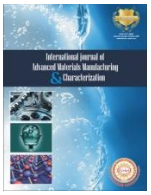


Advanced Materials
Manufacturing & Characterization

journal home page: www.ijammc-griet.com

Friction Stir Welding of Aluminum 6082 with Mild Steel and its Joint Analyses

Sajin G. Sajan, Manish Meshram, Pankaj, Palli Srinivas, Suhash R. Dey*

Department of Materials Science and Engineering, Indian Institute of Technology Hyderabad, Ordnance Factory Estate, Yeddumailaram-502205.

ARTICLE INFO

Article history:
Received 10 Nov 2012
Accepted 26 Dec 2012

Keywords:
Friction stir welding;
Dissimilar materials,
Tensile strength;
Energy dispersive spectroscopy.

ABSTRACT

Friction stir welding is carried out on 6mm thick plates of Al 6082 alloy and mild steel, where various welding parameters like, tool rotation speed (rpm), welding speed (mm/min) have been optimized and a suitable range for all parameters is achieved. After welding, good samples are selected and small specimens are cut from it perpendicular to the weld direction for microhardness and tensile tests. In this research study, the significance of placing the material on advancing and retreating sides especially during the welding of dissimilar materials has been checked, with the help of microstructural characterization technique like energy dispersive spectroscopy (EDS) analyses

Introduction

Energy-saving and reduction in CO_2 emission are the two important challenging issues facing our world today. One of the effective counter-measures is the reduction in weight of automobiles that contributes to the maximum pollution. It is estimated that 10% of vehicle weight reduction results in 8–10% of fuel economy improvement [1]. Nowadays, generally the vehicle weight reduction is achieved by (a) replacing the high density steel by new aluminum alloys and/or (b) by using advanced light weight high strength steels. As cost is a problem for both of the above mentioned methods, there is a huge demand for joining conventional steel and aluminum alloys, in vital parts of vehicle like chassis module, doors, trunk lid etc. So introduction of aluminum components in a standard steel car body is an attractive compromise between cost and performance.

The diverse physical properties like melting point, thermal conductivity of steel and aluminum, make it difficult to join, especially by conventional fusion welding, as it will introduce welding defects like solidification and liquation cracks, porosity, intermetallics (due to high temperature) etc. Besides, there is low solid solubility of Fe in Al, which eventually leads to the formation of brittle intermetallic compounds (IMCs).

Earlier investigations by T.Watanabe et al. showed that the feasible way to join steel and aluminum is by Friction Stir Welding (FSW) [2]. They were able to join 2 mm thick plates and have obtained a joint tensile strength about 86% of that of Al base metal [3]. Chen and Kovacevic also have demonstrated the joining of Al 6061 and mild steel plates having 6-mm thickness [4]. Jiang and Kovacevic obtained a steel/Al weld having higher average joining strength and hardness value than base Al [5]. Intermetallic compounds at the interface and blocky steel particles were observed in the weld. Six different phases were identified in the binary phase diagram of Fe-Al system [6] and formation of large amounts of intermetallics will drastically degrade the mechanical properties (tensile strength, etc) [7]. Complete interface microstructural analysis has been done on the inertia friction welds [8]. Various sizes of steel fragments were found in the entire region of nugget (weld) zone [9]. Recently, researchers reported a detailed analysis of how IMC layer of distinct thickness and composition (obtained by heat treatments), which influenced the mechanical properties of dissimilar joints of 2 mm steel and Al alloys (with and without Si) [10].

Friction Stir Welding (FSW)

FSW is an innovative solid-state joining process invented and patented by The Welding Institute (TWI), UK in 1991 [11], in which a non-consumable rotating cylindrical tool with a shoulder and a specially designed pin, harder than the material to be welded is inserted into the butt lines of the base metal plates and subsequently travelled along the joint line [12]. Frictional heat generated due to the rubbing action of tool-shoulder part against the work piece makes it soft and plastically deform and the rotation and transverse movement of tool-pin

---

- Corresponding author: Suhash R. Dey

- Doi: http://dx.doi.org/10.11127/ijammc.2013.02.033

part facilitates the joining along the interface line of two pieces. It has been one of the most significant developments in the last two decades because of its eco-friendliness, energy efficiency and versatility. This innovative technology makes it simple to join steel and aluminum, and improves the potential of coupling aluminum parts to steel in vehicle bodies, and has other wide range of industrial applications.

Aquatic transportation vehicles prefer hulls made of steel and aluminum alloys, in which they make bottom part below the water surface-steel and above the water surface-aluminum alloys; to lower the centre of gravity, as well reduction in the overall weight of the ship [13].

