Detailed Study on Dissimilar Welding of Low Carbon Steel with AA1050 using TIG Welding

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Abstract

This paper aimed at the detailed study to weld dissimilar metals of 2mm AA1050 aluminium alloy and 1mm Low carbon steel. Process window for Tungsten Inert Gas Welding was identified. In TIG welding, joining ferrous with non ferrous by butt joint is not feasible since it has different thermal properties and melting point. So, lap joint is tried in which, Low carbon steel is placed on the top side and aluminium is placed below. Low carbon steel is plasticized, which is more or less equal to the melting point of aluminium, which will be enough to fuse the molten aluminium with the plasticized low carbon steel. This process is analogous to that of self brazing process. Special type of fixtures was developed for holding the workpiece. The results of microstructure, tensile strength, Vickers micro hardness and XRD analysis were discussed. Lap welds could be obtained with different combinations, but only within narrow operating windows. Extremely hard phases were obtained with fusion zones resulting in very brittle welds which were prone to cracking. The results indicated that TIG welding process is one of the feasible processes to weld dissimilar metals like Low Carbon Steel and aluminium alloy.

1. Introduction

Joining dissimilar metals is essential nowadays in manufacturing and constructing advanced machineries and equipments. Dissimilar joints can be used to create mechanically robust joints between parts composed of dissimilar metals in marine, automotives, aerospace, boiler and medical applications. Different kinds of metals feature different physical, chemical and metallurgical properties: some are stronger, some have high weldablity, some are high corrosion resistant, some are easily machinable, etc. Dissimilar weld is therefore required to compose different properties of metals in order to minimize material cost, maximize the performance and reduce the vulnerability to failure and maintenance. In recent times there has been an increase in the interest of the use of welding techniques to join dissimilar metals mainly ferrous with non ferrous.

Pure Aluminium has little strength, but possesses high electrical conductivity, reflectivity and corrosion resistance. Aluminium is the most commonly used and commercially available metal due to its light weight and high strength to weight ratio. The steel / Aluminium combination nowadays also has applications in small ship/yacht-building [1]. The car industry focuses to improve fuel efficiency. One of the solutions is to reduce the weight of the car body. Replacing of steel parts by aluminium is very effective to achieve large weight reduction [2]. Further aquatic transportation vehicles prefer hulls made of steel and aluminium alloys; the under-water surface is made of steel, whereas, above the water surface, it is possible to use aluminium alloy. This structure not only lowers the centre of gravity of the vehicles, but also achieves a greater weight reduction [4]. Lighter means of transport permits saving on fuel consumption and contribute to the environmental protection due to the reduction of green house gases [8]. It has been known that the difficulty of dissimilar metal joining between steel and aluminium alloy is caused with the brittle intermetallic reaction phase formation [9]. The formation of brittle intermetallic compounds varies according to the welding conditions and has to be avoided as much as possible. Indeed, it has been shown that those intermetallic compounds can weaken the weld joint because of high micro-hardness [8].

Tungsten Inert Gas welding is suitable welding process for joining thin sections of similar metals. It is one of the possible welding processes for joining dissimilar metal between steel/aluminum alloys by using self-brazing technique due to its possibility to produce partial penetration weld in steel sheet. It is difficult to join steel to aluminum by fusion welding. The main challenge in the fusion of Aluminium to steel is the large difference in the melting temperatures. Further, the difference in thermal expansion coefficient is large, which leads stress in the joint interface [1]. In addition to the temperature difference, the formation of intermetallic compounds such as $FeAl_3$ and Fe_2Al_5 has a major role in welding dissimilar joints [6]. Better results can be expected when the amount of Aluminium rich intermetallic compounds are reduced to the major extent [3].

However, few researches were done in order to investigate on TIG Welding in joining steel and aluminium alloys. Thus, in the present paper, detailed study on using TIG welding in joining of dissimilar metals like low carbon steel and aluminium alloy has been carried out.

