Productivity improvement in butt joining of thick stainless steel plates through the usage of activated TIG welding

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Received: 14 June 2020 / Accepted: 22 February 2021 / Published online: 4 March 2021
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Abstract

Activated tungsten inert gas (A-TIG) welding is one variant of conventional TIG welding where a thin layer of suitable activating flux is deposited on the parent components prior to constituting the arc in order to harness enhanced penetration. Despite several benefits, industries are still reluctant in overwhelmingly using this new variant. This article attempts to highlight the productivity benefits in employing A-TIG welding either together with or superseding TIG welding during butt joining of 10-mm-thick AISI-316L austenitic stainless steel components. Initially, three single-component fluxes (Cr_2O_3 , Fe_2O_3 , and SiO_2) are tested in forehand welding technique under varying currents but with straight polarity. Filler rod having similar metallurgical composition is also delivered during homogeneous welding. The extent of capability of each of the three fluxes is analysed by comparing the weld bead geometrical parameters (penetration, puddle width, and reinforcement) with the same obtained in conventional TIG welding under similar set of parameters. While Fe_2O_3 and SiO_2 fluxes are found capable in enhancing penetration and reducing puddle width and heat affected zone, Cr_2O_3 flux failed to exhibit better performance. The article further demonstrates the time saving that can be obtained by adopting flux-assisted TIG for joining 10-mm-thick plates. When joining from both the faces is allowed, about 70% less time is desired if a combination of A-TIG and TIG is employed rather than using only TIG welding. If joining from only one face is allowed, then also usage of flux can reduce welding time by 33%.

Keywords Welding · Activated flux · Activated TIG · Productivity · Penetration · Welding time

1 Introduction

Gas tungsten arc welding (GTAW), colloquially known as tungsten inert gas (TIG) welding, is one fusion welding process where electrically conductive metallic components are permanently jointed together through weld bead formation. An electrical arc, constituted between the components to be joined and the nonconsumable tungsten electrode, supplies necessary heat for fusing the faying surfaces and surrounding areas for coalescence formation. Although TIG welding is preferred for autogenous mode of joining, filler metal can be supplied

separately if the root gap is substantial. Inert gas (such as argon) is commonly supplied to provide a shield over the high-temperature arc and molten weld bead (puddle). If carried out properly with optimum set of process parameters, it can offer a defect-free reliable joint having good appearance requiring minimum effort. Despite having numerous benefits, the process capability is limited by the shallow penetration. Typically, it fetches maximum of about 3.5 mm penetration in single pass in butt joining in square edges [1].

While joining thicker components (say, thickness of more than 4 mm), edge preparation and/or multiple

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passes are desired to manipulate the actual depth of penetration. As standardized in ISO 9692-1:2013, edge preparation in TIG welding involves designing the roots of the thick weldable components in such a way that reduces actual thickness of components having narrow root gap to a minimum value [2]. Thus, the root gap at the top surface is increased through bevelling or grooving. Edge preparation is always a time-consuming and unproductive task. Additionally, prepared edges usually require multiple passes to completely fill the entire root gap. This ultimately increases total welding time. Additionally, multiple passes also proliferate the total heat input into the components, which, in turn, widens the heat affected zone (HAZ) and also leads to undesirable metallurgical changes surrounding the weld bead [3]. Furthermore, larger root gaps require more volume of expensive filler material. This, together with reduced productivity, turns the entire process economically inefficient.

Such limitations paved the way for accelerated development of the conventional TIG welding process. As a consequence, several novel variants of the existing process have emerged [4], which include activated TIG (A-TIG), flux bounded TIG (FB-TIG), keyhole TIG (K-TIG), deep penetration TIG (DP-TIG), twin-electrode TIG (T-TIG), high-frequency pulse TIG (H-TIG), hybrid laser TIG (LA-TIG), etc. Activated tungsten inert gas (A-TIG) welding is a variant of well-known GTAW process where a thin layer of suitable activating flux is deposited on the base components prior to establishing the electric arc. Fluxes for A-TIG welding typically include oxides (such as Al_2O_3 , CaO , TiO_2 , Cr_2O_3 , FeO , MnO_2 , ZrO_2 , MoO_3 , SiO_2 , etc.) and halides (such as NiF_2 , FeF_2 , CaF_2 , AlF_3 , etc.) [5, 6]. Either a single-component flux or a homogeneous blend of two or more such flux powders in appropriate proportion can be utilized [7]. Such activating flux powders are mixed with suitable solvents like acetone, methanol, or ethanol for making a semisolid paste that can be easily applied on the base plates either manually or automatically. Nowadays, dispenser-based commercial activating fluxes are also available that can be simply sprayed on the intended surfaces of the base plates [8]. Thickness of the coating layer is one crucial factor and typically remains within 20–80 micron [9]. Once the solvent dries out, welding can be carried out after establishing the arc preferably on an adjacent supporting bare plate.

