JOINING OF STEEL AND ALUMINIUM ALLOY USING TIG WELDING WITH IMPROVED MECHANICAL PROPERTIES

M.Tech. Thesis

By

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DISCIPLINE OF METALLURGY ENGINEERING AND MATERIALS SCIENCE

INDIAN INSTITUTE OF TECHNOLOGY INDORE

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A THESIS

Submitted in partial fulfillment of the requirements for the award of the degree

of

Master of Technology

by

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **JOINING OF STEEL AND ALUMINIUM ALLOY USING TIG WELDING WITH IMPROVED MECHANICAL PROPERTIES** in the partial fulfillment of the requirements for the award of the degree of **MASTER OF TECHNOLOGY** and submitted in the **DISCIPLINE OF METALLURGY ENGINEERING AND MATERIAL SCIENCE, Indian Institute of Technology Indore**, is an authentic record of my own work carried out during the time period from July 2016 to July 2018 under the supervision of **Dr. Jayaprakash Murugesan,** Assistant Professor, Discipline of Metallurgy Engineering and Material Science.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other institute.

Mr. MILIND CHOUBEY

This is to certify that the above statement made by the candidate is correct to the best of my/our knowledge.

Dr. JAYAPRAKASH MURUGESAN

Mr. MILIND CHOUBEY has successfully given his M.Tech. Oral Examination held on…………………….

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Date:

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MILIND CHOUBEY

DEDICATED TO

MY FAMILY

ABSTRACT

Joining dissimilar metals is essential nowadays in manufacturing and constructing advanced machineries and equipments. Dissimilar weld is used in order to minimize material cost, maximize performance and reduce the vulnerability to failure and maintenance, therefore it can be used to create mechanically robust joints between parts composed of dissimilar metals in marine, automotives, aerospace, boiler, medical applications, transport system. Aluminum Alloy and steel dissimilar welding processes yield unwanted disadvantages in the weld joint due to the large difference between the aluminum alloy and steel melting points and the nearly zero solid solubility between these two metals produces brittle intermetallic compounds (IMCs).

The objective of this thesis was to study the effect of process parameters particularly on the IMC layer thickness and properties of TIG welded dissimilar sheet metal joint. To increase the strength of the dissimilar weld it is necessary to decrease the IMC layer thickness of the welded joint. To decrease the IMC layer thickness the heat input is decreased by lowering the welding current, increasing the heat dissipation rate by using a water cooled copper block setup and using the coating of zinc which is present on Galvanised steel as a barrier layer. The welding of Aluminium 6061 alloy is done with two steels – mild steel and galvanized steel separately. Welding current in the range of 70A and 90A was used as process variables. The welded joints were examined by different characterization techniques such as macroscopic, optical microscopy and scanning electron microscopy, EDS analysis, XRD analysis, tensile testing and micro hardness measurements. From bead on the steel sheet experimental and lap joint experiment, it was seen that on decreasing the heat input, inceasing heat transfer rate and with a barrier layer of zinc the minimum IMC thickness achieved was 11.9 microns, and with normal conditions the maximum IMC thickness observed was 20.5 microns. It was found that the thickness of the IMC layer decreased and the tensile strength of the lap joint increased with the increasing heat transfer rate of welded zone and by introducing a barrier layer.

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LIST OF ABBREVIATIONS

TIG	Tungsten Inert Gas
GTAW	Gas Tungsten Arc Welding
IMC	Intermetallic Compound
NDT	Non-Destructive Test
TWB	Tailor Welded Blank
OVAT	One Variables At One Time
Fe	Ferum
Al	Aluminium
Zn	Zinc
Si	Silicon
Mg	Magnesium
GI	Galvanized Iron/ Galvanised Steel
AC	Alternate Current
DC	Direct Current
°C	Degree Celcius
Ao	Area
P	Load
mm	Milimeter
μm	Micrometer
kN	kilo Newton
sec	Second
δ	Specimens Gage Length
Lo	Original Gage Length
HV	Hardness Value
MPa	Mega Pascal
BoSS	Bead on the Steel Sheet

Chapter 1 INTRODUCTION

1.1 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. Figure 1.1 shows some examples of dissimilar weld joints:

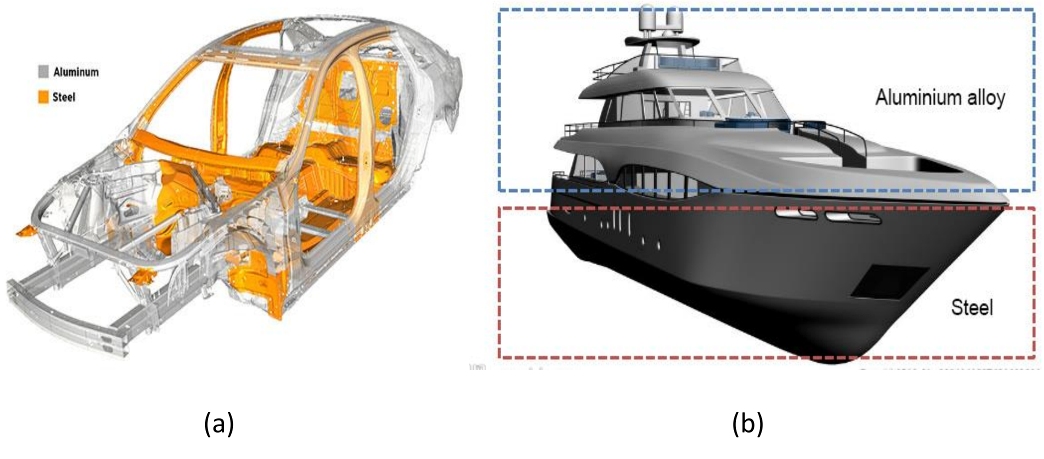


Figure 1.1 : Some typical applications of aluminium-Steel weld : (a) frame of car , (b) body of ship. *[1]*

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. 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. 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. Lighter means of transport permits saving on fuel consumption and contribute to the environmental protection due to the reduction of green house gases. 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. 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. Tungsten Inert Gas welding is suitable welding process for joining thin sections of similar metals. 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. 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. Better results can be expected when the amount of Aluminium rich intermetallic compounds are reduced to the major extent.

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

1.2 Dissimilar Welding

Dissimilar welding or Tailor Welded Blank (TWB) is a growing requirement of welding. At the moment, it is a new development technique and has becomes a hot research field in study. The most famous joining metals are aluminium and steel dissimilar welding. The advantages obtain a cost favorable and weight optimization body with a high stiffness, no waste and energy saving stated that dissimilar metals have different chemistries, so they have different physical properties such as melting temperature. Many who have involved with joining metal with different melt temperature experience frustration. This is due to the difficulties arising when trying to melt different metal together at same weld temperature.

Joining of two dissimilar materials has been an attraction in recent years because of their advanced capabilities. The example of the combination two dissimilar materials is between aluminum and steel due to their potential in automotive applications. Proper welding process and the welding technique is a significant consideration in TWB process. The selection of the welding technique depends on the making of a sound, mixture of aluminum and steel at the interface. Figure 1.2 shows the example of dissimilar material welded joint.

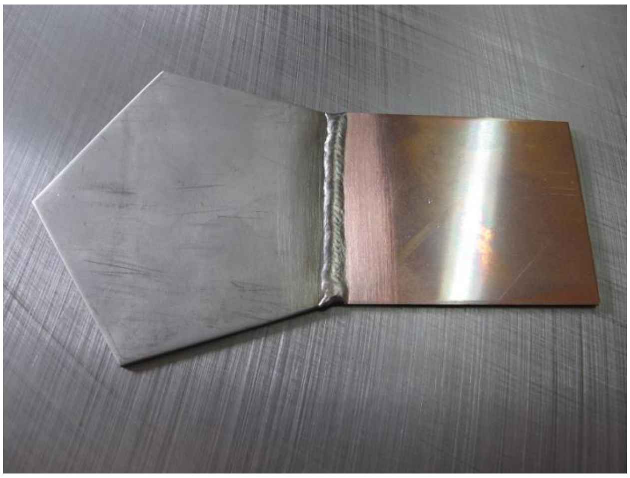


Figure 1.2 : Dissimilar material weld joint. *[2]*

1.3 Different processes for joining of Dissimilar Materials

The process of joining of two materials permanently through localized coalescence resulting from a suitable combination of temperature, pressure and metallurgical conditions is termed as welding. It can be achieved by using heat or pressure or both, with or without addition of filler material at the interface. Depending upon the combination of temperature and pressure, many joining processes have been developed. Based on the state of joining, the joining processes can be broadly classified as: (1) Liquid state welding (Fusion welding), (2) Solid /liquid state welding and (3) Solid state welding. Fig.1.3 presents classification of various joining processes.

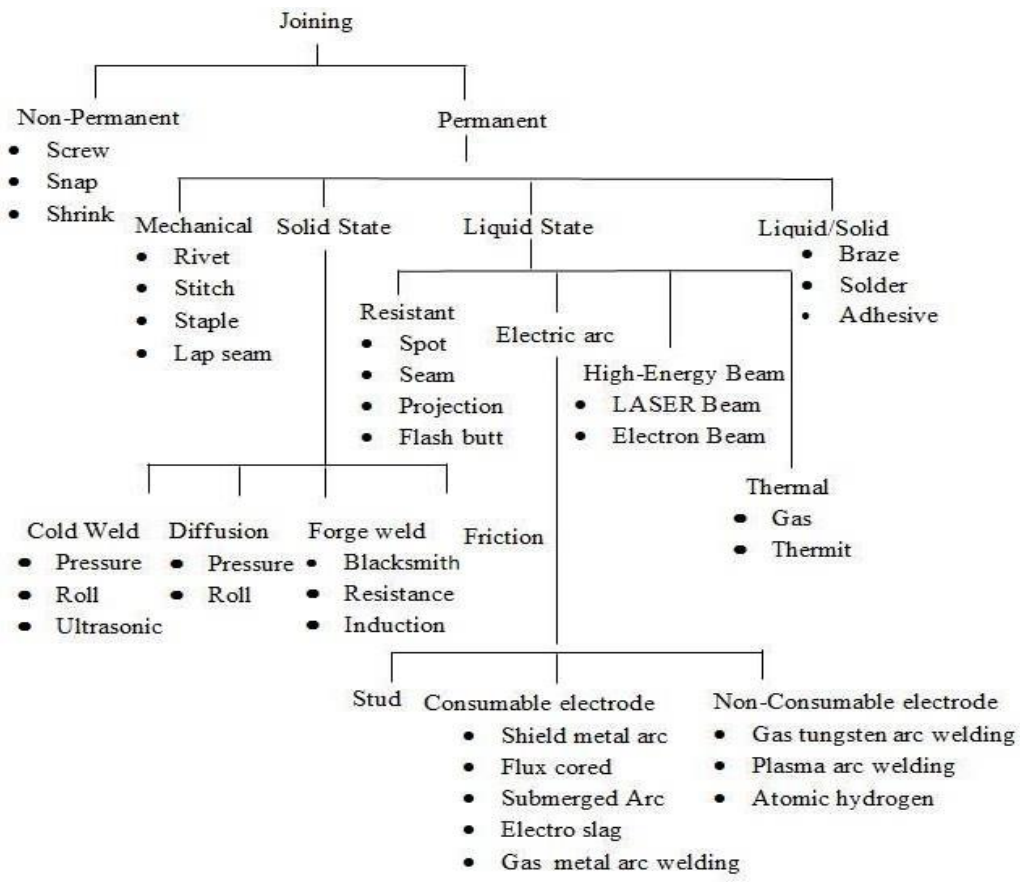


Figure 1.3 : Different joining processes

1.4 TIG Welding

Tungsten inert gas (TIG) arc welding–brazing is a latest technique and becomes a hot research field in joining of aluminum alloy to steel. In this process, the sheets and filler metals are heated or melted by arc. One of the commonly used techniques for joining ferrous and non-ferrous metals is TIG welding. TIG welding process offers quite a few advantages like joining of dissimilar metals, low heat effected zone, and absence of slag. TIG is suitable for joining thin sections because of its limited heat inputs. The feeding rate of the filler metal is somewhat independent of the welding current, hence allowing a variation in the relative amount of the fusion of the base metal and the fusion of the filler metal. Hence, the management of dilution and energy input to the weld can be achieved not including changing the size of the weld. Since the GTAW process is a very clean welding process, it can be used to weld reactive metals, such as titanium and zirconium, aluminum, and magnesium. On the other hand, the deposition rate in GTAW is low. Too much welding current scan will effect melting of the tungsten electrode and produce brittle tungsten inclusions in the weld metal. Still, by using preheated filler metals, the deposition rate can be improved. The arc welding process constitutes an important segment of welding in manufacturing. The figure 1.4 shows the GTAW process.

