Experimental Investigation and Micro Structural Characteristics of GTAW and FSW Welded Dissimilar Aluminum Alloys

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Abstract.

Current paper shares the study on optimization of parameters for GTAW and FSW Aluminum alloys. Base metals chosen were AA6061 and AA7075, filler metal used for TIG welding is AA4043. Welding Current, Welding speed and gas flow rate were taken as input parameters for GTAW and axial load, weld speed and tool rotation were chosen as variables for FSW. L9 orthogonal array is used for design of experiments. Analysis of variance is used for ranking the parameters. It was found that an average tensile strength of 127MPa is found for GTAW samples and 151 MPa for FSW samples. Thus an overall 19% increase in strength is achieved. Micro structural analysis is done to investigate the reason for variation of strength. It was found that the formation of Mg-Si precipitates has affected the increase in strength for FSW samples.

1 Introduction

Many methods which are available for joining aluminum are gas metal arc welding, gas tungsten arc welding, joining by using adhesives, brazing, soldering, riveting, friction stir welding, laser welding, ultrasonic welding [1-6]. When welding aluminum it typically creates a soft region in the base metal and fusion zone [7]. Aluminum can also be brazed or soldered to many materials which include concrete, wood, ceramics. Manual aluminum brazing is difficult due to its variable colour change before melting. Aluminum oxide will prevent proper bonding between base metals. Many strong acids and fluxes can be used to weaker the oxidation. The alloys which are used for brazing must have low melting temperature that is below 660°C. Aluminum alloys with high magnesium can lower the melting temperature and can result for pure joint[8].

Because of higher thermal conductivity of Al alloys larger heat input is required to weld Al alloys. Because of difference in thermal conductivity Arc welding of different Al alloys (dissimilar) will give problems. High thermal conductivity will lead will make the heat to flow easily and low conductivity will lead to excess melting of material. So fusion welding of dissimilar Aluminum is interminable. Many researchers have studied the joining of dissimilar Al alloys by friction stir welding since the temperature achieved will be less than the melting point. Satisfactory results were obtained when harder material is placed on advancing position.(9-13)

AA7075 is a precipitation-hardened aluminum alloy commonly used in aerospace applications owing to its high strength. In the traditional tungsten inert gas and laser welding processes, decorative structure establishes in the fusion zone which result in the radical decrease in the strength which is one of the important mechanical properties [14]. The friction stir welding process is a solid-state welding process, so the solidification microstructure is not present in the welded metals and the presence of brittle inter dendritic and eutectic phases is avoided [15]. Generally, joints between dissimilar materials of 6061-T6 and 7075-T6 in aerospace structures are mostly prepared by riveting. This process causes stress concentration and due to which the final joints weight is increased, thereby limiting the application in the aerospace industry. Friction stir welding is used to increase the quality of the welding without the major loss of strength and corrosion. The process was used first in 1991 by TWI for joining of the aluminum amalgams.[16].

Geometrical parameters like the height of the pin and also the shape and the shoulder end details have its effect on both metal flow and the heat generation matured to frictional forces developed. With respect to this the super imposed on the rotating tool should be controlled throughout the process because the pressure developed on the tools shoulder end shows the amount of heat developed during the process. Dickerson and przydatek discovered that friction stir welded butt joints are defect free if all the precautions are followed accordingly and tuned with in a tolerance box for a particular alloy[17]. Many analysts have come to know during their research that the relation between adjustable parameters, fatigue...
characteristics, and mechanical and metallurgic properties of the weld in welding are equivalent to the aluminum amalgam[18-27].

2 Materials and Methods
There are different situations where different series of Aluminum are to be joined due to various service conditions. So proper joining process should be employed for better performance. Base metals chosen for present project were AA6061 and AA7075. Material composition and general properties of base elements were shown in Table 1 and Table 2.

Table 1: Chemical Composition Of Base and Filler metals

| S. No | Chemical Composition | % Composition of base metal AA6061 | % Composition of base metal AA7075 | % Composition of filler metal AA4043 |
|-------|----------------------|-----------------------------------|-----------------------------------|--------------------------------------|
| 1     | Silicon              | 0.7                               | 0.4                               | 4.5 – 6.0                            |
| 2     | Iron                 | 0.6                               | 0.5                               | 0.80                                 |
| 3     | Copper               | 0.3                               | 1.5                               | 0.30                                 |
| 4     | Manganese            | 0.05                              | 0.3                               | 0.05                                 |
| 5     | Magnesium            | 0.9                               | 2.5                               | 0.05                                 |
| 6     | Zinc                 | 0.2                               | 5.6                               | 0.10                                 |
| 7     | Titanium             | 0.1                               | 0.2                               | 0.20                                 |
| 8     | Beryllium            | -                                 | -                                 | 0.0003                               |
| 9     | Chromium             | 0.25                              | 0.25                              | -                                    |
| 10    | Aluminium            | 96.85                             | 87.1-91.4                         | Rest                                 |
| 11    | Other                | 0.05                              | 0.15                              | -                                    |

