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Effect of Various Fluxes on Different Metals and Alloys in A-TIG Process: A Review

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ABSTRACT

Welding is the process of coalescence of two metals/alloys for creating a seamless joint, is a quintessential fabrication process utilised in almost every manufacturing sector. There is a range of welding processes that are used according to their features and the requirement of the fabricator. The tungsten inert gas (TIG) welding process is an extensively used welding process owing to its inherent characteristics like high weld quality, surface cleanliness, and autogenous welding mode. Unfortunately, the TIG process suffers some drawbacks, the most pronounced one is the shallow weld bead and low depth of penetration (DOP). This renders the process unusable for welding thicker sections in a single pass and consequently requires multiple passes which adds to the expenditure. A modification to this process is the A-TIG welding where A stands for Activated, the method utilises activating flux material to augment the penetration depth and depth to width ratio (DWR) of the weld bead. The current work is comprehensive and focuses mainly on the basics of the A-TIG process, understanding of weld pool dynamics that are governing the depth of penetration, analysis of various flux materials for their effects on different metals/alloys and finally the outcomes fetched from using A-TIG process on different commercially important alloys.

Keywords: TIG; depth of penetration; depth to width ratio; activating fluxes; A-TIG

INTRODUCTION

Welding is the union or coalescence of two metals/alloys by the means of heat or by pressure or both where there is melting of metals and formation of the weld pool, filler metal may be used as per the requirement. Welding is an important fabrication technique which is employed in every manufacturing sector. Welding has evolved from conventional carbon arc welding to advanced welding techniques like Gas tungsten arc welding (GTAW), Flux cored arc welding (FCAW), Laser beam welding (LBW), Spot resistance welding, and friction stir welding (FSW) etc. (Ahmadi et al. 2015). TIG or better known as tungsten inert gas is a fusion welding process which is extensively used for its lucrative features. A non-consumable tungsten electrode is utilized to produce an arc creating molten weld pool which is protected from atmospheric contamination by using appropriate shielding gases. The TIG process finds its usage in myriad range of industries having applications in chemical, food industry, gas turbines, heat exchangers, pressure vessels, mining sector etc. where different ferrous and non-ferrous metals and alloys are fabricated using TIG (Bhattacharya 2015). For fabrication of Ti and alloys which are utilized in various sectors as aerospace, electricity, marine, chemical and automotive because of its outstanding specific strength and pitting and oxidation resistance, TIG process is highly recommended due to the generation of high-quality weldments (Gao et al. 2017). TIG process retains its properties like virtuous quality weld joint with outstanding surface appearance in all welding positions making it more lucrative than other welding processes (Kumar et al. 2019). The property of stable heat source and optimum equipment cost makes TIG process widely acceptable for stainless steel welding (Tathgir et al. 2019; *Pocket Welding Guide* 1997). Schematic of TIG process given in Figure. 1.

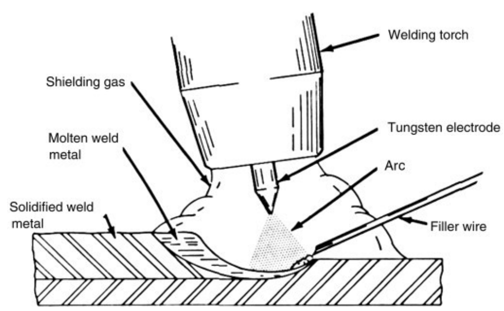

FIGURE 1. Schematic of GTAW process [8]

For welding thin gauge components, edge joints and flanges, welders broadly refrain using filler metals, so TIG process becomes most suitable and thus used in many manufacturing industries (Tseng et al. 2011). Different polarities are used in TIG process as per requirement as shown in Figure. 2.

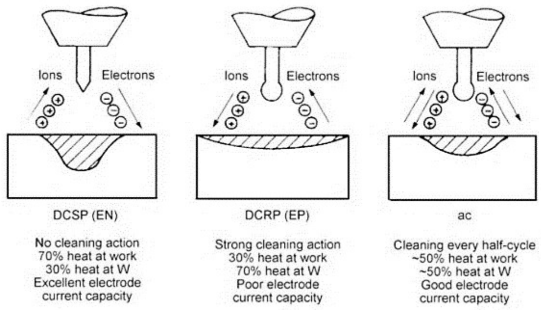

FIGURE 2. Schematic of Different polarities in GTAW process (Jaakko 2017)

