Study the correlation between Microhardness, Microstructure & In-situ thermal analysis of PCATIG weldedments of Al-SiC composite

Sivachidambaram Pichumani 1, Raghuraman Srinivasan 2, Venkatraman Ramamoorthi 3.

1PhD Research Scholar, 2Corresponding Author, 3Professor, School of Mechanical Engineering, SASTRA University, Thanjavur, India – 613401.

1sivachidambaram@mech.sastra.edu, 2raghu@mech.sastra.edu, 3venkat@sastra.edu.

Abstract

Activated TIG welding has been performed on Al – 8% SiC composite 5mm plate with various fluxes such as Al2O3, MnO2, CaO, MgO, SiO2 & TiO2. Microstructure, Microhardness and cooling rate are observed. Correlation between micro hardness, microstructure and cooling rate of Pulsed Current TIG welding and Pulsed Current Activated TIG welding on Al-SiC composite has been studied. Combining the pulsed current TIG and activated TIG welding (PC-A-TIG) on Al-SiC composite showed very fine superior weld microstructure on PCATIG – SiO2 & PCATIG – TiO2 which resulted in higher micro hardness values around 70 – 75 Hv. Micro hardness are observed in different locations of weld surface such as 1mm, 2mm & 3mm below the weld surface and it also observed along the weld zone to heat affected zone upto 12mm for the profiling the micro hardness value around the weldment. Microstructure observed in weld centre for observed on weld zone & heat affected zone. Minimum micro hardness value between 63 – 65 Hv found in PCA TIG – MnO2, PCATIG – CaO & PCATIG – MgO due to intermediate micro structure between coarse and fine. PCATIG – Al2O3 weld zone & heat affected zone and heat affected zone of PCATIG – MnO2, PCATIG – CaO & PCATIG – MgO shows coarse microstructure. This resulted in reduced micro hardness around 55 – 60 Hv. Coarse micro structure in weld zone and heat affected zone have least cooling rate. Fine micro structure in weld zone is due to higher cooling rate. Heat affected zone directly depends on temperature gradient between the weld centre and weldment heat affected zone.

1. Introduction

Gas Tungsten Arc Welding (GTAW) also known as Tungsten Inert Gas (TIG) welding showed high quality weld than other arc welding process. Non ferrous metals requires the quality weld with reduced defects and improved mechanical properties of the weld which showed, TIG is more suitable
welding process. However, its shallow weld penetration causes lesser production rate. Increase in weld passes for thick sections lead to higher input in the weld which reduces the weld strength [1] by producing the coarse grain microstructure [2].

To reduce the heat input into weld the Activated TIG welding (ATIG) a new variant was found out. ATIG welding process was developed in early 1960's by the Paton Welding Institute, Ukraine to improve the weld penetration [3, 4]. By improving the weld penetration, number weld passes get reduced by reducing the weld pass the heat input given the weld material is also get reduced [5]. The activated flux TIG welding may have two types of mechanisms that are mostly accepted, first one is based on the reverse Marangoni convection effect [6, 7, 8], and the other one is based on arc construction effect [9, 10].

During reverse Marangonic convection, surface tension of weld pool becomes negative to positive by changing temperature co-efficient form positive to negative this lead to transfer heat flow rate in weld pool from weld pool edges to weld pool centre [11, 12]. This increases the heat concentration in weld pool centre and lead to increased weld penetration with decrease in weld width. This theory was proposed by Heiple and Roper [13, 14, 15]. During welding, active flux is dissociated into positive ions and negative ions. Positive ions on base material surface attracts the welding arc and negative ions cover the outer surface of the welding arc & acts as shield to cover welding arc [16, 17, 18]. Due to these arc gets constricted and heat of welding arc concentrated at weld region [19, 20]. This gave increased weld penetration with decreased weld width. This arc constriction theory was proposed by Lucas and Howse.

Pulsed current TIG (PCTIG) welding shows the improved mechanical behaviour than TIG welding. Improved mechanical properties on PCTIG weld is due to fine grain microstructure when compared to constant current TIG welding gave coarse grain structure [21]. During PCTIG welding, peak current gives adequate penetration, base current is responsible to maintain stable arc, pulse frequency & pulse on time gives enough time to transfer heat from the arc to weld material during peak current time, cool down the weld pool during base current time and transfer heat from weld zone to heat affected zone & also to base material region [22].

