Influence of Activated Fluxes on the Bead Shape of A-TIG Welds on Carbon and Low-Alloy Steels in Comparison with Stainless Steel AISI 304L

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Abstract: The article presents results of comparative A-TIG welding tests involving selected unalloyed and fine-grained steels, as well as high-strength steel WELDOX 1300 and austenitic stainless steel AISI 304L. The tests involved the use of single ingredient activated fluxes (Cr₂O₃, TiO₂, SiO₂, Fe₂O₃, NaF, and AlF₃). In cases of carbon and low-alloy steels, the tests revealed that the greatest increase in penetration depth was observed in the steels which had been well deoxidized and purified during their production in steelworks. The tests revealed that among the activated fluxes, the TiO₂ and SiO₂ oxides always led to an increase in penetration depth during A-TIG welding, regardless of the type and grade of steel. The degree of the aforesaid increase was restricted within the range of 30% to more than 200%.

Keywords: A-TIG; A-GTAW; depth of penetration; macrostructure; S235JR+N; S355J2+N; P265GH; WELDOX 1300; AISI 304L

1. Introduction

A-TIG (A-GTAW) welding with activated flux is a TIG (Tunsten Inert Gas) or GTA (Gas Tungsten Arc) welding method that was first used in the E.O. Paton Electric Welding Institute, Ukraine at the end of the 1950s and the beginning of the 1960s [1]. Initially, the A-TIG method was used in the welding of titanium, next, in the welding of martensitic high-strength steels (Re ≈ 1500 MPa), and finally, in the welding of stainless steels. After the publication of the first test results, subsequent research-related articles were published rather rarely and irregularly. The renaissance of the interest in the A-TIG method took place in the mid-1990s, which was manifested by a sudden increase in the number of scientific and technical articles published after 1995. The authors of the articles were scientists representing research centers from all over the world. The subject of the significant majority of research works has been the effect of the A-TIG method on the welding of stainless, primarily austenitic, steels (ASS). The foregoing is fully understandable as the advantages resulting from the use of activated fluxes during the TIG welding of the aforesaid group of materials are most spectacular, including a nearly two-fold increase in penetration depth and the minimization of welding distortions resulting from the specific shape of welds in cross-section [2]. Issues accompanying the A-TIG welding of low-alloy and unalloyed steels are relatively rarely discussed in scientific publications.

There can be several reasons for a relatively low number of conducted tests concerning the A-TIG welding of unalloyed and low-alloy steels. However, it seems that such a situation can be primarily ascribed to the fact that the most common method used in the welding of the aforesaid groups of steel is MAG (Metal Active Gas) technology, characterized by higher efficiency than the TIG method. The TIG method is used rather rarely in the welding of unalloyed and low-alloy steels. Its main application areas include the joining of pipelines (e.g., in power generation systems), the welding of joints characterized by specific structure, and welding without the use of filler metals. The lack of filler metal during welding is
typical of the A-TIG welding process, which indicates the purposefulness of tests aimed
to determine the possibility of replacing the TIG method with the A-TIG process and to
identify advantages resulting from the aforesaid replacement.

The analysis of previous publications concerning the A-TIG welding of carbon and low-
alloy steels revealed that the authors discussed results related to the use of oxides, fluorides,
chlorides, carbonates, and their mixtures [3–8]. Depending on the scope of research, the
articles presented the effect of individual ingredients on the depth of penetration, structure,
hardness, and mechanical properties of welded joints. Nearly all of the works emphasized
the positive effect of SiO$_2$ and TiO$_2$ on the depth of penetration, restricted between 40–50%
and more than 200%. However, publication [9] mentioned the reverse effect of titanium
oxide, i.e., a decrease in penetration depth by 35%. In turn, work [10] described a slight
increase (by approximately 30%) in penetration depth when using individually developed
activated flux during the welding of mild steels. The analysis of publications revealed
that the tests were performed using various carbon [9] or low-alloy steel grades: SA516
GR-70 [5], DMR-249A [6], AISI 4130 [7], and BS700MC [8]. Some publications [3,4] did not
specify the grades of steels or their chemical composition. The tests involved the application
of various welding process parameters (current and welding rate) as well as the use of
plates having various thicknesses (from 5 mm to 8 mm) and various dimensions (from
very small, i.e., 60 mm × 80 mm up to standard dimensions of 150 mm × 300 mm) [5–10].
The above-presented factors affect welding thermal conditions and the behavior of liquid
metal in the weld pool. However, it should also be noted that even in relation to the same
conditions used during the welding of the same grade of steel, the effect of flux may vary
depending on the pre-weld condition of the plate surface (e.g., the presence of scale after
hot rolling, the presence of an oxidized layer after normalizing, or another type of heat
treatment). All this impedes not only the formulation of general conclusions based on the
results of tests of only one steel grade but also makes it more difficult to draw appropriate
conclusions on the basis of the comparative analysis of research results obtained under
various conditions.