DCEN or direct current electrode negative is used mainly where the electrode is affixed to the negative terminal, 30% of heat of weld is gets accumulated on the electrode tip while 70% gets transmitted to the workpiece which keeps the electrode cool and gives deeper penetration. In the DCEP or direct current electrode positive mode, the electrode is coupled to positive terminal, 70% of heat gets accumulated on the electrode tip while 30% gets transmitted to the workpiece making electrode hotter than workpiece, this mode is generally not preferred due to excessive heating of tungsten electrode but is utilized for Al welding due the cleaning action. Lastly, alternating current mode is also used which makes equal heat distribution at both electrode and workpiece which gives reasonably good penetration and oxide cleaning action (Afolalu et al. 2019). Despite of having many advantages, TIG process suffers some drawbacks. There is lesser DOP in single pass which necessitates the groove preparation and usage of filler metal while welding plates of thickness greater than 3mm and increases the cost of product (Jadav et al. 2021; Pandya et al. 2020). The shallow weld pool, low deposition rate and lesser dilution is generated due lower energy density of the TIG arc, this condition results in lower productivity when compared to other welding processes (Tathgir et al. 2014; Bhattacharya et al 2015; Kumar et al. 2019; Tathgir et al. 2019). While welding Ti and alloys, unrestrained grain growth is observed in welding thermal cycle. There is also deterioration of mechanical properties due to accumulation of heat during each pass which results in more coarse-grained weldments (Gao et al. 2017). The poor tolerance is exhibited due to certain impurities, which include cast-to-cast variation in many metals and alloys, as shown in Figure 3 (Tseng et al. 2011; Fujii et al. 2008; Shyu et al. 2008).

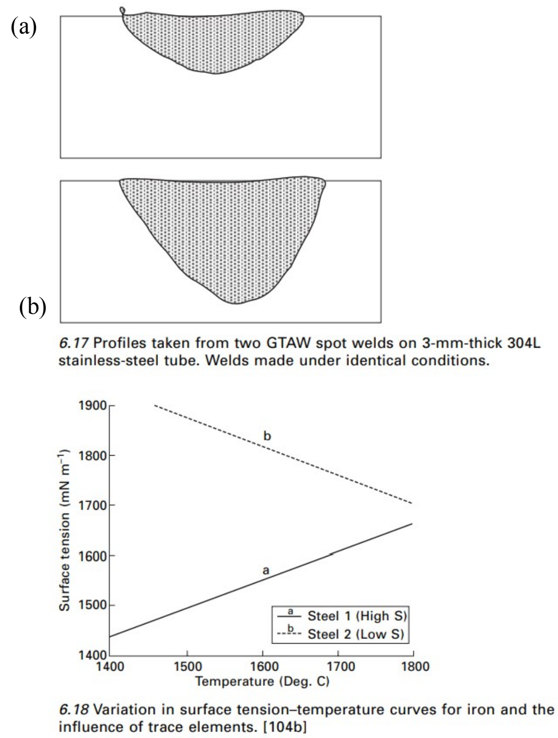

FIGURE 3. (a) Cast to cast variation in GTAW (b) Graph of surface tension vs temperature (Norrish 2006)

From experience and observations, the need for improvement in the TIG process was the need of the hour. It was truism that enhancement in the welding current and depletion of scan speed during welding process would improve the DOP. But the results showed grain coarsening of weld joint (Kumar et al. 2019). Comparison of penetration obtained in different welding processes given in Figure. 4. After years of perseverant work in enhancing the penetration achieved in single pass TIG process at same heat input resulted in the emergence of A-TIG process.

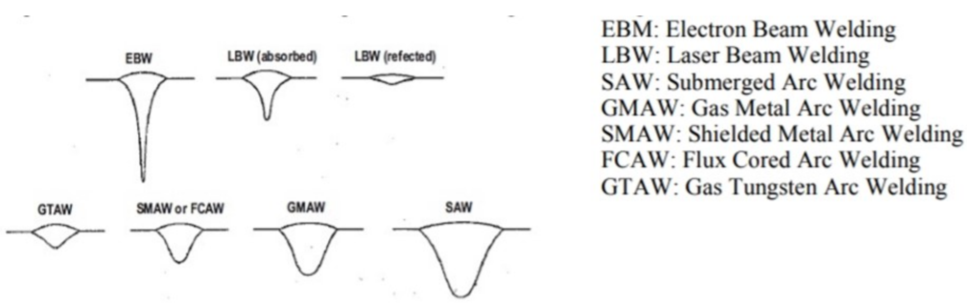

FIGURE 4. Contrast of penetration obtained in different welding processes (Santhana et al. 2012)

The procedure of A-TIG are given in Figure. 5. The first usage of activating flux was reported by Evgeny Oskarovich (EO) patent institute in the 1960's at Kiev in Ukraine. Clear increase in DOP was observed, this marked the beginning for research of different flux materials. Fluxes are accessible in aerosol or paste form where powder form oxides are mixed with solvents like acetone, carbinol or ethanol in appropriate quantity, which later on heating gets evaporated leaving behind the flux layer (Singh et al. 2020).