This reduces the width of the heat affected zone and thermally induced stresses. Due to heat input difference during the PCTIG welding between peak current and base current, weld pool cooled immediately and higher heat concentration on weld pool is reduced [23]. This gave fine grain microstructure on weld zone. Finer the grain size has increased grain boundaries which gave improved mechanical behaviour for PCTIG welded samples. Major Problem in welding of aluminium is hot cracking this can be reduced by reduced heat input and choosing of correct filler material.

Tensile properties, fatigue properties, impact toughness and hardness were increased by achieving fine equiaxed grain microstructure on weld zone by reduced heat input. Due to reduced heat on weld zone, heterogeneous nucleation sites will survive on weld pool which converts columnar denetritic grain into fine equiaxed grain [24]. Liquidation cracks in the Heat affected zone acts as the
strong initiation sites for the solidification cracks which occur in weld zone, Healing of liquation cracks through back filling reduce the solidification crack in the weld zone. Pulsed current and Arc oscillation technique gives equiaxed fine grain structure which resist the hot cracking through the increased grain boundaries but in CCTIG have columnar grain structure this will have lesser grain boundaries [25].

Combining the pulsed current TIG and activated TIG welding (PC-A-TIG) on Al-SiC composite showed higher chance getting superior weld microstructure. So investigation of weld strength of Al-SiC composite with ATIG and PCATIG welding shows significance.

2. Experiments

Autogenous welding was performed on Al - 8% SiC composite material with a plate thickness of 5mm using ADOR CHAMPTIG 300AD welding machine. Other welding parameters considered during welding are provided in table 1. Welded samples were shown in figure 1-2.

| Table 1: Welding parameter during CCTIG, PCTIG, ATIG and PCATIG welding |
|---------------------------------------------------------------|
| **Parameter** | **Condition** |                                  |
| Current Type      | AC Current                        |
| Constant Current TIG | 110 A                             |
| Electrode Diameter | 3.2 mm                            |
| Electrode Material | 2% Th - Tungsten Electrode        |
| Arc Length        | 2 mm                               |
| Arc Voltage       | 18V                                |
| Welding Speed     | 2 mm/s                             |
| Argon Flow Rate   | 18 l/min                           |
| Active Layer Coating | 0.5-1 mg/cm²                    |
| Active fluxes     | Al₂O₃, CaO, MgO, SiO₂, TiO₂ & MnO₂|
| Heat Input        | 990w                               |
| Peak Current      | 160A                               |
| Base Current      | 60A                                |
| Pulse On Time     | 50%                                |
| Pulse Frequency   | 5Hz                                |

During welding, cooling rate at 10mm away weld zone was calculated from time - temperature profile acquired using data acquisition system (DAQ) through LabView software coupled with National Instrument NI cDAQ 9174 kit which employs a temperature acquiring module -NI 9211 with K type thermocouple.

Using standard metallographic procedure the welded samples were prepared for microstructure observation from microscopic image analyzer. Vickers micro hardness of different region such as weld zone, heat affect zone and base material were measured with load of 500g with 10 seconds as indentation time performed using Shimadzu micro hardness tester.
3. Results & Discussion

3.1 Micro hardness – PCTIG & PCATIG welded samples

Table 2: PCTIG & PCATIG welded samples micro hardness

| Welding conditions | Weld centre (HV) | 3mm away from weld centre (HV) | 7mm away from weld centre (HV) |
|--------------------|------------------|--------------------------------|-------------------------------|
|                    | Average | Standard deviation | Average | Standard deviation | Average | Standard deviation |
| PCTIG              | 66.64   | 4.42               | 60.12   | 2.32               | 56.03   | 2.64               |
| PCATIG-Al₂O₃       | 63.51   | 3.07               | 59.53   | 2.28               | 56.53   | 1.50               |
| PCATIG-CaO         | 58.69   | 1.23               | 55.38   | 1.79               | 52.07   | 1.47               |
| PCATIG-MgO         | 64.91   | 1.80               | 61.20   | 2.13               | 56.93   | 1.77               |
| PCATIG-SiO₂        | 71.72   | 3.64               | 65.92   | 2.57               | 61.92   | 0.85               |
| PCATIG-TiO₂        | 67.10   | 2.50               | 61.38   | 2.94               | 56.27   | 1.92               |
| PCATIG-MnO₂        | 63.78   | 2.16               | 58.71   | 2.61               | 55.02   | 1.98               |

