A Study to Increase Weld Penetration in P91 Steel During TIG Welding by using Activating Fluxes

Akhilesh Kumar Singh1, Mayank Kumar1, Vidyut Dey1, Ram Naresh Rai1,
1Department of Production Engineering, National Institute of Technology, Agartala, Tripura (w) - 799046, India

Abstract: Activated Flux TIG (ATIG) welding is a unique joining process, invented at Paton Institute of electric welding in 1960. ATIG welding process is also known as flux zoned TIG (FZTIG). In this process, a thin layer of activating flux is applied along the line on the surface of the material where the welding is to be carried out. The ATIG process aids to increase the weld penetration in thick materials. Activating fluxes used in the literature show the use of oxides like TiO2, SiO2, Cr2O3, ZnO, CaO, Fe2O3, and MnO2 during welding of steels. In the present study, ATIG was carried out on P-91 steel. Though, Tungsten Inert Gas welding gives excellent quality welds, but the penetration obtained in such welding is still demanding. P91 steel which is ferritic steel is used in high temperature applications. As this steel is, generally, used in thick sections, fabrication of such structures with TIG welding is limited, due to its low depth of penetration. To increase the depth of penetration in P91 while welding with ATIG, the role of various oxides were investigated. Apart from the oxides mentioned above, in the present study the role of B2O3, V2O5 and MgO, during ATIG welding of P91 was investigated. It was seen that, compared to TIG welding, there was phenomenal increase in weld penetration during ATIG welding. Amongst all the oxides used in this study, maximum penetration was achieved in case of B2O3. The measurements of weld penetration, bead width and heat affected zone of the weldings were carried out using an image analysis technique.

Keywords: Autogenous TIG welding, Bead-On-Plate, Different types of fluxes, Weld penetration, Bead width, HAZ-width.

1. INTRODUCTION

Activated Flux TIG welding (ATIG) (or flux zoned TIG (FZTIG)) is a unique welding process, invented at Paton Institute of electric welding in 1960 [1-4]. In this process a thin layer of fluxes is covered on weld surface of the plate after that an TIG welding is performed on it. Literature shows numbers of fluxes (i.e. TiO2, SiO2, Cr2O3, ZnO, CaO, Fe2O3, MnO2, etc.) were used for ATIG welding according to their weld specimen to increase the weld penetration, fluxes can be used in the form of single or mixed fluxes in ATIG welding [5-10]. Before pasting the fluxes on weld surface, the flux is mixed with a binder and a solvent. These bind the flux paste on the metal surface in the form of coated layer. Flux plays an important role to enhance the penetration with the help of convection flow of liquid metal. The weld pool is governed by various types of forces while doing ATIG welding [11-14]. In the present study, these modified processes were tried out to enhance weld penetration on P91 steel plates of thickness 6 mm.
Grade P91 steel is basically a Creep Strength Enhanced Ferritic Steel (CSEF) which has high thermal conductivity, good steam corrosion resistance [15-18]. This steel has been developed at Oak Ridge National laboratory by adding Vanadium to 9Cr-1Mo (P9) steel. This steel is extensively used in high-temperature applications like steam generators, power plants, etc. [19-20]. In the present study, several fluxes were utilized to improve the depth of weld penetration on the conventional TIG welding which improved the weld penetration twice or thrice to that of the conventional TIG welding process.

2. EXPERIMENTAL PROCEDURE

To carry out an investigation on the effect of the autogenous TIG welding, bead-on-plate (BOP) welds were carried on P91 steel plates of thickness 6 mm with different activating fluxes. The Grade P91 steel plates used in the study. The chemical composition of P91 steel is shown in Table 1.

Table 1. Chemical composition of P91 steel plate used

| Chemical Composition | Cr % | Mo % | V % | N2 % | C % | Si % | Mn % | P % | S % | Ni % | Al % |
|----------------------|------|------|-----|------|-----|------|------|-----|-----|------|------|
| P91 Steel Plate (6 mm Thickness) | 8.81 | 0.97 | 0.24 | 0.046 | 0.093 | 0.32 | 0.44 | 0.018 | 0.007 | 0.15 | 0.015 |

The experimental TIG welding parameters for P91 Plates are shown in Table 2 while the constant parameters for ATIG welding are shown in Table 3. Bead-on-plate welding was carried out on a 6 mm thick P91 plates using the weld parameters combination of “Lower-Current (150 A), Higher-Welding Speed (25 cm/min)” and “Higher-Current (250 A), Lower-Welding Speed (15 cm/min)” at a constant gas flow rate i.e. 10 L/min. The intensity of heat energy in low current and high welding speed is ‘Low’ whereas intensity at high current and low welding speed is ‘High’. The symbols TIG-L and TIG-H in Table 2 denote TIG welding performed at low intensity heat and high intensity heat respectively.