A noticeable increase in DOP of around 1.5 to 4 times with decrease in weld width was observed. The overall production was enhanced as this eliminated edge preparation and reduced the number of passes (Bhattacharya 2015; Gao et al. 2015). From further experimental work, it was noted that A-TIG weldments possessed either better or same metallurgical and mechanical properties. Up to 300% improvement in DOP was attained by using A-TIG (Modenesi et al. 2000). Optimum DOP was achieved in A-TIG single pass as compared to conventional tungsten inert gas (C-TIG) process (Maduraimuthu et al. 2011). Sakthivel et al. (2011) noticed the precedence of A-TIG compare to C-TIG in welding of 6 mm thickness 316L SS plates. When the flux is subjected to high temperatures, the solvent gets evaporated while the oxides in the flux gets vaporised which then affects the arc geometry, weld pool characteristics and finally the DOP of the arc. Various mechanisms and models where proposed by scientists throughout the world to understand the role of activating elements of flux for increasing the depth of penetration and arc constriction (Kumar et al. 2019; Pandya et al. 2020).

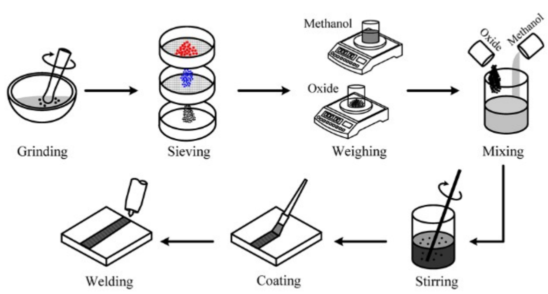

FIGURE 5. Procedure of A-TIG welding (Tseng et al. 2014)

WELD POOL DYNAMICS AND PROPOSED MODELS FOR INCREASED DOP:

There is an intense interaction of forces like Marangoni forces (forces induced by surface tension alterations due to temperature change), Electromagnetic or Lorentz forces, arc force (electrical current flow generating magnetic field), plasma shear or aerodynamic drag forces (due to the flow of gas plasma jets over the pool surface) and buoyancy force (flow induced by density differences in the pool due to the temperature gradient) etc. in the weld pool (Norrish, 2006) as described in the Figure. 6.

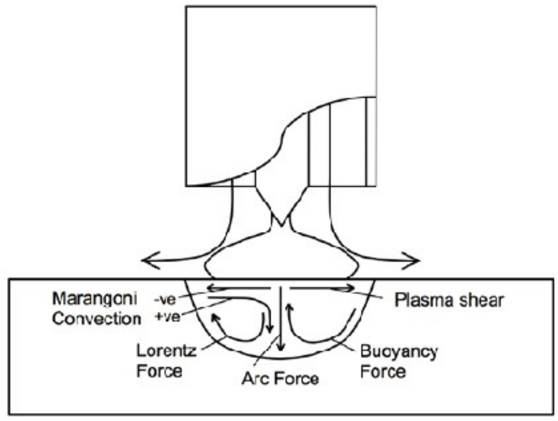

FIGURE 6. Schematic showing different forces acting on weld pool (Kang et al. 2009)

The first noticeable outcome of activating flux was reported in 1965 for titanium-based alloys whereas in 1968 similar effect was reported for steels. The physical change in process i.e. change in arc voltage ensured the effect of flux. It was claimed that wetting action of flux on molten weld pool altered surface tension. Moreover, composition of flux could be changed to modify surface tension (Kumar et al. 2009). The Figure. 7 below shows the contrast in DOP in C-TIG and A-TIG.

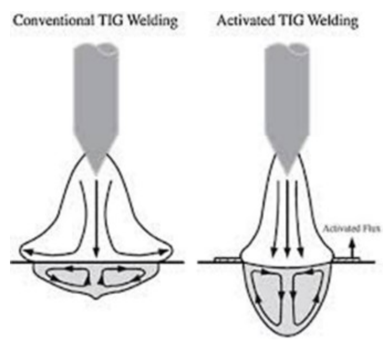

FIGURE 7. C-TIC et al. 2017)

MARANGONI EFFECT AND ITS REVERSAL

James Thomason (1855) first identified the Marangoni convection effect in A-TIG and the theoretical report was given by Gibbs in 1879 (Pandya et al. 2020). The Marangoni effect is known for altering the weld pool form in the TIG process. The alteration in the fluid flow of melted weld pool is associated to thermal coefficient of surface tension (TCST). If TCST turns out to be negative, then peripheral regions of molten weld pool are cooler having high surface tension. This induces an outward flow, creating wide shallow weld pool. This is known as Marangoni effect. When TCST is positive, flow gets reversed and gets concentrated towards centre. This causes an inward flow resulting in narrower deep weld pool with same welding conditions [Lowke et al. 2005; Lu et al. 2003]. Schematic of Marangoni convection given in Figure. 8.