Because of this, presented below are results of tests concerning the A-TIG welding
of selected unalloyed steels and fine-grained steels obtained applying the same welding
conditions and parameters, and compared with results obtained in relation to high-strength
steel WELDOX 1300 and austenitic stainless steel AISI 304L.

2. Test Materials and Methods

The comparative tests of A-TIG welding involved the use of 8 mm thick plates (300 mm ×
300 mm) made of unalloyed (carbon) steel S235JR+N as well as fine-grained steel grades
P265GH (for pressure vessels) and S355J2+N. The selection of the above-named steels
resulted from their significantly varying deoxidation degrees but relatively similar chemical
composition, particularly as regards the content of sulfur (Table 1). As is known, in terms
of steel, the content of sulfur and that of oxygen have the most significant impact on the
movement of liquid metal in the weld pool [11,12]. This, in turn, affects the shape of
welds and, consequently, the depth of penetration. If the content of sulfur is similar, the
most important factor is oxygen. Steel S235JR+N was selected because of the fact that it
was rimmed steel, which means that its production was not accompanied by deoxidation
(which was manifested by a silicon content of 0.009%—see Table 1). In turn, steel grades
P265GH and S355J2+N are fully killed steels characterized by similar metallurgical purity;
the content of silicon in steel P265GH amounted to 0.17%, whereas that in steel S355J2+N
amounted to 0.29% (Table 1).

For comparative purposes, bead-on-plate welds were made on a 7 mm thick plate
made of low-alloy high-strength steel WELDOX 1300 and on an 8 mm thick plate made
of austenitic stainless steel AISI 304L (1.4307/X2CrNi18-9). The chemical compositions of
the above-named steels are also presented in Table 1. Steel WELDOX 1300 was selected
because of the fact that, in addition to containing alloying elements and being subjected to
appropriate rolling technology, the steel had undergone thorough metallurgical purification, including deep deoxidation [13].

| Steel Grade   | Data Source | Contents of Chemical Elements, wt.% |
|---------------|-------------|------------------------------------|
| S235JR+N      | analysis    | C: 0.114, Mn: 0.50, Si: 0.009, P: 0.015, S: 0.012, B: - |
| P265GH        | analysis    | C: 0.145, Mn: 0.66, Si: 0.17, P: 0.010, S: 0.014, B: - |
| S355J2+N      | analysis    | C: 0.173, Mn: 1.32, Si: 0.29, P: 0.017, S: 0.011, B: - |
| WELDOX 1300   | analysis    | C: 0.236, Mn: 0.885, Si: 0.22, P: 0.0047, S: 0.0008, B: 0.493, Cr: 1.348, Ni: 0.401 |
| AISI 304L     | analysis    | C: 0.026, Mn: 1.41, Si: 0.47, P: 0.029, S: 0.005, B: - |

Table 1. Chemical composition of steel grades.