Table 2: General properties of base metals.

| S.No  | Physical, Mechanical, Thermal Properties | AA 6061       | AA7075       |
|-------|------------------------------------------|---------------|--------------|
| 1     | Density                                 | 2.7 g/cc      | 2.81 g/cc    |
| 2     | Hardness, Vickers                       | 107           | 175          |
| 3     | Ultimate Tensile Strength               | 310 Mpa       | 572 Mpa      |
| 4     | Tensile Yield Strength                  | 276 Mpa       | 503 Mpa      |
| 5     | Melting Point                           | 582 - 652 °C  | 477 - 635 °C |
| 6     | Specific Heat Capacity                   | 0.896 J/g.°C  | 0.96 J/g.°C  |
| 7     | Thermal Conductivity                    | 167 W/m-K     | 130 W/m-K    |

Rolled AA6061 and AA7075 plates of 2mm thick were taken and they are sheared to a size of 75x75 mm each. A V Notch is grinded at one of the ends of the specimens as shown in Fig 1. Before welding Surfaces were marinated with NaOH and HNO3 and they are wire brushed and degreased. Both plates were clamped to a copper backing plate. Rather than performing full factorial experiment design which will increase the number of experiments and cost, in this paper Taguchi method is used which provide simple, efficient and systematic approach to optimize designs for performance quality and cost. L9 orthogonal array is used to perform the experiments as shown in table 3. Both plates were TIG welded with AA4043 of 2mm diameter as filler rod. Welding Current, Welding Speed and Gas flow rate was taken as input parameters for TIG welding. After TIG welding another 9 set of specimens were taken for FSW. Tool rotation, Welding speed and axial load were taken as parameters. Tool material used was AISI H13 tool steel with taper pin. After welding the coupons were machined as per ASME standards by using electronic Elpuls 40A CNC wire cut EDM machine, Tensile tests were conducted on Computerized Universal testing machine TUE-C-600. Micro hardness for the highest strength specimens were found by using Vickers hardness testing machine. As shown in Fig 2. Microscopic images were captured by etching the specimens by Kellers reagent. Further FESEM analysis was done in ARCI, Hyderabad on Gemini 500 (M/s Carl Zeiss) equipment.
3 Results and Discussion

3.1 Tensile Test

The specimens for Tensile test were prepared as per ASTM E8 standard I section, on CNC Wire cut EDM machine. It is observed that the fracture is occurred at the joint. The tensile strengths for both TIG and FSW welded specimens were plotted in Fig 3. During the tensile test, all the examples constantly fizzled in the weld area. This shows the weld locale is nearly more vulnerable than different districts and thus the joint properties are constrained by weld district synthetic arrangement and microstructure. The transverse ductile properties of the welded joints recommend that the FSW joints show better tractable properties relative to the GTAW joints. It was found that in TIG welding at a current of 140 A, weld speed of 70mm/min and gas flow rate of 10 Lit/Min a maximum strength of 148MPa is achieved. The tensile strength of FSW welded sample at 1200 rpm tool rotation, 60mm/min welding speed and 5KN welding speed a maximum tensile strength of 180MPa is found to be maximum. Thus an 21.6 % increase of strength is observed.
3.2 Hardness Test

Tensile strength and Hardness are connected to each other since they depend upon the formation of metal. The more hardness the material possess the more brittle it becomes and eventually tensile strength gets decreased so in order to evaluate the behavior of metal both tensile and hardness of the joint is need to be analyzed. Hardness for the sample with high tensile strength is chose and values are determined. The graphs for hardness are shown in Fig 4 and Fig 5. In all coupons it was found that the hardness value seen decreasing from weld center.

![Fig 4: Micro Hardness for GTAW samples](image)

![Fig 5: Micro Hardness for FSW welded samples](image)

3.3 Analysis Of Variance (ANOVA)

Analysis of variance is used to determine the importance of one or more factors by comparing the response means at the various levels of factors. It works by comparing the variance between the group means and the variance within the groups. ANOVA table lists the sources of variation, their degrees of freedom, the total sum of squares and mean squares, F-statistics and P-Values. All these are used to determine whether the factors are significantly related to the response or not. Sum of squares between the factors and sum of squares within the factors (error) is used to calculate the total sum of squares.