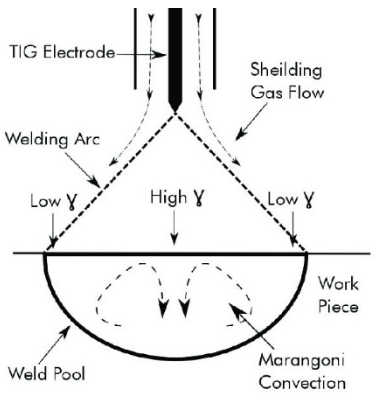

FIGURE 8. Schematic of Marangoni convection (Reyes et al. 2009)

The reversal of Marangoni convection i.e. changing TCST from negative to positive by surface active elements in the molten pool was suggested by Heiple and Roper et al (1982). A simulation modelling work was performed by Wang et al. (2015) investigating the alterations in Marangoni effect and surface tension shear stress. The weld pool geometry became deeper and narrower when $d\gamma/dT$ (γ represents surface tension and T is absolute temperature) value changed from negative to positive. Later, he observed that at $d\gamma/dT = 0$, a miniscule negative vector which was produced by buoyancy effect (outside) and electromagnetic force (inside). The observation superseded Marangoni effect as a superior force as compared with buoyancy effect and electromagnetic force. Many mechanisms came forward for altered DOP. Simonik et al. (1976) suggested a theory depending on the absorption of electron by flux elements generating negatively charged ions.

SIMONIK'S OBSERVATION

Simonik states that the arc constriction was promoted by the flux elements through absorption of peripheral electrons of the arc. He had made his observations by working on Ti with fluxes formed of calcium fluoride and aluminium fluoride. As displayed in Figure. 9, halogen entering in the arc and discharge as neutral atom, molecules, positively or negatively charged ions. At arc discharge center, high energy electrons lead, the state of fluorides and chlorides is neutral with miniscule level of positively charged states. Molecules of halogen seizes electrons creating negative ions. This reduction of peripheral electrons lowers conductivity of arc and leads to arc constriction (Simonik 1976).

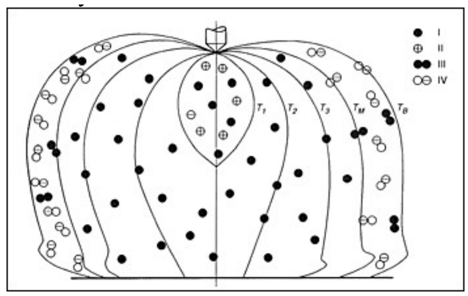

FIGURE 9. Arrangement of halogen particles in number of stages at

OSTROVSKII'S OBSERVATION

Based on Simonik's observations, Ostrovskii carried out work in similar direction and proposed a theory which states that Lorentz force is responsible for increased penetration. This electromagnetic force greatly depends on welding current. As the radius of anode in A-TIG process is considerably small compared to other arc welding processes, the axial component of Lorentz force induces the directional flow of molten metal from surface towards the centre which enhances DOP (Ostrovskii 1977).

LUCAS AND HOWSE OBSERVATION

They worked on the same principle as Simonik on the arc constriction by electron absorption. Electron absorption was controlled by fitting of electrons to vaporised molecules. The dissociated atoms formed negative charge particles. It was noted that, electron attachment would only take place in region of weak electric field i.e., at the peripheral zone of arc column. This restricts current flow towards the centre that increases current density at anode causing narrower deeper weld pool (Lucas, 1996).

ROLE AND EFFECT OF ACTIVATING FLUXES

Since the beginning of research in A-TIG, many potent flux materials are a subject of research. One component flux where utilised first, afterwards multicomponent where also used. Alteration in welding parameters where also analysed with scrutiny to check their effect on DOP. Below provides a list of some recent researches in this direction in a chronological order, providing information regarding characteristic findings in the respective research work.

The Table 1 summaries recent researches on different flux materials and their findings.