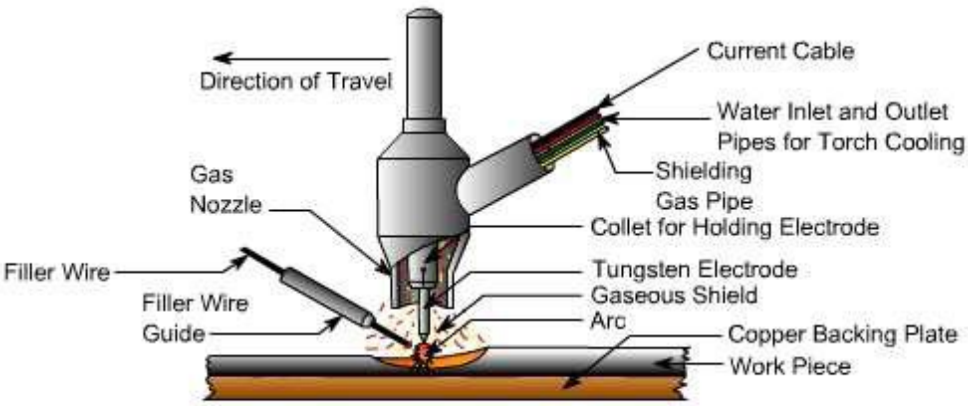


Figure 1.4 : The GTAW process *[3]*

1.5 Types of welding current used in TIG welding

a. **DCSP (Direct Current Straight Polarity)**: In this type of TIG welding direct current is used. Tungsten electrode is connected to the negative terminal of power supply. This type of connection is the most common and widely used DC welding process. With the tungsten being connected to the negative terminal it will only receive 30% of the welding energy (heat). The resulting weld shows good penetration and a narrow profile.

b. **DCRP (Direct Current Reverse Polarity):** In this type of TIG welding setting tungsten electrode is connected to the positive terminal of power supply. This type of connection is used very rarely because most heat is on the tungsten, thus the tungsten can easily overheat and burn away. DCRP produces a shallow, wide profile and is mainly used on very light material at low Amp.

c. **AC (Alternating Current):** It is the preferred welding current for most white metals, e.g. aluminium and magnesium. The heat input to the tungsten is averaged out as the AC wave passes from one side of the wave to the other. On the half cycle, where the tungsten electrode is positive, electrons will flow from base material to the tungsten. This will result in the lifting of any oxide skin on the base material. This side of the wave form is called the cleaning half. As the wave moves to the point where the tungsten electrode becomes negative the electrons will flow from the welding tungsten electrode to the base material. This side of the cycle is called the penetration half of the AC wave forms.

1.6 Advantages of TIG welding

TIG welding process has specific advantages over other arc welding process as follows -

I. Narrow concentrated arc

II. Able to weld ferrous and non-ferrous metals

III. Does not use flux or leave any slag (shielding gas is used to protect the weld-pool and tungsten electrode)

IV. No spatter and fumes during TIG welding

1.7 Applications of TIG Welding

The TIG welding process is best suited for metal plate of thickness around 5- 6 mm. Thicker material plate can also be welded by TIG using multi passes which results in high heat inputs, and leading to distortion and reduction in mechanical properties of the base metal. In TIG welding high quality welds can be achieved due to high degree of control in heat input and filler additions separately. TIG welding can be performed in all positions and the process is useful for tube and pipe joint. The TIG welding is a highly controllable and clean process needs very little finishing or sometimes no finishing. This welding process can be used for both manual and automatic operations. The TIG welding process is extensively
used in the so-called high-tech industry applications such as

I. Nuclear industry

II. Aircraft

III. Food processing industry

IV. Maintenance and repair work

V. Precision manufacturing industry

VI. Automobile industry

1.8 Process parameters of TIG welding

The parameters that affect the quality and outcome of the TIG welding process are given below.

a) Welding Current

Higher current in TIG welding can lead to splatter and work piece become damage. Again lower current setting in TIG welding lead to sticking of the filler wire. Sometimes larger heat affected area can be found for lower welding current, as high temperatures need to applied for longer periods of time to deposit the same amount of filling materials. Fixed current mode will vary the voltage in order to maintain a constant arc current.

b) Welding Voltage

Welding Voltage can be fixed or adjustable depending on the TIG welding equipment. A high initial voltage allows for easy arc initiation and a greater range of working tip distance. Too high voltage, can lead to large variable in welding quality.

c) Inert Gases:

The choice of shielding gas is depends on the working metals and effects on the welding cost, weld temperature, arc stability, weld speed, splatter, electrode life etc. it also affects the finished weld penetration depth and surface profile, porosity, corrosion resistance, strength, hardness and brittleness of the weld material. Argon or Helium may be used successfully for TIG welding applications. For welding of extremely thin material pure argon is used. Argon generally provides an arc which operates more smoothly and quietly. Penetration of arc is less when Argon is used than the arc obtained by the use of Helium. For these reasons argon is preferred for most of the applications, except where higher heat and penetration is required for welding metals of high heat conductivity in larger thicknesses. Aluminium and copper are metals of high heat conductivity and are examples of the type of material for which helium is advantageous in welding relatively thick sections. Pure argon can be used for welding of structural steels, low alloyed steels, stainless steels, aluminium, copper, titanium and magnesium. Argon hydrogen mixture is used for welding of some grades of stainless steels and nickel alloys.

d) Welding speed:

Welding speed is an important parameter for TIG welding. If the welding speed is increased, power or heat input per unit length of weld is decreases, therefore less weld reinforcement results and penetration of welding decreases. Welding speed or travel speed is primarily control the bead size and penetration of weld. It is interdependent with current. Excessive high welding speed decreases wetting action, increases tendency of undercut, porosity and uneven bead shapes while slower welding speed reduces the tendency to porosity.

Figure 1.5 gives the methodology to be followed for the research work.

1.9 Organization of the Thesis

This thesis is organized in following chapters:

Chapter 1 presents the basic introduction of dissimilar welds and TIG welding process

Chapter 2 presents review of the relevant past work, objective and scope of study.

Chapter 3 presents details of the experimental apparatus of TIG process used in the present work, experimentation.

Chapter 4 discusses the results of experiments conducted on the weld of Al alloy with mild steel and galvanized steel.

Chapter 5 presents conclusions of the present research work along with scope of the future work.

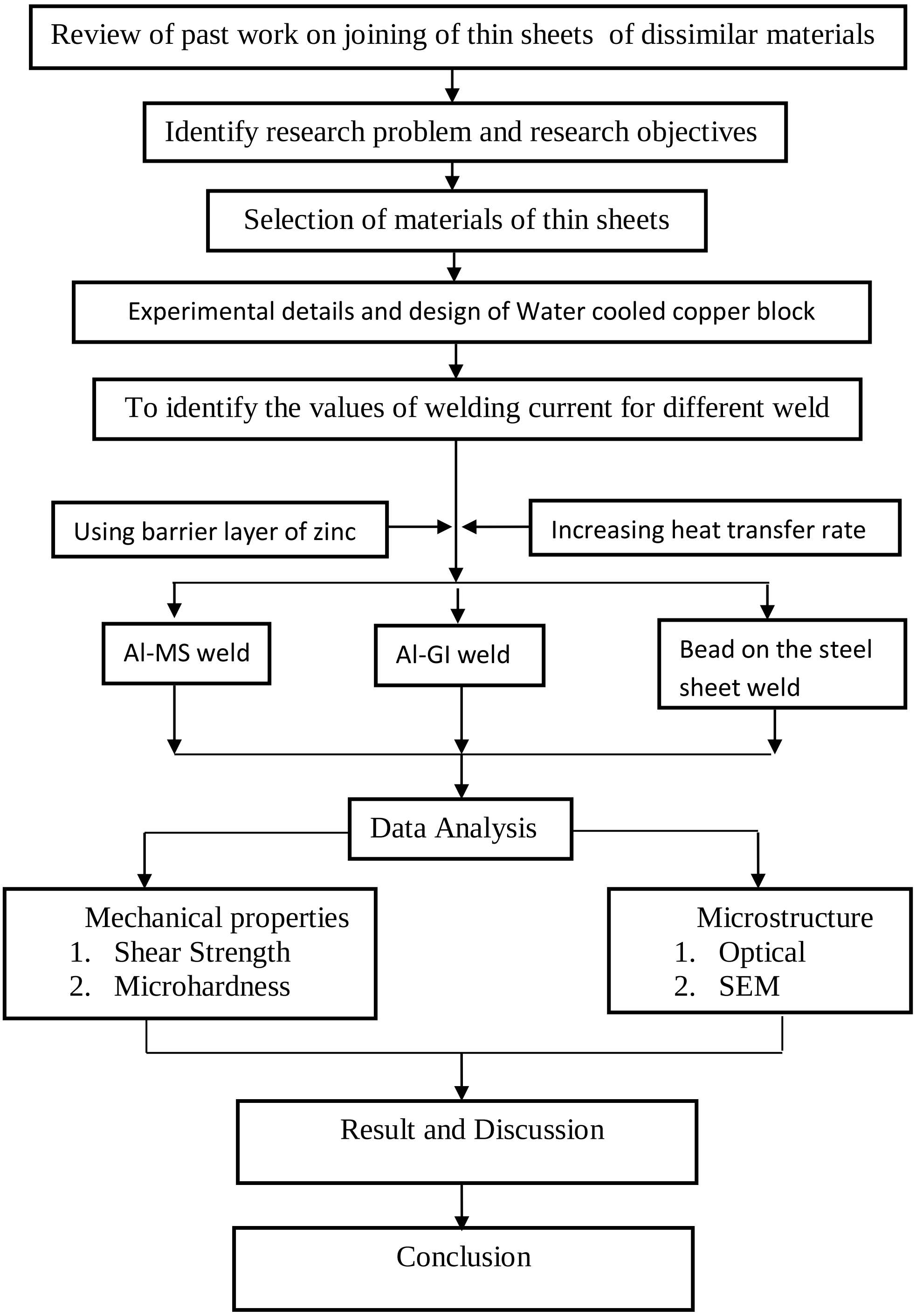


Figure 1.5 : Methodology Flow Chart

Chapter 2 LITERATURE REVIEW

2.1 Review of Past Work on Joining of Dissimilar and Similar Materials

Aisha Al Ismail et.al [9] analysed the mechanical integrity of tig-mig hybrid weldments. TIG and MIG weldments are performed independently and the results are compared in welding stainless steel and mild steel materials. In this attempt, this work is extended by developing a hybrid welding method combining TIG and MIG welding methods to weld dissimilar metallic materials.

L.H.Shah et.al [10] investigated aluminum-stainless steel dissimilar weld quality using different filler metals. Aluminum AA6061 and stainless steel SUS304 were lap-welded by using Metal Inert Gas (MIG) welding with aluminum filler ER5356 (Group 1) and stainless steel filler ER308LSi (Group 2). The fracture in the tensile test yielded the highest tensile strength of 104.4 MPa with aluminum fillers. The tensile strength of Group 1 joints ranging from 47.8 to 104.4 MPa was collectively higher than Group 2 joints, between 20.24 to 61.76 MPa. Based on the investigation throughout this study, it can be concluded that the welding voltage of 18 V and aluminum filler ER5356 is the optimum filler in joining the dissimilar metals aluminum AA6061 and stainless steel SUS 304.

Chawinee Pothong et.al [11] studied the effects of Aluminium Alloy Surface Preparation in TIG Dissimilar Metals Welding between Mild Steel and 5052 Aluminium Alloy and concluded that the surface preparation of aluminium alloy plates affected the thickness and width of intermetallic reaction layer, which directly influenced the load resistance of the joints. Cleaned aluminium alloy faying surface provided high wettability of molten aluminium alloy on the mild steel surface. Moreover, cleaned faying surface of aluminium alloy provided suitable condition for joining.

San-bao LIN et.al [12] concluded that the interfacial layer comprises three different parts: the reaction layer about 3.0 μm in thickness in the welded seam side; the diffusion layer about 4.0 μm in thickness in the center of the layer; the diffusion layer 2.0 μm in thickness in the steel side. The IMCs layer transfers from (α-Al + $FeAl_3$) in the welded seam side to (Fe_2Al_5+ $FeAl_2$) in the center of the layer to ($FeAl_2$+ FeAl) in the steel side.

Rakesh Chaudhari et.al [13] studied the reliability of dissimilar metal using Fusion Welding and concluded that stress concentration is a major issue triggering premature failure. The experimental observations with LBW show an asymmetry in joints, due to different melting points of metals which causes penetration on the other metal of high melting point. By varying welding speeds, intermetallic layer thickness also varied and spawned coarser microstructure in aluminum alloy.

Tušek J et.al [14] performed Welding of Tailor-welded blanks of 2.14 mm AA5456 Al alloy using welding current (40-90) A, welding speed (210-230) mm/min. Microstructures of all the welds were studied and correlated with the mechanical properties. 10-15% improvement in mechanical properties was observed after planishing due to or redistribution of internal stresses in the weld.

Moniz B et.al [15] developed a finite element model to predict the evolution of residual stress and distortion dependence on the yield stress-temp for 3.2 mm 2024 Al alloy by TIG welding.

Wor LC et.al [16] analysed the stress behavior of Tailor welded blanks and effect of geometry configurations on the residual stress distributions in TIG weld from predicted data and compared it with data obtained by X-Ray diffraction method. Attempts were made to analyse the residual stresses produced in the TIG welding process using 2D and 3D finite element analysis. For welding of 10 mm thick 304 grade stainless steel welding current in the range 80-225 A, voltage 15 V, and welding velocity in the range of 90-192 mm/min were employed.

Ishak M et.al [17] investigated the effect filler material and hydrogen in argon as shielding gas for TIG welding of 316L austenitic stainless steel. They used current 115 A, welding speed 100 mm/min and gas flow rate 10 l/min for welding of 4 mm thick plate. For all shielding media, hardness of weld metal is lower than that of HAZ and base metal. Penetration depth, weld bead width and mean grain size in the weld metal increases with increasing hydrogen content. The highest tensile strength was obtained for the sample welded under shielding gas of 1.5%H_2–Ar.

Ghazali FA et. al [18] investigated the effect of process parameters i.e. plate thickness, welding heat input on distortion of Al alloy 5A12 during TIG welding. For welding they used current (60-100) A, welding speed (800-1400) mm/min and thickness of w/p (2.5-6) mm. The results show that the plate thickness and welding heat input have great effect on the dynamic process and residual distortion of out-of-plane.

Charde N [19] proposed a spot welding method to improve weld penetration and compared with the traditional TIG welding method under different welding parameters i.e welding speed, arc length and current. They used gas flow rate 10 l/min, welding speed (90-300) mm/min, current (100-200) A and thickness of w/p 10 mm. The results show that the changes in the welding parameters directly impact the oxygen concentration in the weld pool and the temperature distribution on the pool surface.