The main objectives of this work are to find the suitable welding parameters for the joining of 6-mm plates of Al 6082 alloy and mild steel and to study the significance of advancing and retreating sides in dissimilar welding through hardness profile, tensile tests and energy dispersive spectrometry (EDS) analyses of the interface which shows the diffusion of elements into the other regions.

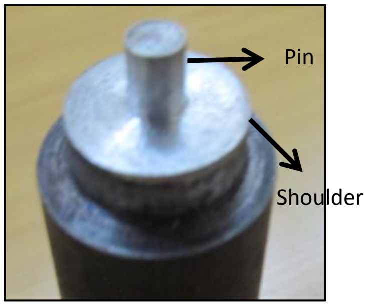
Experimental Procedures and Studies

Materials and Experimental set up

Experiments in this study are performed in the ETA Friction Stir Welding machine (specifications given in Table 1). The dimensions of both aluminum 6082 and mild steel (110 mm x 50 mm x 6 mm) was butt welded using 7 kW horizontal head milling machine (Fig.2). Chemical compositions of the work pieces are given in Table 2. Tool material of AISI 4140 tool steel [13] having cylindrical pin was used for the welding. (Fig.1).

Table 1. ETA Friction Stir Welding Machine Specifications
Capacity: 10 TonesVertical Bed

	Minimum	Maximum
Spindle speed	1 RPM	3000 RPM
Transverse speed	16 microns/sec	3000 mm/min
Plunge speed	16 microns/sec	2000 mm/min



Shoulder diameter

(SD) – 25 mm

Pin diameter

(PD) – 6 mm

Fig. 1 AISI 4140 tool steel

Table 2. Nominal chemical composition of 6082 Alloy and mild steel

6082 Al alloy	Cu 0.1 Zn 0.2	Mn 0.7 Ti 0.1	Mg 0.8 Si 1.0	Cr 0.25 Al balance	
Mild steel	C 0.18 S < 0.05	Mn 0.75 P < 0.04		Fe balance	

Fig. 2 FSW Machine showing fixture and horizontal feed

Optimization of the welding parameters

Main difficulty encountered in a FSW is the process optimization. Different parameters like tool rotation (rpm), welding speed (mm/min), tool plunge depth (mm), axial force (N), tool design etc. are involved in deciding the sufficient heat generation for the effective (quality) solid state joining of materials [14]. Additionally, in case of dissimilar metals like steel and aluminum, offsetting is also highly important [3].

Fig. 3 Process of optimization of steps from a – f.

Table 3. Aluminum was kept on the retreating side and steel on the advancing side and the table (bold and underlined) shows the weld that was successful.

Process parameters	Unit	Samples set 1	Samples set 2	Samples set 3	Samples set 4	Samples set 5
Rotation speed	rpm	600 - 800	<u>**500**</u>	<u>**400**</u>	300	250 – 200
Transverse speed	mm/min	10 – 80	10 – 40	<u>**10**</u> and <u>**15**</u>	1, <u>5</u>, 10, 15	1 - 20
Offset	mm	1	1	1	1	1
Plunge depth	mm	0.15	0.15	0.15	0.15	0.15
Axial force	KN	7	7	7	7	7

Offset (1mm), axial force (7 KN) and tilt angle of 3 degree were kept constant. Plunge depth was little bit varied and 0.15 mm is found sufficient for the proper joint. From the figure 3, (a, b, c) are the samples coming under set 1 and set 5 (Table 3). These two sets are the two extreme limits of heat generation. Rpm is highest in set 1 and due to the overheat generation, aluminum began to melt and samples are not joined properly. Reverse happened in set 5 as due to insufficient heat generation (less rpm) samples are not able to join.

As when it reached to 500 rpm and welding speed around 20 mm/min, material started to join. Sample f is in from set 3 which is joined well as there are no welding defects as far as observed with naked eye. Set 4 samples are also welded with 300 rpm and 5 mm/min welding speed. First half of the sample d (from set 2) is given a plunge depth of 0.1 mm, in which the shoulder is not able to touch properly and when a plunge depth of 0.15 mm is given in the second half, the pressure is sufficient enough to make the shoulder touch the surface properly.

Results and Discussions: Significance of advancing side and retreating sides in dissimilar welding (a comparative study)
Tensile strength

Tensile specimens of required dimension are prepared by Electric Discharge Machine (EDM). Then the tensile test has been carried out with the help of Material Testing System (MTS) of 100kN. From among all the samples of aluminum in the retreating side, 400 rpm and 10 mm/min got the maximum tensile strength of 35 MPa. Steel and aluminum is not joined properly. But when the aluminum is kept on the advancing side and steel on the retreating side; a particular parameter (300 rpm and 5 mm/min), gave a significant increase in the tensile strength to a value of 160 MPa. The welding parameters of both the types are mentioned in Table 4.

