Activated flux induced Tungsten inert gas welding of Ferrous alloys – A Review

Rakesh. N1, K. Rameshkumar2

1Department of Mechanical Engineering, Amrita Vishwa Vidyapeetham, Amritapuri, India
2Department of Mechanical Engineering, Amrita Vishwa Vidyapeetham, Coimbatore, India

E mail: rakeshn@am.amrita.edu

Abstract. Ferrous alloys are employed in a range of fields, including aerospace, construction, automobiles and chemical processing. One of the most used welding processes for the fusion of ferrous metals is gas tungsten arc (GTA) welding or Tungsten Inert Gas (TIG) welding. Due to the lower amount of penetration accomplished using only one pass, welding is less frequent in some industrial situations. Fluxes have been discovered to improve the penetration depth of GTA welding, resulting in increased productivity. The research on Activated flux induced TIG (A-TIG) welding of ferrous alloys is discussed in this publication. The effect of fluxes during TIG welding, the effect of weld parameters on weld morphology, and the usage of fluxes in dissimilar welds of ferrous alloys are all discussed in this study. The mechanisms involved in enhancement of penetration depth, the types of fluxes used, the effect of fluxes on mechanical properties and microstructures are discussed. The study also gives an insight on areas less explored.

1. Introduction
Ferrous alloys have a diverse range of applications in the area of aerospace, automotive, construction, chemical processing industries. A number of welding processes such as shielded metal arc welding, friction stir welding, metal inert gas welding, submerged arc welding are employed to weld thin sections of ferrous alloys. Electron beam welding, laser beam welding and plasma arc welding are used for welding thick plates [38-41]. However, all these processes have their own limitations which prevent the frequent use of these processes [27]. One of the most used welding processes for joining ferrous metals is gas tungsten arc (GTA) welding. Tungsten Inert Gas (TIG) welding is another name for GTA welding. In this procedure, a tungsten electrode is utilized to create an arc. Gases such as argon or helium that shield are used to protect the oxidation of the weld zone and other ambient contaminants during welding. TIG welding has a number of benefits over other welding techniques, including the ability to weld various materials, no production of spatter or slag, no sparks, and no smoke, and the ability to weld in all positions. The procedure has several significant limitations, including the need for operators with high levels of competence, an increased UV radiation level, c)
Excellent coordination between the eyes and the hands, and d) the difficulty to achieve a larger penetration weld volume in a single pass [22]. Since TIG welding delivers a lower weld depth in a single pass, it is becoming less common in various industrial applications, which is one of these restrictions. As a result, the number of passes required to complete the welding will rise, as will the time it takes to complete the weldment.

2. Activated flux TIG welding (A-TIG)
Several attempts have been made to increase TIG welding penetration depth. The fluxes used in GTA welding have recently improved the depth of penetration, resulting in increased production. Activated flux TIG welding (F-GTAW) or flux assisted GTAW (F-GTAW) are two terms for the same method (A-TIG). Oxides, chlorides, and fluorides are the most common fluxes used to improve penetration depth. There have been a few investigations to test if adding fluxes in the TIG welding process will enhance penetration. The studies conducted were mostly on the ramification of Individual flux’s effect on weld microstructure and morphology, strength of weldment. Figure 1 and 2 shows the TIG welding & A-TIG welding process and corresponding deeper weld depth for the stainless steel material. The impact of various fluxes on penetration intensity and bead geometry is shown in Figure 3 [1]. The effect of fluxes during TIG welding of ferrous alloys, the consequence of weld parameters on weld morphology, and the usage of fluxes in dissimilar welds of ferrous alloys are all discussed in this study.