Table 2 TIG Welding Parameters for P91 Plates

| Parameters Symbol | Current (A) | Welding Speed (cm/min) | Gas Flow Rate (L/min) |
|-------------------|-------------|------------------------|-----------------------|
| C                 | TIG-L       | 150                    | 25                    |
| WS                | TIG-H       | 250                    | 15                    |
| GF                |             |                        | 10                    |

Table 3 Equipment and Parameters used for A-TIG Welding

| A-TIG Welding Parameters |
|--------------------------|
| S. No.  | Welding Parameters | Ranges  |
|---------|--------------------|---------|
| 1       | Electrode Diameter | 2.4 mm  |
| 2       | Electrode Tip Angle | 20°     |
| 3       | Electrode Length (from Torch) | 5 mm |
| Sample No. | IUPAC* Name of Fluxes                | Molecular formula of flux | Density $\rho$ (g/cm$^3$) | Flux Appearance                      |
|-----------|------------------------------------|---------------------------|---------------------------|-------------------------------------|
| A-1       | Titanium (IV) oxide                 | TiO$_2$                   | 4.23                      | White solid, odorless               |
| A-2       | Boron trioxide                      | B$_2$O$_3$                | 2.46                      | Boron trioxide is one of the oxides of boron. It is a white, glassy solid |
| A-3       | Zinc oxide Pure                     | ZnO                       | 5.61                      | White solid, odorless               |
| A-4       | Chromium (VI) oxide purified        | Cr$_2$O$_3$               | 2.70                      | Dark purple solid, odorless         |
| A-5       | Vanadium pentoxide                  | V$_2$O$_5$                | 3.36                      | Vanadium (V) oxide is the inorganic compound, it is a brown/yellow solid |
| A-6       | Silicon dioxide                     | SiO$_2$                   | 2.65                      | Transparent crystals                |
| A-7       | Manganese dioxide powder technical  | MnO$_2$                   | 5.03                      | Brown-black solid, odorless         |
| A-8       | Magnesium oxide                     | MgO                       | 3.58                      | White powder, Odorless              |

In this process a thin layer of activating flux is covered on weld surface of the P91 steel plates, a brief explanation and preparation procedures of activating flux is shown in Fig.1(a) and Fig.1(b) show flux coating on P91 steel plates.

![Fig. 1 (a) Preparation procedures of activated flux (A-TIG) welding [1]; (b) Flux coating on P91 steel plates](image)

The numbers of activated flux which are used in TIG welding to improve the weld penetration is shown in Table 4. The ATIG process aids to increase the weld penetration in thick materials by single pass without any edge preparation or use of filler metal.

![Table 4 Physical characteristics of oxide fluxes](table)

| Sample No. | IUPAC* Name of Fluxes                | Molecular formula of flux | Density $\rho$ (g/cm$^3$) | Flux Appearance                      |
|-----------|------------------------------------|---------------------------|---------------------------|-------------------------------------|
| A-1       | Titanium (IV) oxide                 | TiO$_2$                   | 4.23                      | White solid, odorless               |
| A-2       | Boron trioxide                      | B$_2$O$_3$                | 2.46                      | Boron trioxide is one of the oxides of boron. It is a white, glassy solid |
| A-3       | Zinc oxide Pure                     | ZnO                       | 5.61                      | White solid, odorless               |
| A-4       | Chromium (VI) oxide purified        | Cr$_2$O$_3$               | 2.70                      | Dark purple solid, odorless         |
| A-5       | Vanadium pentoxide                  | V$_2$O$_5$                | 3.36                      | Vanadium (V) oxide is the inorganic compound, it is a brown/yellow solid |
| A-6       | Silicon dioxide                     | SiO$_2$                   | 2.65                      | Transparent crystals                |
| A-7       | Manganese dioxide powder technical  | MnO$_2$                   | 5.03                      | Brown-black solid, odorless         |
| A-8       | Magnesium oxide                     | MgO                       | 3.58                      | White powder, Odorless              |
3. EXPERIMENTAL SETUP

In this study, P-91 steel plate - specimens were cut to the dimensions of 100 mm x 50 mm x 6 mm. Thereafter, those were welded Bead-On-Plate (BOP) using an activating fluxes (ATIG) technique. The control parameters like welding current and weld speed were varied at two levels and gas flow rate remain constant in both the cases as shown in Table 2. The welding setup used for the purpose is shown in Fig. 2.

Fig. 2 Experimental Setup for TIG welding.

4. RESULTS AND DISCUSSION

After each bead-on-plate weld on P-91 steel plates, by using different activating fluxes, sufficient time was provided to cool the plates in air shown in Fig. 3. Thereafter, the specimens were cut, polished and etched, using 5% Nital solution, to reveal the welded bead geometry. These etched welded specimens of 6 mm thickness were photographed using a Fujifilm-digital camera. The photographs of the welded specimens are shown in Fig. 4.