Table 2 shows the average micro hardness value of CCTIG & PCATIG weldment on weld centre, 3mm away from weld centre & 7mm away from weld centre. Standard deviation is also tabulated. Figure 3, shows the micro hardness 1mm below the weld surface. Figure 4 shows the micro
hardness value 2mm below the weld surface. Figure 5 shows the micro hardness values of 3mm below weld surface. Here micro hardness values are observed in different locations from weld centre to 12mm away from the weld centre. Micro hardness value did not have much change after 10mm away from the weld centre which is more or less equal to the base material micro hardness.

**Figure 3:** Micro hardness of PCTIG & PCATIG welded samples 1mm below the weld surface

**Figure 4:** Micro hardness of PCTIG & PCATIG welded samples 2mm below the weld surface
3.2 Microstructure – Base material, PCTIG and PCATIG welded samples

Figure 5: Micro hardness of PCTIG & PCATIG welded samples 3mm below the weld surface

Figure 6: Microstructure of base material (Al – 8% SiC composite), PCTIG welded samples
Figure 6, shows the micro structure of base material, PCTIG welded samples. Figure 7, shows PCATIG – Al₂O₃, PCATIG – CaO & PCATIG – MgO micro structure of weld zone, 3mm away from weld zone & 7mm away from the weld zone otherwise called as heat affected zone.

![Microstructure images](image)

**Figure 7**: Microstructure of PCATIG welded samples with active fluxes such as Al₂O₃, CaO & MgO

Figure 8 shows the micro structure of PCATIG – MnO₂, PCATIG – SiO₂ & PCATIG – TiO₂ weldments. From Figure-6, the following results are observed, very fine grain microstructure is observed in base material and fine grain size microstructure in weld zone and in HAZ. Figure 7 shows PCATIG – CaO & PCATIG – MgO is also showed coarse grain structure which is similar to PCTIG welded microstructure. Intermediate size between fine and coarse microstructure is found in heat affected zone in PCATIG – MnO₂ & PCATIG – Al₂O₃. Figure-8 shows PCATIG –SiO₂ & PCATIG – TiO₂ is having very fine grain microstructure in both weld zone and fine grain microstructure heat affected zone. Base material showed very fine grain microstructure.
Figure 8: Microstructure of PCATIG welded samples with active fluxes such as TiO$_2$, SiO$_2$ & MnO$_2$.

3.3 Cooling rate – PCTIG & PCATIG welded samples

Table 3: PCTIG & PCATIG welded samples cooling rate

| PCTIG welding condition | PCTIG | PCATIG - Al$_2$O$_3$ | PCATIG - CaO | PCATIG - MgO | PCATIG - SiO$_2$ | PCATIG - TiO$_2$ | PCATIG - MnO$_2$ |
|-------------------------|-------|----------------------|--------------|--------------|-----------------|-----------------|-----------------|
| Rate of cooling (K/s)   | 291   | 286                  | 289          | 288          | 295            | 294            | 288             |

Table 3 shows the cooling rate CCTIG & ATIG weldments of various active fluxes are recorded and tabulated. Highest cooling rate is observed in PCATIG-SiO$_2$ followed by PCATIG – TiO$_2$ of 295K/s & 294K/s. Lowest cooling rate is observed in PCATIG – CaO & PCATIG – Al$_2$O$_3$ of 289K/s & 286K/s. Higher cooling rate produces the fine grain microstructure and lower cooling rate.
produces the coarse grain microstructure in weld zone and heat affected zone. This is due to the temperature gradient observed in weld zone and between weld zone & heat affected zone.