TABLE 1. Researches of different flux materials and their findings

Sr No	Flux material used	Alloy used for A-TIG	Characteristic findings of research	Researcher
1	AF305	aluminium alloy	Polarity affects DOP	Huang et al. 2007
2	SiO2	austenitic stainless steel	Above critical value (70ppm) of oxygen in helium as shielding gas enhances Marangoni effect and electromagnetic convection resulting increased DOP.	Fujii et al. 2008
3	TiO2 , SiO2, Cr2O3, MoO3	JIS 304 SS	Higher welding current with different proportions of activating flux (30% TiO2 + 25% SiO2 + 25% Cr2O3 + 20% MoO3) enhanced DWR	Huang 2010
4	SiO2, MoO3, Cr2O3, TiO2, MnO2	hot rolled duplex SS 2205	Maximum DOP observed with MoO3, Cr2O3 and SiO2.	Chern et al. 2011
5	30–50%TiO2, 25– 40% SiO2, 10–20% Cr2 O3,5–15% CuO and 5–15% NiO	AISI 304LN , AISI 316LN	A penetration enhancing activating flux (PEAF) in paste form is utilised for A-TIG up to 12mm thickness plate.	Muthukumaran et al. 2012
6	Ultrafine activating fluxes	AlMg4.5Mn0.7 S235JR	Improved quality of weld joints with increase in productivity.	Parshin et al. 2013
7	Cr2O3, MgCO3	mild steel	- MgCO3 had least effect. - Cr2O3 gave double penetration compared to C-TIG. - Mixture of both fluxes in ratio 1:1 gave medium results. Vickers hardness test showed lower value than C-TIG.	Er singh et al. 2015
8	Cr2O3, SiO2, TiO2	SS 316 L	Effect of coating density on DWR. Maximum DOP observed at 2.1, 2.4 and 3.6 mg/cm with Cr2O3, SiO2, TiO2 fluxes, respectively.	Ahmadi et al. 2015
9	AF305	aluminium alloy	AC welding yields more DOP than DC	2016 Shao et al. 2016
10	Cr2O3, FeO, Fe2O, MnO, SiO2, Al2O3	304 SS	- Al2O3 didn't affected DOP. - SiO2 had best results. No significant alterations observed in hardness values of C-TIG and A-TIG.	2017 Kumar et al. 2017
11	MnO2, Na2O4, MgCl2, Cacl2, ZnO	AA-6082	- Arc penetration better with MgCl2 than 2019 CaCl2. - Na2SO4 degraded strength and produced porosity in the weldment. - ZnO increased weldability of weldment. - Slag inclusions observed while using Na2SO4, MnO2 and CaCL2. MgCl2 flux had best results.	2019 Kumar et al. 2019
12	SiO2, Cr2O3	409 ferritic stainless steel	- Increased DOP, with SiO2 4.9mm and 2019 Cr2O3 4mm. - Increased DOP with increase in current from 100A to 160A - SiO2 has pronounced effect.	2019 Vidyarthya et al. 2019

continue ...

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13	halide fluxes oxide fluxes	stainless steel	Halide fluxes contributed to arc constriction and oxide fluxes towards Marangoni effect.	2020	Pandya et al. 2020
14	nano SiO2	Incolloy 925	- Tensile strength improved by 41%(889.6 ± 4.5 MPa) and 30.8%(821 ± 6.1 MPa) after ageing 4h and 8h respectively, paralleled to AW(627.5 ± 5.0 MPa) conditions and - The notch toughness value had diminished by 48.15%(42 ± 3.8 J) and 62.96% (30 ± 4.5 J) when exposed to 4h and 8h respectively paralleled to solutionized and annealed alloy.	20202	Sujai et al. 2020

Apart from above given research work, many other research works have provided extensive information about effect of flux on mechanical and microstructural properties while simultaneously increasing DOP while using single or multi component flux materials. Zhao et al. (Zhao et al. 2006) in his research on activating fluxes noted that by increasing the oxygen and sulphur content up to an optimal level can enhance DOP and DWR while there was decrease in the metal bead width shown in Figure 10. The optimal content for oxygen is 280ppm and for sulphur 125ppm where sulphur has more pronounced effect then oxygen. Beyond this optimal value there is no appreciable change in the weld bead geometry. Tseng et al. (2012) compared TiO2 and SiO2 fluxes, under same welding conditions the penetrating capability with nearly 240% TiO2 fluxes and 292% SiO2 fluxes showcased as cross- sectional macrograph in Figure 11 .