2. Experimental Set Up

TABLE I:
CHEMICAL COMPOSITION OF LOW CARBON STEEL

ELEMENT	C	Mn	Si	P	Cr	Ni	Ti	FE
% OF WT	.06	.23	.06	.02	.045	.045	.002	99.4

TABLE.II
CHEMICAL COMPOSITION OF AA 1050

ELEMENT	Al	Si	FE
% OF WT	99.5	0.25	0.25

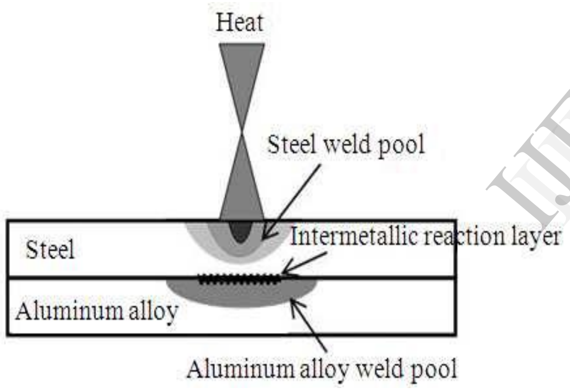


Fig. 1: Schematic diagram of the interface during dissimilar metals welding between low carbon steel and aluminium alloy

Materials used: 1mm thick Low carbon steel and 2mm thick AA1050 aluminium alloy were used. Their chemical compositions and mechanical properties are shown in Table I and II, respectively. Both steel and aluminium alloy were prepared in size of 300 x 150mm. The experiment was started by immerging steel sheet in 12% HCl for 2min at 80°C in order to remove oxide layer.

TIG Welding: Gas Tungsten Arc Welding [GTAW] or Tungsten Inert Gas [TIG] welding employs a non consumable tungsten electrode with an envelope of inert shielding gas [Argon, Helium] to protect both the electrode and the weld pool from the detrimental effects of surrounding atmospheric gasses. This experiment, TIG welding is done using Lincoln machine, Polarity: Direct Current Electrode Negative [DCEN], Welding current and welding speed are 130, 135, 140Amps and 3.2, 3.5, 3.8mm/sec respectively, Voltage 16V, Frequency 60Hz, The arc distance, electrode type, electrode size and electrode tip angle was 2.4mm, EWTh-2, 3mm in diameter and Vertical respectively. Pure argon gas with 20L/min was used for preventing oxidation of molten steel. A special type of fixture is prepared for proper welding. The specially designed fixture is shown in fig.2. Schematic representation of dissimilar weld is shown in the fig.3.

Fig. 2: Specially designed fixture

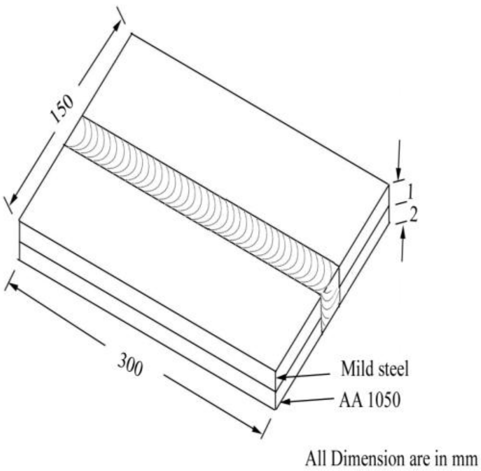


Fig.3: Schematic representation of dissimilar weld

TABLE.III
MECHANICAL PROPERTIES OF MATERIALS

Metal	UTS [MPa]	Hardness [VHN]
Low carbon steel	460	152
AA 1050	110	63

III. RESULTS AND DISCUSSION:

The macroscopic observations were carried out in order to obtain the depth of weld. Fig.4 shows the macroscopic observation of steel weld pool obtained with electrical current of 130, 135A and 3.2, 3.5mm/sec of welding speed. From the Figures, it is clear that, the partial penetration of molten zone of steel sheet can be obtained by TIG welding process. Also Fig.4 shows the depth of weld obtained with various apparent heat input for joining.