Even though the first known published work related to A-TIG welding dates back to 1965 [10], exhaustive research work on this new technique has been carried out over the last couple of decades. An effort to find out the effects of oxide fluxes on surface appearance, weld morphology, angular distortion, and weld defect in autogenous A-TIG welding was made by Kuo et al. (2011) [11]. Effects of six activating fluxes on weld bead morphology

were studied by Dhandha et al. (2015) [12]. Apart from improving appearance, such fluxes were found capable in enhancing penetration and reducing weld bead width. While investigating performance of three-component flux mixture, Venkatesan et al. (2017) [13] concluded that 87.7% SiO_2 + 12.3% TiO_2 + 0% Cr_2O_3 mixture provides best result in terms of penetration and aspect ratio. Modenesi et al. (2015) [14] investigated influences of flux density in altering penetration during Cr_2O_3 flux-based A-TIG welding of 5-mm-thick stainless steel plates. It was observed that 15–60 g/m² flux density when deposited on the surface provided best results, while lower and higher densities outside this range provided inferior results. Pamnani et al. (2017) [15] evaluated the roles of A-TIG welding process parameters for maximizing the penetration and concluded that welding current, torch speed, and arc gap are crucial parameters with decreasing order of significance. In TiO_2 flux-based A-TIG welding, Tathgir et al. (2015) [16] reported excess penetration while bead-on-plate joining of 5.0-mm-thick AISI 316L steel plates. An attempt to optimize the important A-TIG welding parameters such as electrode gap, welding speed, current and voltage for a given aspect ratio was made by Magudeeswaran et al. (2014) [17]. The appropriate welding parameters for an aspect ratio of 1.24 were found to be 1.0 mm electrode gap, 130 mm/min welding speed, 140A current, and 12 V voltage.

For joining thicker plates, A-TIG welding offers numerous benefits in terms of welding quality, productivity, and cost-effectiveness. Application of activating flux helps constricting the electric arc, which, in turn, steeply increases the heat density [18]. The presence of flux also reverses the Marangoni flow into the molten weld bead, which leads to the flow of hot molten metal deep into the root gap leading to increased penetration [19]. These two factors together can fetch up to threefold increment in penetration depth in a single pass in square edge butt joining. Fujii et al. (2008) [20] showed that 9.4 mm penetration is achievable in a single pass in bead-on-plate A-TIG welding of stainless steel plates. Constricted arc also helps in reducing width of the weld bead as well as heat affected zone. Achieving deeper penetration in single pass without any edge preparation helps in improving productivity. However, additional time associated with the preparation and deposition of activating flux must be considered for productivity analysis of A-TIG welding. There are insufficient works on productivity analysis in A-TIG welding. This article attempts to provide a picture on productivity benefits during A-TIG welding of thicker plates with different fluxes.

Objective of this article is to investigate the roles of three single-component fluxes (Cr_2O_3 , Fe_2O_3 , and SiO_2) in modifying weld bead morphology during A-TIG welding of 10-mm-thick AISI-316L austenitic stainless steel

components using similar grade of filler metal. The capability of individual fluxes in providing deeper penetration and narrower weld puddle as compared to conventional TIG welding is analysed. Variation in microhardness across the weld bead for TIG and A-TIG is also examined. The article further provides discussion on the reduction in total welding time under different scenarios when A-TIG is used along with or instead of TIG welding during joining of thicker components.

2 Experimental details

Stainless steel (AISI-316L) plates having 100 mm length, 50 mm width and 10 mm thickness are chosen as base metal for this investigation. Two such plates are welded along the length in butt joining configuration maintaining a root gap of about 2.0 mm. Joining is carried out in square edge without edge preparation. Filler metal having composition similar to that of the base plate (indicates homogeneous welding) is also supplied during welding. Metallurgical composition of important elements of the base metal is displayed in Table 1.

A-TIG welding procedure is similar to that of the conventional TIG welding, except an additional step of applying activated flux layer on the parent components prior to establishing the electric arc. In this investigation, the as-received powdered flux ingredients (Cr_2O_3 , Fe_2O_3 , and SiO_2) are separately blended with acetone solvent. Since these fluxes do not actually dissolve into the solvent, a semisolid paste is prepared. Accordingly, four single-component flux pastes, one for each flux ingredient, are prepared. The mixing ratio among powdered flux and the solvent is not imperative as acetone is highly volatile in normal room temperature. However, care is taken while preparing the mixture to make a sufficiently liquidus paste so that the same can be easily applied on the base plates. This paste is then manually deposited on the cleaned base plates with the help of a soft brush. Care is also taken to maintain homogeneity and consistency in thickness and density of the flux ingredient on the coated layer. Measured average thickness of this layer is observed to be 43 μm . Schematic representation of forehead welding procedure is depicted in Fig. 1. Flux paste is deposited on the faying surfaces as well as on the surrounding areas (with 20 mm width from root gap) at top surface of both the plates. No flux is applied on the bottom of the base plates. Sufficient time (typically in the order of one minute) is

elapsed after the deposition of flux layer in order to allow complete evaporation of the solvent acetone. Once the flux layer dries out, the plates are placed beneath the TIG welding torch to establish the arc. Each flux component is tested independently to find out the extent of its capability in modifying the weld bead (puddle) geometry. KEMPPI Master TIG (MLS 3003ACDC, Finland) machine is used in this work. The torch is moved linearly along the root gap (i.e. no zigzag movement). Apart from the A-TIG welding, conventional TIG welding (without any flux) is also performed for the sake of comparison.