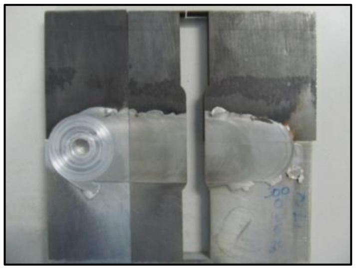


Fig. 4 Tensile sample taken out from the sample by EDM cutting

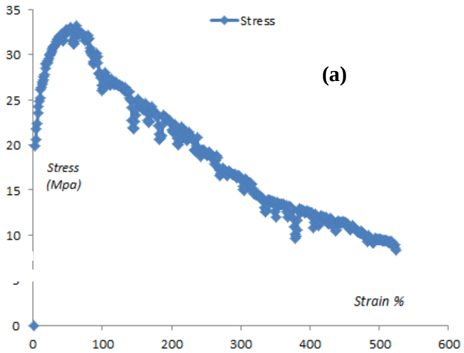
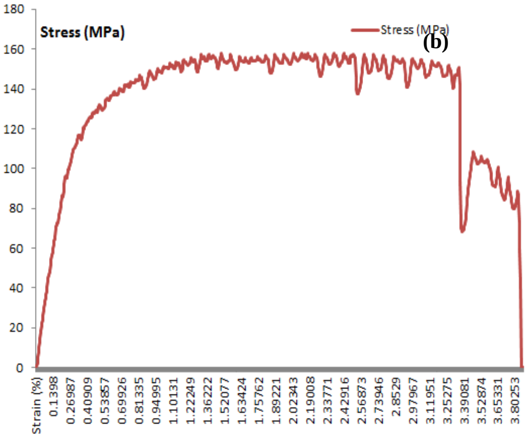


Fig. 5(a) Steel kept in the advancing side



(b) Aluminum kept in advancing side

As can be seen in Fig. 5 that there is not much strength and elongation in the joint as aluminum has not diffused properly into steel or vice versa. Maximum tensile strength of only 34 MPa is achieved. It indirectly infers that more diffusion has taken place when aluminum is kept in the advancing side. One problem that occurred in aluminum in advancing side is formation of void (fig. 6). Mishra et al. [15] reported that voids generally form on the advancing side and the reason they pointed out were the insufficient forging pressure and the high welding speed. If the travel speed is fast, the deformed material will cool before the material can fully fill the region directly behind the tool. Also if insufficient heat is generated, the material will not flow properly and leads to the formation of voids. Though the void is formed in this weld, we have observed the proper diffusion of materials in the interface (in EDS studies presented later). On the other hand the sample in which steel is kept in the advancing side sudden failure occurred as the joint is not properly welded.

Fig. 6 Formation of void in the advancing side

Microhardness distribution

Base metal steel has got an average hardness value of 125 HV and that of Al 6082 alloy has a value of 85 HV. It is noticed that maximum hardness value (150 HV) of steel kept on the advancing side in fig. 7(a) is comparatively less (260 HV) than the aluminum kept on the advancing side in fig. 7(b). Another observation is that a significant difference of hardness is observed at the exact interface (95 HV in first case and 250 HV in the second case), which shows the joint strength was higher for the Al advancing side, thus matching with the earlier tensile strength of the two joints. Image of the indenter is captured by the camera at the interface (fig. 8(a)). A sudden jump in the hardness value (180 HV) is observed in the aluminum region in fig. 7(b) is due to the indentation happened on a steel particle found in Al matrix (fig. 8(b)). So many steel particles are found spread all over the Al matrix near to interface, when observed through optical microscope (Fig. 9). All these observations are taken for the Al advancing sample.

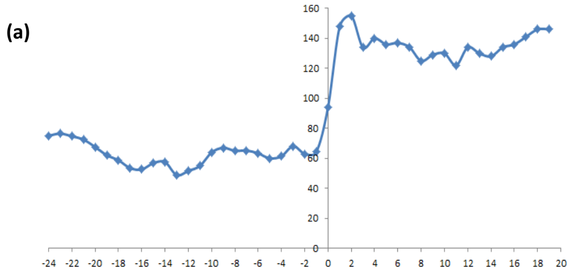
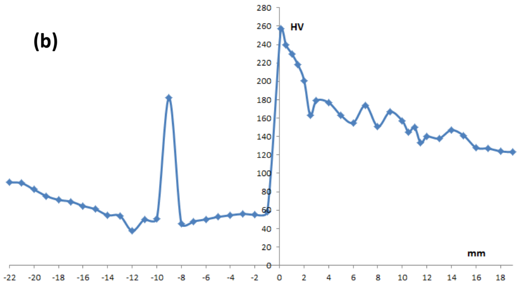


Fig. 7 Hardness profile: **(a)** Steel in the advancing side



(b) Aluminum in the advancing side.