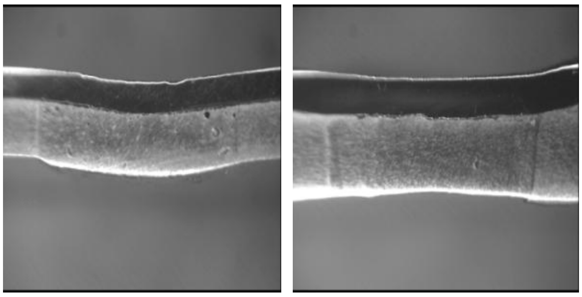


Fig.4: Macroscopic view of welded joint at different currents

The finding are, many welding conditions produce the partial penetration welding in 1mm thickness steel sheet. Moreover, the depth of weld is increased when heat input is increased. Thus, it can be referred that TIG welding process is possible to join dissimilar metals by self brazing process in limiting welding heat input. Some of the defects are also clearly visible. Porosity is prominently seen in 135Amps and in 140A.

The microstructure reveals distinct weld metal, heat affected zone [HAZ] and base metal zones. In order to get more ideas regarding the microstructure, images were taken at higher magnifications also. All the specimens are prepared, etched and microstructure images are taken at different magnifications. Partial etching is done carefully. 3% Nital is used for low carbon steel and Keller's reagent is used as etchant for Aluminium. Low carbon steel is etched first and aluminium is etched secondly.

The grain size is coarse in the base metal; it gets reduced in grain size in the HAZ and still becomes finer in the weld metal zone. The grains for 130A are viewed in 200x magnification. The base metal grains were coarser, and is equally distributed. Distinct area of Base metal and HAZ is also clear. It also reveals that the HAZ has the smaller grains when compared to Base metal. This refinement is mainly due to transfer of heat. The distance of the HAZ will be depending upon the thermal conductivity of the metal.

The image 'c' reveals the HAZ and Weld zone of the low carbon steel. The picture expose that the grains get refined more from the base metal zone to the weld zone. In the steel side base metals of all the specimens, microstructure shows elongated grains of ferrite and spheriodized pearlite distributed throughout the matrix and on the

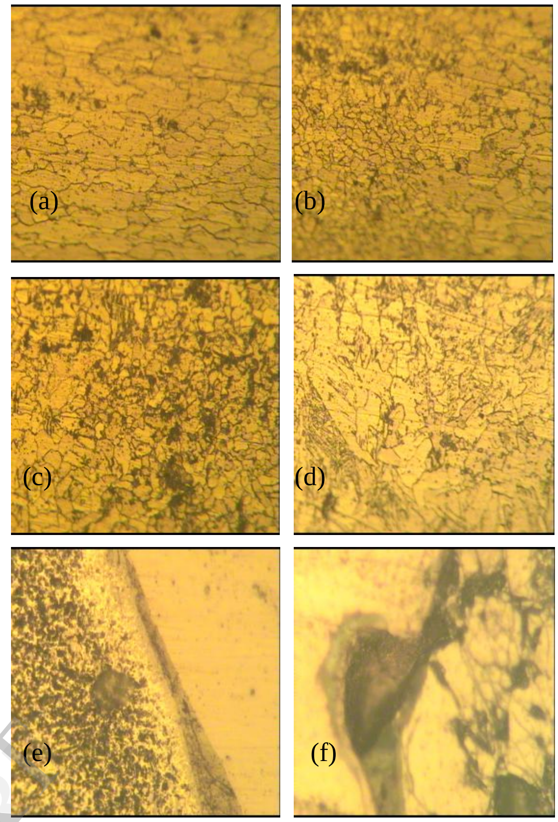


Fig. 5. [a] Base metal [b] Heat Affected Zone and Base Metal [c] Heat Affected Zone and Weld metal [d] Weld zone [e] Fusion zone with Dark Aluminium and Bright Mild Steel [f] Intermetallics for 130A, 16V, 3.2mm/sec, 200x.