The base plates are clamped tightly with the fixture on order to reduce the degree of postwelding distortion. Two supporting bare plates, one at the entrance side and one at exit side, are also placed adjacent to the root gap of the original base plates (Fig. 1). Establishing the electric arc is easier with the bare plate. Additionally, such backing plates help in achieving a uniform weld bead on the actual base plates that is free from the apparent anomaly associated with the constitution and termination of the arc. Accordingly, arc is constituted on a bare supporting plate and the same is terminated on the other bare plate. About 10 mm approach and 10 mm overrun are considered. The arc length is kept constant to 3 mm in all trials. Trial runs suggested that 1.2–2.0 kJ/mm heat input is required to obtain satisfactory welding of the concerned base metals. While the base metals failed to fuse properly at lower heat input, higher heat input beyond this range is associated with negative reinforcement, distorted weld bead, high distortion, and poor weld bead appearance. Keeping the heat input within this range, the current is varied from 120 to 150A with 10A interval. Several other process parameters are provided in Table 2.

A vehicle is employed to hold and move the TIG welding torch. The speed is set to 60 mm/min (i.e. 1 mm/s). However, the filler material that comes in the form of 2.0-mm-diameter rod is delivered manually into the welding zone. By means of practical experience, the filler delivery rate is attempted to keep constant across all the experiments (however, there exists a case-to-case chance of inevitable small variation as it is applied manually). The tip of the nonconsumable tungsten electrode is sharpened each time prior to establishing the arc. In few cases, the refractory cap of the welding torch breaks abruptly during the process leading to disruption of filler deposition. Such experiments are repeated.

After normal air cooling, the satisfactory joined plates are halved by cutting crosswise with the help of a hand

Table 1 Composition of crucial chemical elements in base metal (vol%)

C	Si	Mn	Cr	Mo	Ni	Fe
0.057	0.423	1.17	18.18	0.267	7.91	< 70.57

Fig. 1 A-TIG welding procedure: **a** top view of the base plates showing root gap and supporting plates, **b** side view of the plates showing torch inclination, and **c** typical pictures of the plates in different stages

Table 2 Operating summary for the experimentation

Parameter	Value
Joining technique	Square edge butt joining
Welding technique	Forehand welding
Welding position	Downhand, 60° angle with horizontal
Base metals	Austenitic stainless steel AISI-316L
Filler metal	AISI-316L, 2.0-mm-diameter rod
Electrode	2.4 mm diameter, 2% thoriated tungsten
Activating flux	No flux, Cr ₂ O ₃ , Fe ₂ O ₃ , and SiO ₂
Welding current	120, 130, 140, 150A
Closed circuit voltage	Varies independently
Travel speed	1.0 mm/s
Weld bead length	50 mm
Arc length	3.0 mm
Welding polarity	DCEN/DCSP
Root gap	2.0 mm
Shielding gas	Argon (15 L/min)
Postwelding cooling	Normal air cooling
Pre- or post-heating	No

grinding machine to expose the weld zone. The exposed surfaces are further finished by successively polishing with belt grinder, disc grinder, and polisher with emery papers of varying grades, and finally buffing using velvet cloth with alumina abrasive paste. After obtaining the highly

finished surface, the plates are etched by immersing it within Kalling's No 2 Reagent (a homogeneous mixture of 100 ml concentrated hydrochloric acid, 100 mL ethanol, and 5 g cupric chloride) [21] for about two minutes so that the clear dichotomy became visible in bare eyes. These specimens are then placed under a tool maker's microscope (TM 510 Mitutoyo, Japan) to measure depth of penetration (P), weld bead width (W), and reinforcement (R) for each specimen, as schematically shown in Fig. 2. The specimens are also placed under a Vickers Microhardness Tester (Omni Tech, MVH- S Auto) to measure microhardness through indentation against a load of 500 g. Average microhardness of the base plate is found to be 223VHN (Vickers Hardness Number).

3 Results

3.1 Rate of heat input in TIG and A-TIG welding

The welding current, which was a manually controllable parameter, was varied in between 120 and 150A. The closed circuit voltage varied independently based on the activation potential required to dislodge avalanche of electrons for maintaining the electric arc. Although the base metals are kept unchanged across all the experiments, slight variation in closed circuit voltage is noticed

Fig. 2 Schematic representation of different weld bead geometrical parameters

owing to the varying properties of the activating flux that is deposited on the plate surface for A-TIG welding. The rate of heat input per unit length of the weld bead (measured in kJ/mm) on the base metal can be calculated using welding current (I , in Ampere), closed circuit voltage (V , in Volt), and torch travel speed (S , in mm/s), as given in Eq. (1). The arc efficiency (η) is considered as 75%, in line with the suggestions of Berthier et al. (2012) [22]:

$$\text{Heat Input} = \frac{\eta \times V \times I}{1000 \times S} \quad (1)$$

The closed circuit voltage is the measure of potential difference required for maintaining the electric arc during welding. On the other hand, arc is nothing but the continuous flow of avalanche of electrons flowing from negative polarity to positive polarity through the narrow arc gap. Accordingly, the closed circuit voltage depends on the several properties including the activation potential of the base plates, electron emission characteristics of the electrode, arc length, and intermediate fluid in the arc gap.