Sathari NAA et. al [20] proposed a single pass/double pass techniques on friction stir welding process for the welding of 9 mm thick Cr13Ni5Mo stainless steel by using pure He as inner shielding layer and mixture of He and CO2 gas as the outer shielding layer. Welding current and welding speed considered for the experimentation in the range of 120-140 A and 90-300 mm/min respectively. The double– shielded TIG welding process display efficiency 2-4 times greater than that of traditional TIG welding. A change in the direction of the surface tension affects the fusion zone profile which results a larger weld depth. This process allows a high welding efficiency comparing with traditional TIG welding.

Hafizi W et. al [21] investigated the influence of the interfacial reaction between the Al alloy (2014) matrix and SiC particle reinforcement on the fracture behaviour in resistance spot weld of Al matrix composites. Resisitance Spot Welding was carried out on 4 mm thick AA2014/SiC/Xp sheets using current setting in the range of 37-155 A and voltage of 14-16.7 V. From experimental results it was found that, the failure occurred in the weld metal with a tensile strength lower than 50% of the parent material. Fracture of the welded joint was controlled by interface deboning through the interface reaction Layer. Probability of interfacial failure increases in the weld zone due to formation of Aluminium-carbide which lowers the matrix/reinforcement interface strength.

Abd Razak NA et.al [22] performed TIG welding of 2.5 mm thick Nickel based 718 alloy using welding current in the range of 44-115 A, voltage 13-15 V and welding speed 67 mm/min. the influence of magnetic arc oscillation on the fatigue behaviour of the TIG weldments in two different post-weld heat treatment conditions were studied.

Fukumoto S et. al [23] performed MIG welding on corrosion behavior of AISI 1020 carbon steel and SiCp /6061 Al composites without and with Al-Si filler using He-Ar mixed as shielding gas. For the welding authors uses gas flow rate 6.9 l/min, welding speed 1800 mm/min, current-60 A. The results show that addition of 50 vol.% helium in shielding gas improves the arc stability, and quality of welding improves when the Al–Si filler is added. The microstructure of the welded joint shows non-uniformity with SiC particles distributing in the weld centre.

Zhang H et. al [24] analysed microstructure, element distribution, phase constituents and micro hardness for welding joint of Mo-Cu composite and 18-8 stainless steel plates of thickness 2.5 mm carried out by MIG welding process with Cr-Ni fillet wires. Welding has done with speed (49.8-64.2)mm/min, gas flow rate-8 l/min, arc voltage-(28-32) V and welding current -90 A. Formation of γ-Fe(Ni) phases and Fe0.54Mo0.73 compound must contributed to the high micro hardness. The results indicate that austenite and ferrite phases were obtained in the weld metal. The micro hardness near the fusion zone at Mo–Cu composite side increased from weld metal to fusion zone, and the peak value appeared near the boundary between fusion zone and Mo–Cu composite.

Hatifi MM et. al [25] investigated the MIG welding of 3 mm thick AISI 316L stainless steel plate at different welding position. Pure argon gas and mixture of argon with nitrogen (1-4 vol.%) were used as shielding gas with a flow rate of 8 l/min during top and back sides of welds. Effects of welding speeds and nitrogen contents in argon shielding gas on pulse currents were study to achieve an acceptable weld bead profile with complete penetration. It was found that increasing nitrogen contents in argon gas decreases the pulse currents and increasing welding speed will increase the pulse current.

Razali AR et.al [26] Corrosion of welded and un-welded Aluminum Alloy 6061 T6 was investigated by immersing specimens in 3.5% (wt) NaCl solution. Optical Microscopy and Scanning Electron Microscopy were used to investigate the microstructure evolution and the failure pattern of the specimens. Results revealed that corrosion current of the heat affected zone (HAZ) was higher than the base metal (BM). Corrosion potential for HAZ was more negative than the BM. Significant pitting corrosion was observed on the HAZ compared to the BM.

Akhtar Z et.al [27] A critical review has been discussed in the paper concerning dissimilar welding of aluminum and steel. Based on the review of several previous studies on aluminum–steel welding, a number of common aspects are observed. For arc welding, TIG welding is generally preferred. As regards to parent metals, aluminum 5XXX and 6XXX series are excellent aluminum candidates. When other steel groups or codes are considered, a non-corrosive flux or a flux-cored filler can be utilized to improve mixture and limit IMC formation. A preheating technique in the form of hybrid welding is also proposed to develop a sound mixture between aluminum and steel. However, a precise preheating heat input is crucial to yield the best quality joint. Thus, this research area should be further explored.

Wei Zhou [28] studied the problems in Welding of High Strength Aluminium Alloys. Heat treatment or tempering affects corrosion resistance and mechanical strength by controlling the distribution of alloying elements between solid solution and insoluble precipitates. To minimise SCC susceptibility, over-ageing treatments (T7) may be utilised at some sacrifice of tensile strength. However, tempering or heating during welding may be undesirable and reduce SCC resistance of the welded joints.

Radha Raman Mishra et.al [29] studied the tensile strength of MIG and TIG welded dissimilar joints of mild steel and stainless steel. Stainless steel of grades 202, 304, 310 and 316 were welded with mild steel by Tungsten Inert Gas (TIG) and Metal Inert Gas (MIG) welding processes. The percentage dilutions of joints were calculated and tensile strength of dissimilar metal joints was investigated. The results were compared for different joints made by TIG and MIG welding processes and it was observed that TIG welded dissimilar metal joints have better physical properties than MIG welded joints.

2.2 Problem Statement

In the real world, it would really hard to have a dissimilar welding process because it's new development technique and have different material properties. Even though dissimilar welding have a advantages, it also have a drawback due to its attribution to the large difference between their melting points, the nearly zero solid solubility of iron in aluminum, and the formation of brittle intermetallic compound (IMC) such as Fe_2Al_5 and $FeAl_3$ which can cause a detrimental effect on the mechanical property of the workpiece. Due to this reason, there is a demand to fabricate it. Therefore, the details investigation will be done on the dissimilar welding of aluminium alloy and steel sheet. Both of the materials will be lap joined and self brazed by the TIG welding process and researching of the microstructure and mechanical properties of the dissimilar welding will be done.

2.3 Objective

The primary aim of this work is to optimize the parameters for TIG welding of dissimilar metals with particular reference of weld of aluminium alloy with mild steel and galvanized steel separately. The physical and mechanical properties of welded joints will be determined. The properties will be correlated with the microstructure of the welded joint.

The importance of this research works are given below-

1) To develop a joint between Mild steel to Al alloy and Galvanised steel to Al alloy by TIG welding.

2) To decrease the Intermetallic layer thickness.

   a) By introducing a barrier layer of zinc present on the galvanized steel to decrease the diffusion of Fe in Al.

   b) By increasing cooling rate using the Water cooled copper block setup.

3) To study the effect of weld current on strength of welded joints.

4) To study microstructural and mechanical properties of joint.

5) To estimate the amount of load that could be applied to each type of weld before the welded joints fails or rupture.

2.4 Scope Of Study

The scopes of study in this project are:

1) Fabrication of the lap joint dissimilar welding of aluminium-galvanized steel with different aluminium filler by using the tungsten inert gas (TIG).

2) Investigate the mechanical properties of the joint using tensile test and Microhardness test.

3) Analyzed the microstructure of the joint using the Optical Microscope and SEM.

4) Investigate the Al-Fe compounds using XRD technique.

Chapter 3 EXPERIMENTAL DETAILS

3.1 Material Selection

The base materials thickness used in this research are Al6061 aluminium alloy plate of 3 mm, galvanized steel plates with a thickness of 2.5 mm and Mild steel sheet of thickness 1 mm. All types of plate were cut into 90 mm × 70 mm using a MVS-C 6/31 shearing machine. The filler metal utilized were Si-rich ER4043 (5 wt.%) filler rods. The chemical composition of the base materials and filler metal is shown in Table 1.

Table 1 : Material composition in wt.%.

Material	Fe	C	Mn	Cu	Si	Mg	Al
Al 6061	**<0.7**	**_**	**<0.15**	**0.15-0.4**	**0.4 – 0.8**	**0.8-1.2**	**95.8-98.6**
Mild Steel	**99.51**	**0.077**	**0.277**	**< 0.005**	**0.016**	**0.001**	**0.025**
Galvanised Steel (GS)	**98.6**	**0.068**	**0.286**	**0.0083**	**<0.005**	**_**	**0.028**
ER4043	**<0.8**	**_**	**<0.05**	**<0.3**	**4.5-6.0**	**<0.05**	**Bal**

3.1.1 Aluminium 6061 (Al-Mg-Si Alloys)

There are many types of aluminium. The aluminium chosen for this research arealuminium 6061. Aluminium 6061 is in the 6xxx series and has good weldability. The 6xxx alloys have moderately higher strength coupled with excellent corrosion resistance. It also have a higher strength and broad use in welded structural, such as truck and marine frames and railroad cars and pipelines. The aluminium melting point is 660 °C.

The characteristic of 6xxx series materials are:

- Heat treatable
- High corrosion resistance, excellent extrudability, moderate strength
- Typical ultimate tensile strength range is 124-400 MPa.
- Building and construction, highway, automotive, marine application

3.1.2 Galvanized Steel

Galvanized steel is coated in a layer of zinc to help the metal resist corrosion. The zinc layer protected the metal by forming a physical barrier, usually around 15 μm in thickness. When using galvanized steel, no flux was required to ensure wetting of the zinc-coated steel surface. It is due to the good metallurgical compatibility between Fe, Al and Zn. It also one of the favored as a means of protective coating because of its low cost, ease of application and comparatively long maintenance free service life. The melting and boiling point of galvanized steel is depending on the zinc layer which coats the steel surface. The zinc layer melting point is 420 °C.

3.1.3 Fillers metal

The filler that will be used in the study is ER4043. This type of fillers will have a great cause in preventing growth of the IMC layer and minimizing its thickness due to its alloying elements. Si composition in Al based filler metal are used to be in charge of the growth of brittle Al–Fe IMC layer by replacing Al–Fe phases with a smaller amount detrimental Al-Fe–Si phases.

Sample Preperation

The Al and steel plates were cut into sample sizes of 7cm X 9cm by plate shearing machine shown in Figure 3.1. The whole process followed during the research work is explained briefly by experimental plan in Figure 3.2.

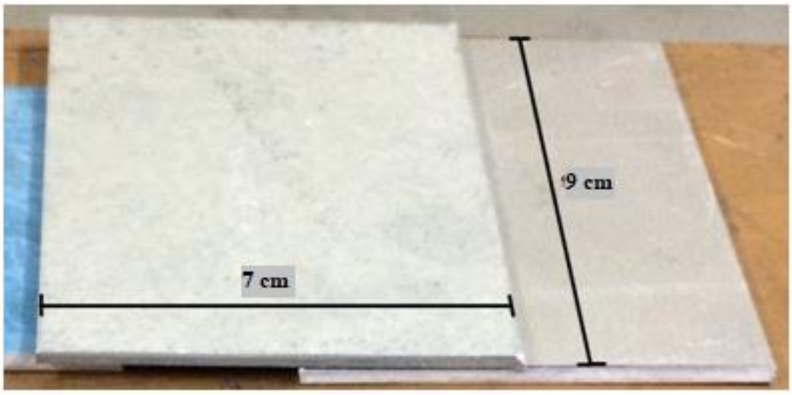


Figure 3.1 : Dimensions of welding plates for TIG welding

Experimental Plan

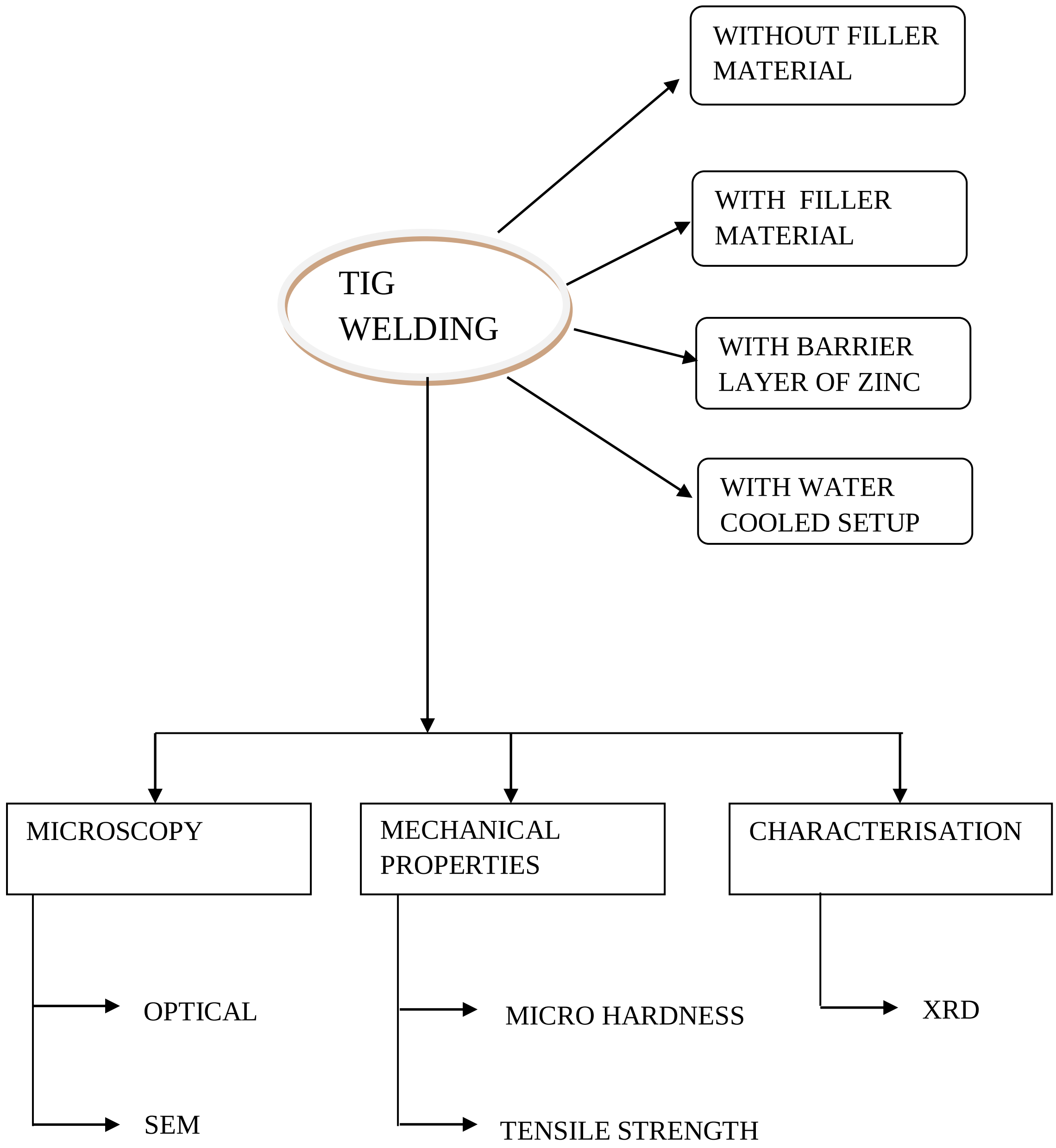


Figure 3.2 : Experimental Plan

3.2 TIG Welding Process

Figure 3.3 : TIG Model Miller welding machine.