Fig. 3 shows ATIG-BOP welded P-91 Steel Plates after welding.
| Sample No. | Sample Name | TIG - L | TIG - H |
|------------|-------------|---------|---------|
| N          | Without ATIG | ![Etched specimen of HAZ and TIG-L N](image) | ![Etched specimen of HAZ and TIG-H N](image) |
| A-1        | TiO$_2$     | ![Etched specimen of ATIG-1](image) | ![Etched specimen of ATIG-2](image) |
| A-2        | B$_2$O$_3$  | ![Etched specimen of ATIG-3](image) | ![Etched specimen of ATIG-4](image) |
| A-3        | ZnO         | ![Etched specimen of ATIG-5](image) | ![Etched specimen of ATIG-6](image) |
| A-4        | Cr$_2$O$_3$ | ![Etched specimen of ATIG-7](image) | ![Etched specimen of ATIG-8](image) |
| A-5        | V$_2$O$_5$  | ![Etched specimen of ATIG-9](image) | ![Etched specimen of ATIG-10](image) |
| A-6        | SiO$_2$     | ![Etched specimen of ATIG-11](image) | ![Etched specimen of ATIG-12](image) |
| A-7        | MnO$_2$     | ![Etched specimen of ATIG-13](image) | ![Etched specimen of ATIG-14](image) |
| A-8        | MgO         | ![Etched specimen of ATIG-15](image) | ![Etched specimen of ATIG-16](image) |

Fig. 4 Etched specimens of the BOP welded P-91 Steel Plates with thickness 6 mm

4.1. Mechanism for increased penetration
In ATIG welding process, a number of different mechanisms have been proposed which played a significant role to improve weld penetration by a surface coating of flux while doing ATIG welding. It has been established in this study that the penetration achieved in ATIG process is two to three times that of the conventional TIG welding process. Literatures shows that, due to a change in the thermal coefficient of surface tension, the number of different mechanisms have
been proposed for in ATIG welding are: (1) Marangoni effect, (2) Effect of arc constriction due to flux pasting technique, (3) Buoyancy force, (4) Electromagnetic or Lorenz force, these all play significant role to increase penetration [5], [13].

4.2. Effect on Weld Bead Geometric Dimensions

Weld bead geometric dimensions (i.e. bead penetration) of BOP were measured with help of an image analysis technique [21] are shown in Fig.5. Activating fluxes which were used on P91 steel plates to carry out ATIG welding in present study (i.e. TiO₂, B₂O₃, ZnO, Cr₂O₃, V₂O₅, SiO₂, MnO₂ and MgO) played an important role to increase the depth of penetration were investigated. The oxides mentioned above, in the present study first time the role of B₂O₃, V₂O₅ and MgO, were used during ATIG welding of P91 was investigated. It was seen in Fig. 5, compared to normal TIG welded (N-TIG) sample (without any fluxes) in both the cases of parameter, there was phenomenal increase in weld penetration during ATIG welding. Amongst all the oxides used in this study, maximum penetration was achieved in case of (A-2)-B₂O₃ (i.e. Boron-trioxide). The second highest weld penetration was found when Titanium (IV) oxide (A-1).

Fig. 5 shows the weld penetration (i.e. BP) dimensions, according to parameter TIG-L and TIG-H of BOP welded on P-91 steel plates

5. CONCLUSION

In this study, first time the role of B₂O₃, V₂O₅ and MgO, were used during ATIG welding of P91 was investigated. The study shows that use of fluxes improved weld bead penetration twice to thrice as compared to normal TIG welding. The results show that amongst all the fluxes, Boron-trioxide has the greatest influence on the heat flow during welding. Since this was a preliminary study, the influence of the width and height of fluxes was not investigated. Also, there is ample scope to develop an analytical model to establish the reasons for better penetration while Boron-trioxide is used.
REFERENCES