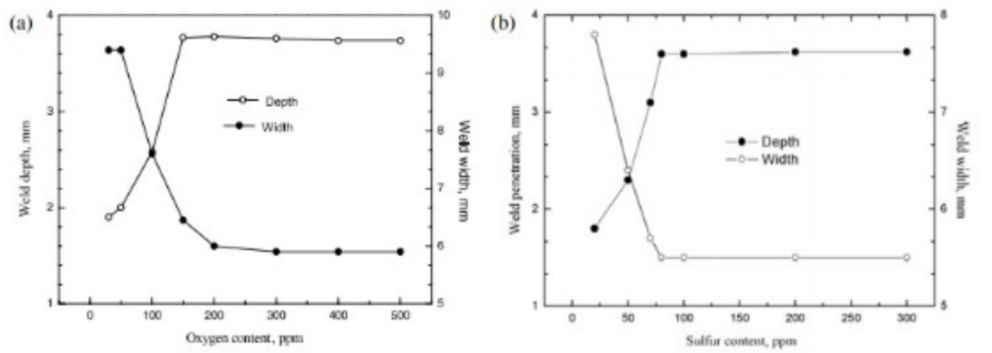


FIGURE 10. Effect of oxygen (a) and sulphur (b) content on the weld depth and width (Zhao et al. 2006)

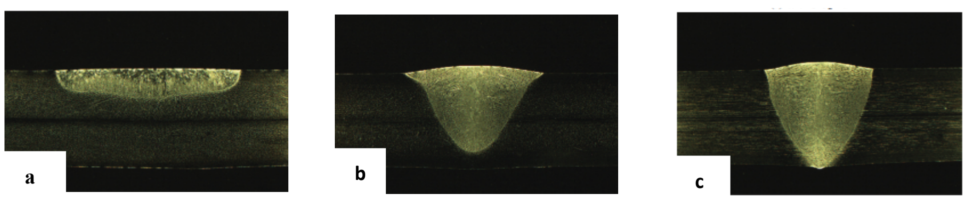


FIGURE 11. Cross-sectional macrograph of TIG welds produced a) without flux, b) with TiO2 flux and c) with SiO2 flux (Tseng et al. 2012)

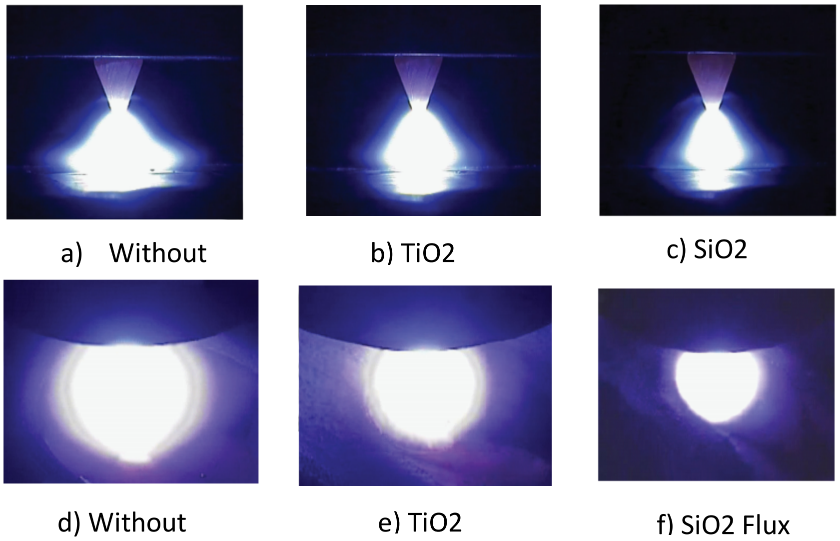
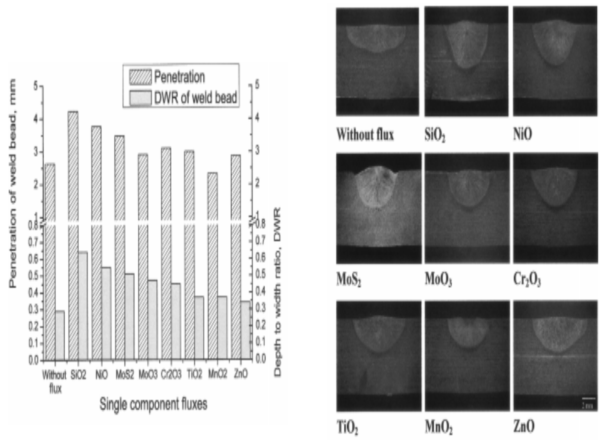


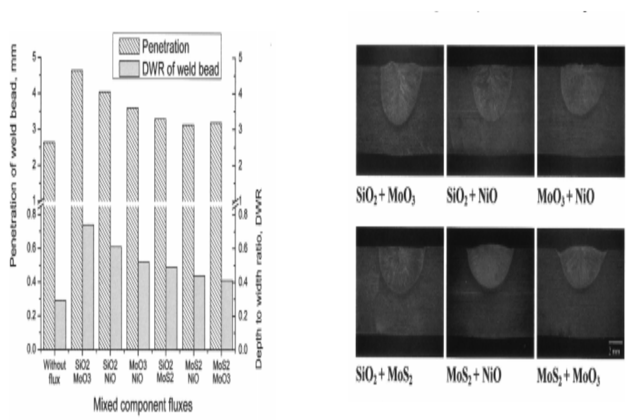
FIGURE 1. a-c: Plasma column in TIG welding with/without fluxes and d-f: Anode root in TIG welding (Tseng et al.)