The welding tests involved the use of single-component fluxes in the form of oxides (Cr$_2$O$_3$, TiO$_2$, SiO$_2$, and Fe$_2$O$_3$) or fluorides (NaF and AlF$_3$). The components were ground in a ceramic mortar and, next, sifted through a laboratory sieve having a mesh of 0.056 mm. Before application, the component was mixed with a quick-evaporating liquid (acetone) in order to obtain dense suspended matter. The flux prepared in this way was applied onto plate surfaces using a brush. This method of applying the activating flux is currently used in all investigations concerning the A-TIG process. In order to achieve similar flux thickness and minimize the impact of this factor on test results, the paste density was always the same; the application of flux was always conducted by the same person, performing the same brush movements.

All experimental welds were made under the same conditions, without the use of the filler metal (autogenous TIG welding), using a current of 200 A and a welding rate of 150 mm/min. The arc voltage was restricted within the range of 10.4 V to 12.8 V; the heat input was restricted within the range of 0.499 kJ/mm to 0.614 kJ/mm. The station for mechanized welding was composed of a LORCH V40 welding power source and a Promotech DC-20 drive unit (enabling the precise movement of the welding torch at a preset welding rate). The flow rate of shielding argon was restricted within the range of 9 l/min to 10 l/min. The welding tests were performed using DC with reversed polarity on a tungsten electrode (ø 2.4 mm) with the addition of thorium oxide (grade WT20 in accordance with EN ISO 6848).

All of the welds were subjected to the visual validation of surface condition and macrostructural tests aimed to identify their dimensions (Figure 1). The specimens subjected to microstructural observation were etched using Adler’s reagent. The measurements of the width of the welds were performed every 50 mm (between measurement points) along the entire length of the test welds. The specimens subjected to macrostructural tests were sampled from the central part of the test weld.

Figure 1. Schematic diagram of the bead-on-plate weld (DP—depth of penetration; W—width).

3. Test Results and Analysis

The results of the macrostructural tests of the welds made on individual steel grades using various activated fluxes (Cr$_2$O$_3$, TiO$_2$, SiO$_2$, Fe$_2$O$_3$, NaF, and AlF$_3$) are presented in
Figures 2–5, whereas the results of penetration depth and weld width measurements are presented in Figures 6 and 7.

**Figure 2.** Macrostructure of the welds made on steel S235JR+N using (a) conventional TIG without flux and A-TIG with various fluxes: (b) TiO$_2$ (c) SiO$_2$ (d) Cr$_2$O$_3$ (e) Fe$_2$O$_3$ (f) NaF (g) AlF$_3$.

The analysis of the dimensions of the bead-on-plate welds made of unalloyed steel grades S235JR+N, S355J2+N, and P265GH revealed (Figure 6) that penetration depth increased in nearly all of the cases, regardless of flux application. However, the aforesaid increase was not significant and amounted to a maximum of 30%. Only in relation to steel S235JR+N welded using Cr$_2$O$_3$ and NaF was it possible to notice a decrease in penetration depth. However, the aforesaid reduction was not significant. The greatest increase in penetration depth was observed in relation to steel S355J2+N, whereas the lowest increase in penetration depth was observed with steel grade S235RJ+N. It was also noticed that TiO$_2$ and SiO$_2$ had a very similar effect on penetration depth, regardless of the substratum type. In turn, the effect of Cr$_2$O$_3$, Fe$_2$O$_3$, NaF, and AlF$_3$ varied depending on the steel grade. It should be noted that the greatest increase in penetration depth accompanied the welding of steel S355J2+N using Fe$_2$O$_3$, whereas the very same oxide had no influence on penetration depth in steel S235JR+N. A similar result was observed during the welding process involving the use of NaF.
As regards the unalloyed and the fine-grained steels, the analysis of the macrostructures of the experimental welds revealed (Figures 2–5) that additional information about the effect of activators could be provided not only by penetration depth but also by the dimensions (visible in the metallographic specimens) of the heat-affected zone (HAZ). The obtainment of such information was not possible during the welding of the austenitic stainless steels as the HAZ was very narrow and nearly invisible (Figure 5). As regards steel S235JR+N, the tests revealed that the shape and the dimensions of the HAZ remained nearly unchanged (Figure 8). Significantly different was the case with steel S355J2+N. The welding of the aforesaid steel using TiO$_2$, SiO$_2$ and Fe$_2$O$_3$ resulted in a significant increase in the HAZ depth, much greater than could be implied by the increase in penetration depth. Interestingly, the width of the HAZ changed only slightly. On one hand, the change in the HAZ dimensions could result from the thermal conductivity and the initial structure of the steel, yet, on the other, it could also indicate the direction of liquid metal pool movement in the weld and the transfer of energy (which could be indicated by the dimensions of the welds and of the HAZ made on steel P265GH using TiO$_2$ (Figure 4b) and NaF (Figure 4f).
In both cases, the depth of penetration was the same, yet the depth of the HAZ of the weld made using NaF was greater than that of the HAZ of the weld made using TiO$_2$.