Total sum of squares = Sum of squares between the factors + sum of squares within the factors

\[ \sum_{i=1}^{n} (y_i - \bar{y})^2 \]  

Where \( y_i \) = value of tensile strength of a particular level. 
\( \bar{y} \) = mean of the tensile strength.

Mean of squares is calculated by dividing the sum of squares by the degrees of freedom. F-statistics is found by dividing the mean of squares by the error mean of squares. P-value is used to determine whether the factor is significant or not. If the P-Value is less than 0.05, then the particular factor is considered as significant.

\[ \text{Percentage of contribution} = \frac{\text{sum of squares of individual factor}}{\text{Total sum of squares}} \]  

Eq-2
Process parameters chosen were shown in Table 3. The main effects of plots of S/N ratio for TIG and Friction stir welding are shown below. These graphs can be used to know the optimum input parameters for maximum tensile strength. In TIG welding at a welding current of 140Amps, welding speed of 70 mm/min, Gas flow rate 10 L/min a maximum tensile strength of 148Mpa is obtained. In friction stir welding at a Tool rotation speed of 1200RPM, Welding speed of 60 mm/min and Axial force 5KN, a maximum tensile strength of 180Mpa is obtained. From Fig 8 it can be observed that in GTAW current, speed and flow rate has taken first, second and third preferences. Whereas in FSW Tool rotation, welding speed and load has taken first, second and third place respectively. The graphs are shown in Fig 7 and Fig 8. F values and P values are shown in Table 4. The regression equations found from anova are shown in Eq 4 and Eq 5.

Table 3: Process Parameters for FSW and GTAW

| Factor               | FSW Type  | Levels | Values       | Factor               | GTAW Type | Levels | Values       |
|----------------------|-----------|--------|--------------|----------------------|-----------|--------|--------------|
| Tool Rotation (Rpm)  | Fixed     | 3      | 800, 1000, 1200 | Welding Current (A)  | Fixed     | 3      | 100, 120, 140 |
| Welding Speed (Mm/Min) | Fixed   | 3      | 60, 70, 80   | Welding Speed (Mm/Min) | Fixed     | 3      | 70, 80, 90   |
| Axial Load (Kn)      | Fixed     | 3      | 3, 4, 5      | Gas Flow Rate (Lit/Min) | Fixed     | 3      | 8, 9, 10     |

Table 4: Analysis variation

| Source                | FSW DF | Adj SS | Adj MS | F-Value | P-Value | GTAW DF | Adj SS | Adj MS | F-Value | P-Value |
|-----------------------|--------|--------|--------|---------|---------|---------|--------|--------|---------|---------|
| Tool Rotation (Rpm)   | 2      | 1824.89| 912.44 | 25.99   | 0.037   | 2       | 450.89 | 225.44 | 15.98   | 0.059   |
| Welding Speed (Mm/Min)| 2      | 661.56 | 330.78 | 9.42    | 0.096   | 2       | 398.22 | 199.11 | 14.11   | 0.066   |
| Axial Load (Kn)       | 2      | 160.22 | 80.11  | 2.28    | 0.305   | 2       | 59.56  | 29.78  | 2.11    | 0.322   |
| Error                 | 2      | 70.22  | 35.11  |         |         | 2       | 28.22  |        | 14.11   |         |
| Total                 | 8      | 2716.89|        |         |         | 8       | 936.89 |        |         |         |
The Regression equation For FSW is

\[
\text{Tensile Strength(Mpa)} = 151.11 - 18.44 \text{ Tool Rotation(Rpm)}_{800} + 2.22 \text{ Tool Rotation(Rpm)}_{1000} + 16.22 \text{ Tool Rotation(Rpm)}_{1200} + 10.56 \text{ Welding Speed(Mm/Min)}_{60} - 0.11 \text{ Welding Speed(Mm/Min)}_{70} - 10.44 \text{ Welding Speed(Mm/Min)}_{80} - 2.11 \text{ Axial Load(Kn)}_{3} - 3.78 \text{ Axial Load(Kn)}_{4} + 5.89 \text{ Axial Load(Kn)}_{5} \quad \text{Eq 4}
\]