After the cutting process, the aluminium 6061 was lap-joined to the galvanized iron using the commercially available Miller Dynasty 200 TIG arc welding machine. The process was carried out by using AC-TIG welding sources with the welding current at 70 A and 90 A. To position the top material in place, an additional plate with the same thickness was stacked at the bottom of the top plate and fixed accordingly. In order to find the optimum variables, several types of conditions were investigated. In order to differentiate the results, the specimens were coded based on the variable parameters, which are the type of filler used and the material positioning for lap joining and Bead on the steel sheet experiment. Two samples were welded for each designated code. The types of welding performed are- Welding using filler material and welding without filler material. Figure 3.3 shows the Model Miller TIG welding machine is used in this experiment.

3.2.1 Welding using Filler Material

This type of welding includes the Aluminium 6061, Mild Steel Sheet, Galvanised Steel Sheet and ER4043 filler material. The steel sheets were kept below the aluminium sheet while welding. The welding is done across the length of 9 mm to make a Lap Joint. Figure 3.4 shows the welded sample of Al-Steel Lap weld. The variables selected for this experiment were-

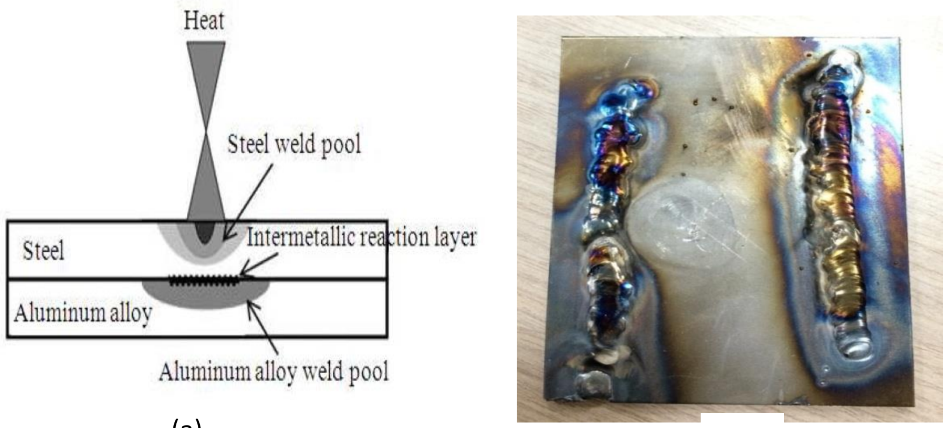
- Mild Steel (1 mm), Galvanised Steel (2.5mm) and Aluminium 6061 (3 mm) thickness
- Filler material : Aluminium wire 4043
- Weld of Aluminium Alloy with- (1) Mild Steel, (2) Zinc Coated Galvanised Steel
- Welding current : 70-90A
- Arc length : 3-4 mm
- Gas Flow rate: 8-10 lit per min
- Direct Current Electrode Positive

Figure 3.4 : Welding using filler material

3.2.2 Bead on the Steel Sheet (BoSS) experiment

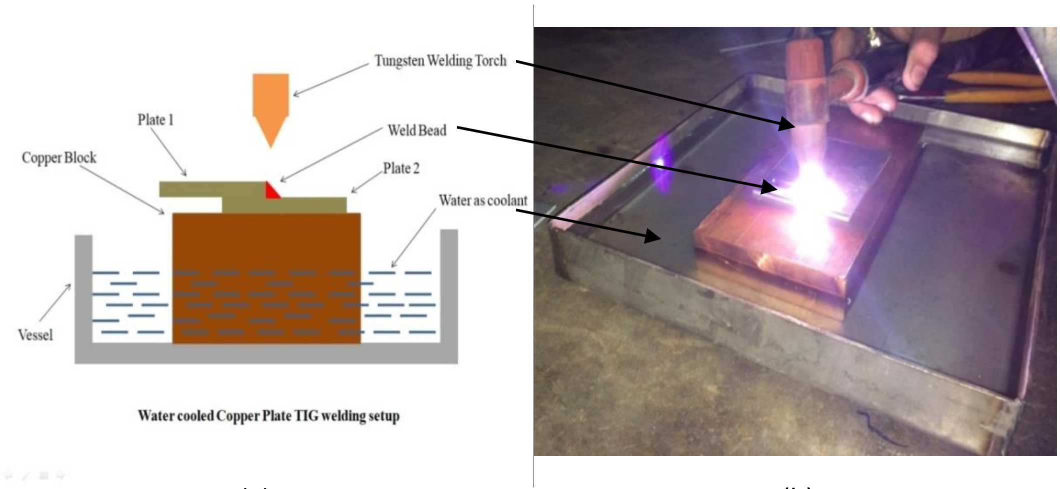
This type of welding includes Aluminium 6061 and Mild steel. The steel sheet is kept above the aluminium sheet completely overlapping the latter one. The welding is done across the length of 9 mm. Figure 3.5(a) shows the schematic of BoSS experiment and Figure 3.5(b) shows top view of the welded plater by BoSS experiment. The variables selected for this welding were:

- Mild Steel (1mm) and Aluminium 6061 (3mm)
- Welding speed= 0.55, 0.60, 0.65 m per min
- Welding current= 30 – 100 A
- Direct Current Electrode Negative used



(a) (b)

Figure 3.5 : Bead on the steel sheet experiment- (a) schematic of experiment *[4]*, (b) welded joint



(a) (b)

Figure 3.6 : Water cooled copper block setup - (a) Schematic of experiment setup, (b) setup of experiment

3.3 Water Cooled Copper Block Experiment

Since the thickness of the IMC layer depends on the heat input, i.e., the temperature of the welded joint. Therefore the thickness of the IMC layer can be controlled by increasing the heat transfer rate of the welded zone or by increasing the weld speed. The method here used for increasing the heat transfer rate is by installing a water cooled copper block. The temperature of water used was 15ºC approximately. The dimensions of the copper block were 4” x 8” x1.5”. The water was continuously changed to maintain the temperature of setup at 15ºC. Figure 3.6 (a) shows the schematic of water cooled copper block setup, while Figure 3.6 (b) shows the actual setup.

3.4 Microstructure Analysis

Samles for the microstructure analysis were made by Wire EDM machine and the dimensions of the samples were 1 cm X 2 cm. They were then mounted by cold setting compound. Optical microscope was used to examine the samples. The microscopic images for analysis were taken using 100X and 500X magnifications. Figure 3.7 shows the Leica inverted microscope used for microstructural imaging.

3.5 Fracture and Mechanical Property Analysis

Shear tests were used to evaluate the shear strength of the welded specimens. The aluminium–galvanized iron samples were pulled to failure at a constant rate. The test was carried out by the tensile test machine and the samples were prepared with reference to the ASTM E8-09 standard. The fracture mechanics were also analysed after the shear test. Figure 3.8 shows the image of the Tinius Olsen tensile testing machine used for the tensile testing of the welded samples.

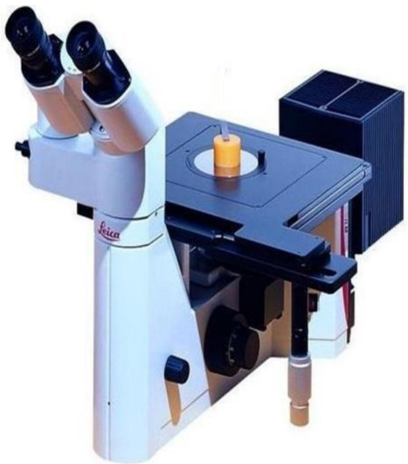


Figure 3.7 : Leica inverted microscope *[4]*

Figure 3.8 : Tinius Olsen Tensile Test Machine *[5]*

3.6 Microhardness Analysis

Microhardness testing is done by forcing a diamond shaped indenter with a fixed shape and size into the surface of specimen using a specific load. There are two methods used in finding microhardness: Knoop and Vickers. Knoop testing uses a rhombus indenter to leave an indention with a 7 to 1 ratio between long and short diagonals. The microhardness number (HK) is found by the ratio of load applied to unrecovered area of the indention. Vickers testing, which is the process used in this project, uses a square-based indenter with angles of 136˚ angles to leave an indention. The microhardness number (HV) is found by the ratio of the load to the surface area of the indention. In this experiment the load used for indentation was 15 kgf and is denoted by HV0.015 .

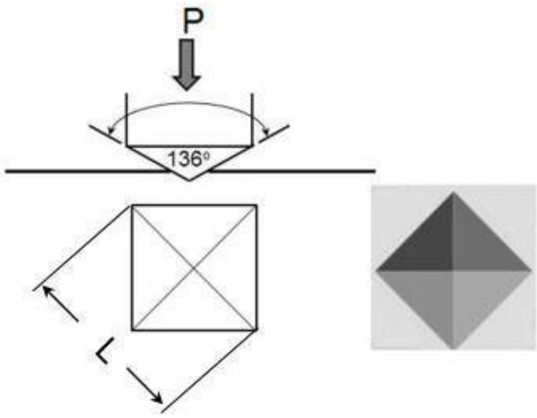
Vickers hardness number (HV) is obtained by using following formula in which applied load is divided by surface area of the indentation which is calculated from the diagonal length of the impression.

$$HV = 1.854\, P / L^2$$

Where, *P* is the load applied and d is the length of diagonal of indentation.

Figure 3.9 (a) shows the Vickers Microhardness Tester used for the present experiment and Figure 3.9 (b) shows the dimensions of the diamond indenter used for indentation.

(a)



(b)

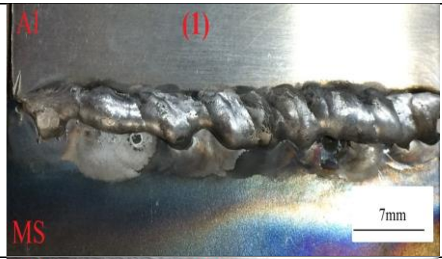
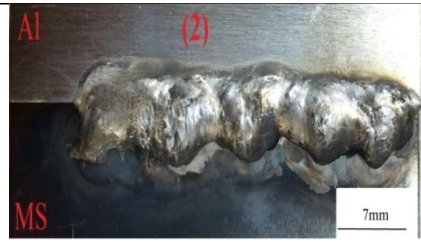
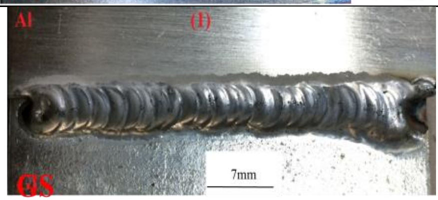
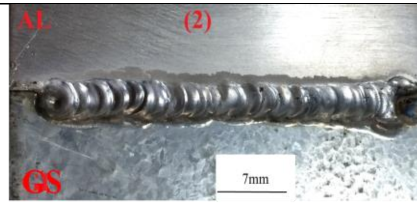
Figure 3.9 : Vickers Microhardness- (a) testing machine *[6]*, (b) Diamond indenter *[7]*

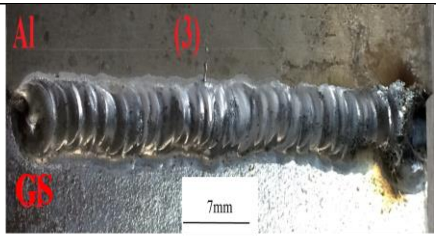
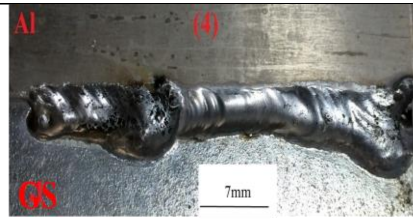
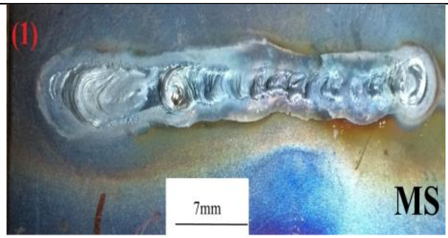
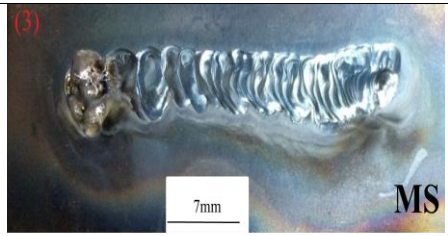
Chapter 4 RESULTS AND DISCUSSION

4.1 Weld Appearance

Table 2 shows the weld appearance and outer defects detection, i.e. the regions marked were observed primarily at the start and end of the welding, which is unavoidable in manual welding. However, the overall weld beads showed a good quality finish. The Al-GI group specimens show good bead continuity and the best weld appearance due to minimal surface defects. Defects such as cracks, porosity, cavities and a lack of fusion can constitute a cause of decreased joint strength and integrity [35]. The prominent defect that occurred on the specimens is the existence of pores, particularly in the GI-Al group specimens. Porosities were easily formed in deeply penetrated weld beads. Since a low welding speed was detrimental to ensuring good brazing on the steel surface, the trapped air bubbles generated from the electrode tip during welding formed the porosities observed [34]. From the weld results it was concluded that when the weld current was was kept below 70A, the joint was very weak and even broke by little force in the case of lap joint of Al and MS, therefore the minimum current input was 70A. Similarly, the Bead on the steel sheet result showed that when the current was kept below 70A the sheets were not welded and when the current was kept above 100A the steel sheet eroded and holes were visible as the steel sheet thickness was very less, i.e., 1mm. Therefore, the current ranges best for te welding of Al-Steel joints were taken between 70A and 90A.