![Figure 4](image.png)

**Figure 4.** Macrostructure of the welds made on boiler steel P265GH using (a) conventional TIG without flux and A-TIG with various fluxes: (b) TiO$_2$ (c) SiO$_2$ (d) Cr$_2$O$_3$ (e) Fe$_2$O$_3$ (f) NaF (g) AlF$_3$.

The comparison of the effect of the activated fluxes on penetration depth during the A-TIG welding of the unalloyed steels and stainless steel AISI 304L revealed a similarly favorable effect of the TiO$_2$, SiO$_2$, and Fe$_2$O$_3$ oxides as regards both steel groups. The effect of oxides or, more precisely, oxygen provided by the oxides to the weld pool, is well explained by the Marangoni convection, cited in many scientific publications. A different influence could be observed in terms of the fluorides (Figure 5). The use of NaF and AlF$_3$ resulted in the reduction of penetration depth in steel AISI 304L and in an increase in penetration depth in steel S355J2+N (Figure 6).

Additional information for analysis was provided by the results of the tests related to penetration depth during the A-TIG welding of high-strength steel WELDOX 1300, characterized by very high metallurgical purity. The tests revealed that the use of TiO$_2$, SiO$_2$, and Cr$_2$O$_3$ resulted in more than a two-fold increase in penetration depth in comparison with that obtained using traditional TIG welding without flux (Figures 9 and 10). As regards penetration depth, differences between TIG and A-TIG welding were clearly visible, which was not the case with steels S235JR+N, S355J2+N, and P265GH. Interestingly, the use of the
TiO$_2$ and SiO$_2$ oxides resulted in the obtainment of nearly the same penetration depth in cases of all of the unalloyed and low-alloy steels (Figure 10).

![Figure 5. Macrostructure of the welds made on austenitic stainless steel AISI 304L using (a) conventional TIG without flux and A-TIG with various fluxes: (b) TiO$_2$ (c) SiO$_2$ (d) Cr$_2$O$_3$ (e) Fe$_2$O$_3$ (f) NaF (g) AlF$_3$.](image)

The test results concerning the A-TIG welding of the unalloyed and low-alloy steels revealed that penetration depth increased in the steels characterized by increasingly high deoxidation and metallurgical purity. Obviously, not each activator was responsible for an increase in penetration depth, yet the use of the TiO$_2$ and SiO$_2$ oxides proved undoubtedly favorable. The favorable influence of Cr$_2$O$_3$ could be observed along with the increasingly high quality of the unalloyed and low-alloy steels. In relation to the aforesaid oxide, it was also observed that, depending on steel grades, the depth of penetration changed significantly, yet the width of the welds remained nearly the same, regardless of the type and the grade of steel (Figures 6 and 7). A similar, yet less evident, correlation could be observed during the welding tests involving the use of iron oxide (Fe$_2$O$_3$).
Figure 6. Correlation between the depth of penetration and the types of activated fluxes.

Figure 7. Correlation between the average width of the weld and the types of activated fluxes.
Figure 8. Effect of the activated fluxes on the HAZ dimensions.