When a layer of electricity nonconductive flux [23] is deposited on the base plates, the flux layer restricts free flow of electrons to and from the base plate surface. Such restriction increases the actual activation potential of the base plates, and hence, higher potential difference is required for maintaining the arc. Accordingly, the closed circuit voltage and corresponding heat input (theoretical) change during welding the coated plates. Therefore, A-TIG welding is likely to exhibit higher closed circuit voltage as compared to the conventional TIG welding under same welding current. However, the arc constriction phenomenon, which occurs during activated flux assisted welding, can also influence closed circuit voltage.

A constricted arc has lesser cross-sectional area, and thus electrons pass through a narrower spot on the coated based plate. For a constricted arc, comparatively smaller area of the flux-coated surface actively participates in electron liberation. Hence, the arc can be maintained with less potential difference. As discussed in Sect. 3.2, constriction of the arc is observed with Fe_2O_3 and SiO_2 A-TIG, while

Cr_2O_3 A-TIG failed to exhibit a constricted arc. Thus, closed circuit voltage (or heat input) is less for Fe_2O_3 and SiO_2 flux-based A-TIG despite the presence of activated flux on the plate surface (Fig. 3).

3.2 Weld bead morphology in TIG and A-TIG welding

Three geometrical parameters, namely penetration (P), weld bead width (W) and reinforcement (R), are considered for characterization of the weld bead. As shown in Fig. 4, both the penetration and weld bead width gradually increase with the welding current. This is true for conventional TIG welding as well as for A-TIG welding with all three fluxes under investigation. With increase in welding current, the rate of heat input per unit length of base plate increases. This, on the one hand, helps in melting down deeper layers of the base plate as heat quickly flows into the vertically downward direction owing to the higher thermal conductivity of the base metal. On the other hand, increased amount of heat input per unit cross-sectional area improves the fluidity of the molten metal. As a

Fig. 3 Variation in the rate of heat input for conventional TIG and A-TIG welding with three fluxes under investigation

Fig. 4 Comparison among penetration, weld bead width, and reinforcement for varying welding current for **a** conventional TIG, and **b–d** A-TIG welding with Cr_2O_3 , Fe_2O_3 , and SiO_2 fluxes, respectively.

consequence of these two favourable factors, the molten metal can easily penetrate deep into the root gap leading to an enhanced penetration.

A collateral effect of increased rate of heat input per unit length of weld bead is the unimpeded conduction of heat in lateral direction of the metallic base plates. While heat penetration in vertically downward direction is advantageous (as it enhances penetration), the heat flow in lateral direction is detrimental as it increases the weld bead width. It can also undesirably increase the heat affected zone (HAZ) and lead to severe microstructural damage surrounding the joint. The increasing nature of weld bead width with current can also be clearly observed from Fig. 4 for TIG and all cases of A-TIG welding. Frequent catastrophic breakage of the refractory cap located at the tip of TIG welding torch is also observed at higher heat input. This increased tendency of breakage can be attributed to the forehand welding technique where the torch exists just above the deposited puddle, and thus, the refractory cap continuously experiences heat. At higher current, the ceramic cap is incessantly exposed to hotter puddle leading to random breakage. In this investigation, the filler metal deposition rate is kept invariable across all the trials. Accordingly, a simultaneous increase in both penetration and weld bead width results in gradual drop in reinforcement (R) as the volume of filler metal deposited per unit length of the weld bead is unchanged. This

The picture of a cross section of weld bead obtained for 140A welding current is typically shown in the corresponding plot

gradual descending tendency of reinforcement with increase in current can be observed in Fig. 4.

3.3 Extent of capability of different activating fluxes in modifying weld bead

Although the penetration increases with current in conventional TIG welding, only marginal improvement in penetration is observed with increase in heat input (Fig. 5a). While it fetches 2.65 mm penetration at 120A current (1.18 kJ/mm heat input), the same increases to 3.36 mm for 150A (1.78 kJ/mm). This is equal to about 53% increment in penetration when current is increased from 120 to 150A. This limited penetration clearly indicates the incapability of conventional TIG welding while joining thicker components. Using the highest level of current, only about 33% of the entire 10 mm depth (equal to plate thickness) can be filled in a single pass in square-edge butt joining.

Cr_2O_3 flux-based A-TIG welding exhibits somewhat higher penetration as compared to conventional TIG welding, but fails to provide significantly deeper penetration. While 2.71 mm penetration is recorded at 120A (1.47 kJ/mm), the same increased to 4.11 mm at 150A (1.97 kJ/mm). Accordingly, it fetches about 51% improvement in penetration when current is increased from 120 to 150A. Such rate of rise in penetration with welding current is similar to that observed in conventional TIG welding. However,

Fig. 5 Bar chart showing actual **a** penetration, **b** weld bead width, and **c** reinforcement for conventional TIG, and A-TIG welding with Cr_2O_3 , Fe_2O_3 , and SiO_2 fluxes

actual penetration achieved with Cr_2O_3 flux with highest level of current is slightly higher (4.11 mm > 3.36 mm). It can fill about 41% of the entire depth in a single pass in butt joining of 10-mm-thick plates. It is worth mentioning that the beneficial effects of Cr_2O_3 flux can be clearly perceived at higher currents (Fig. 5a). At lower currents (120A and 130A), the penetration in Cr_2O_3 A-TIG welding is more or less similar to that obtained in TIG welding. The weld bead is also wider in Cr_2O_3 A-TIG welding at lower currents (Fig. 5b). This scenario changes at higher currents. At 140A and 150A, penetration in Cr_2O_3 A-TIG welding is

conspicuously higher, while weld bead is narrower as compared to the corresponding cases of TIG welding.