Table 2 : Photographs of joints obtained in the experiments along with corresponding combination of the considered variable parameters, and the visual observation.

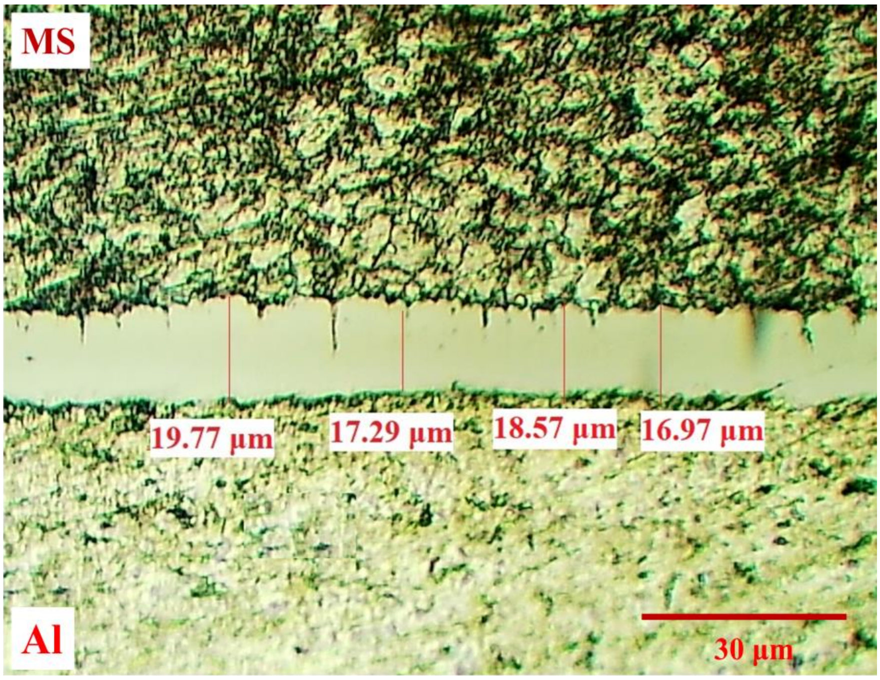
Exp. No.	Values of current and type of weld	Photograph of the joint	Observation	Exp No.	Values of current and type of weld	Photograph of the joint	Observation
1.	70 A; Al-MS		Strength was not good	2.	90 A; Al-MS		Strength decreased as compared to (1)
3.	70 A; Al-MS (Water cooled copper block setup)		Strength was better amongst all Al-MS weld	4.	90 A; Al-MS (Water cooled copper block setup)		Strength decreased as compared to (3)
5.	70 A; Al-GI		Good weld Strength much higher than Al-MS weld	6.	90 A; Al-GI		Good weld

7.	70 A; (Water cooled copper block setup)		Strength best among all experime nts	8.	90 A; (Water cooled copper block setup)		Good joint
9.	70 A; BoSS (Al-MS)		Minimum current required for BoSS	10.	90 A; BoSS (Al-MS)		IMC thickness increased
11.	70 A; BoSS (Al-MS) (Water cooled copper block setup)		Joint was good	12.	90 A; BoSS (Al-MS) (Water cooled copper block setup)		Strength decreased as compared to (11)

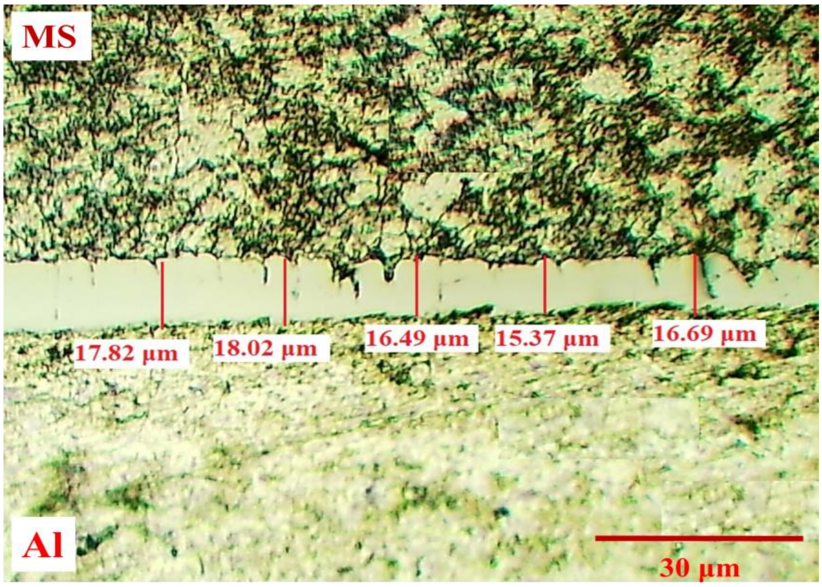
4.2 Microstructure and Mechanical Properties

The tests shows the IMC layers of the four groups with 500× magnification. The samples which utilized water cooled copper plate setup, have a thinner IMC layer, with values measured between approximately 11µm and 18µm compared to samples which used normal atmospheric conditions had values between approximately 12µm and 20.5µm. A thicker IMC layer will have a detrimental effect on the strength of the weld specimens due to its brittle nature and potential crack initiation region [32]. Therefore, mitigation of IMC layer formation will produce a higher tensile strength and better weld joint. Ghazali FA [18] stated that, for an IMC layer less than 15 µm, the assemblies present sound joint and high interface strength. Si additions in the filler metal have been reported to effectively prevent the growth of an IMC layer [29]. However, previous reports indicate that Si has a 0.8–6 wt.% solubility in the Al-Fe IMC system [34, 35]. Figure 4.1, Figure 4.2 and Figure 4.3 gives the microscopic view of the fusion zone showing the intermetallic layer of Al-MS weld, Al-GI weld and BoSS experiment respectively.

4.2.1 Aluminium-Mild Steel Weld



(a)

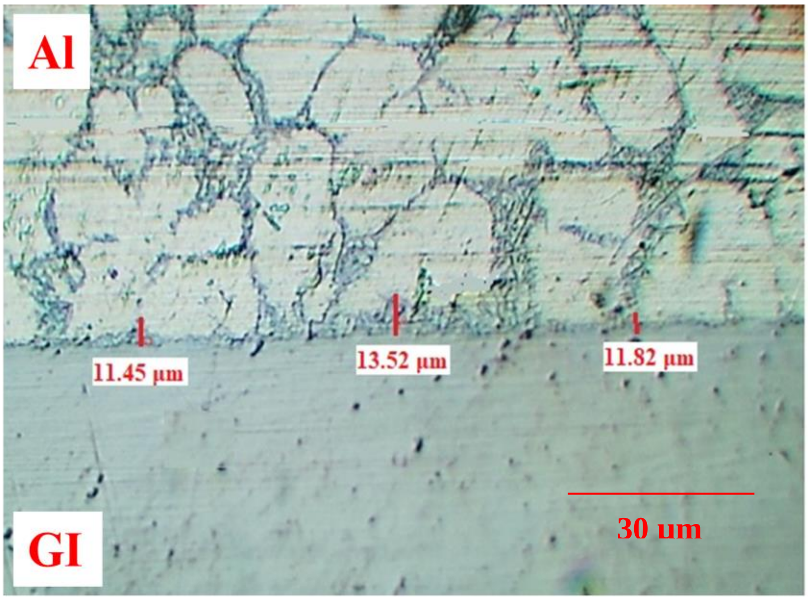


(b)

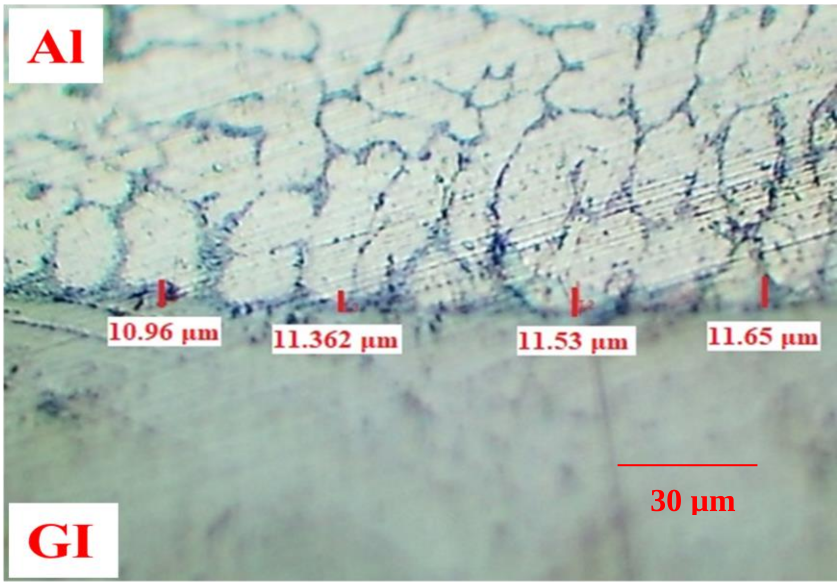
Figure 4.1 : Microscopic images of Al-MS weld at (a) 70A weld current, (b) water cooled setup weld at 70 A

Figure 4.1(b) shows the decrease in the IMC layer thickness when heat transfer rate was increased as compared to the normal condition weld in Figure 4.1(a). It was also observed that on increasing the heat input the IMC thickness increased.

4.2.2 Aluminium-Galvanised steel weld



(a)

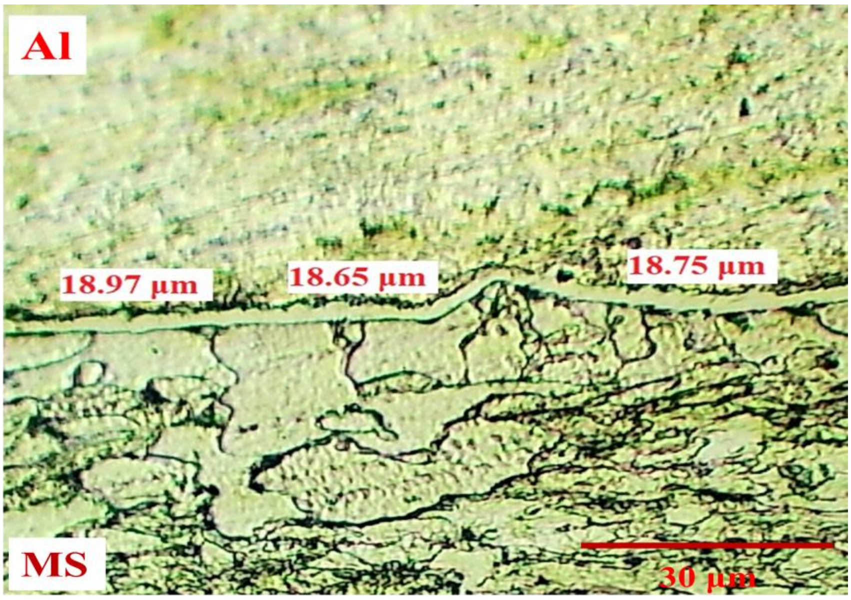


(b)

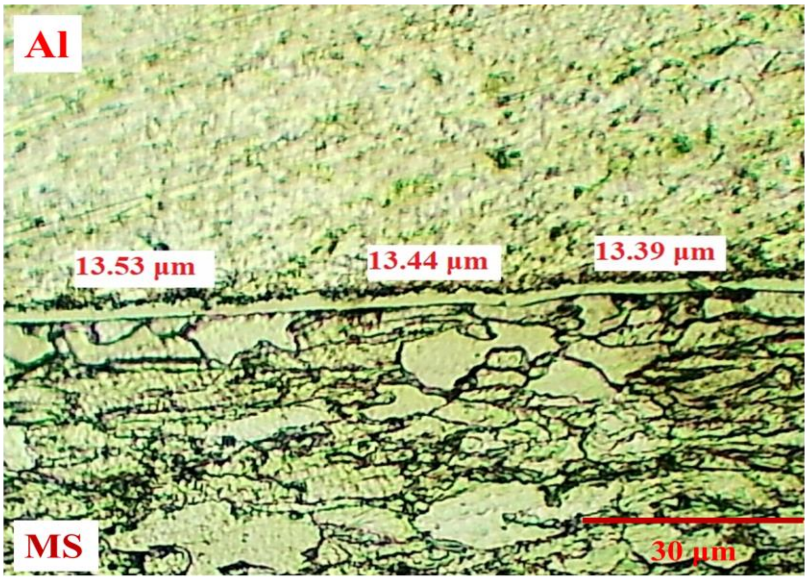
Figure 4.2 : Microscopic images of Al-GI weld at (a) 70A weld current, (b) water cooled setup weld at 70 A

Here, the decrease in the IMC layer thickness can be seen when the heat transfer rate was increased at 70A shown in Figure 4.2(b) as compared to the thicker IMC layer in 70A weld current shoen in Figure 4.2(a).