As shown in Figure. 12, the plasma column of SiO2 flux exhibited enhanced arc constriction than with TiO2 and anode root prepared by SiO2 flux showed additional condensation than TiO2 flux. There was also a noticeable greater a mount of ferrite in the microstructure of A-TIG weldment noticed paralleled to conventional TIG welding. Lin et al. (Lin et al. 2012) did an extensive study on the influence of single component and multi component fluxes on the DWR and penetration achieved on Inconel 718 alloy. The A-TIG welding with single component fluxes like SiO2, NiO, MoS2, and MoO3 formed remarkable Marangoni effect which escalated DWR and penetration as shown in Figure 13. Looking the higher DWR of samples, single component fluxes were mixed in the ratio of 50 wt. % each. The mixed component flux were SiO2-MoO3, SiO2-NiO, MoO3-NiO, SiO2- MoS2, MoS2-NiO, and MoS2-MoO3. As shown in Figure. 14, SiO2-MoO3 mixed flux seems utmost substantial. The improvement noticed in the DWR was of 28% a t 60 to 75 degrees of electrode angle. Srirangan et al. (2015) investigated the effects of SiO2, ZnO and their combination with same welding parameters. It was observed that SiO2 had more pronounced effect in increasing DOP. ZnO flux when used in conjunction of SiO2 flux, had a detrimental effect of the DO P. The weldments of SiO2 flux exhibited elongated grains which were more susceptible to cracking whereas ZnO flux showed a fine-grained structure in the weld zone, shown in Figure 15. The usage of more than one flux together has also became a trend among researchers. Kumar et al. (2018) had studied the affect of tri component flux on Inconel 718 super alloy. Initially, the experimental work was directed towards understanding effect of welding current on DOP. The notable effect on DOP was observed while using tri-component flux. This is summarised well in table 2.



a. Weld bead geometry of b. Cross-section of Welds in

FIGURE 13. Outcome of single component flux on TIG welds (Lin



a. Weld bead geometry of welds in A-TIG

b. Cross-section of Welds in A-TIG

FI s

(Lin et al. 2012)

TABLE 2. DOP and weld width characteristics at different values of welding current

Welding Process	Welding current (A)	DOP (mm)	Weld width (mm)
TIG	120	1.2	5.499
TIG	140	1.503	6.260
TIG	160	3.330	9.732
A-TIG	120	5.175	8.058
A-TIG	140	5.432	6.22
A-TIG	160	6.003	6.869

On analysing AFM images as shown in figure 16, of the A-TIG welded zone, higher roughness was observed. According to authors it was caused by presence of trapped oxide particles in C-TIG welded zones. While analysing the mechanical properties, some anomalies were observed for A-TIG and C-TIG welded zones. The Hardness of both were more than base alloy, which may be attributed to good interfacial bonding, nucleation in existence of oxide flux and process temperatures. The hardness profile is shown in figure 17.

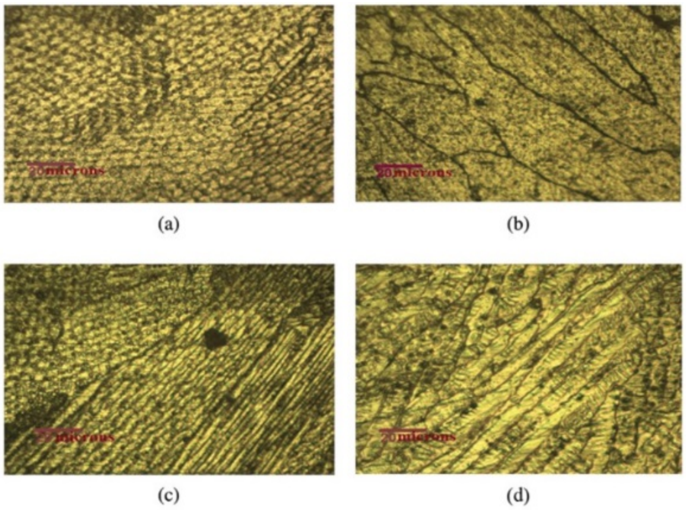


FIGURE 15. (a) Weld zone microstructure (without flux) x200. (b) Macrostructure for A-TIG welding with (SiO2 flux) x200. (c). Weld zone microstructure (ZnO flux) x200. (d) Weld zone microstructure (50% SiO2 + 50% ZnO flux) x200. Srirangan et al. (2015)