(a) **(b)**

Fig. 8 Microhardness indentor image (a) at the interface (b) on a steel particle in the Al matrix

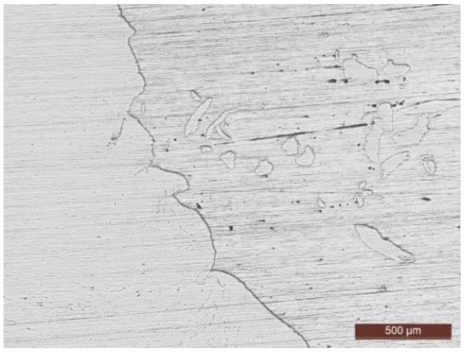


Fig. 9 Optical microscope image showing the numerous steel particles in the Al matrix near to the interface in aluminum advancing side specimen.

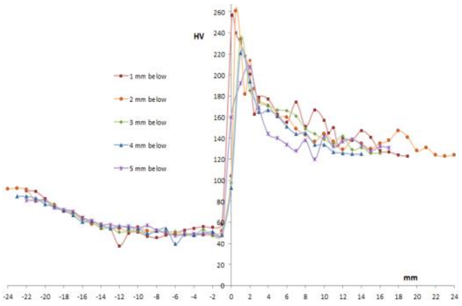


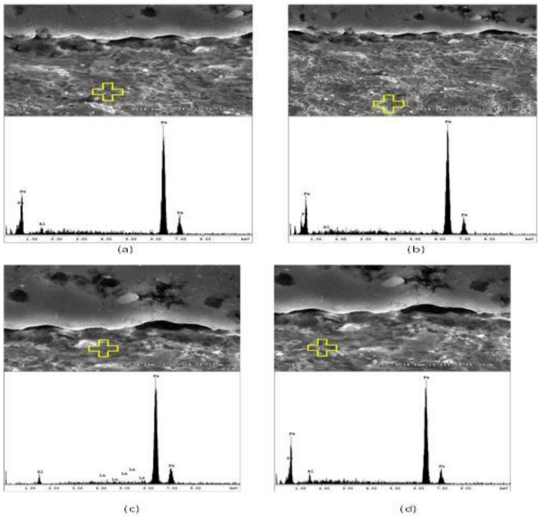
Fig. 10 Microhardness distribution taken from top to bottom of the transverse section in the Al advancing sample

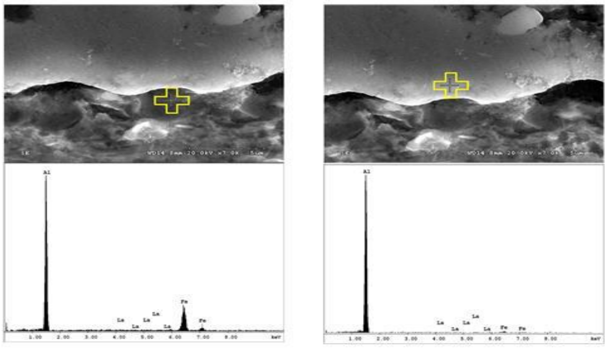
Hardness distribution of the better sample (Al advancing side) is measured from top to bottom of the transverse section and observed that a shift in the peak hardness value towards the base metal steel side very close to the interface. As we measured hardness value for top to bottom peak value got shifted towards the steel base. There is not much difference in the hardness value in the aluminum region.

Energy Dispersive Spectroscopy (EDS) analyses of the joint interfaces (Al advancing side)

EDS point analyses are taken in the steel region away from the interface which projected only Fe component (Fig. 11 (a) and (b)). But when the analysis is performed much more near to the interface in the steel region itself, small Al component is observed, which shows that little Al has come over to steel side [Fig. 11 (c) and (d)]. EDS when taken very close to the interface in the steel side, Al component is observed more than Fe component [Fig. 11 (e)], which shows the homogeneous distribution of Al into steel region. Interesting fact is that when EDS is taken on the Al region, Fe component is totally absent which shows that steel has not mixed homogeneously into Al side. This is contradictory to the optical microscope image data which shows that bulky steel particles moved into aluminum matrix.

