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TIG welding with single-component fluxes

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Abstract

Gas tungsten arc welding is fundamental in those applications where it is important to control the weld bead shape and the metallurgical characteristics. This process is, however, of low productivity, particularly in the welding of large components. The activated flux TIG (ATIG) welding process, developed by the Paton Welding Institute in the 1960s, is now considered as a feasible alternative to increase the process productivity. ATIG welding uses a thin layer of an active flux that results in a great increase in weld penetration. This effect is, generally, connected to the capture of electrons in the outer parts of the arc by elements of high electronegativity, which constrict the arc causing an effect similar to that used in plasma arc welding. Generally, the literature does not present the flux formulations for ATIG welding, the few formulations that were found to have a complex nature. The present work evaluates the use of ATIG welding for the austenitic stainless steels with fluxes of only one major component. The changes in weld geometry were compared to variations in the electrical signals from the arc and the arc shape. The effect of the flux on the weld microstructure was also studied. The results indicate that even the very simple flux that was used can greatly increase the penetration of the weld bead. © 2000 Elsevier Science S.A. All rights reserved.

Keywords: TIG welding; Weld bead; Stainless steel

1. Introduction

The TIG welding process (or GTAW) is used when a good weld appearance and a high quality of the weld are required. In this process, an electric arc is formed between a tungsten electrode and the base metal. The arc region is protected by an inert gas or mixture of gases. The tungsten electrode is heated to temperatures high enough for the emission of the necessary electrons for the operation of the arc.

The main disadvantages of the TIG process include: (a) its relatively shallow penetration capability, particularly in single pass welding operations; (b) the high sensibility of the weld bead shape to variations of the chemical composition of the base metal; and (c) its low productivity.

Usually, in the TIG welding of stainless steels with argon shielding, full penetration welding is restricted to joints of a maximum thickness of 3 mm and to relatively low welding speed. Although the welding speed can be increased substantially (up to 160%) when helium or hydrogen is used as part of the shielding gas mixture, bead penetration can only be increased slightly (1–2 mm) [1,2]. The capacity to improve the penetration by the selection of the shielding mixture is further limited by the need to use inert or slightly reducing gases, restricting this selection basically to argon and helium mixtures.

The plasma arc welding process can be used as an alternative to the TIG process, allowing the welding of a 10 mm thick joint in only one pass. However, plasma welding is much more complex and presents greater initial and operational costs than that for the TIG process.

A variant of conventional TIG welding, which uses active fluxes (Active Flux TIG Welding or ATIG), was developed (in the 1960s) for the welding of titanium in the Paton Institute of Electric Welding [1,3]. This process is characterized by the application of a fine layer of a flux on the surface of the base metal. During welding, the heat of the arc melts and vaporizes part of this flux. As a result, the penetration of the weld bead can be increased greatly and its sensibility to the chemical composition of the base metal reduced. Results from the literature indicate that joints with a thickness of 6 mm, or even of 10 mm, can be welded in a single pass with the ATIG process [1].

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Some authors [1,3–7] associate the greater penetration of ATIG welding to a constriction of the electric arc caused by the presence of some components of the flux (mainly oxygen and fluorine) in the arc. This effect would increase the anode current density and the arc force acting on the welding pool and, therefore the penetration of the welding bead, similarly to what happens in plasma arc welding. Alternatively, it has been proposed that the increase in weld penetration results from a change in the liquid flow of the weld pool due to the flux interacting with the liquid metal.

The literature, possibly for commercial reasons, generally does not present the composition of the fluxes used in this process. The few examples that were found tend to present a complex formulation, hindering the analysis of the function of its components.

In this work, the ATIG welding of austenitic stainless steels with fluxes of simple composition was studied, in order to evaluate the effect of single components on the process. The changes of bead shape were compared with alterations in arc voltage and shape. The influence of the sulfur (a strong surface active element for iron) content of the fluxes on the bead shape was also studied. It was shown that, even with these extremely simple fluxes, an important increase of penetration can be obtained in ATIG welding. However, this effect could not be associated directly with changes in arc voltage or sulfur content. It was also observed that the fluxes did not cause major alterations in weld microstructure.

2. Methodology

The materials used as fluxes were dried, ground to under 400# and stored in a stove at 50°C until they were used. Specimens (125 mm × 50 mm) for the welding trials were prepared from AISI 304 austenitic stainless steel plates with a thickness ranging from 5 to 8 mm. These specimens were ground, straightened and cleaned with acetone. The flux was prepared by mixing one of the materials given in Table 1 with acetone. This mixture was applied manually on half of the top surface of a test piece just before welding (Fig. 1).