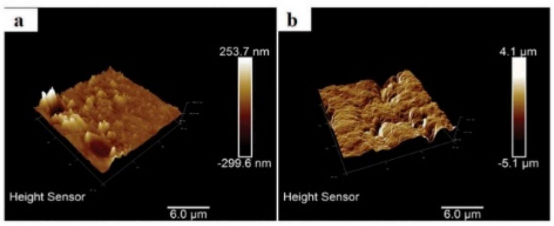


FIGURE 16. AFM of (a) C-TIG and (b) A-TIG showing 33-Dimension surface roughness (Kumar et al. 2018)

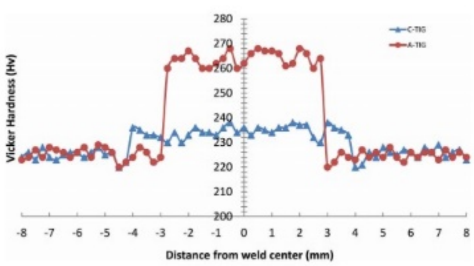


FIGURE 17. Hardness of C-TIG and A-TIG weld joints (Kumar et al. 2018)

The UTS measured was 826 MPa and 611 MPa for A-TIG and C-TIG respectively. The alloying effect by oxides in the flux had a major role in increasing UTS. The C-TIG welded zone had more percentage elongation as compared to A-TIG. No change in ductile behaviour was confirmed by FESEM images, comprising of characteristic dimple microstructure for both A-TIG and C-TIG welded samples. One surprizing effect noticed in this experimentation work was about the electrode tip morphology. As seen in the Figure 18, C-TIG electrode had moderate while A-TIG had higher deterioration. According to author, this condition had been arisen by strong oxidizing environment, caused by production of free electrons in ionization state, leading to swelling of the electrode.

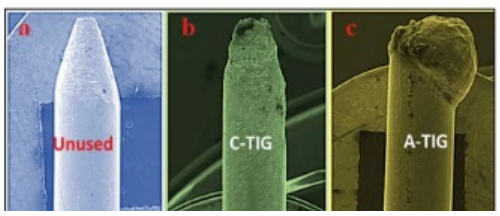


FIGURE 18. Effects of flux mixture on welding electrode (Kumar et al. 2018)

CONCLUSIONS

Apart from its lucrative features, the TIG welding process possesses the main disadvantage of low depth of penetration.

The usage of activated fluxes out to be a topic of research since many decades. The inversion of Marangoni convection forces is considered to be most acceptable theory and is also backed up by many scientific endeavours, yet the exact relationship between activating elements and their effect on weld pool dynamics is not known. There is an extensive research in understanding various arc constriction models and also in knowing the flux's effect in enhancing DOP. The Table 3 summaries Effects of different fluxes on various alloys. The most impeccable effect was of SiO2 and TiO2 as flux materials. Flux material are now also used together in varied proportion to yield better results which were not possible by using single flux material. The mechanical properties attained by A-TIG weldments had anomalous values when compared to C-TIG weldments.

TABLE 3. Effects of different fluxes on various alloys

Sr no	Material	Flux	Density of flux (g/Cm³)	Appearance of flux	Estimated penetration depth (mm)	Researcher
1.	Carbon steel (SA516 Gr70)	TiO2	4.23	White solid, odourless	5	Vora et al. (2019)
2.	Ferritic stainless steel (SS409)	Cr2O3	2.70	Dark purple solid, odourless	8	Venkatesan et al. (2014)
3.	Martensite stainless steel (SS410)	SiO2, CrO3	2.65, 2,7	Transparent crystals, Dark red granular solid	6,8	Li et al. (2012)
4.	P91 steel:	ZnO	5.61	White solid, odourless	5	Dhandha et al. (2015), singh et al. (2017)
5.	Magnesium alloy	CaCl3	1.83,	White powder hygroscopic,	8	S et al (2017) , Xie et al. (2015)
6.	C-276 alloy	SiO2	2.65	transparent crystals	7	Manikandan et al. (2018)
7.	Inconel 718	Cr2O3	2.70	Dark purple solid, odourless	More than 8	Kumar et al. (2018)
8.	Inconel X750	MoO3	4.69	White to pale yellow crystalline solid,	7	Ramkumar et al. (2016)
9.	Aluminium alloy	CaF2	3.18,	White crystalline solid	More than 6	Parshin et al. (2013), Li et al. (2017)
10.	Inconel 600	SiO2 &TiO2 (50-50)	2.65 &4.23	Transparent crystals, White solid (odourless)	9	Chandrasekar et al. (2017)
11.	Inconel 800H	V2O5	3.4	Yellow to red crystalline powder	More than 5	Srirangan et al. (2016).

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DECLARATION OF COMPETING INTEREST

None

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