4.2.3 Bead on the steel sheet



(a)



(b)

Figure 4.3 : Microscopic images of Bead on the steel sheet weld at (a) 70A weld current, (b) water cooled setup weld at 70 A

Table 3 : IMC layer Thickness

Condition	Al-MS Weld (µm)	Al-GI Weld (µm)	BoSS (µm)
70A	18.15±1.28	12.26±1.1	18.79±0.16
90A	20.48±4	12.02±1.3	18.7±1.8
Copper Cooled 70A	18.75±1.25	11.9±2.2	17.95±1.1
Copper Cooled 90A	20.2±1.41	12.6±0.15	19.1±0.5
Water cooled 70A	16.87±1.08	11.38±0.3	13.45±0.07
Water cooled 90A	18.54±1.46	12.18±0.8	16.13±0.63

Table 3 shows the thickness of IMC layer formed in different welding conditions. The values shows the Standard Deviation data of the IMC thickness measured. From the results of microstructure analysis it can be concluded that the IMC layer thickness was increasing with the increase in temperature of the fusion zone. The minimum thickness was observed in the Al-GI weld done with water cooled setup and at lower weld current of 70A. While, the maximum thickness was observed for the Al-MS weld at 90A weld current and normal cooling conditions. Therefore, it is suggested to use low heat input for the welding of Al and Fe welding, use Galvanised Steel instead of MS and new conditions can be developed to further increase the heat transfer rate.

4.3 SEM Analysis

Energy Dispersive Spectroscopy analysis is a technique used to identify the elemental composition of material. Results below showing the data generated by EDS analysis consists of spectra showing peaks corresponding to the elements making up the true composition of the joint samples having maximum tensile strength obtained in following experiments respectively. Upon comparing chemical composition data obtained from EDS of the joints prepared with the chemical composition of the base material, it confirms that there are no significant changes in chemical composition of autogenous joints prepared using TIG welding process. Test was conducted on the samples welded at 70A of each weld condition and is given in following figures.

1. Al-MS Weld

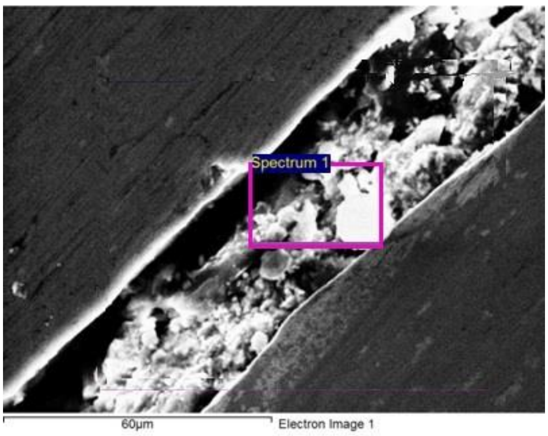
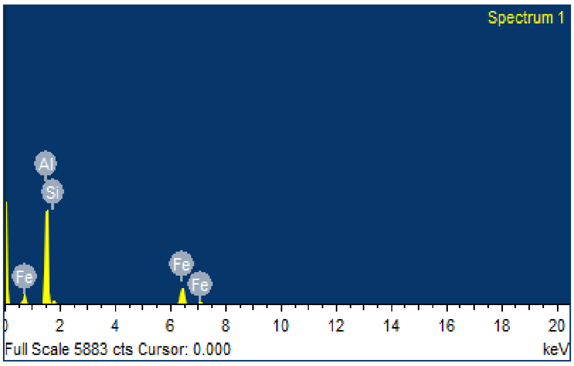


Figure 4.4 : SEM image of Al-MS IMC



Element	Weight%	Atomic%
Al K	57.77	72.11
Si K	4.19	5.02
Fe K	37.26	22.47
Mn K	0.78	0.40
Totals	100.00	

Figure 4.5 : EDS elemental analysis of Al-MS weld and its composition data

2. Al-GI Weld

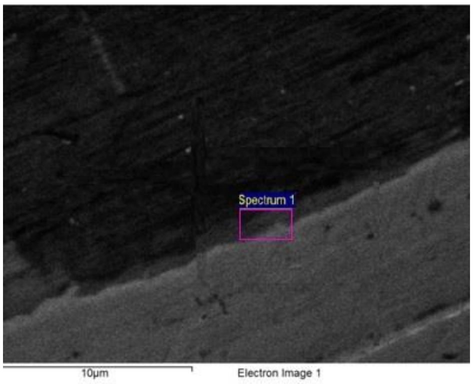
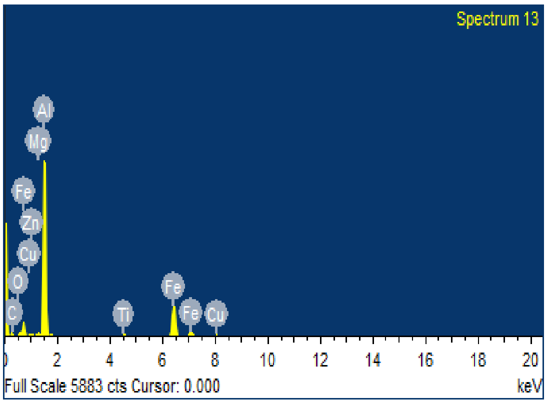


Figure 4.6: SEM image of Al-GI weld



Element	Weight%	Atomic%
C K	2.63	1.68
O K	3.97	6.40
Mg K	1.14	1.18
Al K	46.88	43.85
Mn K	0.47	0.25
Fe K	41.62	43.55
Cu K	2.37	0.96
Zn K	1.33	0.52
Totals	100.00	

Figure 4.7: EDS element analysis of Al-GI weld and its composition data

3. Bead on the Steel Sheet

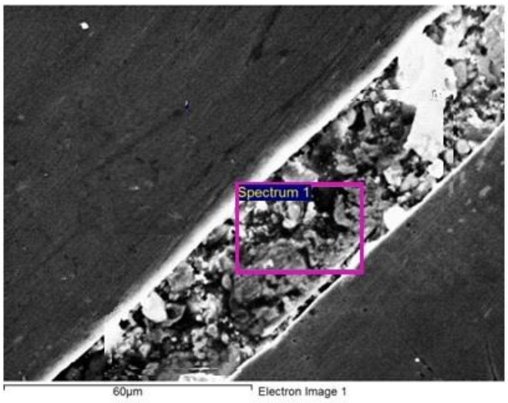


Figure 4.8: SEM image of Bead on the Steel Sheet IMC

Element	Weight%	Atomic%
C K	2.11	1.1
Al K	54.02	52.02
Fe K	42.87	45.97
Mg K	1.22	1.08
Mn K	0.52	0.36
Totals	100.00	

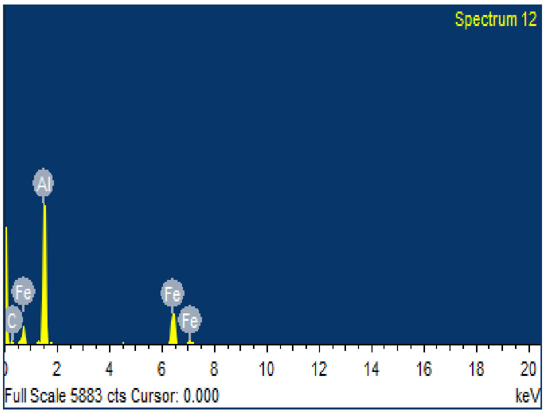


Figure 4.9 : EDS elemental analysis of Bead on the Steel Sheet weld and its composition data

Figures 4.4, 4.6 and 4.8 shows the SEM image of the welded joint at 70A welding current of Al-MS weld, Al-GI weld and BoSS weld respectively. Figures 4.5, 4.7 and 4.9 gives the elemental analysis and composition data of the welded joints of Al-MS weld, Al-GI weld and BoSS weld respectively.

4.4 XRD Analysis

Table 4 : Peak List

Formula	Pos 2-theta (deg)	d-spacing [Å]	h	k	l
$FeAl_3$	39.86	2.260	-	-	-
Fe_2Al_5	44.14	2.050	-4	0	4
$FeAl_2$	44.14	2.050	-	-	-
FeAl	44.31	2.043	1	1	0
Fe_3Al	44.37	2.040	2	2	0
$FeAl_3$	64.18	1.450	-	-	-
Fe_3Al	64.18	1.450	4	0	0
Fe_3Al	81.51	1.180	4	2	2

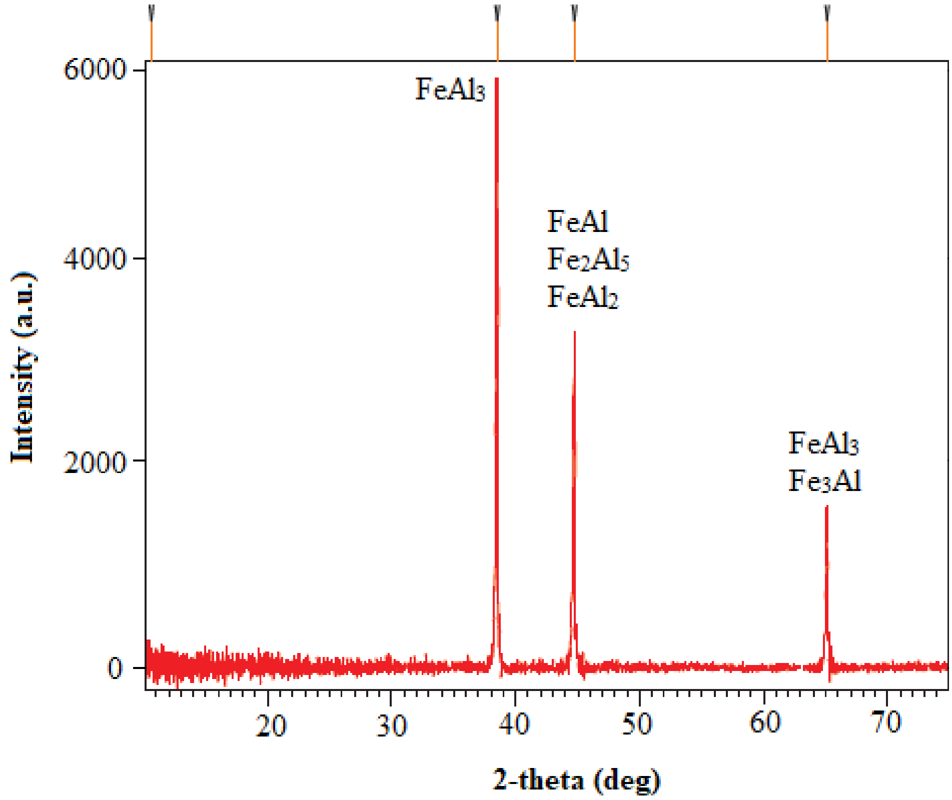
The XRD result of the weld joint is shown in the table 4. It is observed that a number of crystalline phases were formed. The results of XRD also revealed the presence of Fe-rich compounds [FeAl and Fe3Al] and Al-rich compounds [FeAl2, Fe2Al5and FeAl3] in the matrix.

The XRD analysis was done on 3 samples of different welding type at 70A each as it was observed that the 70A weld conditions gave better results as compared to other weld current conditions.

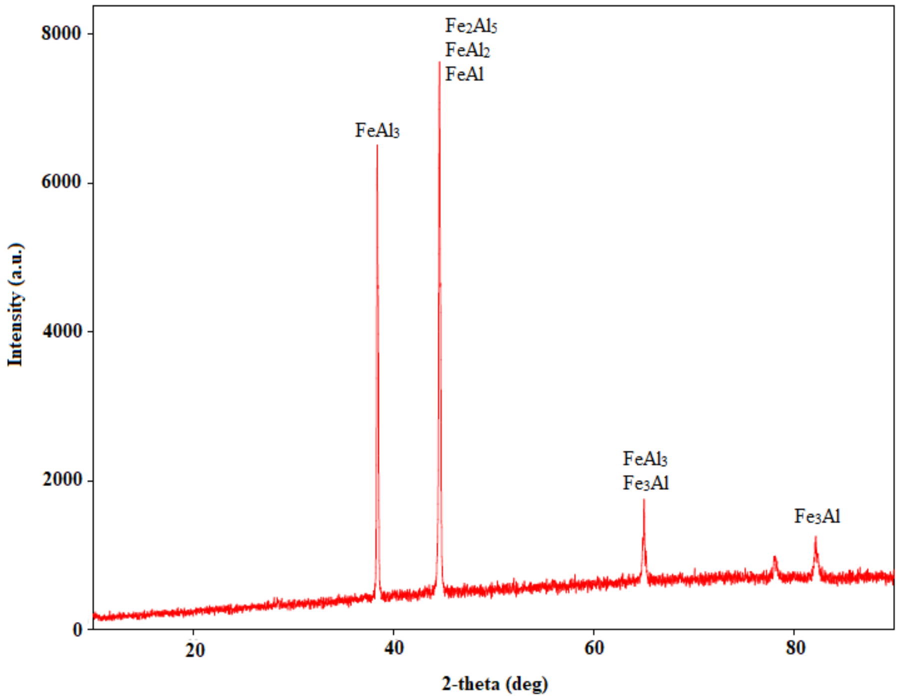
The compounds were confirmed using the JCPDS files which are as follows-

1. Fe2Al5 - 00-001-1228
2. FeAl3 - 00-001-1265
3. Fe3Al - 00-006-0695
4. FeAl2 - 00-034-0570
5. FeAl - 01-073-8033

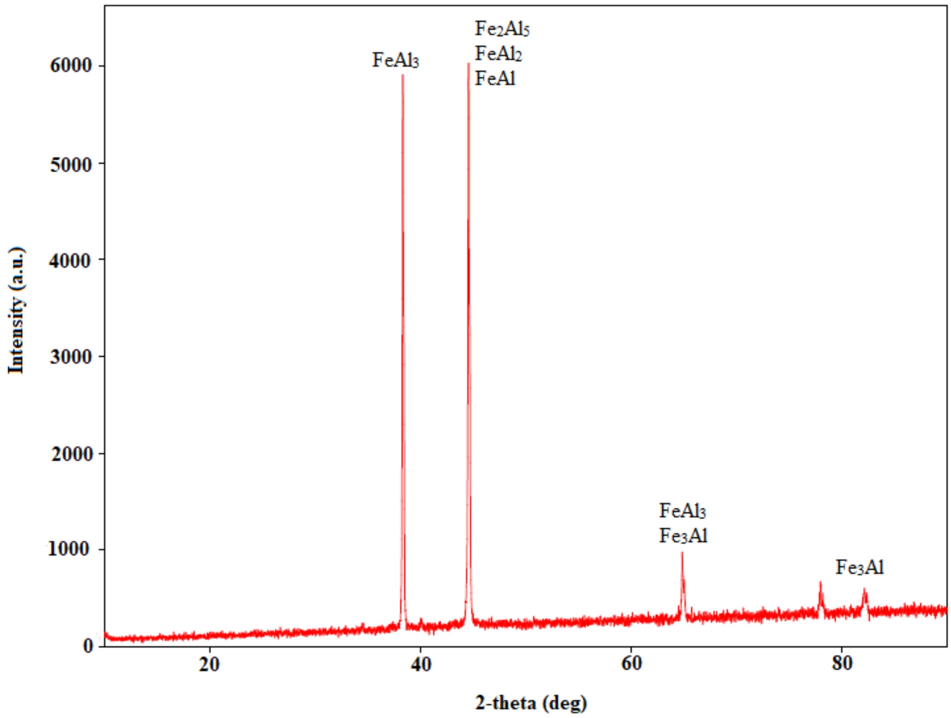
Figures 4.10 (a), 4.10 (b) and 4.10 (c) shows the XRD analysis of thr composition of the IMC layer in the welded samples of Al-MS, Al-GI and BoSS experiments respectively.