Fe_2O_3 flux is capable of offering significantly higher penetration with the similar level of currents. It shows 6.28 mm penetration with 120A current (1.26 kJ/mm heat input), while the same increased to 8.07 mm at 150A (1.64 kJ/mm). This corresponds to about 28% improvement in penetration when current is increased from 120 to 150A. Such improvement is inferior to the same observed for conventional TIG welding. However, the actual penetration achieved with Fe_2O_3 flux with the similar level of current is certainly high. In fact, Fe_2O_3 flux recorded 134–140% enhancement in penetration when comparison is made with that of TIG welding. Moreover, about 80% of the entire depth can be filled in a single pass in butt joining of 10-mm-thick plates using Fe_2O_3 flux.

SiO_2 flux displays the best result among all three fluxes investigated here. Its capability in enhancing penetration is somewhat larger than that of Fe_2O_3 flux. SiO_2 flux-based A-TIG welding shows 6.89 mm penetration at 120A current (1.30 kJ/mm heat input), while it increases to 9.15 mm with 150A (1.74 kJ/mm). This equals to about 81% increment in penetration when current is increased from 120 to 150A. Accordingly, the percentage increment in penetration within the levels of current investigated here is best with SiO_2 flux. In addition, the actual penetration achieved is also reasonably high. It records 160–174% increment in penetration as compared to conventional TIG welding for varying levels of current. It can also fill about 91% of the entire depth in a single pass in butt joining of 10-mm-thick plates.

3.4 Relative changes in penetration, width and reinforcement

Looking back to Fig. 4, it can be observed that the relative position of penetration and width curves are changing in four plots. While the penetration is significantly lower than the weld bead width for conventional TIG and Cr_2O_3 flux-based A-TIG welding, the gap reduces for Fe_2O_3 A-TIG. With SiO_2 flux, the gap further contracted, and the penetration becomes almost same with the weld bead width at 150A current. On the other hand, the reinforcement is higher than penetration at lower currents for conventional TIG and Cr_2O_3 A-TIG. To further understand this changing pattern, two relative parameters (PSF and RFF) are introduced in this context. The Penetration Shape Factor (PSF) is the ratio between weld bead width to the penetration (i.e. $\text{PSF} = W/P$). The Reinforcement Form Factor (RFF) is the ratio between weld bead width to reinforcement (i.e. $\text{RFF} = W/R$). The percentage variation in PSF and RFF for different cases are shown in Fig. 6.

Fig. 6 Variations in PSF and RFF with welding current for conventional TIG, and A-TIG with Cr₂O₃, Fe₂O₃, and SiO₂ fluxes

With conventional TIG welding, the PSF is substantially high, which indicates that the weld bead width is significantly higher than the corresponding penetration. There is only marginal variation in PSF with increase in current. Qualitatively, the width is 3.60–3.73 times higher than the penetration within the current values investigated here. Though the PSF values for Cr₂O₃ A-TIG are higher than that for TIG in lower current, the scenario reverses at higher current. A gradual drop of PSF with increase in current can be noticed. Despite the reduction pattern, the width is as much as 2.82 times higher than the corresponding penetration at the highest level of current used here. PSF is considerably low for Fe₂O₃ A-TIG and is lowest for SiO₂ A-TIG among all the fluxes investigated here. The lowest PSF value recorded here is 1.05 (with SiO₂ A-TIG for 150A). It also indicates that the penetration is always lower than the width for the set of parameters employed in this investigation.

Looking back to Fig. 5, although there is a little variation in weld bead width among TIG and three cases of A-TIG for a given current, this variation is not as steep as the same recorded for the corresponding cases of penetration. For a given current, Fe₂O₃ and SiO₂ A-TIG exhibit remarkably higher penetration with only marginal reduction in width when compared with TIG and Cr₂O₃ A-TIG. Additionally, the consistent dropping nature of PSF with increase in current for all three cases of A-TIG welding indicates that the rate of increase in weld bead width with current is lower than the corresponding rate of increase in penetration. Accordingly, it can be inferred that the activating fluxes play a major role in enhancing penetration, while they have a minor role in contracting weld bead width.

Ascending nature of weld bead width with descending nature of reinforcement with the increase in welding current across all cases of TIG and A-TIG can be clearly observed in Fig. 4. Accordingly, an increasing nature of RFF is expected, and the same can be observed in Fig. 6b. Interestingly, only gradual increase in RFF is recorded (except

for SiO₂ A-TIG) despite consistent increase in width (the numerator) and decrease in reinforcement (the denominator). Only the SiO₂ A-TIG welding exhibits steep increase in RFF with current, which can be attributed to very low values of reinforcement, especially at higher current.

