 4:1 and 1:4]

In the present work on welding of 316 stainless steel, conventional TIG produces wider and shallower weld bead profile than ATIG welding on the whole. Bead width is low in TiO_2 rich flux mixture. However, TiO_2 rich flux mixture has increased the depth of penetration by 23.59% on an average compared to conventional TIG at 120 A current. Whereas SiO_2 dominant flux mixture improved the depth of penetration by 147.5% on an average compared to conventional TIG at 120 A current and Flux mixture with equal proportion of SiO_2 and TiO_2 improved the penetration by 130.5% on an average at 120 A current. For each type of flux mixture, there is sharp increase of depth of penetration with the increase of current. However, for conventional TIG welding, depth of penetration shows almost no change with an increase of current after current reaches a certain point. Further increase in current tends to increase weld bead width.

Full penetration of 5mm is achieved at 0.80 kJ/mm heat input with flux mixtures of 1:1 of SiO_2:TiO_2 at 120 A current. However, the 4:1 mixture of SiO_2:TiO_2 shows similar depth of penetration at a comparatively lower heat input.

4.0 CONCLUSION

From the results observed on TIG and ATIG welding in AISI 316 stainless steel, following conclusions may be drawn.

- In this work, it is found that using the flux, depth of penetration can be increased greatly. Study on different flux mixtures of SiO_2 and TiO_2 reveals that SiO_2 flux has more influence on depth of penetration.
- Large increase in depth of penetration is obtained over conventional TIG welding when a flux mixture of SiO_2 and TiO_2 with a ratio of 4:1 and 1:1 are used.
- Full penetration of 5mm is achieved flats at 120A current, 17.9V voltage and 140Hz condition when equal proportion of SiO_2 and TiO_2 are used.
- Application of flux reduces bead appearance of ATIG weldment to some extent.
- Suitable activated flux improves depth of penetration substantially in ATIG welding. Hence, ATIG has the possibility of wide practical use in industry for its improved productivity and quality.

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