JOINING OF 1050 ALUMINIUM ALLOY WITH 1018 LOW CARBON STEEL BY USING GAS METAL ARC WELDING (GMAW) PROCESS

M.Tech. Thesis

by

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DISCIPLINE OF MECHANICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY INDORE

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A THESIS

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Dherendra Jay Pant

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **"Joining of 1050 Aluminium alloy with 1018 Low Carbon Steel by using gas metal arc welding (GMAW) process"** in the partial fulfilment of the requirements for the award of the degree of **MASTER OF TECHNOLOGY** with specialization in **PRODUCTION and INDUSTRIAL ENGINEERING** and submitted in the **DISCIPLINE OF MECHANICAL ENGINEERING** at **INDIAN INSTITUTE OF TECHNOLOGY INDORE**, is an authentic record of my own work carried out during the time period from May 2014 to July 2016 under the supervision of **Dr. Kazi Sabiruddin** of Discipline of Mechanical Engineering.

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

Dherendra Jay Pant

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

Asst. Prof. Kazi Sabiruddin

Dherendra Jay Pant has successfully passed his M.Tech. Oral Examination held, on 18th July 2016.

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Convener, DPGC
Date:

Signature of PSPC member 1
Date:

Signature of PSPC member 2
Date:

Signature of Chairman, Oral Examination Board with date

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Dherendra Jay Pant

DEDICATED TO MY
PARENTS

ABSTRACT

Joining of aluminium and steel is often difficult because of large difference in thermo-physical properties of aluminium and iron. The solid solubility of iron in aluminium is almost zero (0.01%), which involves the easy formation of brittle intermetallic phases known as intermetallic compounds (IMC) at elevated temperatures which deteriorates the mechanical properties of the joints.

The gas metal arc welding (GMAW) process is used to join 1050 aluminium alloy (5 mm thick) and 1018 low carbon steel (5 mm thick) samples with filler wires (Cu Al-10% Fe, Al-5% Si and Al-12% Si), at different welding parameters (such as voltage and wire feed rate) and different welding conditions (i.e. dry ad wet) in a butt joint configuration.

Different amounts of silicon and copper are introduced into the weld through different filler wires. The effects of alloying elements on the microstructure of the weld and tensile strength of the resultant joint are investigated. Scanning electron microscopy (SEM) and Energy-dispersive X-ray spectroscopy (EDS) are used to characterize the different welding zones of the samples. The microhardness values corresponding to different locations of the weld joint are evaluated using Vickers microhardness tester. Tensile test is also carried out to find the strength of weld joint by using universal testing machine (UTM).

With the increase in silicon content in the weld, the thickness of intermetallic compound (IMC) decreases and the tensile strength of the joint increases. The thickness of the IMC layer could be controlled by Zn and Si-based filler wires. It is found that Cu Al-10% Fe filler wire not compatible with aluminium, Al-5% Si increases the number of blow holes and cracks by increasing voltage and Al-12% Si increases the heat affected zone (HAZ) in steel. 1050 Aluminium and 1018 low carbon steel are successfully joined by gas metal arc welding process. The ultimate tensile strength (UTS) of butt joints made in wet condition by using Al-5% Si and Al-12% Si filler wires are 45.2 MPa and 43.4 MPa respectively.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

V	:	Voltage (Volt)
I	:	Current (Ampere)
Q	:	Linear heat transfer (KJ mm^{-1})
f	:	Wire feed rate (m min^{-1})
U	:	Mean welding voltage
K	:	Thermal conductivity ($Wm^{-1}K^{-1}$)
α	:	Linear thermal expansion coefficient (K^{-1})
S	:	Welding speed (ms^{-1})

ORGANIZATION OF THE THESIS

This thesis is organised into FIVE chapters with following contents:

Chapter 1 requirement of welding, classifications of welding process, different joining techniques use to join aluminium and steel, gas metal arc welding process, process parameters of GMAW, concept of metal transfer in GMAW, advantages, benefits and limitations of GMAW, requirement of Al-steel joint, problems and challenges in joining of 1050 aluminium alloy and 1018 low carbon steel and application of Al-steel joint.

Chapter 2 presents a review of past work on joining of aluminium (or aluminium alloy) and steel by using different joining processes, research gaps is identified based on this review and the research objectives is defined based on the research gap.

Chapter 3 describes planning, experimental setup and details of experiments are carried out for the present work. It presents different process parameters and filler wires use to join 1050 aluminium alloy and 1018 low carbon steel in a butt joint configuration. It also presents various results of preliminary and main experiments.

Chapter 4 presents experimental results and their analysis focusing on the effects of variable input parameters of gas metal arc welding (GMAW) process, joint strength of aluminium alloy and low carbon steel weld joint. It also presents an analysis of the optical micrographs and microhardness test results to characterise joint.

Chapter 5 highlights the conclusions derived from the present work and scope for future work based on the limitations of the present work.

Chapter 1
INTRODUCTION

WELDING, the fusing of the surfaces of two workpieces to form one is a precise, reliable, cost-effective, and “high-tech” method for joining materials. No other technique is as widely used by manufacturers to join metals and alloys efficiently and to add value to their products. Most of the familiar objects in modern society, from buildings and bridges, to vehicles, computers, and medical devices, could not be produced without the use of welding. Welding goes well beyond the bounds of its simple description. Welding today is applied to a wide variety of materials and products, using such advanced technologies as lasers and plasma arcs. The future of welding holds even greater promise as methods are devised for joining dissimilar and non-metallic materials, and for creating products of innovative shapes and designs.

1.1 Requirement of welding

Welding widely applied today due to its cost effectiveness, reliability, and safety. When compared with other joining methods, such as riveting and bolting, welded structures tend to be stronger, lighter-weight, and cheaper to produce. More than 100 processes and process variants comprise the family of welding technologies, and include methods for welding metals, polymers, and ceramics, as well as emerging composite and engineered materials. These various technologies allow a great deal of flexibility in the design of components to be welded. They also encourage designing for optimal cost-effectiveness in productivity and product performance. Welding and joining technologies pervade commercial and defence manufacturing, and are a significant source of value-added in the manufacturing process. Occurring late in the manufacturing stream, the joining process is typically the final step in assembly and plays the major role in ensuring structural performance. Additionally, the emergence of near-net-shape processes to produce sub-components has raised the importance of assembly processes as the next area for increased production efficiency. The role of welding and joining in the repair and life extension of manufactured products is even more critical since these processes are frequently used to repair structures and components that were not originally welded. (American welding society)

Welding is a process of joining similar or dissimilar materials with the application of heat, with or without application of pressure and filler materials.

Weldability is the capacity of being welded into permanent joint having specified properties such as definite weld strength, proper structure etc. Weldability depends on melting point, thermal conductivity, thermal expansion, surface condition and microstructure of the base metals. These characteristics may be controlled or corrected by proper shielding atmosphere, fluxing material, filler material, welding procedure and heat treatment before or after deposition (Little 2001; Parmar 2007).

Classification of welding process

Welding Process is classified as following shown in Fig. 1.1.

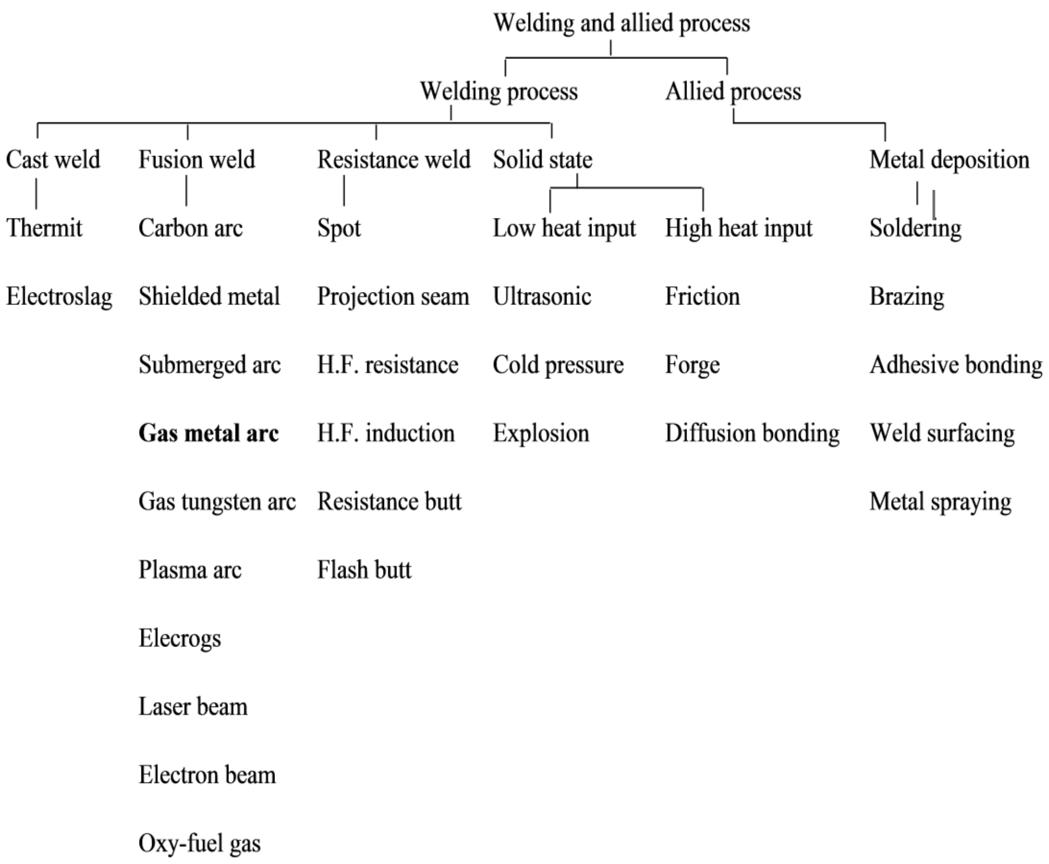


Fig: 1.1 Classifications of the welding process (Little 2001; Parmar 2007).

1.2 Different joining techniques use to join aluminium and steel

There are many joining techniques use to join aluminium with steel as like mechanical fastening, adhesive bonding and welding as shown in Fig. 1.2. Mechanical fastening and adhesive bonding produces temporary and semi-permanent joints by using rivets, nut and bolt, screws, resin and glue, whereas welding produces permanent joint either by using filler material, pressure and by the application of heat. (Dong *et al.* 2012; Kah *et al.* 2014)

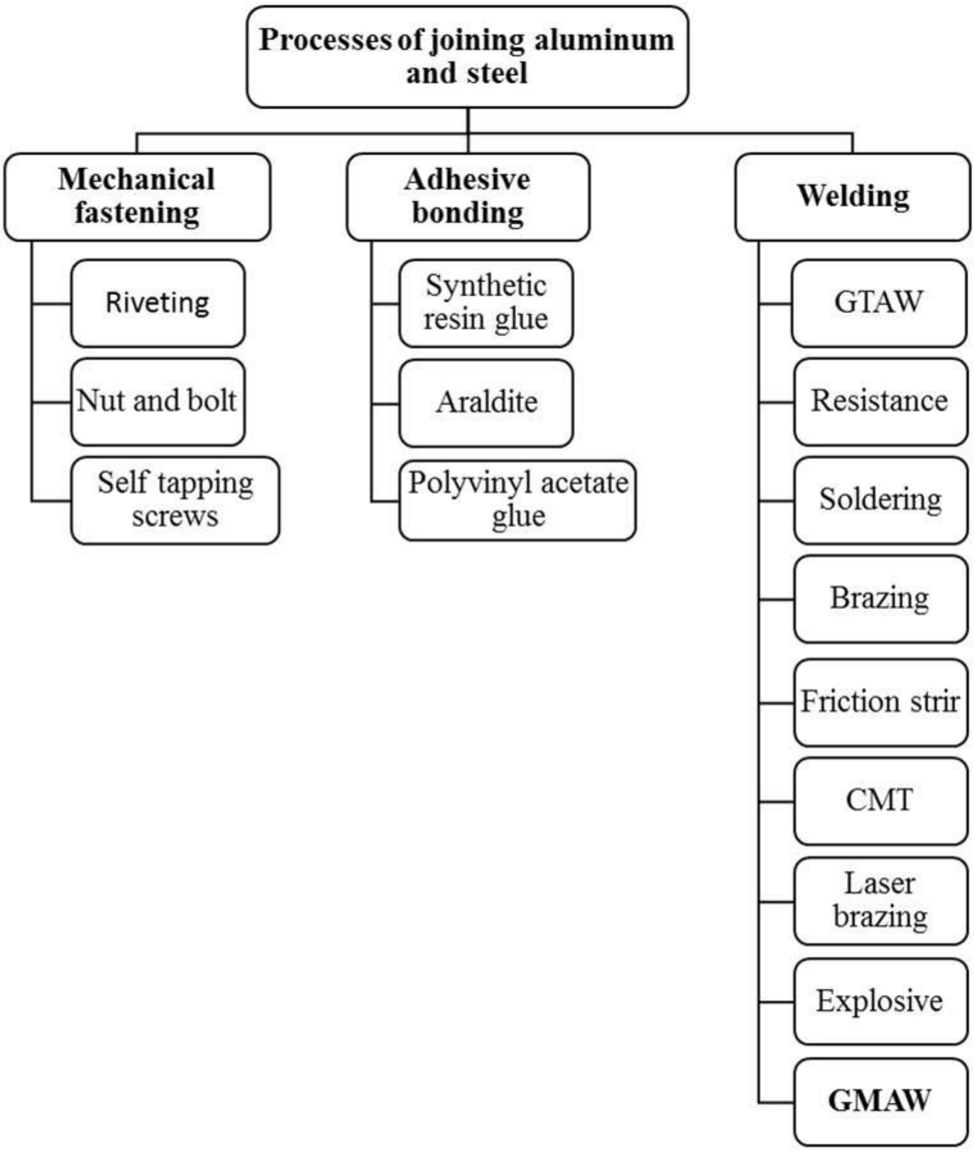


Fig: 1.2 Different joining techniques use to join aluminium and steel.

1.3 Gas metal arc welding (GMAW) process

GMAW is an arc welding process which produces the coalescence of metals gas metal arc welding (GMAW), commonly referred to as MIG welding, is defined as an arc welding process that joins metals by heating them with an electric arc established between a continuously fed filler metal (consumable wire) electrode and the workpiece. Appropriate settings made by the operator to maintain a constant burn-off rate of the wire electrode. Depending upon the power source and wire drive system used, the arc length is maintained automatically. Atmospheric contamination is prevented by using an externally applied shielding gas as shown in Fig. 1.3.