aluminium side, microstructure shows fine black particles of Mg_2Si distributed in a matrix of aluminium solid solution throughout the structure. Fine eutectic cells were also found. In the weld metal, number of dark areas where predominant which may be the intermetallics formed in aluminium region. The dark areas are also seen in the adjacent HAZ closer to the weld metal. It also shows fine grains of ferrite and spheriodized pearlite near the grain boundaries. Microstructure for low carbon steel is also viewed. Moreover same type of characteristics was seen on the microstructural behaviour of low carbon steel in the other specimens also. But the grain sizes are different. When aluminium side is etched and viewed under microstructure, its behaviour is totally different. The etchant used for aluminium is Keller's reagent. More intermetallics are found in the aluminium side when compared to steel side. There is also distinct HAZ and base metal zone. Fusion zone is very difficult to identify, it may be due to the formation of intermetallics. The bright area is composed of steel fragments and is located at the center of the weld zone. The cleavage lines tend to occur along the interface between the fragment and the aluminum matrix. Different sized both finer and coarser intermetallics are seen in the fusion zone. Intermetallics are mainly due to the fusion of steel into aluminium zone. Some of the particles from Steel got detached during welding and penetrate into the aluminium zone. The formation of brittle intermetallic compounds varies according to the welding conditions and has to be avoided as much as possible. In the weld zone, microstructure shows elongated grains of ferrite and spheriodized pearlite distributed throughout the structure. Indeed, it has been shown that those intermetallic compounds can cause a weakening of the welds because of high hardness [6]. Further the results expose that intermetallic reaction layer thickness increase with increasing apparent heat input for joining. From these results, if the joints produced at lower apparent heat input will produce thin intermetallic reaction layer. Improper penetrations of steel into the aluminium are visible. The intermetallic compounds presented on it are grouped as Fe-rich compounds [FeAl and Fe_3Al] and Al-rich compounds [$FeAl_2$, Fe_2Al_5 and $FeAl_3$]. Al-rich intermetallic compounds are brittle, iron-rich intermetallic compounds show slight ductility and high strength [9].

Major problem in the case of automatic TIG welding is, either the arc length has to be varied continuously or the cooling of the work piece has to be done or the job has to be kept in an inclined position calculating the arc length. These alterations are mainly due to the thermal conductivity of the aluminium. Preheating takes place at the initial stage of the process which leads to overheating of the aluminium in due course of welding. It even reaches the melting temperature, which may lead to improper weld. Likewise the joints found at the initial stage are not proper. It is mainly due to the insufficient heat transfer because; minimum time is required for preheating. A good joint is found at the mid region, whereas an improper joint is found at the later zone. It is mainly due to overheating.

Each TIG welded specimen is cut to a 1 inch width, along the vertical direction of the welding pass using CNC EDM wire cut machine so as to reduce distortion. The peel of test is performed on Hornsfield tensometer testing machine. The diagrammatic representation of the peel of test specimen is shown in fig. 6.

The results of Peel of test reveals that the joints made by 135A, 3.5mm/sec possesses high strength when compared to other joints. Further, failure load of the joints is in the range of 15 – 56 MPa, which are lower than that of base metal. Moreover, it was found that the failure load slightly decreased with increasing apparent heat input for joining. An increase in welding power as well as adjusting the traverse speed, increase in strength of the weld joint can be achieved. The fracture path of all the specimens is through the weld itself, but mostly along the fusion line. Some of the samples show shearing of the weld into the Aluminium. The fracture took place mainly at the intermetallics due to the presence of brittle $FeAl_3$. Fig. 7 and fig. 8 reveal the peel of test specimen before and after the test respectively.

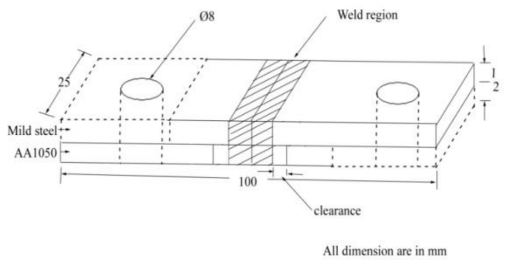


Fig: 6: Schematic representation of peel of test specimen

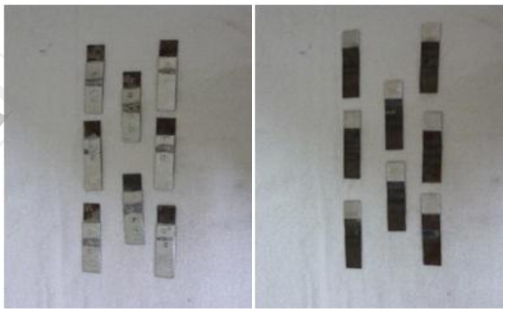


Fig: 7. Peel of test specimen samples (before)