The regression equation for GTAW is

\[
\text{Tensile Strength(Mpa)} = 127.11 - 8.78 \text{ Welding Current(A)}_{100} + 0.22 \text{ Welding Current(A)}_{120} + 8.56 \text{ Welding Current(A)}_{140} + 8.89 \text{ Welding Speed(Mm/Min)}_{70} - 1.78 \text{ Welding Speed(Mm/Min)}_{80} - 7.11 \text{ Welding Speed(Mm/Min)}_{90} - 1.11 \text{ Gas Flow Rate(Lit/Min)}_{8} - 2.44 \text{ Gas Flow Rate(Lit/Min)}_{9} + 3.56 \text{ Gas Flow Rate(Lit/Min)}_{10} \quad \text{Eq 5}
\]

Fig 6: Main Effects Plot For SN ratios GTAW joints

Fig 7: Main Effects Plot For SN ratios FSW joints

Fig 8: Percentage Contribution of Parameters
3.4 Microscopic Study

Usually base metals (BM) exhibit highest strength this is because of involvement of alloying partners like Mg and Si. These two mix together to form a much stronger precipitate Mg$_2$Si. Steady distribution of these precipitates all round the Al matrix gives high strength and hardness. In GTAW base metal gets diluted in weld zone, thus a huge amount of Si is readily available for precipitation, but Mg because of this fusion gets evaporated so the formation of Mg$_2$Si is very low. Whereas in case of FSW since there is no inclusion of filler via fusion the base metal does not get diluted or melted as a result the formation of Mg$_2$Si is high and high strength and hardness is achieved. The microstructures of base and welded specimens were shown in Fig 9.

One more comparison observed between GTAW and FSW samples were size of grains, the longitudinal grains observed in GTAW samples and fine grains were observed in FSW samples. We know that fine grains achieve high properties. In FSW the base metals are brought to plastic deformation because of higher rotation of pin, so the long grains are axed to short and coarse grains are achieved. Because of this the mechanical properties are found improved in FSW joint. When the microstructures are compared in FSW samples the original structure of the grains were completely refined and a new pattern of crystals were formed this process is known as Recrystallization. Even though there is no clear view of grain nucleation but new pattern of grain structure has evoked the study. This might one reason for the high mechanical properties of FSW Joints. FESEM images were shown in Fig 10.

Emission Scanning electron microscope (FESEM) is used for study of grain crystallization, the fractured samples were further studied and images were shown in Fig. 11. The difference in fractured specimens was clearly visible the formation of dimple and smooth zones were seen. An erratic fracture is seen in TIG welded samples. The mechanism of fracture is dimple blowout. The existence of voids and pores in TIG is main cause for fracture.

![Fig 9: (a) AA 6061 Microstructure (b) AA 7075 Microstructure (c)GTAW Microstructure (d) FSW Microstructure](image-url)
Fig 10: (a) FESEM of GTAW (b) FESEM of FSW (c) Striations in FSW (d) Intermetallics

Fig 11: (a) Fracture in FSW (b) Fracture in GTAW

4 Conclusion

From the results and discussions made the following conclusions are drawn,

1. AA6061 and AA7075 Dissimilar Aluminum alloys were joined in the form of butt 2 mm thick sheets by GTAW and FSW. The joint was found successful.
2. An average tensile strength of 127 MPa is achieved by GTAW samples and 151 Mpa for FSW samples. An increase of 20% tensile strength is observed for FSW joints. Presence of magnesium has improved strength in FSW joints.
3. In TIG welding at a welding current of 140Amps, welding speed of 70 mm/min, Gas flow rate 10 L/min a maximum tensile strength of 148Mpa is obtained. In Friction stir welding at a Tool rotation speed of 1200RPM, Welding speed of 60 mm/min and Axial force 5KN, a maximum tensile strength of 180Mpa is obtained.
4. Involvement of β-Mg Si precipitates is main cause for improved mechanical properties of FSW joint.
5. Due to the stirring action longitudinal grains were axed to fine coarse grains in FSW weld area which improved the mechanical properties of joint.
References