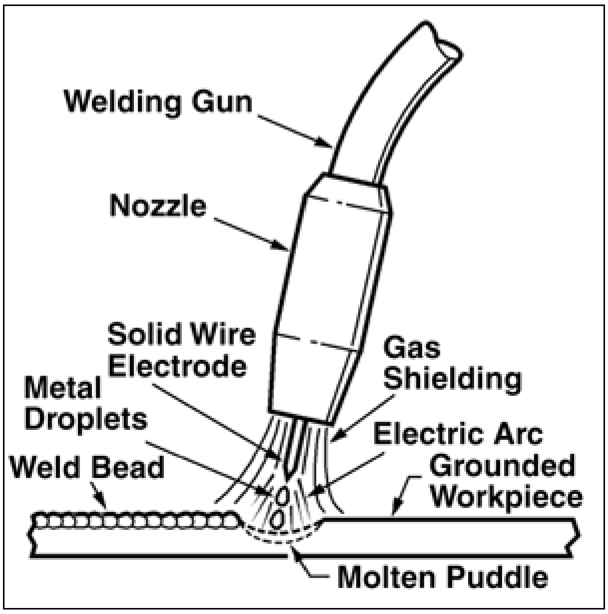


Fig: 1.3 Gas metal arc welding (GMAW) process (Parmar 2007).

GMAW generally uses direct current electrode positive (reverse polarity). Filler metal is transferred to the base metal through one of three main modes of transfer. The mode you choose is dependent on such factors as position of welding, current and voltage range, shielding gas and type of metal being welded. A detailed discussion on modes of metal transfer appears later. GMAW is used for machine, semi-automatic and fully automatic welding of carbon and alloy steels, stainless steels and several classes of non-ferrous metals including copper alloys and aluminum. These processes are used in the pressure vessel and piping industry, on power generation equipment, construction equipment, agricultural equipment and in many other areas that include welded metal fabrications. (Welding Handbook, American Welding Society).

1.4 Process parameters of GMAW

- **Arc voltage:** It is the voltage that appears across the contacts of the circuit breaker during the arcing period. By increasing arc voltage, weld penetration increased, weld bead height decreased, weld bead width increased and vice versa.
- **Wire feed rate:** It is the rate that, how fast the electrode travels down towards base material. As travel speed increases, the amount of time that the arc is over a particular point along the joint is less and resulting decrease in penetration. As travel speed decreases, the amount of time that the arc is over a particular point along the joint is greater and the resulting level of penetration increases.
- **Electrode extension:** The electrode extended from the end of the contact tip to the arc is known as electrode extension. It is also known as electrical stick out (ESO). In GMAW, this is the amount of electrode that is visible to the welder. The electrode extension includes only the length of the electrode, not the extension plus the length of the arc. Increasing electrode extension increases the resistance to the flow of current in the electrode, and the current in the arc is decreased. Decreasing the electrode extension decreases the resistance to the flow of current in the electrode, and the current in the arc increases.
- **Contact tip to work distance (CTWD):** It is measured from the end of the contact tip to the workpiece. Because the current can vary with an increase or decrease in extension, the consistency of the extension is important to the consistency of weld penetration. It is important to maintain a very steady hand during semiautomatic welding.
- **Electrode diameter:** when welding is done with two different diameters of the same electrode and at the same current level, generally more penetration is achieved with the smaller diameter electrode than with the larger diameter electrode.
- **Shield gas flow rate (f_s):** It is the rate at which shield gas is supplied to protect the melt pool from atmospheric contamination. Lower values of the shield gas flow rate allow the atmospheric gases to react with the melt pool resulting in porous and oxidation of melt pool. Higher values result in the spread of molten pool generating dimple like impression over the top surface of the joint. (The Lincoln electric company, 2014)

1.5 Modes of metal transfer in GMAW

Metal transfer refers, how filler metal is deposited to the base metal to form the weld bead. The common modes of metal transfer are short - circuit, globular, axial-spray, and pulsed-spray transfers. The mode of metal transfer is determined by many mitigating factors as base metal type, filler metal composition electrode diameter, polarity, arc current, arc voltage/arc length, shielding gas composition and welding position.

1.5.1 Short-circuit metal transfer

In this mode electrode touches the work and short circuits, causing the metal to transfer as a result of the short. This happens at a rate of 20 to more than 200 times per second. Fig. 1.4 shows pinch effect during short-circuit. The advantage of the short-circuit transfer is its low energy. This method is normally used on thin material ¼ inch or less. This mode of transfer generally calls for smaller-diameter electrodes, such as 0.023, 0.030, 0.035, 0.040, and 0.045 inch. The welding current must be sufficient to melt the electrode, but if it is excessive, it can cause a violent separation of the shorted electrode, leading to excessive spatter. Using adjustable slope and inductance controls can enhance the transfer to minimize spatter, promote a flatter weld profile and can produce excellent bead appearance. (www.thefabricator.com)

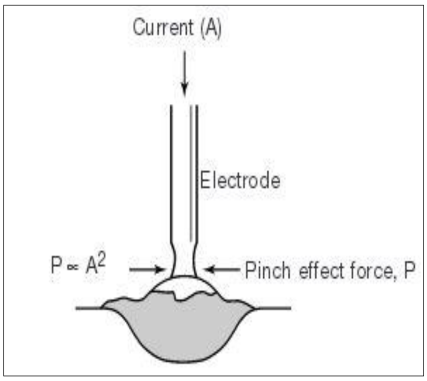


Fig: 1.4 Pinch Effect during short-circuiting transfer, in GMAW.

Advantages of short-circuiting transfer

- All-position (flat, horizontal, vertical up, vertical down and overhead) welding capability.
- Lower heat input reduces weldment distortion.
- Higher electrode efficiency 93% or more.

Limitations of short-circuiting transfer

- Restricted to sheet metal thickness range and open roots of groove joints on heavier sections of base material.
- Poor welding procedure control can result in incomplete fusion and excessive spatter. (www.thefabricator.com)

1.5.2 Globular transfer

Globular transfer means the weld metal transfers across the arc in large droplets, usually larger than the diameter of the electrode being used as shown in Fig.1.5. This mode of transfer generally is used on carbon steel only and uses 100 % CO_2 shielding gas. This method typically used to weld in the flat and horizontal positions because the droplet size is large and would be more difficult to control. This mode generates the most spatter; however, when higher currents are used with CO_2 shielding and a buried arc, spatter can be greatly reduced. A buried arc results excessive reinforcement if travel speed is not controlled. Stainless steel filler wires normally are not used in this mode of transfer because their nickel and chrome content creates a higher electrical resistance than carbon steel filler wire. In addition to the electrical resistance differences, the use of 100 percent CO_2 as a shielding gas could be detrimental to the corrosion resistance of the stainless steel electrodes. (www.thefabricator.com)

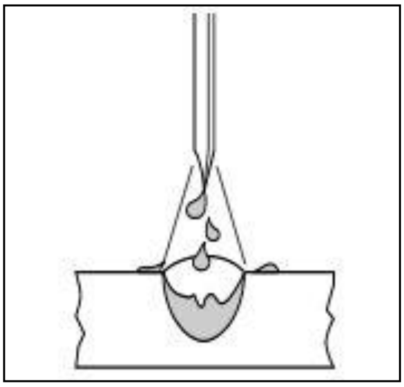


Fig: 1.5 Globular weld metal transfer, in GMAW

Advantages of globular transfer

- Uses inexpensive CO_2 shielding gas, but is frequently used with argon or CO_2 blends.
- Is capable of making welds at very high travel speeds.
- Inexpensive solid or metal-cored electrodes.
- Welding equipment is inexpensive.

Limitations of globular transfer

- Higher spatter levels result in costly cleanup.
- Reduced operator appeal.
- Prone to cold lap or cold shut incomplete fusion defects, which results in costly repairs.
- Weld bead shape is convex, and welds exhibit poor wetting at the toes.
- High spatter level reduces electrode efficiency to a range of 87 – 93%. (www.thefabricator.com)

1.5.3 Axial spray metal transfer

Spray transfer is named for the spray of tiny molten droplets across the arc, similar to spray coming out of a garden hose when the opening is restricted as shown in Fig.1.6. Spray transfer usually is smaller than the diameter of the wire and uses relatively high voltage and wire feed speed. Unlike short-circuit transfer, once the arc is established, it is on at all times. This method produces very little spatter and is most often used on thick metals in the flat and horizontal positions. Spray transfer is achieved with high percentages of argon in the shielding gas, generally a minimum of 80 percent. This mode uses a current level above transition current. The transition current will vary depending on the electrode diameter, shielding gas mixture percentages, and contact tip-to-work distance. When the current level is higher than the transition current, the electrode transfers to the work in very small droplets that can form and detach at the rate of several hundred per second. Sufficient arc voltage is required to ensure that these small droplets never touch the work, achieving a spatter-free weld. Spray transfer also produces a fingerlike penetration profile.

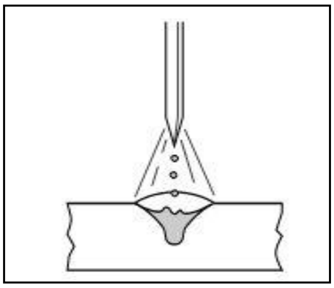


Fig: 1.6 Axial spray metal transfer, in GMAW

Advantages of axial spray transfer

- High deposition rates with less weld spatter and excellent weld bead appearance.
- High electrode efficiency of 98% or more.
- Employs a wide range of filler metal types in an equally wide range of electrode diameters.
- Requires little post-weld cleanup.
- Excellent weld fusion.

Limitations of axial spray transfer

- Restricted to the flat and horizontal welding positions.
- Welding fume generation is higher.
- The higher-radiated heat and the generation of a very bright arc require an extra welder and bystander protection.
- The use of axial spray transfer outdoors requires the use of windscreens.
- Cost of the shielding used to support axial spray transfer is more. (The Lincoln electric company, 2014)

1.5.4 Pulsed spray transfer

In the pulse-spray transfer mode, the power supply cycles between a high spray transfer current and a low background current as shown in Fig.1.7. This allows for super cooling of the weld pool during the background cycle, making it slightly different than a true spray transfer. Ideally, in each cycle one droplet transfers from the electrode to the weld pool. Because of the low background current, this mode of transfer can be used to weld out of position on thick sections with higher energy than the short-circuit transfer, thus producing a higher average current and improved side-wall fusion. Additionally, it can be used to lower heat input and reduce distortion when high travel speeds are not needed or cannot be achieved because of equipment or throughput limitations. Generally, the same shielding gases used for spray transfer are also used for pulsed-spray mode. With a programmable pulse power supply, most solid-wire alloys can be used on some special alloys such as inconel, duplex and superduplex with a customized pulse waveform. (www.thefabricator.com)

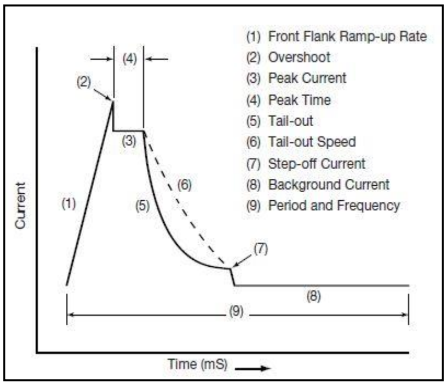


Fig: 1.7 Pulsed spray transfer, in GMAW

Advantages of pulsed spray transfer

- Very less weld spatter with excellent weld bead appearance.
- More resistant to lack of fusion defects than other modes of metal transfer.
- Reduced levels of heat induced distortion.
- Ability to weld out-of-position.
- Lower hydrogen deposit.
- Reduces the tendency for arc blow.
- Low cost high-electrode efficiency of 98%.

Limitations of pulsed spray transfer

- Equipment to support the process is more expensive than traditional systems.
- Blends of argon based shielding gas are more expensive than carbon dioxide.
- Higher arc energy requires the use of additional safety protection for welders and bystanders.
- Add complexity to welding. (The Lincoln electric company, 2014)

1.6 Advantages of GMAW

- The ability to join a wide range of material types and thicknesses.
- Simple equipment components are readily available and affordable.
- GMAW has higher electrode efficiencies, usually between 93% and 98%, when compared to other welding processes.
- Higher welder efficiencies and operator factor, when compared to other open arc welding processes.
- GMAW is easily adapted for high-speed robotic, hard automation and semiautomatic welding applications.
- All-position welding capability.
- Excellent weld bead appearance.
- Lower heat input when compared to other welding processes.
- A minimum of weld spatter and slag makes weld clean up fast and easy.
- Less welding fumes when compared to SMAW (Shielded Metal Arc Welding) and FCAW (Flux-Cored Arc Welding) processes.

1.7 Benefits of GMAW

- Generally, lower cost per length of weld metal deposited when compared to other open arc welding processes.
- Lower cost electrode.
- Less distortion with GMAW-P (Pulsed Spray Transfer Mode), GMAW-S (Short-Circuit Transfer Mode) and STT (Surface Tension Transfer).
- Reduced welding fume generation with minimal post-weld clean up

1.8 Limitations of GMAW

- The lower heat input characteristic of the short-circuiting mode of metal transfer restricts its use to thin materials.
- The higher heat input axial spray transfer generally restricts its use to thicker base materials.
- The higher heat input mode of axial spray is restricted to flat or horizontal welding positions.

- The use of argon based shielding gas for axial spray and pulsed spray transfer modes is more expensive than 100% carbon dioxide (CO_2). (Welding Handbook, American Welding Society).