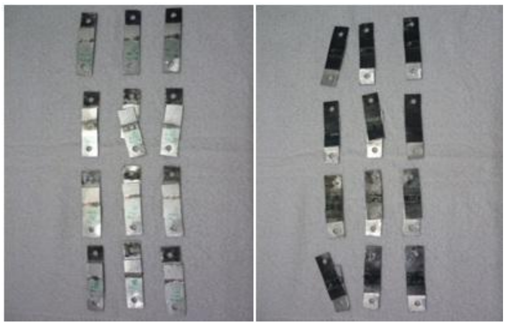
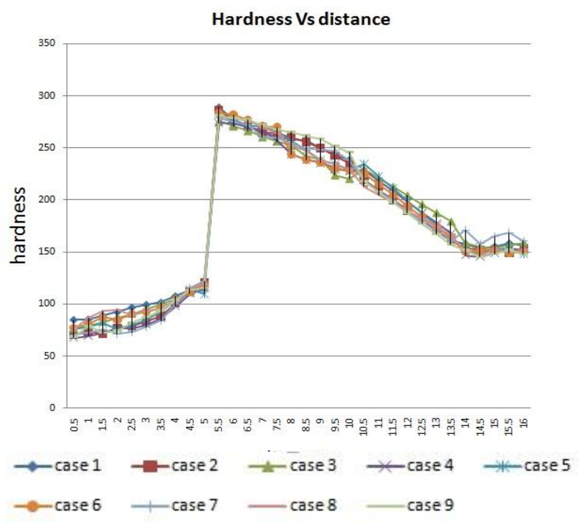


Fig: 8: Peel of test specimen samples (after)

The lower load resistance of joint when compared with base metal A1100-H12 aluminum alloy is caused by the grain growth during welding. High heat input during TIG welding result in thicker intermetallic reaction layer and coarser microstructure in HAZ of aluminum alloy. The coarser microstructure at HAZ of aluminum alloy is the main reason of lower of load resistance of aluminum alloy at heat affected zone [9]. In Stainless steel and Aluminium lap joint, a homogenous chemical composition is observed with low percentage of Aluminium in the weld metal away from the fusion zone. A 10-20% increase in welding power, at constant travel speed, resulted in a 40-65% increase in tensile shear strength [1]. When welding is executed by irradiating a laser from the aluminium side, cracking occurs and sufficient strength cannot be obtained. Brittle intermetallic compound tends to be generated. Therefore, in lap welding, the laser is basically irradiated from the steel side so that, the melting of aluminium alloys can be controlled appropriately. There has also been a report in which an investigation was made on the method of inducing only aluminium alloys to melt with the heat from the steel side by irradiating the high-power laser with a defocusing setting [3].

TABLE IV
RESULTS OF PEEL OF STRENGTH

Sl.No	Current (Amps)	Traverse Speed mm/sec	Electrode Distance mm	Strength MPa
1	130	3.2	2.3	38.65
2	130	3.2	2.4	35.89
3	130	3.2	2.5	29.51
4	130	3.5	2.3	40.35
5	130	3.5	2.4	38.75
6	130	3.5	2.5	35.49
7	130	3.8	2.3	15.75
8	130	3.8	2.4	13.42
9	130	3.8	2.5	11.06
10	135	3.2	2.3	19.95
11	135	3.2	2.4	15.04
12	135	3.2	2.5	14.10
13	135	3.5	2.3	25.90
14	135	3.5	2.4	24.16
15	135	3.5	2.5	19.03
16	135	3.8	2.3	55.55
17	135	3.8	2.4	52.61
18	135	3.8	2.5	47.37
19	140	3.2	2.3	13.45
20	140	3.2	2.4	11.94
21	140	3.2	2.5	9.38
22	140	3.5	2.3	38.00
23	140	3.5	2.4	23.58
24	140	3.5	2.5	25.76
25	140	3.8	2.3	29.00
26	140	3.8	2.4	27.69
27	140	3.8	2.5	23.47