[1] Kuang-Hung Tseng and Po-Yu Lin: UNS S31603 Stainless Steel Tungsten Inert Gas Welds Made with Microparticle and Nanoparticle Oxides, Materials 2014, 7, 4755-4772
[2] W Lucas: Activating flux improving the performance of the TIG process, Welding and Metal Fabrication, 2000, Vol. 68, No. 2, February, pp 710
[3] Paskell, T., Lundin, C., Castner, H. GTAW flux increases weld joint penetration, Welding Journal ,76, Issue 4; 1997, pp. 57-62
[4] Y Huang, D Fan, F Shao, Alternative current flux zoned tungsten inert gas welding process for aluminium alloys, Volume 17, Issue 2 (February 2012), pp. 122127
[5] Kamal H. Dhandha, Vishvesh J. Badheka: Effect of activating fluxes on weld bead morphology of P91 steel bead-on-plate welds by flux assisted tungsten inert gas welding process, Journal of Manufacturing Processes 17 (2015) 48–57
[6] Harold R. Conaway, Thousand Oaks; Bruce E Olsen, Santa Monica; E, Fish, Pinon Hill, all of calif: WELDING COMPOSITIONS, United States Patent, Patent No: 5525163, 1996
[7] Matthew Q. Johnson, Powell, OH (US); Christopher M. Fountain, Upper Arlington, OH (US): PENETRATION FLUX, United States Patent, Patent No: US 6707005 B1, 2004
[8] Matthew Q. Johnson, Powell, OH (US); Christopher M. Fountain, Upper Arlington, OH (US): PENETRATION FLUX, United States Patent, Patent No: US 6664508 B1, 2003
[9] http://www.chemspider.com
[10] Vasudevan Muthukumaran, Arun Kumar Bhaduri, Baldev Raj: Penetration Enhancing Flux Formulation For Tungsten Inert Gas (TIG) Welding Of Austenitic Stainless Steel And Its Application, United States Patent, Patent No: US 8097826 B2, 2012
[11] A. Berthier, P. Paillard, M. Carin, F. Valensi and S. Pellerin. TIG and A-TIG welding experimental investigations and comparison to simulation Part 1: Identification of Marangoni effect, Science and Technology of Welding and Joining; 2012
[12] E. Ahmadi, A. R. Ebrahimi, R. Azari Khosroshahi. Welding of 304L Stainless Steel with Activated Tungsten Inert Gas Process (A-TIG), International Journal of ISSI, Vol.10 (2013), No.1, pp. 27-33
[13] Santhana Babu A.V., Giridharan P.K.: Productivity improvement in flux assisted TIG welding, International Journal on Design & Manufacturing Technologies, Vol. 6, No. 2, July 2012
[14] Jay J. Vora, Vishvesh J. Badheka. Experimental investigation on mechanism and weld morphology of activated TIG welded bead-on-plate weldments of reduced activation ferritic/martensitic steel using oxide fluxes, Journal of Manufacturing Processes; 2015
[15] B. Arivazhagan, M. Vasudevan. A comparative study on the effect of GTAW processes on the microstructure and mechanical properties of P91 steel weld joints, Journal of Manufacturing Processes 16 (2014) 305–311
[16] B. Arivazhagan and M. Vasudevan. A Study of Microstructure and Mechanical Properties of Grade 91 Steel A-TIG Weld Joint, Journal of Materials Engineering and Performance; 2013
[17] C.R. Das, S.K. Albert, J. Swaminathan, A.K. Bhaduri, B. Raj and B.S. Murty, Improvement In Creep Resistance Of Modified 9cr-1mo Steel Weldment By Boron Addition, Vol. 56 Welding In The World (2012).
[18] Daniela Polachova, Marie Svobodova, Pavlina Hajkova, Josef Uzel, Comparison Of Mechanical Properties Of P91 Steel Depending On Temperature And Annealing Time, COMAT, Plzen, Czech Republic, Eu (2012).
[19] H.C. Dey, S.K. Albert, A.K. Bhaduri, G.G. Roy, R. Balakrishnan, S. Panneerselvi, Effect of post-weld heat treatment (PWHT) time and multiple PWHT on mechanical properties of multi-pass TIG weld joints of modified 9Cr-1Mo steel, Weld World 58, (2014) pp. 389–395.

[20] ASTM, Designation: A387/A387M-06a, Standard Specification for Pressure Vessel Plates, Alloy Steel, Chromium-Molybdenum.

[21] Singh, A. K.; Debnath, T.; Dey, V.; Rai, R. N.: An Approach to Maximize Weld Penetration During TIG Welding of P91 Steel Plates by Utilizing Image Processing and Taguchi Orthogonal Array. Journal of The Institution of Engineers (India): Series C, 1-11 (2016)

Akhilesh Kumar Singh is a researcher and research interests in new developments in Welding field, Manufacturing and also include image processing, pattern recognition, computer vision and Soft computational approaches.

Mayank Kumar is an M.Tech scholar and research interests in Manufacturing design, Thermal Analysis-FEM.

Dr. Vidyut Dey is an Assistant Professor in Production Engineering Department & Deputy Registrar Academics, National Institute of Technology Agartala, Tripura-(W), India. He did his M.Tech and Ph.D. from IIT Kharagpur, India. His areas of interest: Casting, Welding, image processing, pattern recognition, computer vision and Soft computational approaches.

Dr. Ram Naresh Rai is an Associate Professor in Production Engineering Department & Dean (R&C), National Institute of Technology Agartala, Tripura-(W), India. He did his Ph.D. from IIT Kharagpur, India. His areas of interest: Foundry-Forging, SG Iron, Steel, Al alloy based composite materials, Grain refinement.