1.9 Requirement of Al-steel joint

There has been a growing requirement of welded structures made of dissimilar metals like aluminium alloy and steel for weight reduction, energy and cost saving, environment concern and high performance. Considering the worldwide crisis of available natural fuel, it is important to save the fuel consumption. One such effective way to save fuel consumption is to reduce the weight of the vehicles. Heavier vehicles have greater inertia and greater rolling resistance, which both contribute to increased fuel consumption. Reducing weight is a very effective way to improve a vehicle's efficiency. Materials such as aluminium alloy, magnesium alloy, plastics and carbon-fibre-reinforced plastic allow can be used to reduce the car bodyweight. Among different materials aluminium alloy seems to be the most promising one. However, in light of the high cost and low strength property of aluminium alloy, the most effective way of using aluminium alloy is to apply it only where it is really needed. For this reason, aluminium alloy has so far been applied to only those car body parts that do not require extremely high strength such as; the hood, trunk, doors and roof (Dong *et al.* 2012; Su *et al.* 2014; Shao *et al.* 2015). Today, measures are being employed in diverse fields such as; energy, ships, aircraft, rail rolling stocks, automobiles and household appliances to encounter the issue of global warming. The automotive industry has been making positive efforts to reduce CO_2 gas emissions through the reduction of the weight of the car bodies. (Sakiyama *et al.* 2013; Ma *et al.* 2014). The joining of steel and aluminium has become an essential research and application focus in this regard. However, it is very difficult to join them together due to the great differences in thermo-physical characteristics of these two metals, such as the melting temperature, thermal expansion and the poor metallurgical compatibility. It is also reported by several authors (Shao *et al.* 2015; Sun *et al.* 2015) that the hard and brittle intermetallic compounds (IMC) are formed during conventional fusion welding process resulting deteriorates the mechanical properties of steel-aluminium joint.

Different challenges and problem associated with joining of aluminium and steel are discussed below.

1.10 Problems in joining of aluminium and steel

It is well known that aluminium is a non-ferrous and steel is a ferrous material. The challenges of joining aluminium and steel are following:

- Different thermo-physical Properties

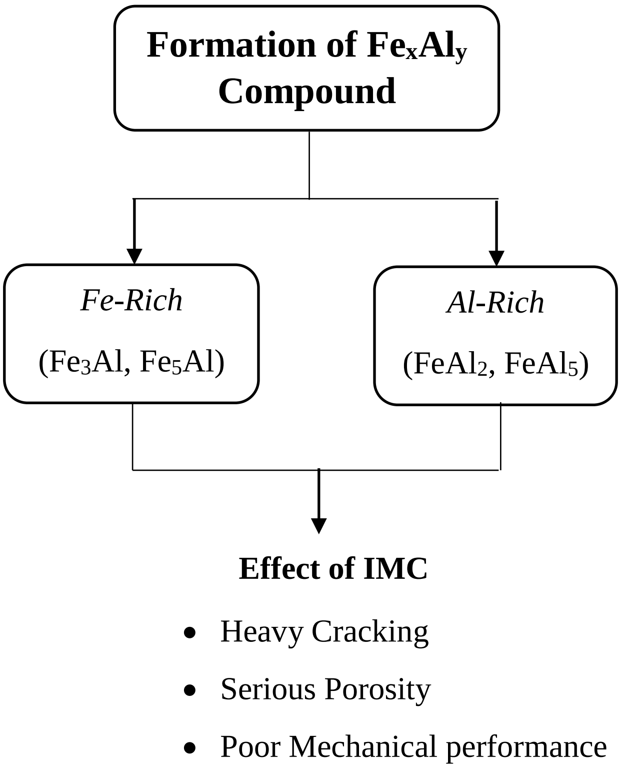
The different thermo-physical properties are as shown in Table. 1.1.

Table: 1.1 Different thermo-physical properties of aluminium and steel.

Properties	**Aluminium**	**Steel**
Thermal conductivity	250 W m^{-1} K^{-1}	50 W m^{-1} K^{-1}
Linear thermal expansion coefficient (α)	69×10^{-6} K^{-1}	$(33\sim39)\times10^{-6}$ K^{-1}
Melting temperature	≈1510°C	660.3 °C

- Poor metallurgical compatibility
- Formation intermetallic compounds (IMC)

Intermetallic compounds are formed (shown in flow chart diagram below) after joining of dissimilar materials. IMC is hard and brittle in nature, resulting weak bond strength and deteriorate the mechanical properties of the weld. (Sierra *et al.* 2008; Song *et al.* 2009)



1.11 Applications of Al-steel joint

Main application of this joint is in automobile industries for body building application. Different application of Al-steel joint is as shown in Fig. 1.8.

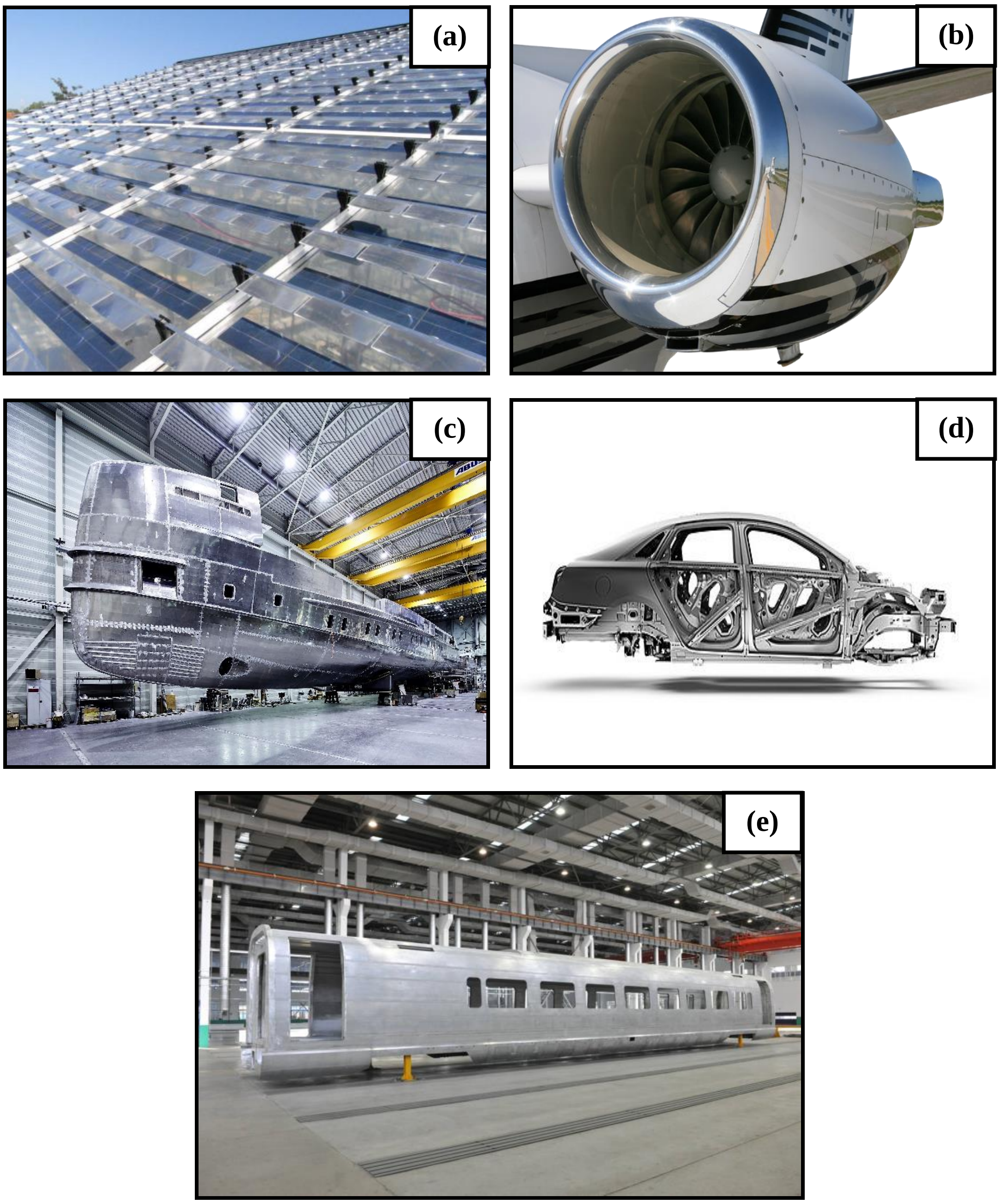


Fig: 1.8 Application of Al-steel joint, (a) Greenhouse roof, (b) Aerospace Structure, (c) Ship Building industry, (d) joining the aluminium subframe to steel body in the automobile industry, (e) Railway coach body.
(Chen *et al.* 2004; Uzun *et al.* 2005; Ma *et al.* 2014).

Chapter 2

REVIEW OF PAST WORK AND RESEARCH OBJECTIVES

2.1 Review of past work on joining of aluminium and steel

Following sections summarises the review of the past work done using different welding processes namely FRICTION, CMT, LASER, GTAW and GMAW for joining of aluminium and steel.

2.1.1 Friction stir welding (FSW)

Fukumoto *et al.* (2000), successfully join 18 mm rods of 5052 Al-Mg alloy and 304 austenitic stainless steel by using friction welding without filler metal. The approximately 300 nm reaction layer of Fe_2Al_5 was formed between the stainless steel and the aluminium alloy. The stacked layers were also produced at both ends of the reaction layer.

Chen and Kovacevic (2004), join 6 mm thick Al 6061 alloy and AISI 1018 steel by the combined effects of fusion and solid state welding. The process is derived from friction stir welding (FSW) but with an adjustable offset of the probe location with respect to the butt line. They were found that the intermetallic phases $Al_{13}Fe_4$ and Al_5Fe_2 exist in the weld zone.

Uzun *et al.* (2005), join 4 mm thick plates of 6013-T4 aluminium alloy and X5CrNi18-10 stainless steel by friction stir welding in a butt joint configuration. They divided weld joint into seven zones: (1) Parent stainless steel (2) HAZ in the stainless steel at advancing side of weld (3) TMAZ in the stainless steel at advancing side of weld (4) Weld nugget (5) TMAZ in the Al alloy at retreating side of weld (6) HAZ in the Al alloy at retreating side of weld (7) Parent Al alloy. They found that hardness value at the retreating side sharply decreased towards the weld nugget because of the thermo-mechanically affected zone in the stainless steel at advancing side of the weld. The hardness of the weld nugget shows variable values because of the presence of the fine or coarse dispersed stainless steel particles in the weld nugget. The hardness value slightly decreases in the TMAZ at the advancing side (Al 6013-T4 alloy side). The minimum hardness value found in HAZ of Al 6013-T4 alloy.

Sun *et al.* (2013), successfully weld 1 mm thick plates of 6061-T6 Al alloy and mild steel by using flat spot friction stir welding technique in a lap joint configuration. Producing weld has a smooth surface without keyholes and no layer of intermetallic compounds but some areas with amorphous atomic configuration were formed, along the Al/Fe joint interface due to the lower heat input. The shear tensile failure load can reach a maximum value of 3607 N.

Xun *et al.* (2015), develop electrically assisted friction stir welding process to join 1.4 mm thick dissimilar Al 6061 aluminium alloy to TRIP 780 advanced high strength steel. They were studied that electrical current can help to promote the formation of a thin layer of IMC for the plunge section of the joint, which is possibly due to a combined effect of accelerated atom diffusion and reduced activation energy for the chemical reaction. They were also studied that Micro-interlock features can be observed for the Al-Fe interface in the welding sections under electrically assisted conditions, which is promising to help restrain crack initiation and propagation in the brittle IMC layer and therefore enhance joint quality.

2.1.2 Cold metal transfer (CMT) welding

Zhang *et al.* (2007), make sound weld joint of 1 mm thick 1060 aluminium and galvanized steel by a modified metal inert gas CMT welding brazing process in a lap joint configuration with 1.2 mm Al-Si filler wire. They found that intermetallic compound layer varied with the heat inputs. Tensile tests of the joints caused fractured in the Al heat affected zone (HAZ), even when the intermetallic compound layer thickness exceeded 40 µm.

Cao *et al.* (2014), join 1 mm thick AA6061-T6 aluminium alloy and 1.5 mm thick bare, galvanized and galvannealed boron steels, by using Al4043 filler wire, having diameter 1.2 mm. The effect of coating on CMT joining of Al alloy to boron steel has been investigated. It was found that a zinc coating on the steel substrate is essential. Pure Zn coating enhanced the wetting of molten filler metal onto the steel, welds with a smooth appearance and low reinforcement were produced. Fe-Zn coating from galvannealed boron steel result, welds with poor quality were produced. Al alloy and galvanized boron steel decreased the growth of brittle Fe-Al intermetallics. Al alloy and Al-Si-coated boron steel joints could not be produced due to a large formation of the brittle $FeAl_3$ intermetallic.

2.1.3 Laser welding

Mathieu *et al.* (2007), join galvanized steel sheet (0.77 mm) to aluminium (>1mm) by using a laser (Nd:YAG with a maximal power of 3.5 kW) braze welding with Zn-based filler wire having 1.6 mm diameter, in a lap joint configuration. A spot size of the beam is between 1-2 mm. They observed that braze welding permits a localised fusion of the materials resulting in a limitation on the growth of fragile phases, as compared to thermal welding process (GTAW or GMAW). They investigated that the causes of failures are not the only cause of the Al/steel joint brittleness, especially when their thickness is below 10 mm, the global geometry of the joints (concavity, wetting, etc.), is a significant factor to take into account.

Sierra *et al.* (2008), perform a comparative study of joining 1.2 mm thick DC 04 galvanized low carbon steel to 6016 aluminium alloy with laser (Nd:YAG power of 3 kW) and GTAW processes separately with and without using of flux. They directly melt aluminium with the laser process, whereas steel with the GTAW process. They were found a 2-40 µm thick intermetallic reaction layers at the interface and when the thickness is above 10 µm cracks were observed in the intermetallic reaction layers. The linear strength of the lap joint, join by laser assemblies can be as high as 250 N/mm with flux, 140 N/mm with without flux because Zn-induced porosities in the FZ (fusion zone) of aluminium led to a severe decrease in the failure strength. With the GTAW process, only galvanized steel to aluminium with flux assembling was investigated, which has strength up to 190 N/mm. The corresponding failures were located in the fusion zone of aluminium. They found Fe_2Al_5 intermetallic layer phase in laser assemblies and of complex FeAlSiZn phases for GTAW assemblies. In both cases, failures are found in the FZ (fusion zone).

Schimek *et al.* (2012), join steel and aluminium by using Nd:YAG laser with a maximum output power of 4 kW with two focus diameters of 600 and 1200 µm. with a weld length of 200 mm were made in order to reach conclusions about the process stability. They found that a high welding depth results in an increasing mix of iron and aluminium, and of crack initiation. Furthermore, lower welding depths in the cross-section between the steel and aluminium are insufficient for high strength welds. Steel-aluminium dissimilar compound formation with a focus diameter of 1200 µm is higher than a focus diameter of 600 µm.