(a)



(b)



(c)

Figure 4.10 : XRD Data at 70A weld current- (a) Al-MS Weld, (b) Al-GI Weld and (c) BoSS Weld

4.5 Fracture and Mechanical Properties Analysis

A shear test was conducted on the samples of each condition welded at 70A and the fracture specimens are shown in Figure 4.11. Dimensions of the specimens were 110mm X 20mm. The arrows show the fracture regions seen from the top and side view. Al-MS group failed at the parallel plane while both Al-GI groups failed at the perpendicular plane with respect to the loading direction. However, close observation reveals a stark contrast of the fracture region of both groups. For the Al-MS group, the fracture occurred at the brittle faying surface, i.e. the IMC layer, while for the Al-GI group the fracture occurred at the ductile aluminium FZ-HAZ region. Numerous reports indicate that dissimilar welding of aluminium–steel will fail at the IMC plane, which correlates with the results of the Al-MS group [21, 27, 30]. However, the Al-GI group failed at the ductile aluminium matrix. It is commonly known that brittle materials generally fail in tension, while ductile materials generally fail in shear [33]. Due to the brittle IMC layer of the Al-MS group being parallel to the loading direction, it withstood the shear loading until the ductile FZ-HAZ region of aluminium, having a smaller cross-sectional surface, yielded.

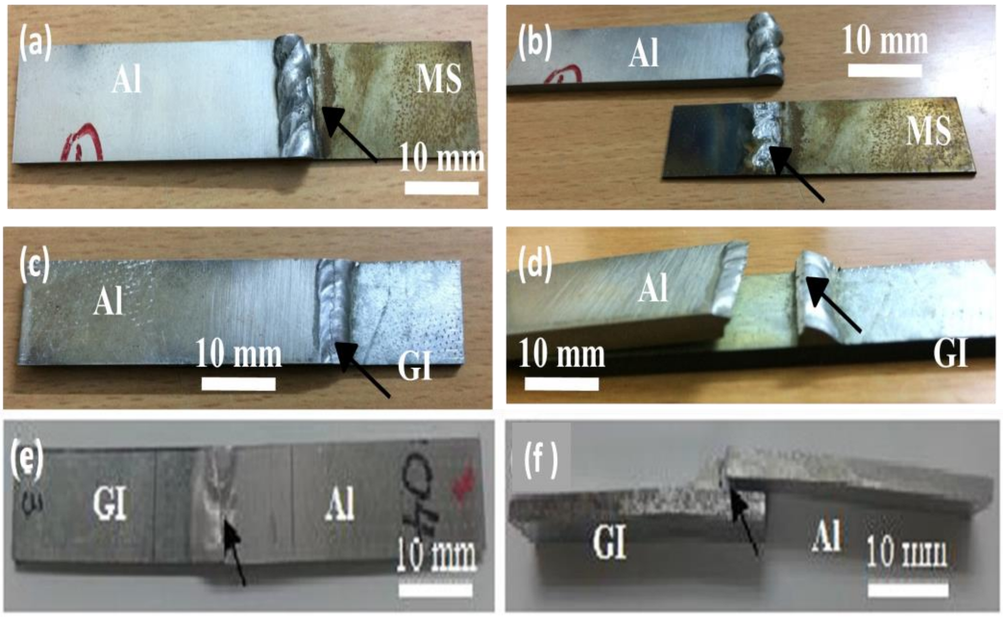


Figure 4.11 : Fracture points for Al-MS (a) top view, (b) front view ; for Al-GI (c) top view, (d) front view; and for Water cooled AL-GI (e)top view, (f) front view

4.5.1 Tensile load for Fracture of lap joint

1. Al-MS Lap Joint

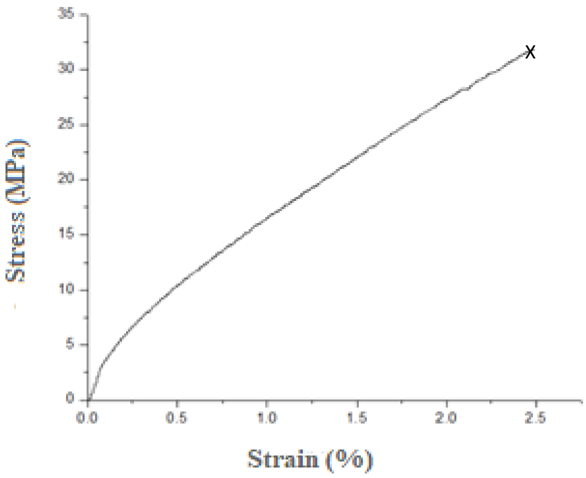


Figure 4.12 : Stress-strain curve for Al-MS weld at 70A

The maximum load (F) required for the fracture of this lap joint was at 1.9kN. The joint got ruptured from the plane of the IMC layer, i.e., parallel to the horizontal plane due to the thicker brittle IMC layer. The tensile stress at which the rupture of joint takes place was 31.9 MPa. The Figure 4.12 shows the stress-strain curve of tensile test done on the Al-MS welded specimen.

2. Al-GI Lap Joint

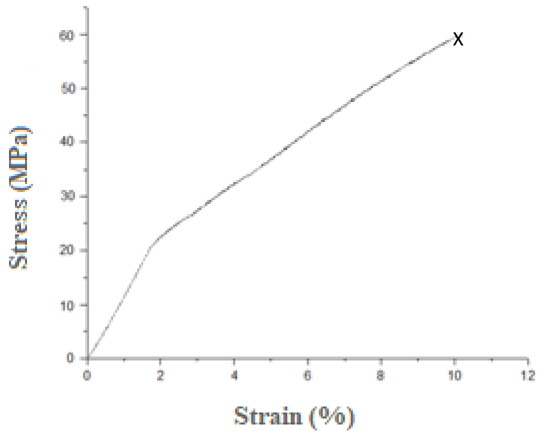


Figure 4.13 : Stress-strain curve for Al-GI weld at 70A

The maximum load (F) required for the fracture of this joint was 3.575kN. The fracture occurred at an angle of approximately 45° from the horizontal plane. The fracture doesn’t occurred from the IMC layer which shows a proper bonding of the metals and the decreased thickness of the IMC layer. Tensile stress at rupture point was 59.6 MPa. The Figure 4.13 shows the stress-strain curve of tensile test done on the Al-GI welded specimen.

3. Al-GI Water cooled lap joint

The maximum load (F) required for the fracture of this joint was 5.067kN. The fracture occurred at an angle of approximately 45° from the horizontal plane. The fracture doesn’t occurred from the IMC layer which shows a proper bonding of the metals and the further decreased thickness of the IMC layer. Due to the rapid cooling of the welded material the IMC layer thickness got decreased resulting in more strengthen bonding of metals. The tensile stress at which the rupture of joint takes place was 84.4 MPa. Figure 4.14 shows the stress-strain curve of tensile test done on the Al-GI water cooled welded specimen.

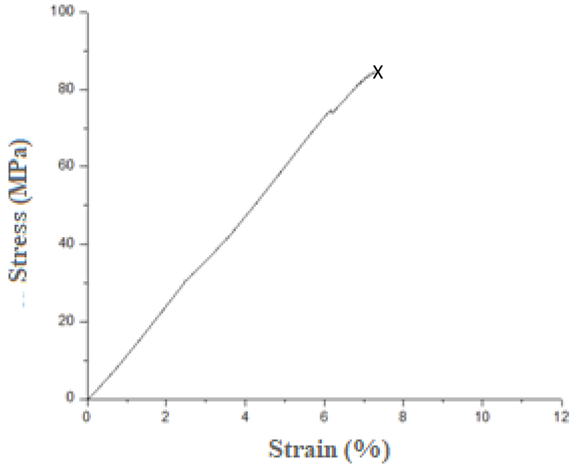


Figure 4.14 : Stress-strain curve for Al-GI water cooled copper weld at 70A

4.5.2 Calculation for Shear Stress

A shear stress, often denoted by τ (tau), is the component of stress coplanar with a material cross section. Shear stress arises from the force vector component arises from the force vector component perpendicular to the material cross section on which it acts. Figure 4.15 shows the schematic of shear stress on lap joint.

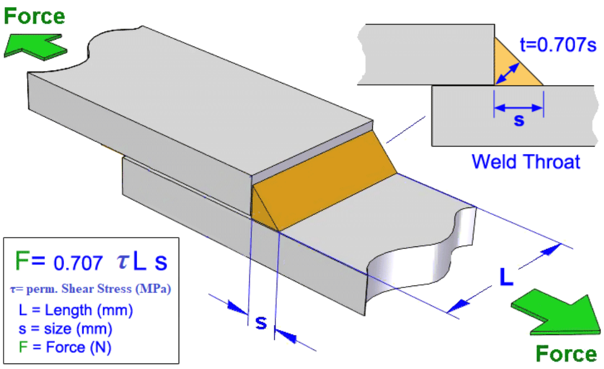


Figure 4.15 : Shear stress on lap joint *[8]*

The Shear stress for the lap joint is given by-

Permissible shear stress (τ) = [Max. load(F) * (sinθ + cosθ)]/ l*s

where, s= leg length of the weld

l= length of the weld

θ= Shear plane angle from horizontal plane

1. Al-MS Lap Joint

For this case since the joint fractured from the IMC layer which is parallel to the horizontal plane, therefore the angle θ becomes 0, the leg length of the weld was measured as s = 5mm and the length of the sample was l = 20mm. With these dimensions,

$\theta = 0^{\circ}$

s = 5mm

l = 20mm

Permissible Shear stress τ = 19 MPa.

2. Al-GI Lap Joint

For this case since the joint fractured from the plane at 45 º to the horizontal plane, therefore the angle θ becomes 45 º, the leg length of the weld was measured as s = 3mm and the length of the sample was l = 20mm. With these dimensions,

$\theta = 45^{\circ}$

s = 3mm

l = 20mm

Permissible Shear stress τ = 84.26 MPa.

3. Al-GI Water cooled lap joint

For this case since the joint fractured from the plane at 45 º to the horizontal plane, therefore the angle θ becomes 45 º, the leg length of the weld was measured as s = 3mm and the length of the sample was l = 20mm. With these dimensions,

$\theta = 45^{\circ}$

s = 3mm

l = 20mm

Permissible Shear stress τ = 119.5 MPa.

The shear strength obtained was 19 MPa, 84.26 MPa and 119.5 MPa for weld of Al-MS, Al-GI and Water cool weld of Al-GI respectively. This clearly shows that the shear values for similar aluminium welding are higher than for dissimilar welding specimens. This is due to the absolute solubility between the base metals of aluminium during welding, compared to the welding–brazing nature of aluminium–galvanized iron dissimilar welding.

Table 5: Mechanical Strength of Joints

Weld Type	Max. Fracture Load (kN)	Shear Strength (MPa)
Al-MS	1.9	19
Al-GI	3.575	84.26
Water cooled Al-GI	5.067	119.5

4.6 Microhardness Test

Vickers's microhardness was evaluated for the transverse sections of the two best joints having the two highest values of ultimate tensile strength for same thickness sheets and for different thickness sheets. Microhardness values at the weld zone were found to be increased in very small amount than that of base material due to decrease in grain size of the base material at the weld zone. It can be concluded that variation in microhardness in the weld zone and along base metal is insignificant which confirms that joint has small HAZ.

The indentations were done starting from Aluminium side across the fusion zone upto the steel sheet. As the hardness increases the strength of the joint decreses. The hardness for the 70A weld sample's base material, HAZ and the fusion zone is shown by the graph in Figure 4.16 with standard deviation. The values denote that the hardness of the aluminium in base material is lower than the fusion zone because of the intermetallic layer formation which causes the rupture from the joint.