3.5 Microhardness of weld bead and HAZ

Heat affected zone (HAZ) is the thermomechanically affected part of the parent component surrounding the weld bead that is not actually fused during welding but underwent metallurgical changes when it experienced subsequent heating and cooling. The microstructural changes, in turn, can alter microhardness. Similar to every fusion welding, A-TIG welding can also alter microhardness of weld bead and HAZ. However, such variation may not match with the same commonly observed in conventional TIG welding because of the two major distinguishing factors, (i) reversal of Marangoni flow of the molten weld metal that happens during A-TIG welding, and (ii) presence of foreign particles (entrapped activating flux or slag particles) within the weld bead, especially in forehand technique. As shown in Fig. 7, the microhardness is measured across the weld bead in 12 successive points (A, B, C, ..., L) in both left and right sides of the joint starting from the centre of the bead. A total of 25 measurements (including the centre one) are taken for each sample. Samples of 140A current for TIG as well as A-TIG are only considered for microhardness analysis. The reference line for measurement is considered at 2.0 mm below the actual component surface. The minimum penetration achieved at 140A current is 3.12 mm. Accordingly, the reference line intersects the weld bead even for the least penetration case. On the other hand, the maximum observed weld bead width is 11.59 mm that too was measured at the top surface of the base plate. Therefore, measurement of microhardness up to 12 mm (i.e. 12 points having 1 mm spacing between

Fig. 7 Microhardness of the welded samples: **a** schematic representation of the locations of microhardness measurement on a fixed reference line, and **b** variation in microhardness in the transverse

direction of weld bead in both the sides for TIG and A-TIG samples obtained for 140A current

two successive points) in transverse direction on each side takes into account the weld bead as well as HAZ region.

Average microhardness of parent component, measured separately prior to welding, is found to be 223 VHN (Vickers Hardness Number). As shown in Fig. 7, the microhardness is higher at the centre of the weld bead, and the same drops to a lower value at certain distance away from the bead centre in transverse direction. Both the sides of a joint exhibit more or less similar variations for a specific case. Conventional TIG and A-TIG with all three fluxes also follow a similar pattern of microhardness variation. However, the microhardness values are maximum for conventional TIG, while Cr₂O₃ A-TIG exhibits microhardness close to that of TIG. Although Fe₂O₃ A-TIG and TiO₂ A-TIG dyadically display similar microhardness values, these are significantly lower as compared to that of TIG. It is also worth mentioning that the forehand (or forward) welding technique, followed throughout this work, inherently preheats the components but fails to offer stress-relieving or annealing effect by virtue of postheating [24].

Accordingly, the lower values of microhardness for Fe₂O₃ A-TIG and TiO₂ A-TIG can be attributed to the conspicuous arc constriction behaviour that also enhances penetration and reduces weld bead width. After welding at a very high heat density, as the puddle cools down at normal ambient temperature, coarse grain formation is expected owing to relatively steeper cooling rate [25]. Coarse grains are associated with lower hardness due to less grain boundaries within the fixed indentation area. A similar observation in gas tungsten constricted arc welding was also reported by Vaithiyanathan et al. (2020) [26].

For Fe₂O₃ A-TIG and TiO₂ A-TIG, microhardness starts dropping after 4 mm transverse distance from the bead centre (Fig. 7). However, for conventional TIG, such drop starts only after 5 mm. For Cr₂O₃ A-TIG too, the dropping tendency can be noticed after 5 mm distance. A constricted arc not only reduces the microhardness values but also indirectly manipulates the microhardness variation in the transverse direction. While the conventional TIG and Cr₂O₃ A-TIG produce a wide and

shallow weld bead, Fe_2O_3 A-TIG and TiO_2 A-TIG fetch a deep and narrow weld bead. The consequence of the varying weld bead geometry on microhardness measurement is illustrated in Fig. 8. For a wider bead, majority of the points of measurement fall within the weld bead, while few remain outside within in HAZ and further in base metal. The situation reverses for a narrow bead as the points of measurement are unchanged. For a narrow bead, only few points remain within the bead, while majority of the points are situated outside. Accordingly, for a particular curve in Fig. 7, less number of points having high value of microhardness indicates a narrow weld bead. This condition is observed for Fe_2O_3 A-TIG and TiO_2 A-TIG welding. Furthermore, a steep reduction in microhardness can also be noticed in HAZ. Although the HAZ width varies, microhardness values drop close to 223 VHN (microhardness for base metal) after a certain distance in all four cases. The cumulative width of weld bead and HAZ for Fe_2O_3 A-TIG and TiO_2 A-TIG is significantly lower than that obtained for Cr_2O_3 A-TIG and TIG, despite the fact that a constricted high intensity arc is obtained in the former case. In reversed Marangoni flow, the hotter molten metal flows downward that facilitates the arc heat to penetrate deep into the root gap in vertical direction, rather than just conducting in transverse direction. Accordingly, the results of a constricted arc are narrow weld bead narrow HAZ but deeper penetration.

4 Discussion on productivity benefits

Despite numerous positive results in several aspects, industries are still reluctant to overwhelmingly utilize this beneficial variant of conventional TIG welding. Based on few simplified assumptions, this section attempts to demonstrate productivity benefits in butt joining of 10-mm-thick plates when A-TIG welding is employed together with or superseding the conventional TIG welding. Based on the configuration of components for a specific application, joining of thick plates can be carried out either from both the faces (obverse and reverse) or only through one face. Productivity benefits in these two possible cases are demonstrated separately considering the cumulative welding time required for application of flux, edge preparation, and depositing the puddle (i.e. welding pass).