Ma *et al.* (2014), join 1 mm thick DP590 galvanized dual phase high strength (DP) steel to (AA) 6061 aluminium alloy sheets by using two pass laser welding in a lap joint configuration. In this technique, welding is done in a two pass. First pass is based on a defocused laser spot which scans across the top of the two overlapped sheets and heats the zinc coating at the faying surface to be melted and partially vaporized, while the second pass is executed with a focused laser spot in order to perform the welding. It could be concluded that under optimal preheating and welding parameters, the thickness of the Al-rich IMCs could be controlled at around 5 µm.

Sun *et al.* (2015), join 2.5 mm thick AA6013 aluminium alloy and Q235 low carbon steel (zinc layer was hot-dip galvanized) in a butt joint configuration by using 10 kW laser with Al-12%Si (ER4043) filler metal having 1.2 mm diameter. To improve the connections between weld metal and steel, the V-shaped groove with 60^{o} was fabricated on the mild steel. The overall thickness of Fe-Al intermetallic compounds layers produced in this experiment were varied from 1.8 µm to 6.2 µm at various welding parameters with a laser power of 2.85-3.05 kW and wire feed speed of 5-7 m/min. In addition, the thickness of the inner layer composed of Fe_2Al_5 phase and the outside layer composed of $FeAl_3$ phase are in the same order of magnitude. In the Al/steel butt joint crack initiates and propagates in the $FeAl_3$ layer and the brazing interface during the tensile test, the maximum tensile strength reached was 120 MPa.

2.1.4 Gas Tungsten arc welding (GTAW)

Sierra *et al.* (2008), join 1.2 mm thick DC 04 low carbon having 20 µm zinc coated layer to 1 mm thick 6016-T4 aluminium alloy by using gas tungsten arc welding (GTAW) in DC electrode negative (DCEN) mode, in overlap configuration. A 3.2 mm diameter tungsten electrode, with a 30° grinding angle, is used. The electrode was always located on galvanised DC 04 low carbon steel. Aluminium melting is done by steel heating. They obtained complex FeAlSiZn phases were the thicknesses of the reaction layers were shown to be in the 2-40 µm range, depending on the use or not of brazing flux. Cracks were observed in the intermetallic reaction layers when their thickness is above 10 µm. Failure strength obtained is about 190 N/mm.

Song *et al.* (2009), successfully braze 3 mm thick 5A06 aluminium alloy and AISI 321 stainless steel plates by TIG welding brazing with pure Al, Al-5%Si and Al-12%Si filler materials. A Single-V groove was opened in the joint, with a bevel angle of 40° in steel side and 30° in the aluminium side. Joint interface with pure aluminium consists of the θ-$FeAl_3$ phase in aluminium side and η-Fe_2Al_5 phase in steel side, while the interfaces with Al-Si filler metals are the 5-τ_{5}-$Al_{7.2}Fe_{1.8}Si$ phase in aluminium side and θ-$Fe(AlSi)_3$ phase in steel side and with 5 wt.% of Si additions, the IMC layer has the optimum mechanical properties, and the tensile strength of the joint reaches 125.2 MPa. The growth mechanism of the IMC layers is controlled by the dissolution and diffusion of Fe atoms in the liquid. At the same time, Si atoms aggregate in the interface and participate the IMC layer's formation.

Dong *et al.* (2012), join 2 mm thick 5A02-H34 aluminium alloy sheets to 1.5 mm thick Q235 galvanized steel sheets by using gas tungsten arc welding (GTAW) with Al-5% Si, Al-12% Si, Al-6% Cu, Al-10% Si-4% Cu and Zn-15% Al filler wires, in a lap joint configuration. They were investigated the effects of alloying elements on the microstructure of the weld and tensile strength of the resultant joint. They were found that the thickness of the intermetallic compound (IMC) layer decreased and the tensile strength of the joint increased with the increase of Si content in the weld. The addition of Si into the weld could suppress the diffusion of Fe from the steel base metal into the weld, which reduces the thickness of intermetallic compounds and improves the tensile strength of the joint. The minimum thickness of the IMC layer could be controlled as about 2 µm. The tensile strength of the dissimilar metal joint reached 136 MPa with Al–12% Si filler wire, 134 MPa with Al-5% Si filler wire, 116 MPa with Al-10% Si-4% Cu filler wire, 110 MPa with Al-6% Cu filler wire and 63 MPa with Zn-15% Al filler wire. Zn-15% Al filler wire resulted in the thick interfacial layer and coarse dendrite microstructure in the weld, which led to a weak joint.

2.1.5 Gas metal arc welding (GMAW)

Su *et al.* (2007), join 1 mm thick sheets of 5052 aluminium alloy and galvanized mild steel in a lap configuration by alternate current double pulse gas metal arc welding with pure Al, Al-5% Si, Al-12% Si and Al-4.5% Mg filler wires having a diameter of 1.2 mm. They found that due to cooling rate difference in the weld seam, the thickness of IMC layer varies along the cross-section of the joint and intermediate part of the IMC layer was thicker than the head and root parts. The diffusion of Si into Fe_2Al_5 sub-layer could restrain the growth of Fe_2Al_5 sub-layer and IMC layer, by which mechanical property improved with the increasing Si content in Fe_2Al_5 phase. The tensile strength of the joints reached 205.70 MPa with Al-12% Si filler wire, 188.75 MPa with Al-5% Si filler wire, 112.47 MPa with Al-5% Mg filler wire and 163.38 MPa with pure Al filler wire. Due to the high hot crack sensitivity of Al-4.5Mg alloy (i.e. 5052 Al), cracks generated at the root of joint made with Al-5% Mg filler, resulting in the poor mechanical property.

Shao *et al.* (2015), join 2 mm thick aluminium and Q235 galvanized mild steel by using pulsed double electrode gas metal arc (Pulsed DE-GMA) welding brazing with filler wire ER5356 to investigate the effect of joining parameters on the microstructure of dissimilar metal joints between aluminium and galvanized steel. They found that joint between aluminium and galvanized steel contains a band of the intermetallic Fe_2Al_5 compound on the steel side and the intermetallic $FeAl_3$ phase on the aluminium side. After Metallographic studied it was showed that the Fe_2Al_5 phase is in plate like shape and $FeAl_3$ phase is in needle like shape. The amount of the intermetallic compound phases gradually decreased as the heat input of base metal reduced. Thermodynamic calculation predicted that the Fe_2Al_5 intermetallic compound layer was formed first on the steel side, while the $FeAl_3$ intermetallic phases precipitated during solidification of the liquid aluminium when temperature gradually reduced.

2.2 Observations from the literature

- Increasing Si content in filler material decreases the thickness of intermetallic compound.
- Alloying element Zn improve wettability of filler wire
- Heat input is direct proportional to thickness of intermetallic compound (IMC) layer formation. So for sound weld, processing time should be less.

2.3 Research gap

From the literature review, it can be found that

- Limited work has been done on joining different grades of steel to different grades of aluminium sheets.
- No work has been done on joining of 1050 aluminium to 1018 low carbon steel having 5 mm thickness especially using gas metal arc welding process.
- No work has been done to understand the joint strength of 1050 aluminium to 1018 low carbon steel joint in butt joint configuration by using gas metal arc welding process.
- No work has been done on joining of 1050 aluminium to 1018 low carbon steel at different welding condition (i.e. dry and wet).
- There are a lot of scopes to join different grades of 1050 aluminium to 1018 low carbon steel to obtain better joint characteristics and strength of the weld.

2.4 Objectives of the present work

- To join 1050 Aluminium with 1018 Low Carbon Steel by using gas metal arc welding process.
- To join 1050 Aluminium with 1018 Low Carbon Steel by using gas metal arc welding process at different welding condition (i.e. dry and wet).
- To investigate suitable condition for successful welding prepare a strong weld joint
- Finding proper filler materials and process parameters for the suitable weld.
- To Study the microstructure and microhardness of the joint.
- To study the strength of the joint.

Chapter 3

PLANNING AND DETAILS OF EXPERIMENTAL WORK

This chapter deals with the selection of materials, planning and details of experimental work. All experiments are divided into two experimental conditions such as dry and wet. The details of both experimental setups and various results of dry and wet experimental conditions are presented.

3.1 Material selection

In the present study, sheets of 1050 aluminium alloy and 1018 low carbon steel of 5 mm thick are chosen for experimental study. Table 3.1 and Table 3.2 represent the nominal composition of 1050 aluminium alloy and 1018 low carbon steel.

Table: 3.1 Nominal compositions of 1050 aluminium alloy.

Elements	**Si**	**Fe**	**Cu**	**Mn**	**Mg**	**Zn**	**Ti**	**Al**
wt.%	0-0.25	0-0.4	0-0.05	0-0.05	0-0.05	0-0.07	0-0.05	Balance

Table: 3.2 Nominal compositions of 1018 low carbon steel.

Elements	**Si**	**Cu**	**C**	**P**	**S**	**Fe**
wt.%	**0.020**	**0.60**	**0.05**	**0.009**	**0.019**	**Balance**

3.2 Consumables

3.2.1 Filler wires

Three filler wires Cu Al-10% Fe, Al-5% Si and Al-12% Si are selected. Table 3.3 and Table 3.4 represent nominal composition and physical properties of all three filler wires. Cu-based filler wire (Cu Al-10% Fe) is chosen for this work because same wire used to join dissimilar materials in the various industries. Two other filler wires are Al-based Al-5% Si and Al-12% Si. The main difference between them is silicon content. The silicon content in Al-based filler wire has a great role to reduce the thickness of intermetallic compound (IMC) and increases the mechanical strength of the weld.

Table: 3.3 Nominal compositions of Cu Al-10% Fe, Al-5% Si and Al-12% Si filler wires.

Filler Wire	**Composition (wt.%)**							
	Si	**Fe**	**Cu**	**Mn**	**Mg**	**Zn**	**Ti**	**Al**
Al-5% Si	4.5-5.0	0.80	0.30	0.050	0.050	0.10	0.20	Bal
Al-12% Si	11-13	0.80	0.30	0.15	0.10	0.20	-	Bal
Cu Al-10% Fe	0.1	1.5	Bal	-	-	0.02	-	8.5-11

Table: 3.4 Physical properties of Cu Al-10% Fe, Al-5% Si and Al-12% Si filler wires

Physical properties	***Al-5% Si***	***Al-12% Si***	***Cu Al-10% Fe***
Melting temperature (ºC)	600-650	573-625	1020-1040
Diameter (mm)	1.6	1.6	1.2

3.2.2 Shielding gas

Argon gas is used to join aluminium with low carbon steel due to its various properties such as:

- ***Chemically inert***
- ***Ionization energy*:** In order to become conductive (i.e. plasma), the gas must be ionized. The ionization energy of argon (15.7 eV) is less than helium (24.5 eV) and argon facilitates better arc starting than helium.
- ***Thermal conductivity*:** High thermal conductivity provides more conduction of the thermal energy into the workpiece. The thermal conductivity also affects the shape of the arc, temperature distribution within the region, penetration pattern and depth. Higher thermal conductivity provides a broader penetration pattern and reduces the depth of penetration. Argon has a lower (10%) thermal conductivity as compared to both helium and hydrogen (The Lincoln Electric Company, 2014)**.**

3.3 Sample preparation

- ❖ **Machining and Sawing:** Workpiece is cut by using power hacksaw (300PH from ITL Industries Limited, Indore) and hand hacksaw before welding in required dimensions.
- ❖ **Grinding and filling:** After cutting, samples are grind and file by using pedestal grinding machine and a flat file to maintain desired dimensions of the work. Surface grinding machine (GSH 6030 Parmar pinnacle, Gujrat) is also used for removing oxide layer present on the surface of the work sample.

3.4 Sample cleaning

- ❖ **Pre-weld cleaning:** Once the sample grinding is done, it is cleaned by using a stainless steel wire brush to remove loose oxides present on the top surface. Then samples are cleaned by acetone for removing loose contaminants like oils, grease, dust, rust etc. If these contaminants are not removed, excessive porosity and other welding defects are formed.

❖ **Post weld cleaning:** Once the welding of samples are done then cleaning of welded samples are carried out by using wire brush of stainless steel for removing slag and spatter present on the surface of the sample.

3.5 Experimental apparatus

The welding of the workpieces is performed by using the gas metal arc welding machine (Fast MIG pulse 450, KEMPPI, Finland) as shown in Fig. 3.1. Technical specifications of the machine are shown in Table 3.5.

It consists of three major units:

- **Wire feed unit:** It mainly controls the filler wire speed.
- **Cooling unit:** It controls the overheating of the welding torch.
- **Controller unit:** It controls the voltage and current characteristics.

Table: 3.5 Technical specification of KEMPPI FastMig 450.

Parameters	**Range**
Welding voltage	8-50 V
Welding current	10-450 A
Open circuit voltage	80 V
Wire speed	0.7-25 m/min
Open circuit power	100 W
Efficiency	88%
Power factor	0.9
Operating temperature	20-40 ^{o}C

Fig: 3.1 KEMPPI FastMig 450

3.6 Experimental setup for dry welding condition

Experiments are performed in dry condition on the setup is shown in Fig. 3.2. In this setup, both aluminium and steel samples are placed on a base plate without root gap. The main purpose of the base plate is to support samples (i.e. aluminium and steel) from the bottom side and to maintain flatness. Samples are clamped by clamping arrangement (clamping plate, nut and bolts). Clamping plates are used to prevent from distortion and movement of the samples during welding.