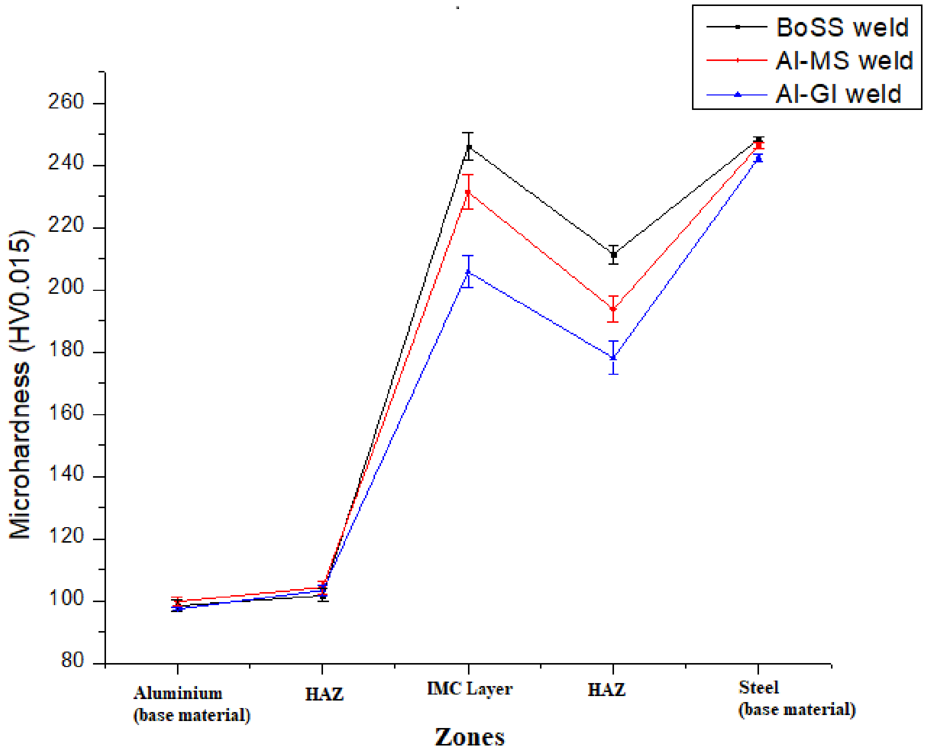


Figure 4.16 : Change in the hardness of material in the base material, HAZ and the fusion zone.

Discussion

The weld appearance shows that the Al-MS joint was not continuous and shows the improper weldability of Al over the MS, while with Galvanised Steel it shows better weld appearance and better strength of joint. The microstructure of weld joints shows that on increasing the weld current, i.e., on increasing the input heat the thickness of the IMC layer increases. Water cooled copper block setup increases the heat dissipation rate and therefore reduces the IMC layer thickness upto some extent. The SEM and XRD analysis gives the composition of IMC layer which proves its formation.
Tensile test shows the inverse relationship between IMC layer thickness and strength of the joint. As the thickness of IMC layer increases, the brittleness of the weld joint increases which increases the hardness of the joint as shown in the microhardness analysis.

Chapter 5 CONCLUSIONS AND SCOPE FOR FUTURE WORK

In this research, the weldability of Aluminium 6061, Mild Steel and Galvanised Steel has been studied. The welding was performed by Tungsten Inert Gas Weld. Following conclusions can be made:

1. When Mild Steel and Aluminium 6061 were welded, the joint was not good and the spreadability of Al over the mild steel was not good and mechanical strength was very less but when Aluminium 6061 was welded with Galvanised steel, its weldability increased due to the barrier layer of zinc on galvanized steel.
2. Microstructure analysis concludes that with the increase in input current the thickness of IMC layer inceases, and can be reduced by using the barrier layer of zinc and increasing the heat dissipation rate of the joint.
3. The reason for the poor weld properties was the formation of Intermetallic Compound Layer (IMC) which includes the compounds FeAl, Fe_3Al, $FeAl_2$, Fe_2Al_5 and $FeAl_3$ concluded from the XRD analysis.
4. On using the zinc coating as barrier layer and water cooled copper plate setup, the shear stress reached to maximum of 119.5 MPa from the minimum of 19 MPa of Al-MS weld which proves that the strength of the joint is inversely proportional to the thickness of the IMC layer.
5. Microhardness test concludes that with the increase in thickness of the IMC layer, the hardness of the joint increases and the rupture takes place from the brittle IMC zone.
6. Optimum conditions for the good Aluminium 6061 and steel TIG welding are weld current of 70A, zinc coating as barrier layer and the water cooled copper block setup.

SCOPE FOR FUTURE WORK

Various types of ultra-high strength steels are increasingly used in today's vehicle bodies. This includes steels for hot stamping such as boron steels and Al-Si coated boron steels. It is of interest to evaluate these additional steel types to increase the application of this welding technique. It is suggested that additional metallographic characterizations should be done to identify exact chemical compositions and microstructures especially at the interface area. The methods can be transmission electron microscopy (TEM) and electron microprobe analysis (EMPA).

To further improve the weld quality, it is recommended that control of welding temperature should be done. Apart from optimisation of welding parameters, it can be done by controlling the temperature of the rotating tool via a tailored cooling system. Temperature control in this way is independent from resulting material circulation like in case of controlling translational speed or rotational speed.

Also, the thickness of the IMC layer can be decreased by increasing the heat transfer rate of the welded portion. For this the setup can be made by using ice, Liquid Nitrogen, etc. for cooling the welded sample rapidly. By performing the experiment with different setups it will be clear that upto how much rate of cooling the strength of the weld will increase, because on melting the material and increasing the heat transfer rate by rapid cooling will make the material more brittle as the grains will become finer in size and the hardness will increases.

Chapter 6 REFERENCES

[1] Carfax,Inc. , www.carfax.com/blog/unibody-vs-body-on-frame-construction

[2] oxtool (2012), www.oxtool.blogspot.com/2012/10/tig-welding-dissimilar-materials/

[3] NPTEL (2009), www.nptel.ac.in/courses/

[4] Leica Microsystems GmbH, www.leica-microsystems.com/products/light-microscopes/inverted-microscopes/

[5] AZO Materials, www.azom.com/article.aspx/

[6] Qualitest, www.worldoftest.com/micro-knoop-vickers-hardness-tester

[7] AZO Materials, www.azom.com/article.aspx/

[8] learneasy (2014), www.learneasy.info/Welded_Joints/Welded_Joints

[9] Aisha Al Ismail, Mutlag Shafi Fuhaid and Murali R V. An experimental analysis on mechanical integrity of tig-mig hybrid weldments. International Journal of Mechanical And Production Engineering, ISSN: 2320-2092, Volume- 5, Issue-4, Aprl.-2017.

[10] L. H. Shah and M. Ishak. Investigation of aluminum-stainless steel dissimilar weld quality using different filler metals. International Journal of Automotive and Mechanical Engineering (IJAME) Volume 8, pp. 1121-1131, July-December 2013 DOI: http://dx.doi.org/10.15282/ijame.8.2013.3.0091

[11] Chawinee Pothong, Pusit Mitsomwang, Tapany Udomphol and Rattana Borrisutthekul. Effects of Aluminium Alloy Surface Preparation in TIG Dissimilar Metals Welding between Mild Steel and 5052 Aluminium Alloy. Proceedings of the 12th International Conference onAluminium Alloys, September 5-9, 2010, Yokohama, Japan pp. 961-965

[12] San-bao LIN, Jian-ling SONG, Guang-chao MA, Chun-li YANG. Dissimilar metals TIG welding-brazing of aluminum alloy to galvanized steel. Front. Mater. Sci. China 2009, 3(1): 78–83 DOI 10.1007/s11706-009-0007-2

[13] Rakesh Chaudhari, Riddhish Parekh, and Asha Ingle. Reliability of Dissimilar Metal Joints using Fusion Welding: A Review. International Conference on Machine Learning, Electrical and Mechanical Engineering (ICMLEME'2014) Jan. 8-9, 2014 Dubai (UAE)

[14] Tušek J, Kampuš Z, Suban M. Welding of tailored blanks of different materials. Journal of Materials Processing Technology. 2001;119:180-4.

[15] Moniz B, Miller R. Welding Skills. Stockton, CA, USA: Recording for the Blind & Dyslexic; 2007.

[16] Wor LC, Rahman MM. Stress behavior of tailor-welded blanks for dissimilar metals using finite element method. International Journal of Automotive and Mechanical Engineering. 2015;11:2541-54.

[17] Ishak M, Noordin NFM, Razali ASK, Shah LHA, Romlay FRM. Effect of filler on weld metal structure of AAa6061 aluminum alloy by tungsten inert gas welding. International Journal of Automotive and Mechanical Engineering. 2015;11:2438-46.

[18] Ghazali FA, Manurung YHP, Mohamed MA, Alias SK, Abdullah S. Effect of process parameters on the mechanical properties and failure behavior of spot welded low carbon steel. Journal of Mechanical Engineering and Sciences. 2015;8:1489-97.

[19] Charde N. Characterization of spot weld growth on dissimilar joints with different thicknesses. Journal of Mechanical Engineering and Sciences. 2012;2:172-80.

[20] Sathari NAA, Shah LH, Razali AR. Investigation of single-pass/double-pass techniques on friction stir welding of aluminium. Journal of Mechanical Engineering and Sciences. 2014;7:1053-61.

[21] Hafizi W, Ishak M, Shah LH, Aisha ISR, Islam MR. Study of resistance spot welding between AISI 301 stainless steel and AISI 1020 carbon steel dissimilar alloys. Journal of Mechanical Engineering and Sciences. 2014;6:793-806.

[22] Abd Razak NA, Ng SS. Investigation of effects of MIG welding on corrosion behaviour of AISI 1010 carbon steel. Journal of Mechanical Engineering and Sciences. 2014;7:1168-78.

[23] Fukumoto S, Tsubakino H, Okita K, Aritoshi M, Tomita T. Amorphization by friction stir welding between 5052 aluminum alloy and 304 stainless steel. Scr Mater. 2000;42:807-12.

[24] Zhang H, Liu J. Microstructure characteristics and mechanical property of aluminum alloy/stainless steel lap joints fabricated by MIG welding-brazing process. Materials Science and Engineering A. 2011;528:6179-85.

[25] Hatifi MM, Firdaus MH, Razlan AY. Modal analysis of dissimilar plate metal joining with different thicknesses using MIG welding. International Journal of Automotive and Mechanical Engineering. 2014;9:1723-33.
[26] Razali AR, Sathari NAA, Ishak M, Shah LH. Mechanical strength of dissimilar AA7075 and AA6061 aluminum alloys using friction stir welding. International Journal of Automotive and Mechanical Engineering. 2015;11:2713-21.
[27] Akhtar Z, Shah LH, Ishak M. Investigation of aluminum-stainless steel dissimilar weld quality using different filler metals. International Journal of Automotive and Mechanical Engineering. 2013;8:1121-31.
[28] Wei Zhou. Problems in welding of high strength aluminium alloys. Singapore Welding Society Newsletter, September 1999
[29] Radha Raman Mishra, Visnu Kumar Tiwari and Rajesha S. A study of tensile strength of MIG and TIG welded dissimilar joints of mild steel and stainless steel. International Journal of Advances in Materials Science and Engineering (IJAMSE) Vol.3, No.2, April 2014.
[30] Sierra G, Peyre P, Beaume FD, Stuart D, Fras G. Galvanised steel to aluminium joining by laser and GTAW processes. Materials Characterization. 2008;59:1705-15.
[31] Bang H, Bang H, Jeon G, Oh I, Ro C. Gas tungsten arc welding assisted hybrid friction stir welding of dissimilar materials Al6061-T6 aluminum alloy and STS304 stainless steel. Materials & Design. 2012;37:48-55.
[32] Mathers G. The welding of aluminium and its alloys. Cambridge, England: Woodhead Publishing Limited; 2002.
[33] Mandal NR. Aluminium welding. 2nd edition ed. Karagpur, India: Narosa Publishing House; 2005.
[34] Dharmedra C, Rao KP, Wilden J, Reich S. Study on laser welding-brazing of zinc coated steel to aluminum alloy with a zinc based filler. Materials Science and Engineering A. 2011;528:1497-503.
[35] Qiu R, Iwamoto C, Satonaka S. The influence of reaction layer on the strength of aluminum/steel joint welded by resistance spot welding. Materials Characterization. 2009;60:156-9.

[36] Lin SB, Song JL, Yang CL, Fan CL, Zhang DW. Brazability of dissimilar metals tungsten inert gas butt welding-brazing between aluminum alloy and stainless steel with Al-Cu filler metal. Materials & Design. 2010;31:2637-42.

[37] Song JL, Lin SB, Yang CL, Fan CL. Effects of Si additions on intermetallic compound layer of aluminum-steel TIG welding-brazing joint. Journal of Alloys and Compound. 2009;488:217-22.

[38] Ishak M, Noordin NFM, Razali ASK, Shah LHA, Romlay FRM. Effect of filler on weld metal structure of AA6061 aluminum alloy by tungsten inert gas welding. International Journal of Automotive and Mechanical Engineering. 2015;11.

[39] Ahmad R, Asmael MBA. Effect of aging time on microstructure and mechanical properties of AA6061 friction stir welding joints. International Journal of Automotive and Mechanical Engineering. 2015;11:2364-72.

[40] Song JL, Lin SB, Yang CL, Ma GC, Liu H. Spreading behavior and microstructure characteristics of dissimilar metals TIG welding-brazing of aluminum alloy to stainless steel. Materials Science and Engineering A. 2009;509:31-40.

[41] ASTM. Standard test methods for tension testing of metallic materials. Annual book of ASTM standards ASTM. 2010.

[42] Nuraini AA, Zainal AS, Hanim MAA. The effects of welding parameters on butt joints using robotic gas metal arc welding. Journal of Mechanical Engineering and Sciences. 2014;6:988-94.

[43] Blondeau R. Metallurgy and mechanics of welding. Hoboken, New Jersey: John Wiley & Sons Inc.; 2008.