Bead-on-plate welds were made with an electronic power supply using a mechanized system in which the test-piece was moved at a constant speed under the TIG torch. Table 2 presents the range of welding conditions used in the trials. The arc was struck and stabilized on a copper plate before it reached the test-piece. In all of the trials, the side of the specimen that was first fused by the arc was that with no flux (TIG welding). Both the arc current and voltage were recorded on a computer using a digital data acquisition system with a sampling rate of $10\ \mathrm{s}^{-1}$. Four images of the electric arc (two corresponding to TIG welding and two to ATIG welding) were obtained with a conventional CCD camera and stored in a computer with a frame grabber. No technique to filter the light from the arc was used to enhance these images.

Table 1
Flux components and their sulfur content

Component	Sulfur (%)
AlF_3	0.049
Al_2O_3	0.004
Cr_3O_3	0.010
CaF_2	0.057
Fe_2O_3	0.27
NaF	0.021
Na_2WO_4	0.11
SiO_2	0.018
TiO_2	0.019

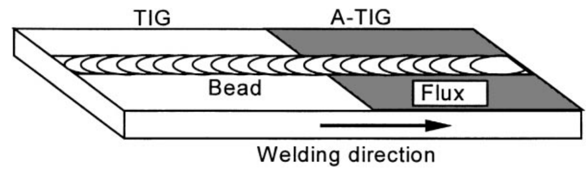

Fig. 1. Schematic representation of the specimen used in the TIG/ATIG welding trials.

The mean values of the arc voltage associated to the TIG and ATIG welding (V_{TIG} and V_{ATIG}, respectively) intervals of each trial were calculated. The parameter ΔV was defined from these values as

$$\Delta V = V_{\mathrm{ATIG}} - V_{\mathrm{TIG}} \qquad (1)$$

Four cross-sections of each weld bead, two for each welding process, were etched with a solution of cupric chloride and observed in a profile projector, to measure the penetration and width of the weld. The transverse area of the weld bead was calculated from these sections using computer software. A variation parameter similar to that defined for arc voltage (Eq. (1)) was defined for each geometric feature of the bead as

$$\Delta\pi = \pi_{\mathrm{ATIG}} - \pi_{\mathrm{TIG}} \qquad (2)$$

where π is a geometric feature (bead penetration, width or

Table 2
Welding conditions

Parameter	Value
Electrode	
Type	W–2% ThO
Diameter	3.2 mm
Angle	60°
Gas	
Type	Ar
Flow	10 l/min
Welding speed	20 cm/min
Arc length	1–3 mm
Bead length	100–120 mm
Current	200–300 A
Plate thickness	5–8 mm

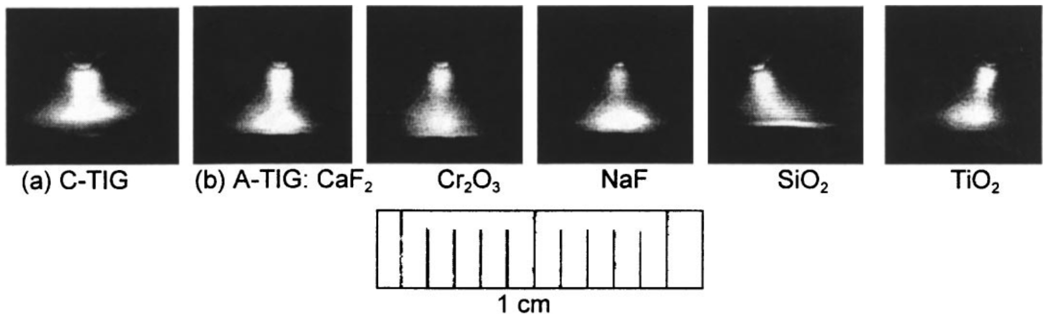

Fig. 2. Images of the arc in welding: (a) CTIG; (b) ATIG.

area) and the other symbols have the same meanings as indicated in Eq. (1).

The δ ferrite content of the base metal and the fused zone, for both conventional TIG and ATIG welding, was determined by a magnetic sensor. Cross-sections of some of the TIG and ATIG weld beads were also prepared for optical metallographic analysis.