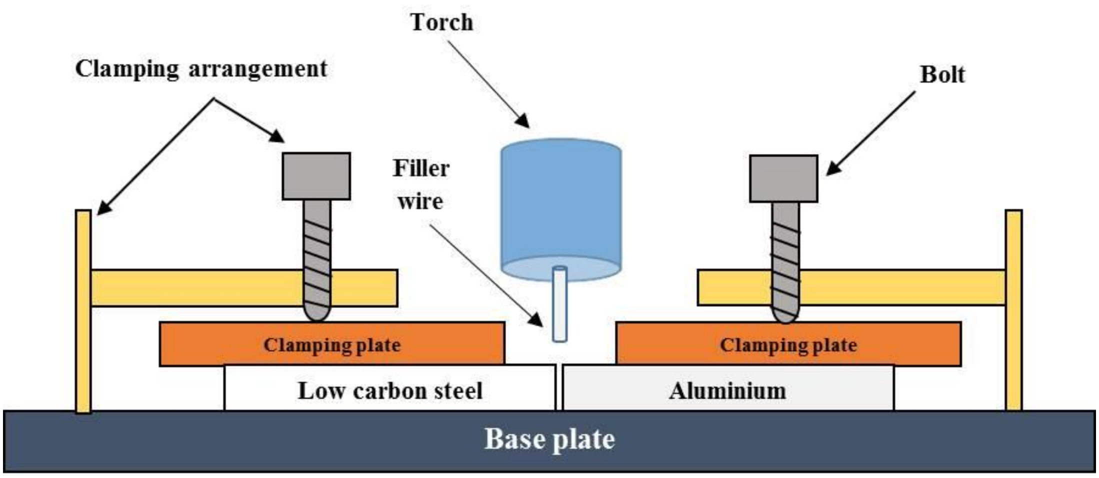


Fig: 3.2 Experiment setup for dry welding condition.

3.7 Methodology of work

Several experiments are planned and performed to determine the feasibility of the filler wires and weld joint as shown in Fig. 3.3. In primary experiments, testing is done on aluminium and steel to check the feasibility of filler wires (Cu Al-10% Fe, Al-5% Si and Al-12% Si). Suitable range of process parameters for joining aluminium and steel are also evaluated. In main experiments, aluminium and steel is joined in a butt joint configuration, at different process parameters (such as voltage and wire feed rate), filler wires (Al-5% Si and Al-12% Si) and wet welding condition, to determine the mechanical properties and microstructure of the joint.

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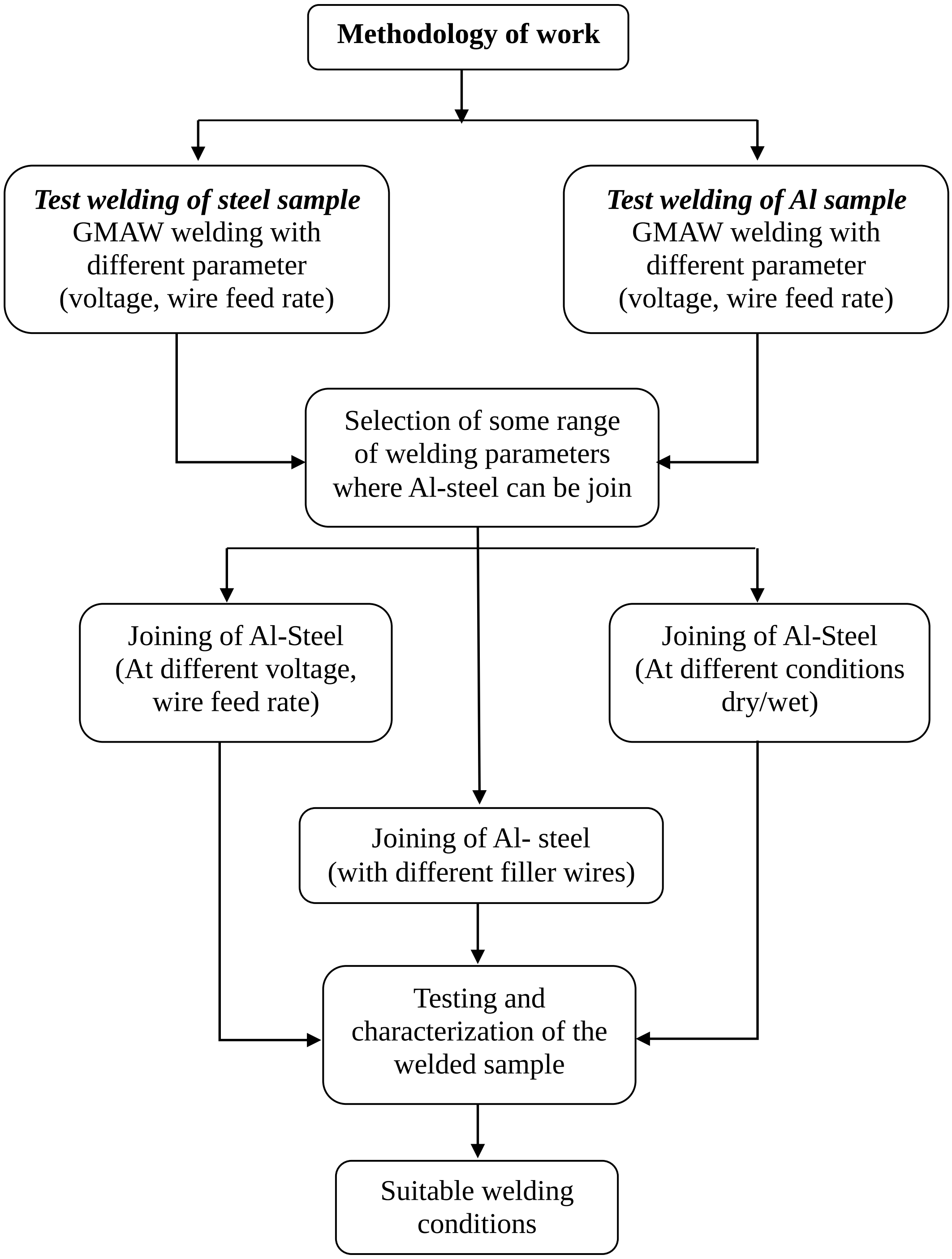


Fig: 3.3 Methodology of work

3.7.1 Preliminary experiments

Preliminary experiments consist of various experimental approaches taken to get a feasible parameter with all three filler wires. In the present work, separate experiments are done on 1050 aluminium alloy and 1018 low carbon steel by using different filler wires Cu Al-10% Fe, Al-5% Si and Al-12% Si, to check feasibility of the weld joint.

3.7.1.1 Experiments by using filler wire Cu Al-10% Fe.

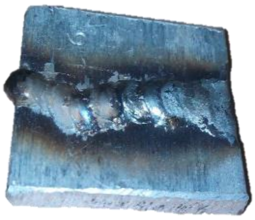
In this experiment, different parameters are used separately on 1018 low carbon steel and 1050 aluminium alloy as shown in Table 3.6. Separate experiments are done on aluminium and steel samples at same parameters as shown in Table 3.7. After separate experiments, aluminium and steel are join in a butt joint configuration shown in Table 3.8 and Fig. 3.4.

Table: 3.6 Range of process parameters used for joining of aluminium and steel by using Cu Al-10% Fe filler wire.

Experiment no.	**Low carbon steel**		**Aluminium**	
	Wire feed rate (m/min)	**Voltage (Volt)**	**Wire feed rate (m/min)**	**Voltage (Volt)**
1	2.6	15.5	2	14
2	2.8	15.8	2.05	14.5
3	3	16	2.10	15
4	3.05	16.5	2.15	15.5
5	3.10	17	2.2	16
6	3.15	17.5	2.2	16.2
7	3.05	16.2	2.2	16.4
8	3.10	16.4	2.2	16.6
9	3.15	16.6	2.2	16.7
10	3.2	16.8	2.2	16.8

Observation: Process parameters used in experiment number 4, 6 and experiment number 8, 9 are suitable for steel and aluminium respectively.

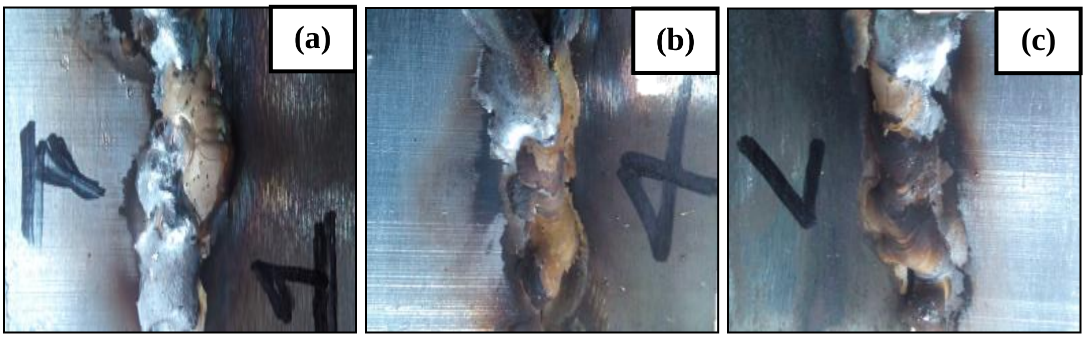
Table: 3.7 Range of process parameters used for aluminium and steel by using Cu Al-10% Fe filler wire.

Exp no.	Low carbon steel	Aluminium	Wire feed rate (m/min)	Voltage (Volt)
1			2.2	16.2
2			2.2	16.4
3			2.2	16.6
4			2.2	16.7
5			2.2	16.8

Observation: At the same parameters aluminium is melting and form suitable weld bead but steel is not melting and destructive weld bead is form.

Table: 3.8 Range of process parameters used for joining aluminium and steel in a butt joint configuration, by using Cu Al-10% Fe filler wire.

Experiment no.	Wire feed rate (m/min)	Voltage (Volt)
1	2	17.2
2	2.10	17
3	2	17.4
4	2	17.8
5	2	17.6
6	2	18
7	2	18.4
8	2	18.2
9	2	18.6
10	2	18.7



Voltage: 17.2 V
Wire feed rate: 2 m/min

Voltage: 17.8 V
Wire feed rate: 2 m/min

Voltage: 18.4 V
Wire feed rate: 2 m/min

Fig: 3.4 Butt joint of aluminium and steel by using Cu Al-10% Fe filler wire.

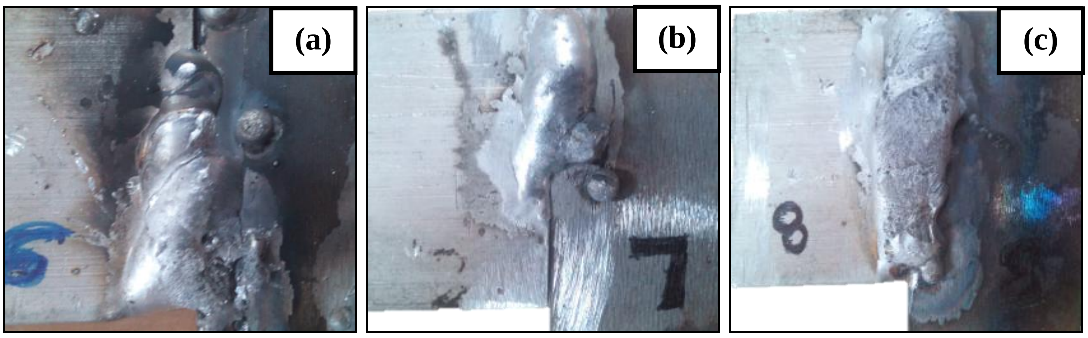
Observation: Cu Al-10% Fe filler wire compatible with low carbon steel but not with aluminium because Cu and Fe are less solid soluble (0.01%) with aluminium.

3.7.1.2 Experiments by using filler wire Al-5% Si.

In this experiment, different process parameters are used to join 1050 aluminium alloy and 1018 low carbon steel, in a butt joint configuration as shown in Table 3.9.

Table: 3.9 Range of process parameters used for joining aluminium and steel in a butt joint configuration, by using Al-5% Si filler wire.

Experiment no.	Wire feed rate (m/min)	Voltage (Volt)
1	2.10	17
2	2.10	17.2
3	2.10	17.4
4	2	17.6
5	2	17.8
6	2	18
7	2.10	18
8	2.15	18
9	2	18
10	2.2	18



Voltage: 18 V	Voltage: 18 V	Voltage: 18 V
Wire feed rate: 2 m/min	Wire feed rate: 2.1 m/min	Wire feed rate: 2.15 m/min

Fig: 3.5 Butt joint of aluminium and steel by using Al-5% Si filler wire.

Observations:

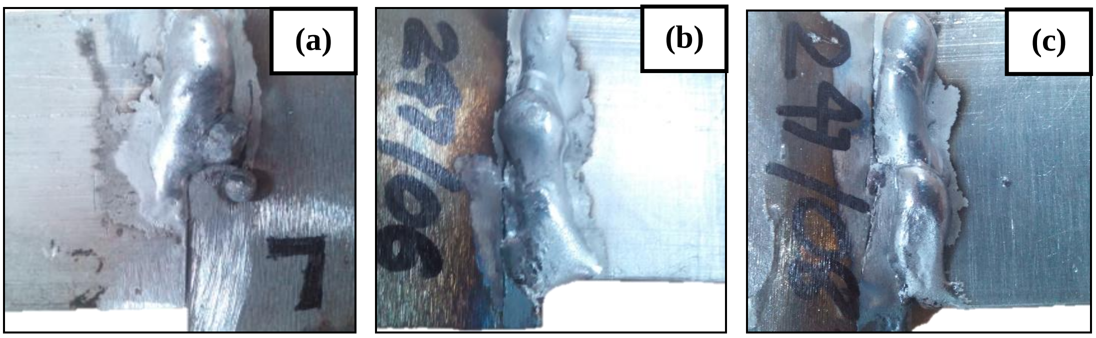
- It is found that low carbon steel is not melting.
- At higher voltage, steel is partially melted but undercut is formed in case of aluminium.
- Reinforcement is more and weld width is less**.**
- Penetration is low.

3.7.1.3 Experiments by using filler wire Al-12% Si.

The different parameters used during this experiment are shown in Table 3.10. Butt joint configuration of aluminium and steel obtained by given set of process parameters and Al-5% Si filler wire are shown in Fig. 3.6.

Table: 3.10 Range of process parameters used for joining aluminium and steel in a butt joint configuration, by using Al-12% Si filler wire.

Experiment no.	Wire feed rate (m/min)	Voltage (Volt)
1	2.10	17
2	2.2	17.2
3	2.10	17.4
4	2.10	17.6
5	2.10	17.8
6	2.10	18
7	2.10	18.2
8	2.2	18.2
9	2.30	18.2
10	2.30	18.3



Voltage: 17 V
Wire feed rate: 2.1 m/min

Voltage: 18 V
Wire feed rate: 2.1 m/min

Voltage: 18.2 V
Wire feed rate: 2.2 m/min

Fig: 3.6 Butt joint of aluminium and steel by using Al-12% Si filler wire.