Though the steel patrticles moved into Al, homogeneous diffusion of Al into steel has taken place at the interface and steel has not diffused into aluminum side.





(e) (f)

Fig. 11 (a) & (b) shows the EDS analysis taken in steel region little far from the interface and only Fe component was seen; (c) & (d) also shows the EDS analysis taken in the steel region much closer to the interface, here Fe and small amount of Al was seen; (e) when it was very close to interface, Al component raised higher than Fe component; (f) analysis taken in Al region very close to interface but there was no evident of Fe component.

Conclusions

Friction stir welding is performed to join 6mm thick plates of Al 6082 alloy and mild steel with varied parameters (like, tool rotation speed (rpm), welding speed (mm/min)) and the joining conditions are optimized. In this dissimilar material joining, the offsetting of the tool with respect to the workpiece and the significance of placing the hard and soft material in the advancing or retreating side of the weld are tested. The soft aluminum when kept on the advancing side provided a drastic increase in the mechanical properties like hardness, tensile and yield strength of the welded joint. EDS analyses on the interface and surrounding areas of the microstructure confirmed that the hot and soft aluminum moved homogeneously into the heated steel region, resulted into proper joining and good mechanical properties of the weld.

Acknowledgement

The authors gratefully acknowledge Professor Satish V. Kailas (Mechanical Engineering, IISc Bangalore, India) for the usage of friction stir welding machine. This research has been funded by DAE, India (No.2012/20/34/1/BRNS).

References

1. W.S. Miller, L. Zhuang, J. Bottema, A.J. Wittebrood, P. De Smet, A. Haszler, A. Vieregge. “Recent development in aluminium alloys for the automotive industry”. Materials Science and Engineering (2000); A280: 37–49.
2. T.Watanabe, H.Takayama, K.Kimapong, N.Hotta, "Joining of Steel to Aluminum Alloy by Interface-Activated Adhesion Welding". Materials Science Forum (2003); 426-432: 4129-4134.
3. Takehiko Watanabe, Hirofumi Takayama, Atsushi Yanagisawa. “Joining of aluminum alloy to steel by friction stir welding”. Journal of Materials Processing Technology (2006); 178: 342–349.
4. C.M. Chen, R. Kovacevic. “Joining of Al 6061 alloy to AISI 1018 steel by combined effects of fusion and solid state welding”. International Journal of Machine Tools & Manufacture (2004); 44: 1205–1214.
5. W H Jiang and R Kovacevic. “Feasibility study of friction stir welding of 6061-T6 aluminium alloy with AISI 1018 steel”. Proc. Instn Mech. Engrs (2004); 218:1323-1331.
6. Aleš FRANC. “Heterogeneous joints between steel and aluminum made by modified MIG process”. Metal 2010.
7. Tsutomu Tanaka,Taiki Morishige and Tomotake Hirata. “Comprehensive analysis of joint strength for dissimilar friction stir welds of mild steel to aluminum alloys”. Scripta Materialia (2009); 61: 756–759.
8. Emel Taban, Jerry E. Gould, John C. Lippold. “Dissimilar friction welding of 6061-T6 aluminum and AISI 1018 steel: Properties and microstructural characterization”. Materials and Design (2010); 31: 2305–2311.
9. Thaiping Chen. “Process parameters study on FSW joint of dissimilar metals for aluminum–steel”. Journal Mater Science (2009); 44:2573–2580.
10. [H. Springer, A. Kostka, J.F. dos Santos, D. Raabe. “Influence of intermetallic phases and Kirkendall-porosity on the mechanical properties of joints between steel and aluminium alloys”. Materials Science and Engineering A (2011); 528: 4630–4642.
11. W.M. Thomas, E.D. Nicholas, J.C. Needham, M.G. Murch, P. Templesmith, C.J. Dawes, G.B. Patent Application No. 9125978.8 (December 1991).
12. R.S. Mishra, Z.Y. Ma. “Friction stir welding and processing”. Materials Science and Engineering (2005); R 50: 1–78.
13. Thaiping Chen, Wei-Bang Lin. “A prime study on FSW joint of dissimilar metals”. Proceedings of the XIth International Congress and Exposition (2008).
14. FU Zhi-hong, HEDi-qui, WANG Hong. “Friction Stir Welding of Aluminum alloys”. Journal of Wuhan University of Technology – Material Science (2004); 19: 61-64.
15. Rajiv S. Mishra. Murray W. Mahoney. “Friction Stir Welding and Processing”. ASM International; 2007: page 12 of 352.