4.1 Joining from both the faces

When joining from both the sides is allowed, 5 mm penetration from each side can serve the purpose. TIG welding cannot fill this depth in a single pass in square edge butt joining as only 3.36 mm penetration is possible with the highest level of current. This requires edge preparation, as V-groove can be made in both the faces. As typically demonstrated in Fig. 9a, each V-groove requires three passes to fill the gap. For simplified demonstration, it can be

Fig. 8 Influence of weld bead geometry on microhardness variation when measurements are taken on similar points at a fixed reference line

(a) Wide and shallow weld bead

(b) Narrow and deep weld bead

$$x_2 > x_1$$

Fig. 9 Illustrative demonstration of successive steps for joining 10-mm-thick components in two different cases for the condition that joining from both the faces is allowed

roughly assumed that preparing each V-groove takes twice the time required for one welding pass. Accordingly, total equivalent time required for joining of 10-mm-thick plates using only TIG welding becomes ten times the $T_{\text{single-pass}}$ as given in Eq. (2). Here, $T_{V\text{-grooving}}^{(\text{both-sided})}$ indicates the time required for cutting small V-groove in one face of both the plates, and $T_{\text{single-pass}}$ is the time associated with one welding pass. The last step for postwelding finishing by grinding is not considered for this analysis as it is one common step for all cases.

$$\begin{aligned}
 T_{\text{Only TIG}}^{(\text{both-sided})} &= \left\{ 2 \times T_{V\text{-grooving}}^{(\text{both-sided})} \right\} + \left\{ 2 \times (3 \times T_{\text{single-pass}}) \right\} \\
 &= \left\{ 2 \times 2 \times T_{\text{single-pass}} \right\} + \left\{ 6 \times T_{\text{single-pass}} \right\} \\
 &= 10 \times T_{\text{single-pass}}
 \end{aligned}
 \quad (2)$$

Apart from the time, edge preparation and multiple passes are associated with higher heat input, which can undesirably increase HAZ. It also requires more volume of costly filler metal to be deposited in order to fill the V-grooves. Now, considering the case of A-TIG welding for this configuration, without any edge preparation, A-TIG welding using Fe_2O_3 and SiO_2 can provide 8.07 mm and 9.15 mm penetration, respectively. However, additional time is required to apply flux coating on the base plates. For the sake of simplified demonstration, it is assumed here that the time for applying coating on both the plates

in one side is equal to the time required for one welding pass ($T_{\text{single-pass}}$). When 8–9 mm penetration is already achieved, then there is no need to carry out A-TIG welding on the other side to fill only 1–2 mm depth. Conventional TIG can be employed to serve this purpose, which can cut down the flux application time. For this scenario of one pass of A-TIG welding in one side and one pass of TIG welding in other side, the total equivalent time is equal to only three times of the $T_{\text{single-pass}}$, as solved in Eq. (3). Therefore, 70% reduction in welding time can be achieved by following this strategy. Furthermore, time and cost associated with groove preparation and large volume of filler deposition give additional savings. However, additional expenditure is required towards the cost of activating flux:

$$\begin{aligned}
 T_{\text{ATIG+TIG}}^{(\text{both-sided})} &= \left\{ 1 \times T_{\text{ATIG}}^{(\text{single-sided})} \right\} + \left\{ 1 \times T_{\text{TIG}}^{(\text{single-sided})} \right\} \\
 &= \left\{ T_{\text{flux-application}}^{(\text{single-sided})} \right\} + \left\{ T_{\text{single-pass}} \right\} + \left\{ T_{\text{single-pass}} \right\} \\
 &= 3 \times T_{\text{single-pass}}
 \end{aligned}
 \quad (3)$$

4.2 Joining from only one face

One inherent benefit obtained in both side joining is reduction of final distortion of the components. However, both side joining may not be allowed in every application. For single-side joining of 10-mm-thick plates by TIG welding, deeper and wider V-groove is required to cut in

one side. It is assumed that cutting a single-sided larger V-groove takes three times more than the time required for one welding pass. Further, to fill such a larger V-groove, six welding passes are required by conventional TIG welding, as shown in Fig. 10a. Accordingly, total equivalent time required to join 10-mm-thick plates in single-side butt joining becomes equal to ten times the $T_{single-pass}$ as given in Eq. (4):

$$\begin{aligned} T_{OnlyTIG}^{(singlesided)} &= \left\{ 1 \times T_{large-V-grooving}^{(singlesided)} \right\} + \left\{ 6 \times T_{single-pass} \right\} \\ &= \left\{ 3 \times T_{single-pass} \right\} + \left\{ 6 \times T_{single-pass} \right\} \\ &= 9 \times T_{single-pass} \end{aligned} \quad (4)$$