Observations:

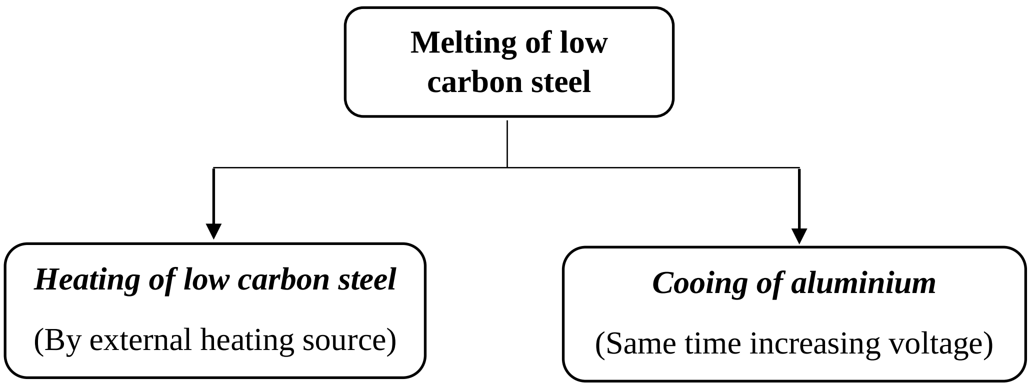
- It is observed that low carbon steel is not melting.
- At higher voltage steel is partially melted but undercut is formed in the aluminium side.
- Reinforcement is more and weld width is less.
- Depth of penetration is high as compared to Al-5% Si filler wire.

3.7.2 Main experiments

It is found from the primary experiments, Cu Al-10%Fe filler wire is compatible with low carbon steel but not with aluminium. It forms cracks and weld strength is low. Al-5% Si and Al-12% Si filler wires are feasible to join aluminium with steel, with a suitable strength because Si increases adhesion between aluminium and steel. Parameters used in primary experiments are suitable to melt aluminium, but not for low carbon steel.

So for melting of low carbon steel two options are there:

1. Preheating of low carbon steel by external heating source.
2. Increase voltage and same time extract heat from aluminium.



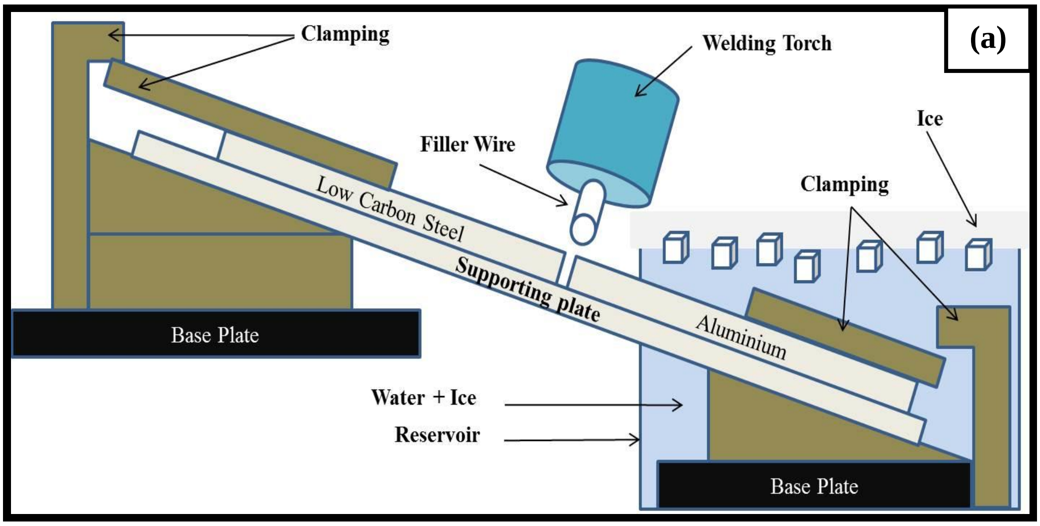
It is found that, the first option is not suitable because hot cracks, blow holes are formed and IMC (intermetallic compound) layer is also observe resulting weak weld joints. Second option is suitable for welding of aluminium and steel for further study. In this experiment, the joints are evaluated by measuring its tensile strength and microhardness. Additionally, the microstructure of joint is also determined. Table 3.11 lists the variable parameters used in the main experiments.

Table: 3.11 Lists the variable process parameters used in the main experiments.

Parameters name	Range
Voltage (Volt)	19-24.6
Wire feed rate (m/min)	2-3.75

3.7.2.1 Experiment setup for wet welding condition

Schematic diagram of the experimental setup is shown in Fig. 3.7a and the working setup made at central workshop IIT Indore is shown in Fig. 3.7b. In the working setup, a water reservoir is used to kept ice and water together. Temperature of the reservoir is maintained around 0-3 °C throughout the welding processes. The aluminium sample is kept in reservoir over the supporting plate with a clamping arrangement. A steel sample is clamped by clamping arrangement over the supporting plate. Supporting plate and clamping are provided to avoid distortion and vibration during welding. Water is stirring throughout the experiment to maintain a uniform temperature in the reservoir.



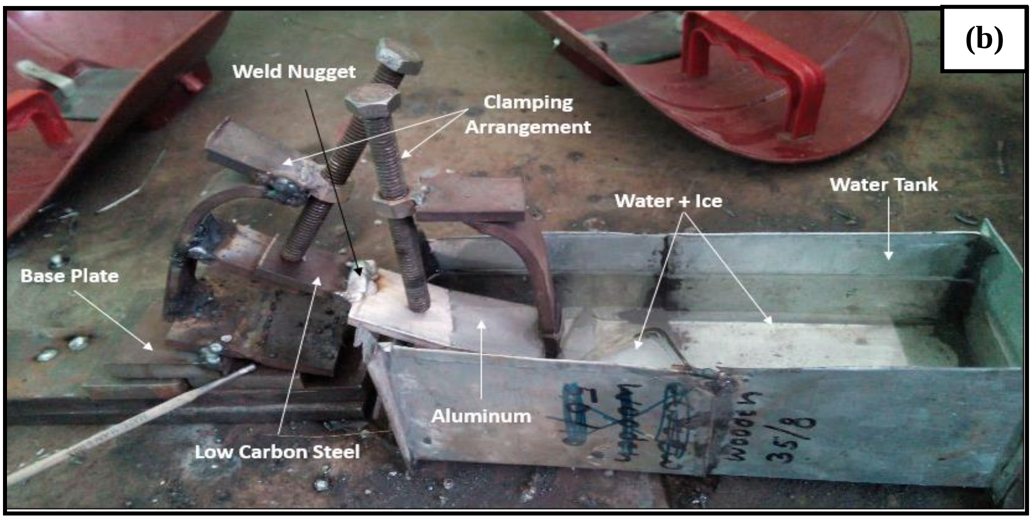


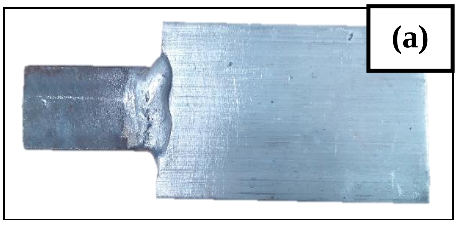
Fig: 3.7 Experimental setup for wet welding condition, (a) Schematic diagram of experimental setup for the wet condition and (b) Actual experimental setup for wet welding condition.

3.7.2.2 Experiments by using filler wire Al-5% Si.

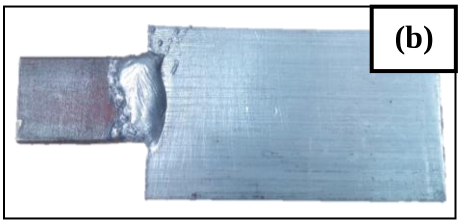
The different parameters used during this experiment are shown in Table 3.12. Butt joint configuration of aluminium and steel obtained by given set of parameters and Al-5% Si filler wire are shown in Fig. 3.8.

Table: 3.12 Range of process parameters used for joining aluminium and steel in a butt joint configuration by using Al-5% Si filler wire.

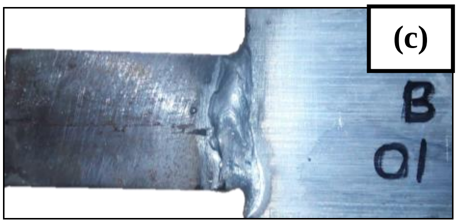
Experiment no.	Wire feed rate (m/min)	Voltage (Volt)
1	2.10	19
2	2	20
3	2.10	20.5
4	2.75	22
5	3	22.5
6	3.5	23
7	3.15	23.5
8	3.75	24
9	3.75	24.5
10	3.75	24.6



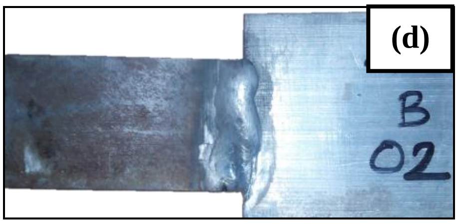
Voltage: 23 V
Wire feed rate: 3.5 m/min



Voltage: 23.5 V
Wire feed rate: 3.15 m/min



Voltage: 24 V
Wire feed rate: 3.75 m/min



Voltage: 24.5 V
Wire feed rate: 3.75 m/min

Fig: 3.8 Joining of aluminium and steel by using Al-5% Si filler wire, in wet condition.

Observations:

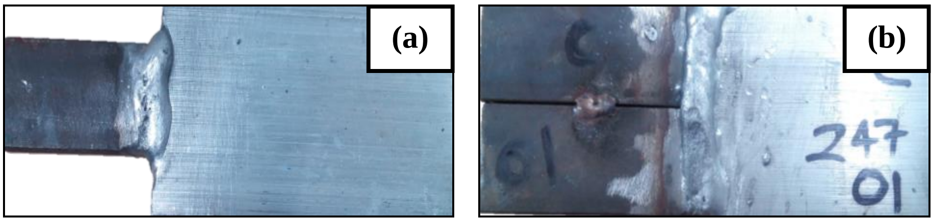
- Reinforcement is low but weld bead width is broad as compared to the dry experimental condition.
- HAZ is high.

3.7.2.3 Experiments by using filler wire Al-12% Si.

The different parameters used during this experiment are shown in Table 3.13. Butt joint configuration of aluminium and steel obtained by given set of parameters and Al-5% Si filler wire are shown in Fig. 3.9.

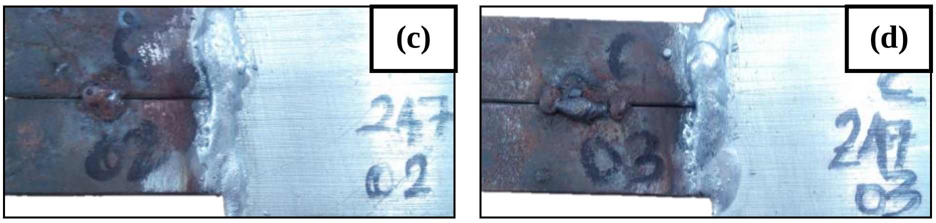
Table: 3.13 Range of process parameters used for joining aluminium and steel in a butt joint configuration by using Al-12% Si filler wire.

Experiment no.	Wire feed rate (m/min)	Voltage (Volt)
1	2.10	19
2	2	20
3	2.10	20.5
4	2.75	22
5	3	22.5
6	3.5	23
7	3.15	23.5
8	3.75	24
9	3.75	24.5
10	3.75	24.6



Voltage: 22 V
Wire feed rate: 2.75 m/min

Voltage: 24 V
Wire feed rate: 3.75 m/min



Voltage: 24.5 V
Wire feed rate: 3.75 m/min

Voltage: 24.6 V
Wire feed rate: 3.75 m/min

Fig: 3.9 Joining of aluminium and steel by using Al-12% Si filler wire, in wet welding condition.

Observations:

- Reinforcement is low but weld bead width is broad as compared to the dry experimental condition.
- HAZ is high as compared to Al-5% Si filler wire.

3.8 Evaluation of the Joint

The ultimate tensile strength of aluminium and steel butt joint has been measured by universal testing machine (H50KL, Tinius Olsen, USA). Microhardness and microstructure are observed for the optimal joint only.

3.8.1 Tensile test

Specimens for tensile strength test are prepared according to ASTM E8 standard and cutting operation is performed by wire electric discharge machining. The geometry of specimen used for tensile testing is shown in Fig. 3.10.

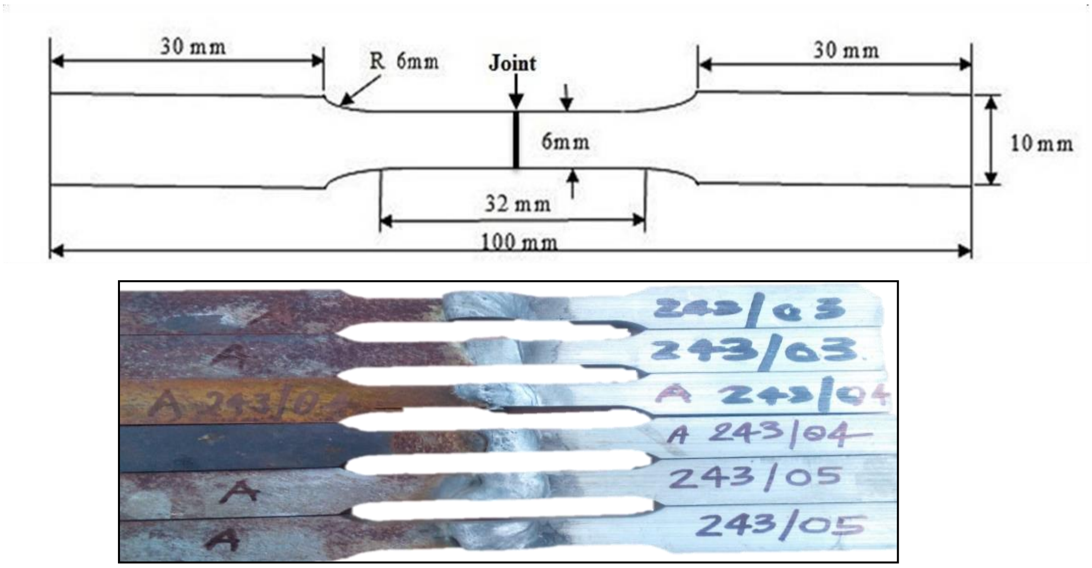


Fig: 3.10 ASTM-E8 standard specimen for determining the tensile strength of the weld joint.