3. Effect of fluxes during TIG welding of ferrous alloys
Vidyarthi et al.,[2] studied single pass, A-TIG welding of the 8 mm thick P91 steel, Weld bead shape, heat input, and angular deformation were examined using CeO₂ and MoO₃ fluxes. A 200% and 300% increase in penetration of a joint were achieved with fluxes, CeO₂ and MoO₃, respectively. Due to Marangoni convection and narrowing of arc, this was deduced. Wu et al.,[3] The effects of ZrO and CaF were investigated on the weld pool’s temperature history and the thermo physical characteristics of the weld bead. When compared to TIG welding, the average temperature at the measuring point rose by 70 °C. Because of the narrowing of the arc and turnaround of Marangoni convection, a maximum penetration of 6.4 mm was attained for 3 percent zirconium oxide and 1 percent calcium fluoride concentrations. Vora et al.,[4] conducted studies on A-TIG welding of 6 mm thick martensitic/ferritic steel utilizing TiO₂ as flux. The microstructures, micro hardness, tensile strength, and impact strength of these welded joints were compared after single and double heat treatment after the weld. Because of the presence of M23C6 and MX carbide precipitates with a high content of Cr, W, and Ta, the double PWHT joint showed a ductility and yield strength improvements.
Vasudevan [5], TIG welding of 10-12 mm thick type 304LN and 316LN stainless steels in a single pass, a multi-component activated flux was created. The use of activated flux in TIG welding of stainless steels 316LN and 304LN resulted in a considerable penetration increase of 10-12 mm. A-
TIG welding greatly increased the cross-sectional strength metrics of 304LN and 316LN stainless steel weld joints. Ramkumar et al.[6] the effect of heat treatment after weld on microstructure of zone of fusion and mechanical qualities of Inconel X750 A-TIG weldments utilizing a compound flux of 50 percent SiO$_2$ + 50 percent MoO$_3$ was investigated. Using the compound flux at 190 A current, complete penetrations was obtained in a single pass. The strength of Inconel X750 weldments that have been heat-treated after weld improved, reaching 1142 MPa, it is more similar to the parent metal strength. Cai et al.[7] Cerium oxide's influence on BS700MC super steel weld penetration, microstructure, and mechanical properties were looked into. It was discovered that utilizing Cerium oxide as a flux, enhanced the penetration of super steel welds. The main cause of increased weld penetration is thought to be a change in Marangoni convection. It was also discovered that a cerium oxide level of 15% resulted in the greatest penetration. Ramkumar et al.[8] the mechanical characteristics of weldments produced by TIG welding 5 mm thick Inconel 718 plates were compared. Fluxes of SiO$_2$ and TiO$_2$ are used to prepare the weldment. With a current of 140 A, complete depth was achieved. Both weldments cracked at the parent metal during the tensile test. When compared to the parent metal, weldments aided by SiO$_2$ and TiO$_2$ flux had improved tensile strength characteristics. Due to the presence of oxide flux inclusions, both weldments had low impact toughness.

Ramkumar et al.[9] ferritic stainless steel AISI 430 weldability was investigated using TIG welding with active fluxes and without. SiO$_2$ and Fe$_2$O$_3$ were employed as fluxes. Both fluxes improved weld penetration as welding current increased. The arc constriction effect and Marangoni flow reversal were the reason. Tensile failure occurred at the parent metal with SiO$_2$ flux due to the occurrence of martensite with a low carbon content, whereas For Fe$_2$O$_3$ weldment, because of the existence of more oxygen, failure occurred at the fusion zone. Vasantharaja et al.[10] during multi-pass TIG and A-TIG welding of 10 mm thick 316LN stainless steel plates, the residual stress distribution and contortion values were investigated. A-TIG weld joints demonstrated less residual stress and deformation due to the lack of filler metal, single pass straight sided edge preparation welding, and a more intense heat source.