1. M. J. Crooks, R. E. Miner, Journal of Metals, 1996, 48, 13–15.
2. Y. Kuritara, Journal of Metals, 45 1993,11, 32–33.
3. G. P. Syukla, D. B. Goel, P. C. Pandey, All India Seminar on Aluminium, New Delhi, 1978.
4. Report of Investigation on the Technical Trend of Patent Applications in 2004: Automobile Weight reduction Technologies, Japan Patent Office, 2005.
5. Fundamentals of Aluminium Metallurgy, doi.org/10.1016/C2016-0-02117-4.
6. Bonenberger, R. Paul (2005). The First Snap-Fit Handbook. 6915Valley Avenue,Cincinnati, Ohio 45244-3029, USA: Hanser Gardner Publications, Inc. ISBN 1-56990-388-3.
7. Pocisus, Alphonsus V. (2012). Adhesion and Adhesives Technology: An Introduction. 6915 Valley Avenue, Cincinnati, Ohio 45244-3029, USA: Hanser Publications. ISBN 978-3-446-43177-5.
8. A. Heidarzadeh, H. Khodaverdizadeh, A. Mahmoudi and E. Nazari. Tensile behavior of friction stir welded AA6061-T4 aluminum alloy joints. Journal OfMaterials&Design 2012; 37:166–173.
9. S. Sheikh, and C. Bolftarini. Preliminary study on the microstructure and mechanical properties of dissimilarfriction stir welds in aircraft aluminum alloys 2024-T351 and 6056-T4 2007; 6:132–142.
10. P. Rao Microstructure and Mechanical Properties of Friction Stir Lap Welded Aluminum Alloy AA2014. Journalof Materials Science & Technology 2011; 28(5): 414–426.
11. M. Koilraj, V. Sundareswaran, S. Vijayan, and S. R. K. Rao, Friction stir welding of dissimilar aluminum alloys AA2219 to AA5083 – Optimization of process parameters using Taguchi technique. Materials and Design 2012;42:1–7.
12. P. Xue, D. R. Ni, D. Wang, B. L. Xiao, and Z. Y. Ma. Effect of friction stir welding parameters on the microstructure and mechanical properties of the dissimilar Al – Cu joints 2011; 528:4683–4689.
13. S. Kotari et al. Mechanical and micro structural behaviour of flux coated GTAW and FSW joined AA6061 aluminium alloy.Materials Today: Proceedings 27 (2020) 1660–1667.
14. R. G. Madhusudhana, P. Sammaiah and T. Mohandas. Influence of welding techniques on microstructure and mechanical properties of AA6061(Al-Mg-Si) gas tungsten arc welds. In Proceedings of National Conference on Processing of metals, Miami, FL, 2002.
15. J. Q. Su, T. W. Nelson, R. Mishra and M. Mahoney. Microstructural investigation of friction stir welded7050-T651 aluminium. ActaMater., 2003, 51, 713–729.
16. C. G. Mahoney and W. H. Bingel. Effects of friction stir welding on microstructure of 7075aluminium. Scripta Mater., 1997, 36, 69–75.
17. W. M. Thomas. Friction stir butt welding. US Patent no.5460, 317, USA, 1991.
18. H. J. Liu, H. Fujii, M. Maeda and K. Nogi. Tensile properties and fracture locations of friction-stir-welded joints of 2017-T351 aluminum alloy. J. Mater. Processing Technol., 2003, 142, 692–696.
19. C. G. Rhodes, M. W. Mahoney, W. H. Bingel,R. A. Spurling and C. C. Bumpton. Effects of friction stirwelding on microstructure of 7075 aluminium. Scripta Mater., 1987, 36(1), 69–75.
20. D. J. Hattingh, C. Blignaut, T. I. Niekerk and M. N. Jamesa. Characterization of the influences of FSW tool geometry on welding forces and weld tensilestrength using an instrumented tool. J. Mater. Processing Technol., 2008, 203, 46–57.
21. A. Barcellona, G. Buffa, and L. Fratini, Process parameters analysis in friction stir welding of AA6082–T6 sheets. Keynote paper of the VII ESAFORM Conference,Trondheim, Norway, 2004, pp. 371–374.
22. T. L. Dickerson, and J. Przydatek, Fatigue of friction stirwelds in aluminum alloys that contain root flaws. Int. J.Fatigue, 2003, 25, 1399–1409.
23. Y. Chen, H. Liu and Feng. J. Friction stir welding characteristics of different heat-treated state 2219 aluminum alloy plates. Mater. Sci. Engng A, 2006, 420, 21–25.
24. P. Cavaliere and F. Panella. Effect of tool position on the fatigue properties of dissimilar 2024–7075 sheets joined by friction stir welding. J. Mater. Processing Technol., 2008, 206, 249–255.
25. P. Cavaliere, De, A. Santis, F. Panella, and A. Squillace. Effect of welding parameters on mechanical and microstructural properties of dissimilar AA6082– AA2024 joints produced by friction stir welding. Mater. Des., 2008, 30, 609–616.
26. S. Kotari, E. Punna, S. M. Gangadhar et al., Dissimilar metals TIG welding-brazing of AZ31 magnesium alloy to 304 stainless steel, Materials Today: Proceedings, matpr.2020.05.553