- Thickness: 5 mm
- Gauge length: 25.5 mm
- Radius of fillet: 6 mm
- Overall length: 100 mm
- Length of reduced section: 32 mm
- Length of grip section: 30 mm
- Width of grip section: 10 mm

Fig: 3.11 Tensile testing machine

Fig. 3.11 shows the universal testing machine (H50KL, Tinius Olsen, USA) with a cross-head speed of 1 mm/min.

3.8.2 Microstructure study

Examination of the microstructure of optimal joint is important to understand the phase transformation across different zones (Base material, Fusion zone, HAZ). In order to characterise the microstructure of optimal joint, a sample (dimension 10 mm x 6 mm) is sectioned in transverse direction using a wire electronic discharge machining (WEDM) (Ecocut, Electronica, India). Sectioned samples are mounted using cold setting resin to facilitate holding the samples during polishing. Sample are then polished on the polishing machine (250 Buehler, Switzerland) using polishing papers of different grades, starting from 220, 400, 600, 800, 1000, 1200, 1500, 2000 and 2500. After this selvyt cloth is used for polishing with a diamond paste of 1 μm to get a mirror finish. These polished samples are then cleaned with isopropanol to remove any dirt or diamond paste adhered to it. After completion of polishing, low carbon steel side is etched by using chemical reagent nital (10% HNO_3 and 90-99% C_2H_6O) for 20-30 seconds. The aluminium side is etched by using chemical reagent keller’s (190 ml distilled water, 5 ml HNO_3, 3 ml HCL and 2 ml HF) for less than 3-5 seconds. The etched samples are observed under the inverted optical microscope (DMIL Leica, Germany). Results of the microstructure of optimal joint are analysed and reported in next chapter.

3.8.3 Microhardness test

The microhardness variation is observed across the joint by a Vickers microhardness tester (VMH-002 Walter UHL, Germany). A load of 200 gm is applied for the duration of 15 seconds at the indentation speed of 25 μm/sec. Result of Vickers microhardness for optimal joint are analysed and reported in next chapter.

Chapter 4

RESULTS AND DISCUSSION

This chapter contents of various experimental results and their analysis such as effect of different working parameters, different filler wires, and different welding conditions on weld joint. Aiming to identify the optimum values for maximum joint strength. Table 4.1 show different experimental parameters.

Table: 4.1 Values of input process parameters and joint strength for different main experiments, in dry and wet welding conditions.

Experiment no.	Voltage (volt)	Wire feed rate (m/min)	Filler wire	Ultimate tensile strength (MPa)
		Dry welding condition		
1	18.2	3.20	Al-5% Si	40.2
2	18.6	3.40	Al-5% Si	38.5
3	19.1	3.60	Al-5% Si	34.3
4	18.2	3.20	Al-12% Si	41.5
5	18.6	3.40	Al-12% Si	39.2
6	19.1	3.60	Al-12% Si	36.8
		Wet welding condition		
7	23.5	3.75	Al-5% Si	43.4
8	24	3.75	Al-5% Si	40.8
9	24.6	3.75	Al-5% Si	38
10	23.5	3.75	Al-12% Si	45.2
11	24	3.75	Al-12% Si	44.3
12	24.6	3.75	Al-12% Si	40.5

4.1 Variation of joint strength

Joint strength is tested by using H50KL, Tinius Olsen tensile tester**.** Fig. 4.1 and 4.2 shows the variation of joint strength prepared by using Al-5% Si filler wire at different welding condition (dry and wet) and the variation of welded joint strength prepared by using Al-12% Si filler wire at different welding condition (dry and wet). It is found from the experiment that the joint strength decreases with increase in voltage and wire feed rate. This observation is valid for all the values of voltage and different wire feed rate.

4.1.1 Dry welding condition

It is seen from the experiment that an optimum joint strength of 40.2 MPa and 41.5 MPa is found by using Al-5% Si filler wire and Al-12% Si filler wire at voltage 18.2 and wire feed rate 3.2 m/min in dry experimental condition. Fig. 4.1 shows the joint strength of the weld prepare by Al-5% Si filler in dry welding condition.

It can be explained from the fact that at higher voltage, a thick layer of intermetallic compound (IMC) forms between steel and weld seam zone as shown in Fig.4.10b. IMC have hard and brittle in nature, so it causes heavy cracking, increases porosity and deteriorates the mechanical properties of the weld joint. Hot cracks and blow holes are formed in weld seam zone shown in Fig. 4.4 b. This hot cracks and blow holes make joint internally weak. Heat input is described by the following relationship:

$$Q = UI/S \quad \ldots\ldots\ldots\ldots \textbf{(4.1)}$$

Where,

Q: Linear heat input in gas metal arc welding process (KJ/mm)

U: Mean welding voltage (v)

I: Current (Ampere)

S: Welding speed (m/min)

Equation 1 shows that maximum joint strength achieved at lower welding voltage and higher welding speed.

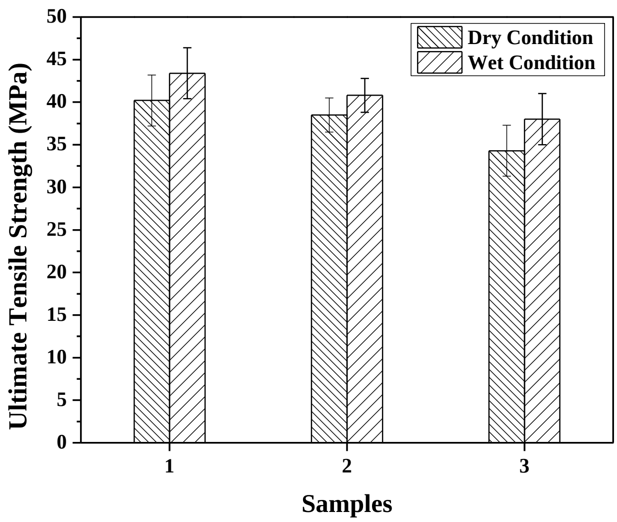


Fig: 4.1 Variation of joint strength in dry and wet welding condition by using Al-5% Si filler wire.

4.1.2 Wet welding condition

It is seen from the experiment that an optimum joint strength of 43.4 MPa and 45.2 MPa is found by using Al-5% Si filler wire and Al-12% Si filler wire at voltage 23.5 and wire feed rate 3.75 m/min in dry experimental condition. Fig. 4.1 shows the joint strength of the weld prepare by Al-5% Si filler in wet welding condition.

It is seen from the experiment that at higher voltage, by using Al-5% Si filler wire Si reacts with Fe particles that present as impurity in Al-Si filler wire. By the time of reaction Fe rich β-needle formed as shown in Fig.4.8c. By using Al-12% Si filler wire it is seen that at weld seam zone globular eutectic Si region formed because the presence of higher amount (11% -13%) of Si in Al-12% Si filler wire as shown in Fig. 4.9c. Globular eutectic Si region is more ductile phase as compared to Fe rich β-needle phase for this reason ultimate tensile strength of weld joint prepared by Al-12% Si filler wire shows higher values of tensile strength as compared to weld joint prepared by Al-5% Si filler wire. Fig.4.2, shows the joint strength of the weld prepare by Al-12% Si filler in dry and wet condition.

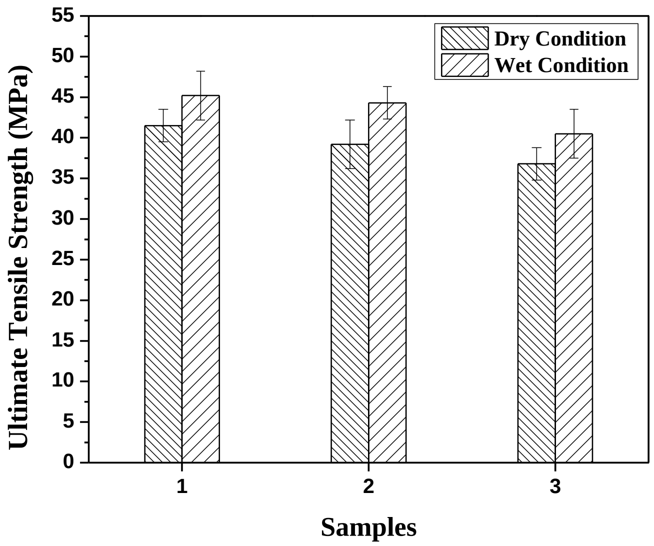


Fig: 4.2 Variation of joint strength in dry and wet welding conditions by using Al-12% Si filler Wire

4.2 Microstructure

Microstructural study is done on the cross sectional surface of the welded samples obtained at different process parameters with two filler wires Al-5% Si and Al-12% Si in dry and wet welding conditions.

4.2.1 Dry welding condition

Filler wire: Al-5% Si

Microstructure of the weld joint is obtained at voltage 17.4 volt and wire feed rate 2 m/min is shown in Fig. 4.3. The α-Al and Al-Si eutectic region present in a columnar crystal zone (Fig 4.3b). It is clear from the microstructure (Fig 4.3a), the fusion line weld seam is separated with aluminium because lack of fusion is observed between filler wire and aluminium. Blow holes are observed in the both weld seam as well as in the columnar region. It is also observed in steel side that the HAZ is very narrow with fine grains and melting is negligible.

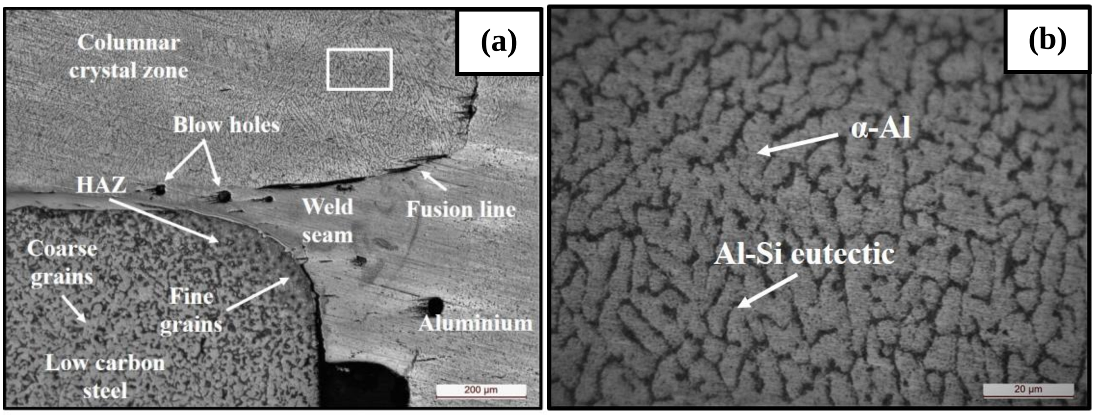


Fig: 4.3 Microstructure of the weld joint prepared by Al-5% Si filler wire with voltage 17.4 and 2 m/min feed rate at the dry welding condition, (a) Weld joint and (b) Enlarge view of columnar crystal zone.

Fig. 4.4a shows the microstructure of weld joint obtained at 17.8 V voltage and 2 m/min wire feed rate. With increasing the voltage of the welding, number of blow holes are increases and hot cracks is also formed (Fig. 4.4b). HAZ is large in low carbon steel as compared to previous microstructure (Fig. 4.3).

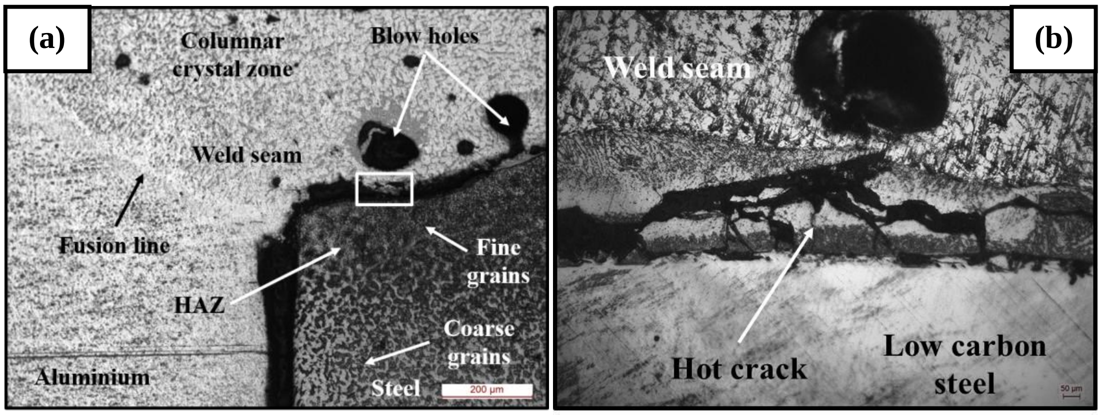


Fig: 4.4 Microstructure of the weld joint prepared by Al-5% Si filler wire at the dry welding condition with voltage 17.8 and 2 m/min feed rate, (a) weld joint and (b) Hot crack.

Filler wire: Al-12% Si

Figure 4.5a represent the optical micrograph of weld joint is obtained at voltage 17.8 V and wire feed rate 2 m/min with Al-12% Si filler wire. The rectangle shown in Fig. 4.5a is columnar crystal zone. This zone consists of α-Al and Al-Si eutectic region as shown in Fig. 4.5b. Less number of blow holes and hot cracks is found as compare to weld obtained by Al-5% Si filler wire. HAZ is found more and fine grains are observed in the welded part as compare with Al-5% Si filler wire welding. Melting of low carbon steel is also more in this case.

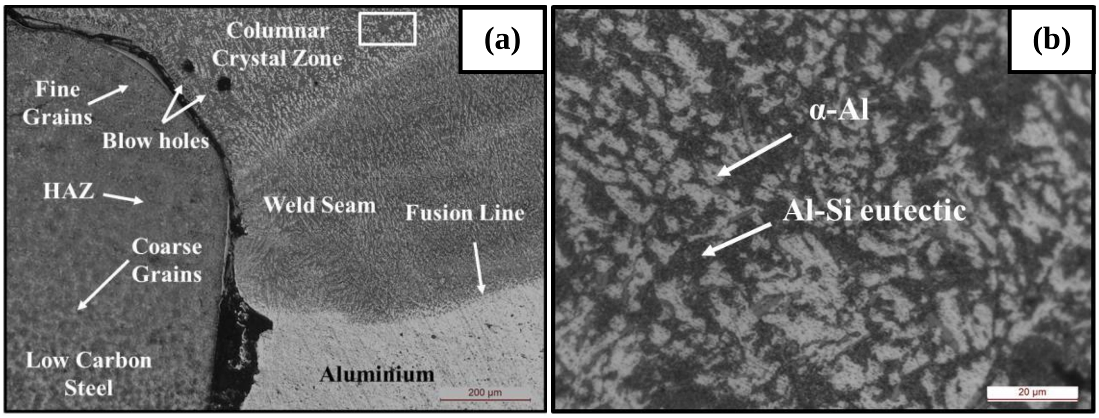


Fig: 4.5 Microstructure of weld joint prepared by Al-12% Si filler wire at the dry welding condition with voltage 17.8 and 2 m/min feed rate, (a) Weld joint and (b) Enlarge view of columnar crystal zone.