Anup Kulkarni et al [1] on GTAW of P91 steel, the consequence of several oxide fluxes (MoO$_3$, Cr$_2$O$_3$, TiO$_2$ and CuO) was investigated. When compared to flux-free welding, in a single pass, activated fluxes increased the depth of weld penetration. In the investigation, TiO$_2$ flux produced the greatest depth-to-width ratio. The penetration depth enhanced when the oxygen concentration was between 30-80 ppm. Dhandha et al, [11] during the A-TIG welding of 6 mm thick P91 steel plates, the outcome of oxide fluxes on weld morphology was examined. Cr$_2$O$_3$, Fe$_2$O$_3$, CaO, ZnO, TiO$_2$ and Mn$_2$O$_3$ were the fluxes employed. Figure 4. It was hypothesised that arc constriction is the primary cause of increased penetration depth and decreased spread of bead. Owing to the oxide elements in the flux, the voltage of arc grew as the flux was used, causing arc constriction. With the application of flux, the heat input also rose. Welding modified 9Cr–1Mo steel plates using Fe$_2$O$_3$, ZnO, Mn$_2$O$_3$, and Cr$_2$O$_3$ fluxes was discovered to be possible. ZnO created a weld with a 320 percent improvement in aspect ratio. Venkatesan et al.[12] on weld morphology, researchers evaluated the ramifications of three single component fluxes TiO$_2$, SiO$_2$, and Cr$_2$O$_3$, as well as a ternary mixture of these fluxes. For greatest penetration, the optimal combination of these three fluxes was given as 87.23 percent SiO$_2$ + 12.76 percent TiO$_2$ + 0 percent Cr$_2$O$_3$. Kumar et al [13] 304 austenitic stainless steel plates, TIG welded, the influence of several oxide fluxes MoO$_3$, Fe$_2$O$_3$, Cr$_2$O$_3$, FeO, SiO$_2$, and Al$_2$O$_3$ on weld shape, mechanical properties and microstructure was investigated, Figure 5. Except for Al$_2$O$_3$, all fluxes improved weld penetration. Of all the fluxes tested, SiO$_2$ provided the best weld penetration. When comparing A-TIG samples to traditional TIG welding samples, the hardness levels of the Fusion Zone (FZ), Heat Affected Zone (HAZ), and Base metal (BM) regions did not exhibit much difference. Vora et al [14] during the bead on plate TIG welding of reduced activation martensitic/ferritic steel, the impact of oxide fluxes with single components CuO, MoO$_3$, Al$_2$O$_3$, NiO, Co$_3$O$_4$ and HgO on weld shape and microstructure was investigated.
In addition, the phenomenon behind the increase in penetration depth was postulated in this paper. In the 6 mm thick RAFM plate, Co$_3$O$_4$, CuO, HgO, and MoO$_3$ fluxes yielded penetration depths of 7.8, 8.1, 5.5, and 5.2 mm, respectively. Co$_3$O$_4$ and CuO were the only fluxes that caused complete penetration. Tseng et al [15] during the bead on plate TIG welding of 6mm thick Type 316L stainless steel plate, oxide fluxes Al$_2$O$_3$, MoO$_3$, MnO$_2$, TiO$_2$ and SiO$_2$ are examined for their effects on weld shape, angular distortion, and hardness, Figure 6. Welds with the greatest depth to width ratio were found to be formed by SiO$_2$ and MoO$_3$ flux. In comparison to typical TIG welding, SiO$_2$ flux generated welds with good root pass penetration, whereas Al$_2$O$_3$ flux caused weld depth to deteriorate.

Ramkumar et al [16] during the GTAW process of 5 mm thick duplex stainless steel UNS S32205 plates thickness, the influence of different oxide fluxes, NiO, MoO$_3$, and SiO$_2$, on microstructure, mechanical, and corrosion properties was investigated. The existence of various types of austenite was discovered in all specimens, and the hardness of the weld region for all specimens was on par with the base metal. It was discovered that NiO and SiO$_2$ specimens had better tensile properties, while NiO had a higher percentage elongation due to less oxide inclusion. Modenesi et al [17] GTAW welding of Plates of austenitic stainless steel AISI 304, thicknesses of 5 to 8 mm was examined using single component fluxes. Effect of sulphur content on weld penetration was also examined. It was discovered that there was no correlation between sulphur content and penetration depth. Fluxes were shown to increase weld penetration by 300 percent in the TIG welding process.

Ahmadi et al [18] during TIG process, the effects of oxide fluxes, such as CuO, SiO$_2$, TiO$_2$ and Cr$_2$O$_3$ on the 316L austenitic stainless steel of 9 mm thickness, mechanical characteristics and ratio of depth to width were examined. The penetration first increased as the flux density increased, but subsequently steadily decreased. When compared to all other fluxes, it was discovered that SiO$_2$ flux provided the most penetration. During the process, the active flux constricts the weld arc. Ramkumar et al [19] during bead on plate TIG welding thickness of 5 mm ferritic stainless steel AISI 430 plate, the effect of SiO$_2$ and Fe$_2$O$_3$ fluxes and weld current on weld shape and mechanical performance was investigated. The depth of penetration of the weld was found to be increased by increasing the current. As a result of the Marangoni flow and arc constriction, SiO$_2$ and Fe$_2$O$_3$ fluxes increased penetration depth. The joints were created in a single pass using A-TIG welding. TIG welding, on the other hand, required two passes. Vora et al [20] during the bead welding of tungsten inert gas of 6mm thick Reduced Activation martensitic/ferritic steels, the influence of six oxide fluxes, namely HgO, MoO$_3$, Co$_3$O$_4$, Al$_2$O$_3$, CuO, and NiO, as well as the carrier solvents, methanol and acetone, on weld bead shape was investigated. This study also identified a mechanism that governs the growth in weld penetration depth.
Figure 6. Weld morphology variations during TIG welding [17]