3. Results and discussion

Fig. 2 shows arc images from some of the tests. In most of the tests, no major difference in arc shape was observed when compared with the conventional TIG and ATIG processes. One exception was found for the welding with the NaF flux that presented a reddish arc. This was possibly associated with the emission of characteristic radiation by vaporized sodium atoms. In some of the trials with SiO_2 flux, the electric arc apparently tended to deflect in the forward direction. This kind of flux also caused the most strong changes in arc voltage, presenting a ΔV of about 2 V: this was at least twice as high as the values found with other fluxes.

Fig. 3 presents the cross-sections of some of the weld beads. Some fluxes, particularly SiO_2, TiO_2, Cr_2O_3 and AlF_3, caused an important increase in penetration when compared with TIG welding. This higher penetration occurred immediately after the transition from TIG to ATIG welding and was, therefore, associated directly with the presence of the flux. The increase of penetration was enough to obtain full penetration welds in trials performed with a current as low as 200 A in 5 mm thick plates.

Fig. 4 suggests that there is no relationship between the variations of weld penetration (ΔP) and arc voltage (ΔV). As ΔV may be associated with changes in the electric arc, this result suggests that the variations in bead penetration should not be linked directly to an effect of the flux on the arc. Therefore, this result does not support the model that associate the increase of penetration in ATIG welding to a constriction of the arc by flux elements vaporized to the arc [1,3–7]. Furthermore, whilst the literature associates this effect mainly with halogen ions, the results of the present work indicate a negligible effect of most of the fluorine components on penetration.

Mechanical constriction of the arc is used successfully in plasma welding to achieve a weld penetration larger than that commonly obtained by conventional TIG welding. Due to the constriction of the arc in plasma welding, this operates in voltage levels (between 20 and 40 V) higher than those commonly found in the TIG process (about 10 V) [8]. The results of the present work indicate much smaller differences of arc voltage (<2.5 V) when comparing TIG and ATIG welding and this differences could not be correlated with the variations of the bead penetration. Therefore, some alternative model should be considered to explain the effect of the flux in ATIG welding.

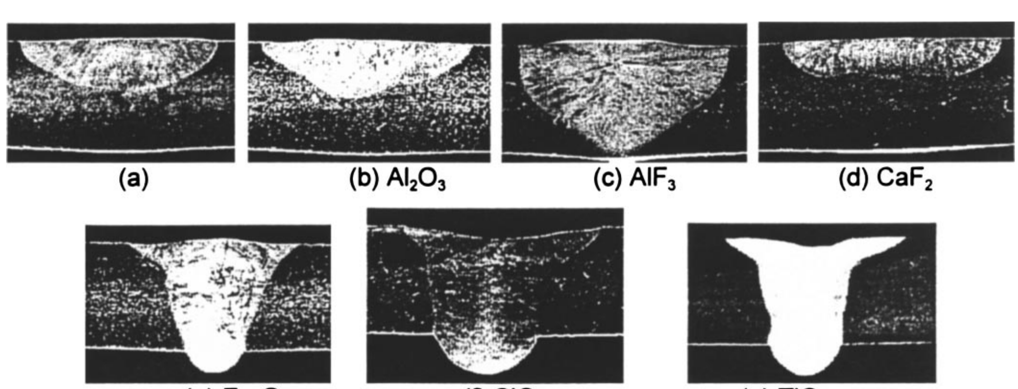

Fig. 3. Cross-sections of the weld beads in 5 mm plates and 220 A for: (a) conventional TIG and (b–g) ATIG welding.

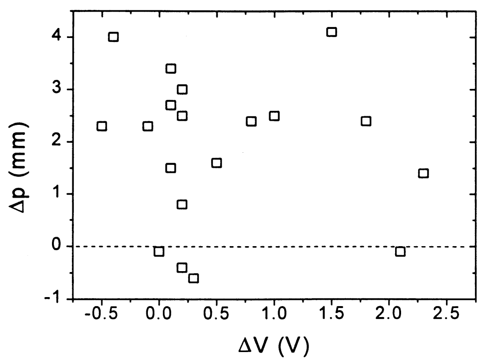

Fig. 4. Relationship between the variation of voltage and weld penetration.

The electric arc can be preferentially attracted by small patches of slag floating on the weld pool and this may influence the bead shape [11]. However, except for tests with a few of the fluxes used, the images of the arc do not indicate any important change in the format of the arc, particularly its deflection towards some specific area of the weld pool. On the other hand, a close observation of the surface of the weld pool shows clearly that it contains a deep depression directly under the arc in ATIG welding.