Case 1: 130A, 3.2mm/sec, 2.3mm; Case 2: 130A, 3.5mm/sec, 2.4mm Case 3: 130A, 3.8mm/sec, 2.5mm; Case 4:135A, 3.2mm/sec, 2.4mm; Case 5: 135A,3.5mm/sec, 2.5mm; Case 6: 135A, 3.8mm/sec, 2.3mm; Case 7:140A,3.2mm/sec, 2.5mm;Case8: 140A, 3.5mm/sec, 2.4mm; Case 9: 140A, 3.8mm/sec, 2.3mm;
Fig. 9: Hardness Vs Distance

Vickers Micro-hardness is tested in all the joints at a spacing distance of 0.5mm from the weld center towards the base metal. Dwell time is 20 sec; load is 2 Kg, using a diamond tip. Micro hardness is also taken on the traverse side in the weld zone. The results are displayed in fig.9. The Vickers hardness of the base materials is Al=63.5, low carbon steel =152. Maximum hardness of 290 was achieved in steel side and 75 in Aluminium side. Same type of behaviour in hardness is seen on all the other specimens also. The hardness value kept on increasing till the weld center is reached on both the Al side and low carbon steel side. This fluctuation in hardness is mainly due to recrystalization of the grains. As the weld center is reached, the temperature increases during welding, which resulted in finer grain structure. Moreover the presence of hard brittle intermetallics was the main reason for the increase in hardness. Intermetallics are hard steel particle which got detached from the parent metal during welding. Increase in hardness also reduces the tensile strength of the joint. Most of the failure is brittle in nature. The high hardness in the fusion zone may be attributed to the formation of intermetallic phases, but to some extent very fine microstructure resulted due to high cooling rates [1]. It is suggested that most intermetallic compound layer is formed mainly by brittle $FeAl_3$ [2]. Sufficient tensile strength is not obtained and impact strength also seems low [3].

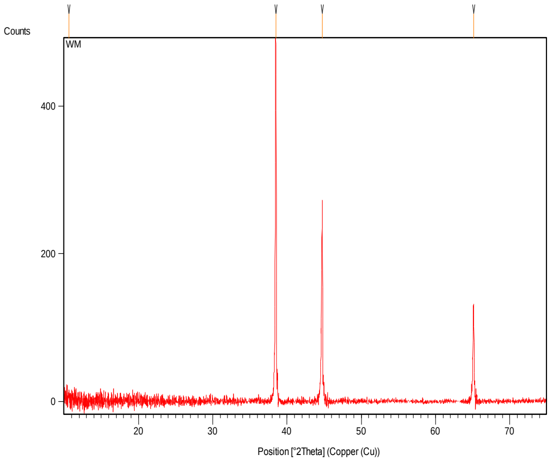


Fig. 9: XRD result

Peak list:

Pos [°2Th.]	Height [cts]	FWHM [°2Th.]	d-spacing [Å]	Rel. Int. [%]
38.4892	328.87	0.2160	2.3370	100.0
44.7630	245.23	0.1680	2.0230	74.57
65.1281	120.57	0.1920	1.4311	36.66

The XRD result of the weld joint is shown in the fig 9. It is observed that a number of crystalline phases were formed. The results of XRD also revealed the presence of Fe-rich compounds [FeAl and Fe_3Al] and Al-rich compounds [$FeAl_2$, Fe_2Al_5 and $FeAl_3$] in the matrix.

IV CONCLUSION

- From the above results, TIG welding of 2mm low carbon steel with 1mm AA1050 is feasible. The process can be explained as a self brazing process, in which the low carbon steel is heated to the melting point of the Aluminium, which is sufficient for fusion of Aluminium with low carbon steel.
- Experiment with 135A, 16V, Speed 3.5mm/sec yielded better strength and hardness when compared to other welding conditions.
- By optimizing the speed, we can increase the depth of penetration as well as the strength of the joint.
- Intermetallics are found between the joint. It is suggested that intermetallic compound layer formed are mainly brittle FeAl, Fe_3Al, $FeAl_2$, Fe_2Al_5 and $FeAl_3$.
- Increase in hardness value is mainly due to recrystalization of the grain structure. As it reaches the weld center, the temperature increases during welding, which results in finer grain structure, moreover the presence of hard brittle intermetallics, are the main reason for the increase in hardness.
- Some of the defects are also clearly visible. Porosity is prominently seen in 130Amps and in 140Amps.

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