4. Conclusion

Correlation between micro hardness, microstructure and cooling rate of Pulsed Current TIG welding and Pulsed Current Activated TIG welding on Al-SiC composite has been studied. Combining the pulsed current TIG and activated TIG welding (PC-A-TIG) on Al-SiC composite showed very fine superior weld microstructure on PCATIG – SiO₂ & PCATIG – TiO₂ which resulted in higher micro hardness. Micro hardness are observed in different locations of weld surface such as 1mm, 2mm & 3mm below the weld surface and it also observed along the weld zone to heat affected zone upto 12mm for the profiling the micro hardness value around the weldment. Microstructure observed in weld centre for observed on the weld zone. 3mm away from the weld centre line shows interaction of weld zone & heat affected zone. 7mm away from the weld centre line shows the heat affected zone. Minimum micro hardness value of found in PCATIG – MnO₂, PCATIG – CaO & PCATIG – MgO due to intermediate micro structure between coarse and fine. PCATIG – Al₂O₃ weld zone & heat affected zone and heat affected zone of PCATIG – MnO₂, PCATIG – CaO & PCATIG – MgO shows coarse microstructure. This resulted in reduced micro hardness. Cooling rate for the different PCTIG & PCATIG welding are recorded and correlation between the micro structures are studied. Coarse micro structure in weld zone and heat affected zone have least cooling rate. Fine micro structure in weld zone should have higher cooling rate. Heat affected zone directly depends on temperature gradient between the weld centre and weldment heat affected zone.

Acknowledgements

This study was supported by SASTRA University authors gratefully acknowledge SASTRA University, Thanjavur, India for the same.

References

[1] LEI Yu-cheng, YUAN Wei-jin, CHEN Xi-zhang, ZHU Fei, CHENG Xiao-nong, In-situ weld-alloying plasma arc welding of SiCp/Al MMC, Transactions of Nonferrous Metals Society of China, 17, 2007, page 313-317.
[2] A. Urena, M.D. Escalera, L. Gil, Influence of interface reactions on fracture mechanisms in TIG arc-welded aluminium matrix composites, Composites Science and Technology, 60, 2000, page 613-622. (PII: S0266-3538(99)00168-2)
[3] Selvi Dev, A. Archibald Stuurt, R.C. Ravi Dev Kumaar, B.S. Murty, K. Prasad Rao, Effect of scandium additions on microstructure and mechanical properties of Al-Zn-Mg alloy welds, Materials Science and Engineering A, 467, 2007, page 132 -138. (doi:10.1016/j.msea.2007.02.080)
[4] R.I. Hsieh, Y.-T. Pan, H.-Y. Lhou, The Study of Minor Elements and Shielding Gas on Penetration in TIG Welding of Type 304 Stainless Steel, Journal of Materials Engineering and Performance, 8(1), February 1999, page 68-74.
[5] Z.D. Zhang, L.M. Liu, Y. Shen, L. Wang, Mechanical properties and microstructure of magnesium alloy gas tungsten arc welded with cadmium chloride flux, Material Characterization, 59, 2008, page 40-46.
[6] Ding Fan, Ruihua Zhang, Yufen Gu, Masao Ushio, Effect of Flux on A-TIG Welding of Mild Steels, Transaction of JWRI, 30, 1, 2001, page 35-40.

[7] Hidetoshi Fujii, Toyoyuki Sato, Shaping Lu, Kiyoshi Nogi, Development of an Advanced A-TIG (AA-TIG) welding method by control of Marangoni convection, Material Science and Engineering A, 495, 2008, page 296-303. (Doi: 10.1016/j.msea.2007.10.116)

[8] Shaping Lu, Dianzhong Li, Hidetoshi Fujii, Kiyoshi Nogi, Time Dependant Weld Shape in Ar-O2 Shielded Stationary GTA Welding, Journal of Material Science and Technology, 23 (5), 2007, page 650-654.