Other authors [2,9–11] have proposed that the shape of the weld bead is controlled by changes in the flow of liquid metal inside the weld pool. The main factors that are considered to control this flow are: (a) forces resulting from the variation of the surface tension along the free surface of the weld pool (the Marangoni effect); (b) electromagnetic forces (Lorentz forces) resulting from the passage of the welding current to the weld pool; (c) gravitational or buoyancy forces; and (d) aerodynamic drag forces caused by the passage of the shielding gas over the weld pool.

As the welding conditions were not changed during a trial except for the flux on the final half of the test plate, electromagnetic, gravitational and drag forces should not have been altered much during the trial. Thus, the changes in bead shape are probably linked to the Marangoni effect. This effect is used extensively to explain changes in the bead shape in austenitic stainless steels and other alloys associated with variations in the content of residual elements, particularly sulfur and oxygen [12–14].

Fig. 5 shows no apparent relationship between the variations of penetration (ΔP) or bead area (ΔA) and the sulfur content of the fluxes. In ATIG welding, if precautions are taken to prevent any contamination and no filler metal is used, the final chemical composition of the weld metal will be determined by the base metal and the flux. Crude estimations indicate that the amount of flux that was applied on the test-piece was very small (<0.08 kg/mm^2). This suggests that the flux could not have had a significant effect on the final sulfur content of the welds, which agrees with the result shown in Fig. 5. Thus, to consider the Marangoni effect as the key mechanism that determines the bead shape changes in ATIG welding, it has to be associated with some other factor.

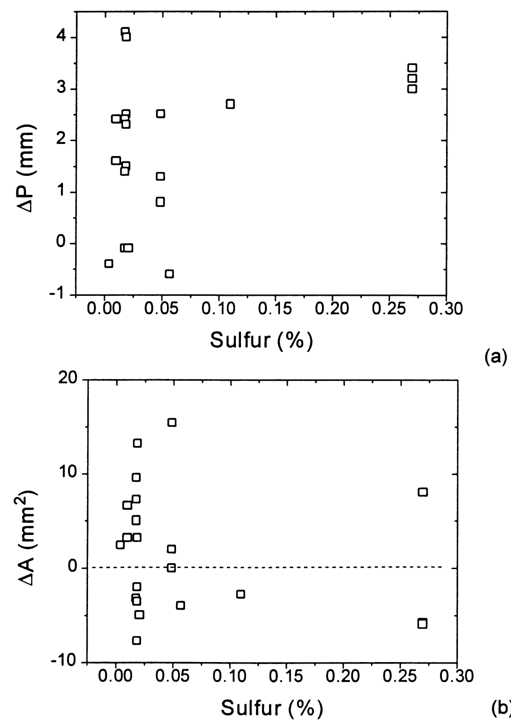

Fig. 5. Effect of the sulfur content in the flux on: (a) the penetration and (b) the bead area variations.

A liquid slag can significantly alter the surface tension of a liquid metal. Data from Jackson [15] indicates that different components can either increase or decrease the surface tension of liquid steel. Thus, in ATIG welding, it could be expected that the slag film in contact with the liquid metal in the weld pool can affect its surface tension in a way similar to that proposed by Heiple and Roper [12] to explain variations in bead shape associated with the presence of residual elements in the weld pool. The details of such mechanism are not yet clear.

Results from tests with the same welding current (200 A) and base metal thickness (6.5 mm) indicate that different oxide components present a very similar potential to increase weld penetration in ATIG welding (Fig. 6). This tendency is also difficult to be explained based on the

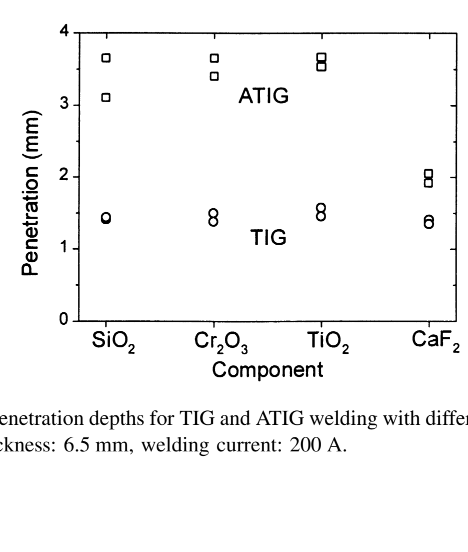

Fig. 6. Penetration depths for TIG and ATIG welding with different fluxes. Plate thickness: 6.5 mm, welding current: 200 A.