Figure 7. Variation of depth of fusion for various steels with and without flux [20]

The highest penetration depth was 7.5 mm and 7.1 mm, respectively, using methanol as the carrier solvent and MoO₃ and Co₃O₄ as fluxes. With acetone as the carrier solvent, the fluxes Co₃O₄ and CuO had the greatest depth of penetration. [21] They also investigated the effects of single component oxide fluxes, such as ZnO, Fe₃O₄, Cr₂O₃, CaO, TiO₂, MnO₂ and bead, on the appearance of surface, geometry of weld, micro-hardness and microstructures of thickness 6 mm low activation martensitic/ferritic steel TIG welded plate, Figure 10. Fluxes of Fe₂O₃ and TiO₂ demonstrated complete weld penetration. Tathgir et [32] the effect of TiO₂ flux at various currents and shielding gas compositions on weld depth, width-to-penetration (WP) ratio, and microhardness during TIG welding of various types of steel, including Duplex 2205, AISI 304, 316, 1020 was investigated. For the experiment, 5 mm thick plates were employed. When TiO₂ flux was used, the penetration intensity of Duplex 2205, AISI 304, 1020, 316 steels rose by 124 %, 44.3 %, 37.8%, 47 %, and respectively, Figure 7.

Mohan Kumar et al [22] the impact of weld input parameters, such as arc length, weld speed, weld width, weld current, penetration depth and weld area during TIG welding of 6 mm thick AISI 321 Austenitic Stainless Steel plate was studied. With a welding speed of 120 mm/min, arc length of 3 mm and welding current of 220 Amps, full penetration of 6 mm was accomplished. During tensile testing, the failure occurred at the base metal.

Figure 8. Effects of oxide fluxes on penetration depth [25]

Figure 9. The impact of oxide fluxes on weld geometry [29]

Kulkarni et al [23] during TIG welding of AISI 316L stainless steel plate 8 mm thickness, the influence of oxide fluxes CuO, MoO₃, Cr₂O₃, TiO₂ and compound flux Cr₂O₃ + TiO₂ on weld shape was investigated, Figure 13. The fluxes were discovered to improve penetration depth. Full penetration was achieved with the multi-component flux. The weld microstructure was austenitic. The micro
hardness value was maximum in the fusion zone and least in the heat impacted zone due to grain coarsening. [35] The impact of oxide fluxes, MoO₃, CuO, SiO₂, Cr₂O₃, and TiO₂ on weld bead shape was explored during TIG welding of dissimilar steel combinations of P91 steel and P22 steel with an 8 mm thickness, Figure 11. The mechanism that governs the rise in penetration depth has also been presented. Fluxes of MoO₃, TiO₂, and Cr₂O₃ were found to have complete penetration. The reversal of Marangoni convection was assumed to be the key cause for enhanced penetration depth.

Figure 10. Effect of fluxes and weld dimension [30]

Figure 11. Effect of fluxes and weld dimension [32]

Kumar et al [24] During bead on plate TIG welding of 3 mm thick AISI 304 stainless steel plate, the influence of single component fluxes TiO₂, Al₂O₃, and CaF₂ on the weld shape, micro-hardness and microstructure was investigated, Figure 14. The depth of penetration of TiO₂ flux was significantly improved, however the weld to width ratio and weld penetration of CaF₂ were not significantly improved. A-TIG weldment has a higher micro hardness rating than TIG weldment.

Figure 12. Effects of fluxes on penetration depth [34]

Figure 13. Effect of fluxes on the weld dimension [35]

4. Influence of welding parameters on weld geometry

Various researchers investigated the characteristics of weld current, arc length, shielding gas composition, welding speed and arc voltage on weld geometry. Due to the supremacy of Marangoni convection over aerodynamic drag force, high current was shown to increase the depth of penetration in the A-TIG welding process [26]. Due to the high heat input, reduced welding pace results in a deep and narrow fusion zone, causing inward Marangoni convection [27]. The type of fluxes employed had an effect on the arc voltage. When compared to metallic fluxes like Al₂O₃, nonmetallic fluxes like SiO₂ increased arc voltage due to their higher resistivity [28]. The initial rise in arc length raises the arc voltage, which improves penetration depth. As the arc length further increases, the arc voltage decreases, resulting in a shallow weld [29]. The shielding gas's ionization potential determines the heat
input and hence the fusion area of the weld zone. The most common shielding gases are argon and helium. On SS304, Austenitic stainless steel, and SS316, many investigations have been conducted on mixing argon and helium with other gases such as oxygen, hydrogen, and nitrogen [30, 31, 32]. The addition of these gases enhanced the d/w ratio.