[9] Shaping Lu, Hidetoshi Fujii, Kiyoshi Nogi, Marangoni convection and weld shape variations in He-CO2 shielded gas tungsten arc welding on SUS304 stainless steel, Journal of Material Science, 5, 2008, page 4583-4591. (Doi: 10.1007/s10853-008-2681-3)

[10] Shaping Lu, Hidetoshi Fujii, Kiyoshi Nogi, Marangoni convection and weld shape variations in Ar-O2 and Ar-CO2 shielded GTA welding, Material Science and Engineering A, 380, 2004, page 290-297. (Doi: 10.1016/j.msea.2004.05.057)

[11] Shaping Lu, Hidetoshi Fujii, Kiyoshi Nogi, Weld Shape variation and Electrode Oxidation Behavior under Ar-(Ar-CO2) Double Shielded GTA Welding, Journal of Material Science and Technology, 26 (2), 2010, page 170-176.

[12] A. Berthier, P. Paillard, M. Carin, S. Pellerin, F. Valensi, TIG and A-TIG welding experimental investigations and comparison with simulation Part -2 - arc constriction and arc temperature, Volume 17, Number 8, 2012, Science and Technology of Welding and Joining, page 616-621.

[13] S. Leconte, P. Paillard, J. Saindrenan, Effect of fluxes containing oxides on tungsten inert gas welding process, Volume 11, Number 1, 2006, Science and Technology of Welding and Joining, page 43-47.

[14] Y.L. Xu, Z.B. Dong, Y.H. Wei, C.L. Yang, Marangoni convection and weld shape variation in A-TIG welding process, Volume 48, 2007, Theoretical and Applied Fracture Mechanics, page 178-186.

[15] Kuang-Hung Tseng, Chih-Yu Hsu, Performance of activated TIG process in austenitic stainless steel welds, Volume 211, 2011, Journal of Materials Processing Technology, page 503-512.

[16] Tian-Shiyi Chen, Kuang-Hung Tseng, Hsien-Lung Tsai, Study of the characteristics of duplex stainless steel activated tungsten inert gas welds, Volume 32, 2011, Materials and Design, page 255-263.

[17] Shaping Lu, Hidetoshi Fuji, Hirohiko Sugiyama, Kiyoshi Nogi, Mechanism and Optimization of Oxide Fluxes for Deep Penetration in Gas Tungsten Arc Welding, Volume 34-A, September 2003, Metallurgical and Materials Transactions A, page 1901-1907.

[18] L.M. Liu, Z.D. Zhang, G. Song, L. Wang, Mechanism and Microstructure of Oxides Fluxes for Gas Tungsten Arc Welding of Magnesium Alloy, Metallurgical and Materials Transactions A, 38A, March 2007, page 649-658. (DOI: 10.1007/s11661-006-9056-7)

[19] ZHANG Guang-jun, LENG Xue-song, WU Lin, Physics characteristic of coupling arc of twin-tungsten TIG welding, Volume 16, 2006, Transactions of Nonferrous Metals Society of China, page 813-817.

[20] Chunli Yang, Sanbao Lin, Fengyao Liu, Lin Wu, Qingtai Zhang, Research on the Mechanism of Penetration Increase by Flux in A-TIG Welding, Journal of Material Science and Technology, 19, 2003, page 225-227.

[21] V. Balasubramanian, V. Ravisankar, G. Madhusudhan Reddy, Effect of pulsed current and post weld aging treatment on tensile properties of argon arc welded high strength aluminium alloys, Material Science and Engineering A, 459, 2007, page 19-34. (Doi:10.1016/j.msea.2006.12.125)

[22] K. Karunakaran, V. Balasubramanian, Effect of pulsed current on temperature distribution, weld bead profiles and characteristics of gas tungsten arc welded aluminum alloy joints, Transactions of Nonferrous Metals Society of China, 21, 2011, page 278-286. (doi: 10.1016/S1003-6326(11)60710-3)

[23] V. Balasubramanian, V. Ravisankar, G. Madhusudhan Reddy, Effect of pulsed current welding on fatigue behaviour of high strength aluminium alloy joints, Materials and Design, 19, 2008, page 492-500. (doi:10.1016/j.matdes.2006.12.015)

[24] V. Balasubramanian, V. Ravisankar, G. Madhusudhan Reddy, Effect of pulsed current welding on mechanical properties of high strength aluminum alloy, International Journal of Advanced Manufacturing Technology, 36, 2008, page 254-262. (doi:10.1007/s00170-006-0848-0)