Figure 9. Macrostructure of the TIG and A-TIG welds on steel WELDOX 1300.
Worth noticing is also the comparison of the influence of SiO\textsubscript{2} and Fe\textsubscript{2}O\textsubscript{3} on penetration depth in steel S235JR+N (Figure 6). Related measurements revealed that the use of SiO\textsubscript{2} led to an increase in penetration depth, whereas the use of Fe\textsubscript{2}O\textsubscript{3} did not produce any visible result. The arc temperature-triggered decomposition of both oxides resulted in providing the liquid pool with additional oxygen, yet only the SiO\textsubscript{2} oxide was responsible for increased penetration depth. The foregoing could imply that not only temperature and the amount of oxygen affected the direction of the movement of liquid metal in the weld pool (Marangoni convection) but also the presence of other chemical elements influencing surface tension, e.g., through the specific course of reactions at the phase boundary and the dynamic formation of thin subsurface layers. As regards steel S355J2+N, characterized by the relatively high amount of Si (Table 1), it should be mentioned that both the use of Fe\textsubscript{2}O\textsubscript{3} and that of SiO\textsubscript{2} (Figure 6) led to an increase in penetration depth.

As mentioned above, a change in the direction of the Marangoni convection is the most commonly indicated reason for an increase in penetration depth. However, there is also a view stating that an increase in penetration depth is the result of the narrowing of the arc, triggered by the combination of free chemical elements of relatively low potentials with oxygen (e.g., Mn −7.4 eV and Fe −7.8 eV). As a result, the aforementioned elements do not enter the welding arc (which would deionize its peripheral areas and result in the narrowing of the arc and, consequently, could lead to the concentration of energy in a smaller area). The additional narrowing of the heated area may also result from the lack of the electric conductivity of activated fluxes, most of which are oxides or halides.

In terms of steel AISI 304L, the analysis of related test results revealed that both of the above-presented conclusions were justified as penetration depth increased in the presence of all oxide activators (Cr\textsubscript{2}O\textsubscript{3}, TiO\textsubscript{2}, SiO\textsubscript{2}, and Fe\textsubscript{2}O\textsubscript{3}), triggering a change in the surface tension of liquid metal in individual areas of the weld pool (Marangoni convection) and the release of oxygen from the above-named oxides as well as the oxidation of chemical elements of relatively low potentials. This, in turn, led to the deionization of the peripheral
areas of the arc and, ultimately, to the narrowing of the arc. However, the theory concerned with the effect of the deionization of the peripheral areas of the arc on the A-TIG welding process was challenged by the lack of an increase or even by a decrease in penetration depth in steel AISI 304L when using sodium and aluminum fluorides (Figure 6). Fluorine entering the welding arc deionized its peripheral areas, which, however, did not lead to an increase in penetration depth during the welding of austenitic stainless steel AISI 304L. It should also be mentioned that the width of the weld obtained when using NaF decreased in comparison with that obtained using the traditional TIG welding method and was exactly the same as the weld width obtained using Fe$_2$O$_3$ (Figure 11). The use of the NaF fluoride and of the Fe$_2$O$_3$ oxide resulted in the narrowing of the arc, which, in both cases, resulted in the narrowing of the weld width. However, only the use of the iron oxide as the activator led to an increase in penetration depth. The foregoing indicates that the above-presented differences depended on processes taking place on the surface of liquid metal and were connected with changes of surface tension in various areas of the weld pool (Marangoni convection). This supposition could also be confirmed by the fact that the use of sodium fluoride (NaF) when making welds on steels S355J2+N and P265GH resulted in an increase in penetration depth (Figure 12). However, the composition of unalloyed steels differed significantly from that of stainless steel AISI 304L, which could be the reason for the varying influence of NaF on the surface tension of liquid metal in the weld pool and on penetration depth.