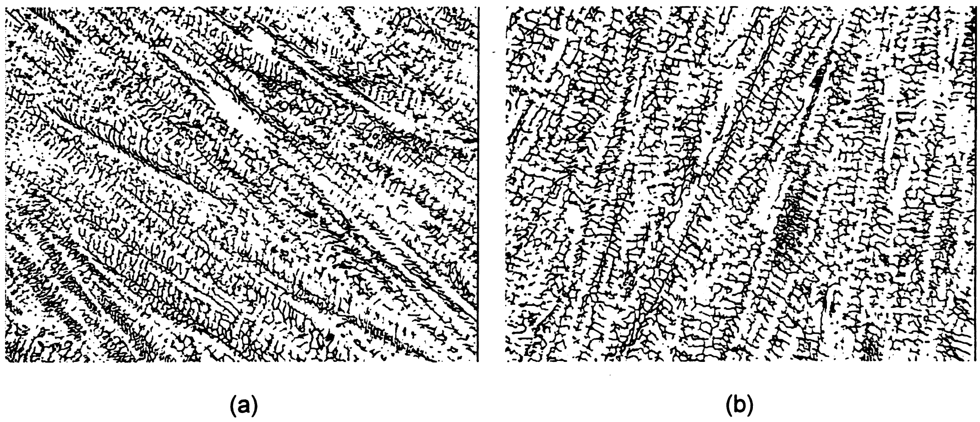

Fig. 7. Weld bead microstructure: (a) CTIG; and (b) ATIG (flux: Fe_2O_3) (magnification: 500×).

mechanisms currently accepted to explain the changes in bead penetration in ATIG welding.

Fig. 7 shows the microstructure of the fusion zone (ZF) obtained by both conventional TIG and ATIG (flux of Fe_2O_3). In both cases a microstructure of austenite and δ ferrite veins typical of this class of material is observed. No major difference was observed between the microstructure of TIG and ATIG welds. The mean δ ferrite contents in the weld zone were 5.7 and 6.1% for the TIG and ATIG processes, respectively, with standard deviations of about 0.8 and of 0.85%, suggesting that the flux did not cause a significant change in the weld metal δ ferrite levels.

However, when the variations of bead penetration and δ ferrite content ($\Delta\delta$) are compared (Fig. 8) a weak relationship between these two parameters may be observed. For those tests in which the weld penetration in TIG and ATIG welds were similar, the δ ferrite contents were also similar. For large values of ΔP, $\Delta\delta$ tended to increase up to a maximum of 2% for some tests. It is not clear if this was caused by a small change in weld metal composition or inclusion content due to the flux. Alternatively, it may have been caused by the greater penetration of the ATIG welds, which caused a greater participation of the central region (that presents some segregation) of the plate in the weld. A similar effect was observed by Silva [16] in the MIG welding of austenitic stainless steels with a shielding gas containing different levels of H_2.

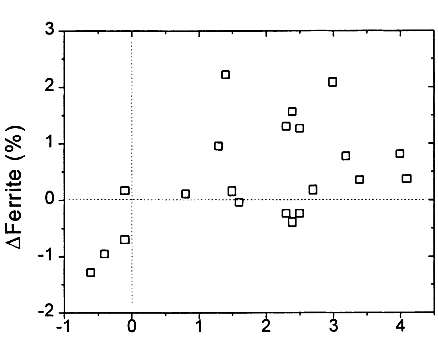

Fig. 8. Relationship between δ ferrite and penetration variations.

4. Conclusions

The results of this work have shown that the use of a flux, even of extremely simple formulation, can greatly increase (up to around 300%) the weld penetration in TIG welding. It was possible to obtain full penetration welds in 5 mm thick plates of austenitic stainless steel with no preparation and currents of about 230 A. The operational characteristics of the ATIG process were not very different from those of conventional TIG welding. The arc voltage changed by <3%, and, in most cases, the voltage variation was <1 V. Comparison of the operational parameters, of the arc shape, and of the geometric parameters of the beads, suggests that factors acting on the weld pool are, possibly, responsible for the changes in weld bead shape.

Therefore, simple fluxes of only one component present an adequate performance for ATIG welding, resulting in a great increase of penetration in comparison to TIG welding, without any important deterioration of the welding conditions or of the microstructure of the welds.

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