5. Effect of fluxes during TIG welding of dissimilar metals

During TIG welding of SA516Gr70 and 304 Austenitic steel, several oxide fluxes were investigated. Full penetration was achieved with ZnO$_2$ and TiO$_2$, and the TiO$_2$ weldment had minimal distortion [33]. TIG welding using oxide fluxes enhanced penetration of JIS G313 and 316 L stainless steel. Penetration was improved by Cr$_2$O$_3$, SiO$_2$, and Fe$_2$O$_3$. SiO$_2$ enhanced tensile strength and reduced angular distortion [34]. Kulkarni et al [35] the impact of oxide fluxes, MoO$_3$, CuO, SiO$_2$, Cr$_2$O$_3$, and TiO$_2$ on weld bead shape was explored during TIG welding of dissimilar steel combinations of P22 steel and P91 steel with an 8 mm thickness, Figure 11. The mechanism that governs the rise in penetration depth has also been presented. Fluxes of MoO$_3$, TiO$_2$, and Cr$_2$O$_3$ were found to have complete penetration. The reversal of Marangoni convection was assumed to be the key cause for enhanced penetration depth. For both pre-heated and post-heated weldments, during the tensile test, the base metal of P22 steel failed. Ramkumar et al.,[36] conducted research on the weldments made of marine grade stainless steel have a microstructure and mechanical characteristics, such as super-austenitic stainless steel and duplex stainless steel (UNS S32750) during TIG dissimilar welding (AISI 316L). Owing to the arc narrowing effect, it was proposed that the penetration intensity increased as welding current rose. The base metal of AISI 316L showed tensile load fractures. The impact of a solid solution of dissolved nitrogen in the austenitic phase improved the tensile characteristics. The existence of delta ferrite enhanced the weld zone hardness in AISI 316L, but Widmanstätten austenite platelets decreased the dissimilar weldment’s impact toughness.

Sharma et al [37] the impact of oxide fluxes, such as MoO$_3$, TiO$_2$, SiO$_2$, Cr$_2$O$_3$, SiO$_3$ on the form of weld beads was investigated during TIG welding of dissimilar steel combinations of 304H austenitic stainless steel and P92 steel of 8 mm thickness, Figure 12. For TiO$_2$ flux, it was discovered that complete penetration was achieved. Only with SiO$_2$ was arc constriction detected. In an A-TIG weldment utilizing TiO$_2$, micro hardness values reduced from 304H ASS to P92 steel. Patel et al [25] during the dissimilar TIG welding of LAFM and 316LN plates of 6 mm thickness, the influence of single component fluxes, TiO$_2$, Fe$_2$O$_3$, CuO, Co$_3$O$_4$, and HgO on weld shape, micro and macro structure, and micro hardness was investigated, Figure 15. The findings were compared to those obtained using a traditional TIG technique. When compared to A-TIG weldment, TIG weldment had a better surface look. The depth of penetration of Co$_3$O$_4$ and TiO$_2$ flux in the weldment was enhanced. The two fluxes both showed an increase in voltage.

6. Conclusion

This research examines the current state of activated flux induced TIG welding of ferrous alloys. The effect of fluxes during TIG welding of ferrous alloys, the effect of weld parameters on weld morphology, and the usage of fluxes in dissimilar welds of ferrous alloys are all discussed in this study. According to the findings, the phenomenon responsible for the rise in penetration depth was reversal of arc constriction and Marangoni convection. The flux tends to increase the arc voltage which and reduces the arc area, arc constriction which aided the depth of penetration. Various types of ferrous alloys were studied and the fluxes mostly used were oxide, chloride and fluoride. Weld penetration and the effect of shielding gas has only been studied in a few cases, the study shall be extended to other ferrous alloys. The impact of flux size and density on penetration depth has received little attention. Few attempts were made on the impact of flux in Tungsten inert gas welding of dissimilar alloys. Possibility of extending it to other types of ferrous alloys can be attempted.
7. References

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