Comparing it with Eq. (2), it can be observed that there is 10% time saving with single-sided TIG joining as compared to both-sided joining; however, the former one requires more filler metal, repeatedly transfers heat

into the same location of the components, widens the weld bead width, and increases distortion. In unchanged scenario, if A-TIG welding is employed, then a narrow V-groove (similar to the case of both-sided TIG welding) is required to cut, though only in one side. Initially, Fe_2O_3 or SiO_2 flux-assisted A-TIG welding can be carried out, and then two TIG welding passes can be employed to fill the rest of the gap (Fig. 10b). Total equivalent time required for this welding strategy is six times the $T_{single-pass}$ as given in Eq. (5). When compared with Eq. (3), flux-assisted A-TIG joining from one side requires twice the time for both-sided joining. Despite such increment, usage of flux can save about 33% time as compared to the similar case of only TIG:

$$\begin{aligned} T_{ATIG+TIG}^{(singlesided)} &= \left\{ 1 \times T_{V-grooving}^{(singlesided)} \right\} + \left\{ 1 \times T_{ATIG}^{(singlesided)} \right\} + \left\{ 2 \times T_{TIG}^{(singlesided)} \right\} \\ &= \left\{ 2 \times T_{single-pass} \right\} + \left\{ T_{flux-application}^{(singlesided)} \right\} + \left\{ T_{single-pass} \right\} \\ &\quad + \left\{ 2 \times T_{single-pass} \right\} = 6 \times T_{single-pass} \end{aligned} \quad (5)$$

Fig. 10 Illustrative demonstration of successive steps for joining 10-mm-thick components in two different cases for the constraint that joining from only one face is allowed

5 Conclusions

In this article, three activating fluxes (Cr_2O_3 , Fe_2O_3 , and SiO_2) are tested individually for activated TIG welding of 10-mm-thick AISI-316L austenitic stainless steel plates under varying currents to explore the capability of each flux in modifying the weld bead morphology. Square edge butt joining is performed under DCEN polarity. The A-TIG welding results are also compared with the same obtained in conventional TIG welding under similar set of parameters. Further, the productivity benefits of employing A-TIG welding in joining thicker components are demonstrated under different scenarios to encourage industrial implementation. Based on the analysis of the result, the following conclusions can be made.

- Closed circuit voltage in A-TIG welding increases due to the increase in activation potential of the plate surface because of the presence of nonconductive flux layer that restricts free passage of electrons for maintaining the arc. However, the same voltage reduces owing to arc constriction in A-TIG welding as smaller cross-sectional area collects electrons (DCEN polarity). Cr_2O_3 A-TIG welding exhibits higher voltage as compared to conventional TIG as this flux failed to constrict the arc. Despite the presence of flux on the plate surface, voltage becomes lower for Fe_2O_3 and SiO_2 A-TIG owing to their capability of constricting the arc.
- The preferred range of welding current for butt joining of 10-mm-thick AISI-316L stainless steel plates is 120–150 A. Higher welding current helps in achieving deeper penetration as the increased rate of heat input improves fluidity of the molten metal. However, the collateral damages of higher current include wider weld bead and HAZ, higher degree of distortion, and frequent breakage of the refractory cap located at the torch tip. Reinforcement gradually drops with the increase in current when filler deposition rate is maintained unchanged.
- In conventional TIG welding, 53% increment in penetration (from 2.65 mm to 3.36 mm) is recorded when current is increased from 120 to 150 A. The corresponding rate of increase in penetration for Cr_2O_3 flux-based A-TIG welding (51%, from 2.71 mm to 4.11 mm) is similar to that for TIG welding. However, actual penetration is marginally higher with Cr_2O_3 A-TIG. In both the cases, weld bead width remains within 9.5–11.5 mm, with wider bead observed at higher current. This flux is incapable of giving an improved performance as compared to conventional TIG welding.
- With 8.07 mm penetration at 150 A current, Fe_2O_3 flux-based A-TIG welding offers 134–140% enhancement

in penetration as compared to TIG welding. SiO_2 flux displays the best result among all three fluxes investigated here as it provides 9.15 mm penetration with 150 A current. It records 160–174% increment in penetration as compared to conventional TIG welding for varying levels of current. Among all the fluxes investigated here, SiO_2 flux shows the lowest PSF and highest RFF (both are desirable).

- Irrespective of the presence or absence of flux, the microhardness remains invariant to a higher value (around 410 VHN) at the weld bead, but the same drops steeply in transverse direction before reaching a minimum (around 223 VHN, equal to the average microhardness of base metal). TIG and Cr_2O_3 -based A-TIG exhibit higher microhardness values as compared to Fe_2O_3 and SiO_2 A-TIG. The cumulative width of weld bead and HAZ for Fe_2O_3 A-TIG and also for SiO_2 A-TIG is significantly lower than that obtained for Cr_2O_3 A-TIG or TIG.
- Application of Fe_2O_3 or SiO_2 flux can save significant time while joining 10-mm-thick plates. When welding from both the faces is allowed, then 70% reduction in welding time can be achieved by employing a combination of A-TIG and TIG, rather than using only TIG welding. The former one also cuts down the requirement of costly filler metal and reduces total heat input by eliminating multiple passes on the same face. Even if welding from only one face is allowed during joining 10-mm-thick plates, then also usage of suitable activating flux can reduce welding time by 33%.

Authors' contributions Not applicable.

Funding Total expenses have been provided by Kalyani Government Engineering College.

Availability of data and materials Not applicable.

Code availability Not applicable.

Compliance with ethical standards

Conflict of interest There are no conflicts of interest/competing interests for publishing this article.

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