4. Summary

The results of the above-presented tests revealed that in cases of the traditional unalloyed and fine-grained steels, certain oxides and fluorides were responsible for an increase in penetration depth by 20–30%. Noticeably, as regards metallurgically pure low-alloy
steel WELDOX 1300, an increase in penetration depth triggered by TiO$_2$, SiO$_2$ and Cr$_2$O$_3$ exceeded 200%. The test results were, as a rule, consistent with the results presented in referenced scientific publications, yet they slightly differed in detail. This fact was undoubtedly connected with the use of various unalloyed and low-alloy steel grades, different conditions of the plate surface, various conditions of experiments, and the specific nature of the A-TIG welding technology (related primarily to the method, in which activated fluxes were applied). Presently, the most popular manner of the application of activated flux is by hand, i.e., using a brush. Obviously, such a method makes it difficult to precisely control the amount of flux placed on the surface of a plate to be welded. The amount of flux may differ not only as regards the type of its primary ingredient but also due to the fact that there may be more flux at the beginning and less at the end of the layer applied on the plate. The author’s multiannual practical experience and numerous research results provided by other researchers revealed that the amount of flux present on the plate surface may significantly affect the results of A-TIG welding [3,14]. To eliminate the above-named difficulties and minimize the effect of the aforesaid factors on welding test results, in the research work discussed in this article, the flux in the form of paste was characterized by similar density, and the process of flux application was always performed by the same person.

The tests revealed that, in comparison with TIG welding without flux, the greatest increase in penetration depth accompanied the A-TIG welding of low-alloy steels characterized by high metallurgical purity. The above-named steels are known to be characterized by a higher yield point and strength. In cases of narrow and deep welds, obtained during A-TIG welding, there is a risk of increased HAZ hardness and worsened mechanical properties. Publication [15] presents tensile test results concerning welded joints made of steel WELDOX 1300 using various welding methods, including the A-TIG process. An A-TIG welded joint subjected to tests described in work [15] was made without the filler metal and with activated flux developed on the basis of the above-named test results. The tests concerning the strength of welded joints made on steel WELDOX 1300 revealed that the strength of the A-TIG joint was only lower by approximately 100 MPa than that of the base material and, at the same time was higher than the strength obtained during traditional TIG welding and MAG welding with the filler metal. In turn, work [16] presents tests related to mechanical properties of A-TIG joints made of steel WELDOX 1100 (also made by the author of this article). The tests revealed that the A-TIG joints satisfied related requirements in terms of mechanical properties and impact energy. The hardness of the HAZ was higher than that of the weld (but only slightly) and did not exceed 419 HV. The only problem, which occurred during the bend test, was observed on the weld face side as the specimen contained cracks that appeared at a bend angle of 120° and 150°. Interestingly, bending on the weld root side was successful; the attainment of a bend angle of 180° was not accompanied by the formation of any scratches or cracks. The above-presented results indicate that, similar to traditional TIG and MAG methods, the use of the A-TIG process enables the attainment of welded joints satisfying related requirements. However, in each case, the mechanical properties of A-TIG joints must be verified before use in specific applications.

One of the practical conclusions drawn on the basis of the above-presented tests is that the A-TIG welding of ordinary structural steels available on the market is characterized by low effectiveness not only in comparison with the commonly used MAG (GTAW) method, but also if compared with the traditional TIG welding process (rarely used in the joining of the aforesaid steels). The advantages of the A-TIG method in comparison with both TIG and MAG processes are noticeable in relation to the welding of steels characterized by higher metallurgical purity, i.e., (usually) low-alloy high-temperature creep-resisting steels and high-strength steels.

5. Concluding Remarks

The analysis of the above-presented test results justified the formulation of the following conclusions:
among the activated fluxes subjected to the tests, the use of silicon and titanium oxides (TiO$_2$ and SiO$_2$) always led to an increase in penetration depth during A-TIG welding, regardless of the type and the grade of steel. The degree of an increase in penetration depth was restricted within the range of 30% to more than 200%;

- in cases of the carbon and low-alloy steels, the greatest increase in penetration depth was observed in the steels which had been previously appropriately deoxidized and purified at the production stage in the steelworks. The purer the unalloyed or low-alloy steel, the more favorable the effect of TiO$_2$ and SiO$_2$;

- influence of other tested oxides and fluorides depended on types and grades of steels. For instance, the sodium and the aluminum fluorides decreased the penetration depth of the weld on the austenitic stainless steel, yet they increased the depth of penetration in cases of fine-grained steels.

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