The SEM micrograph of weld sample prepared at voltage 17.8 and 2 m/min feed rate by using Al-5% Si filler wire are shown in Fig. 4.6. The Si eutectic needles are detected. The thickness of IMC layer is varying from 76 μm to 79 μm and causes reduction in adhesion between steel and weld seam. Fig. 4.7 shows weld seam, HAZ and unaffected zones of aluminium side.

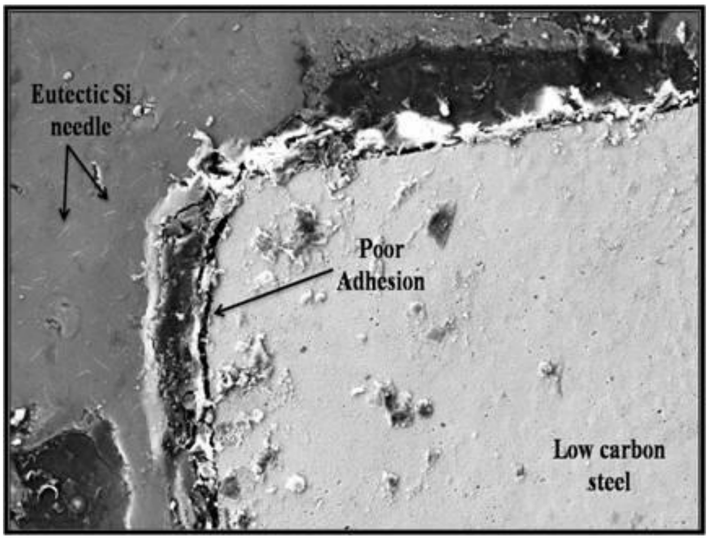


Fig: 4.6 Microstructure of weld prepare by Al-5% Si filler wire at dry welding condition.

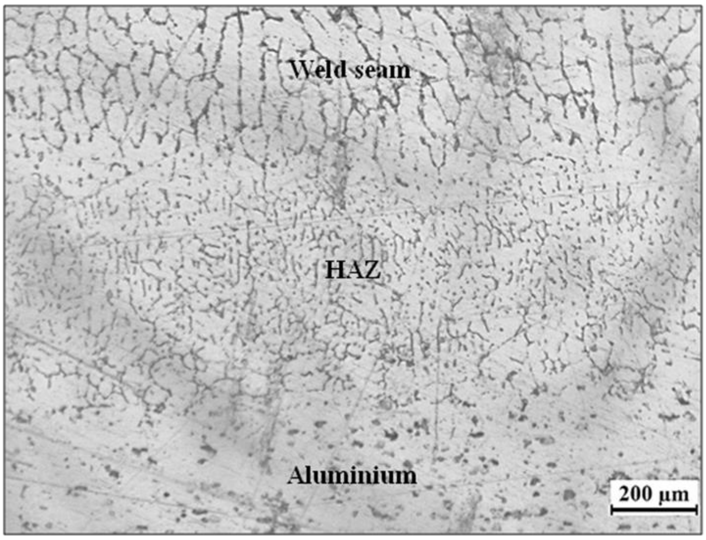


Fig: 4.7 Different zones in aluminium.

4.2.2 Wet welding condition

Filler wire: Al-5% Si

Figure 4.8a represent the optical micrograph of weld joint obtained at voltage 23.5 V and wire feed rate 3.75 m/min. Interface of steel and aluminium with weld seam are clearly seen (Fig. 4.8a). HAZ zone of steel is shown in Fig. 4.8b. Fe-rich β-needle, α-Al and Al-Si globular eutectic silicon phases are found in weld seam zone as shown in Fig. 4.8c. Globular eutectic Si phase is found is less as compare to Fe-rich β-needle. At superheated condition Si reacts with Fe (present as impurity in Al-Si alloy) and form Fe-rich β-needle (Haque *et al.* 2005) and 54-58 μm thick IMC layer is also formed.

Filler wire: Al-12% Si

The optical micrograph of weld sample prepared at voltage 23.5 V and 3.75 m/min feed rate by using Al-12% Si filler wire are shown in Fig. 4.9a. Very fine grains are found in the HAZ zone of steel as shown in Fig. 4.9b. It is observed from Fig. 4.9c that rich globular eutectic Si phase and α-Al phases is present in a weld seam however Fe-rich β-needle phase is missing. Thickness of IMC layer is formed and varying from 34-36 μm.

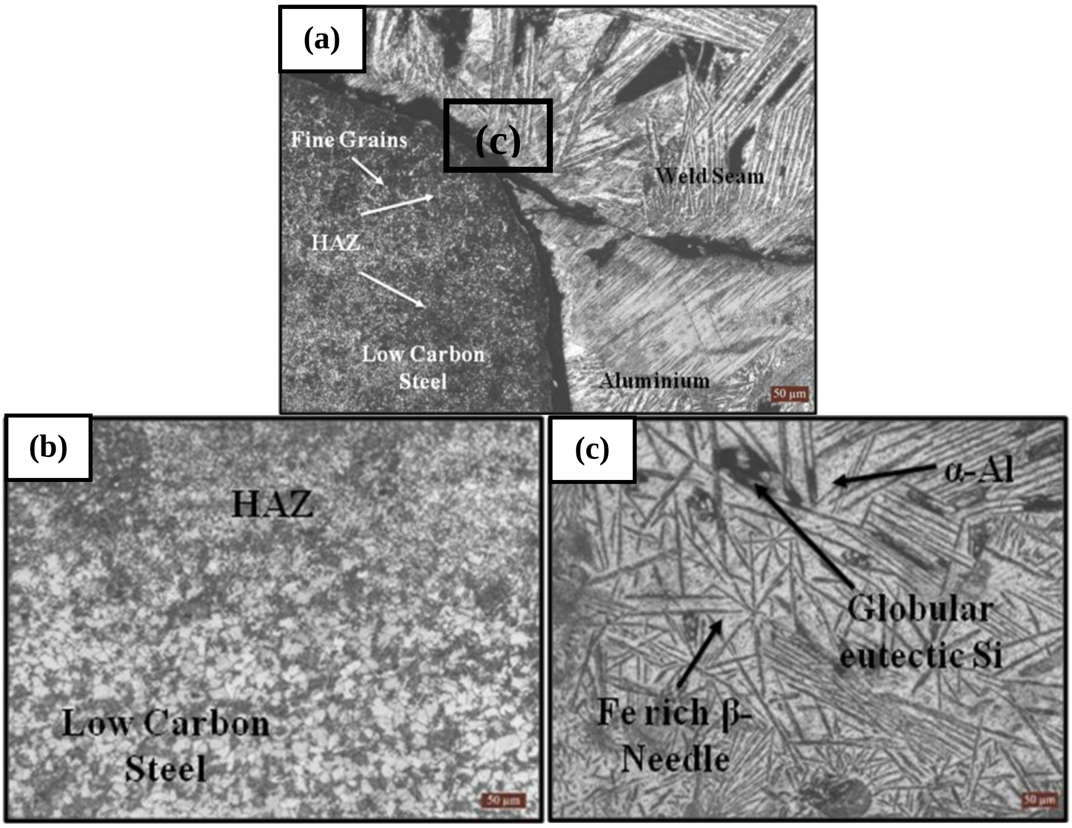


Fig: 4.8 Microstructure of weld joint prepared by Al-5% Si filler wire at wet welding condition, (a) weld joint, (b) HAZ in steel and (c) Weld seam zone

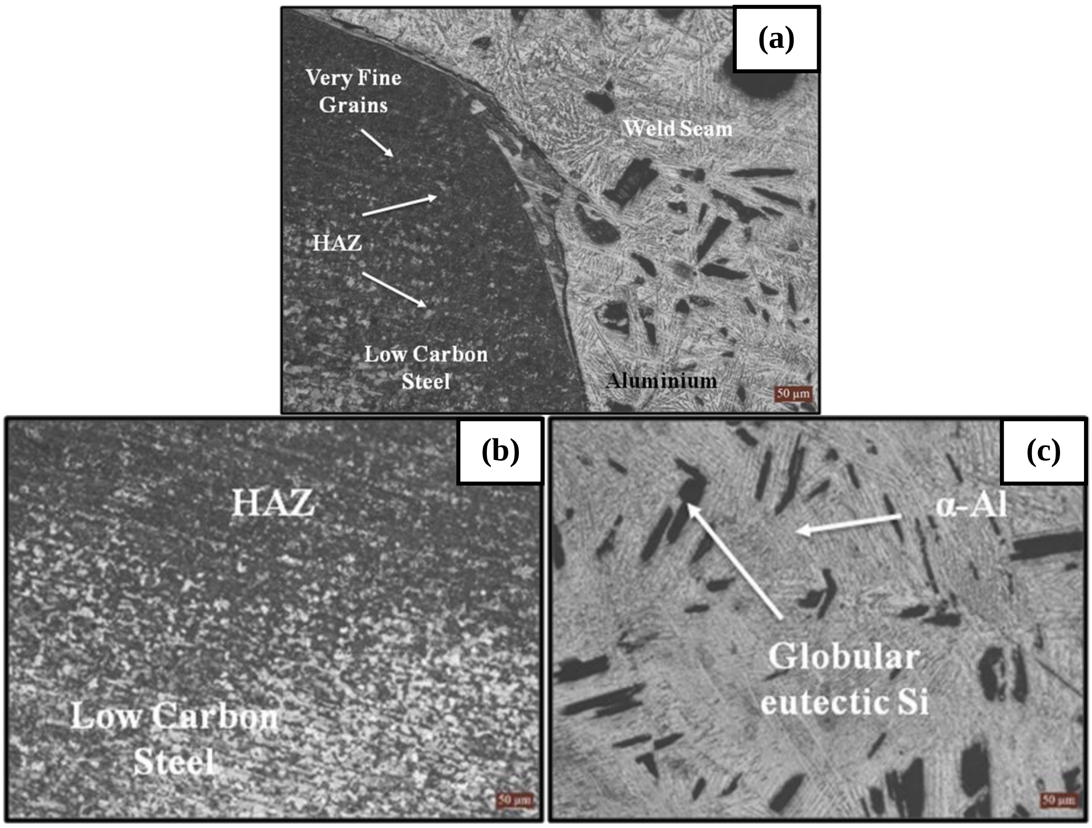


Fig: 4.9 Microstructure of weld joint prepared by Al-12% Si filler wire at wet welding condition, (a) Weld joint, (b) HAZ in steel and (c) Weld seam zone.

Fig. 4.10a shows the IMC layer distribution in the weld sample prepared by Al-12% Si filler wire. Fig. 4.10b shows adhesion between weld seam zone and low carbon steel.

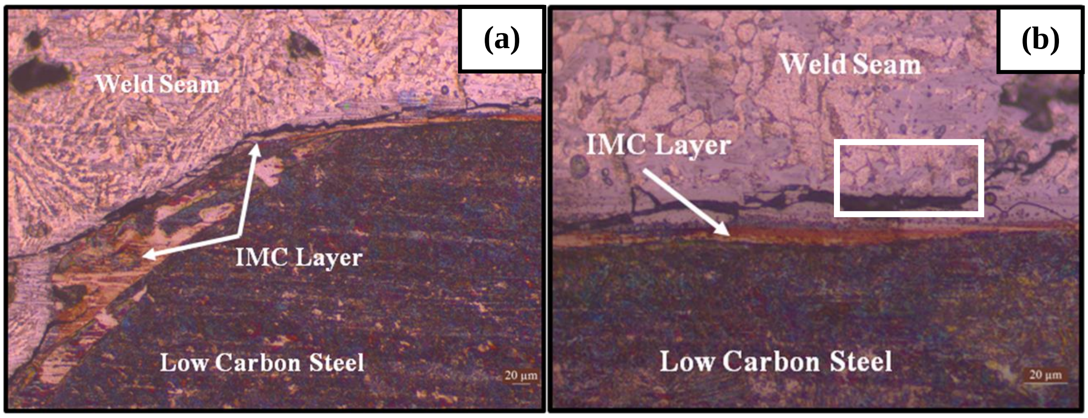


Fig: 4.10 Intermetallic compound (IMC) formation, (a) IMC layer distribution in the weld sample prepared by Al-12% Si filler wire at wet welding condition, (b) Adhesion between steel and weld seam.

4.3 Microhardness

Microhardness test is performed by using Vickers microhardness tester at 200 gm load, 15 seconds dwell time and 25 μm/sec indentation speed. Five consecutive microhardness measurements are taken at different locations as shown in Fig. 4.11. The values of microhardness at different locations (Fig. 4.11) in case of different filler wires, conditions and process parameters are shown in Table 4.4 and Table 4.5.

Table: 4.2 Represent process parameters and microhardness result at dry and wet welding condition.

Dry welding condition								
Process parameters			**Microhardness ($HV_{0.2}$)**					
Wire feed rate (m/min)	**Voltage (Volt)**	**Filler wire**	**a**	**b**	**c**	**d**	**e**	**f**
2	17.8	Al-5% Si	161	179	49	47	51	55
2	17.8	Al-12% Si	170	165	73	51	61	50
Wet welding condition								
3.75	23	Al-5% Si	169	166	49	60	75	63
3.75	23	Al-12% Si	160	163	58	65	78	59

Variation of microhardness with respect to different locations for two filler wires in both dry and wet welding conditions is also represented by Fig. 4.12a and Fig. 4.12b. Indent marks obtained in microhardness test for different samples are shown in Fig. 4.13. The different locations are as follow:

A: Base metal (1018 low carbon steel)

B: HAZ in steel

C: Weld seam

D: Fusion zone

E: HAZ in aluminium

F: Base Metal (1050 aluminium alloy)

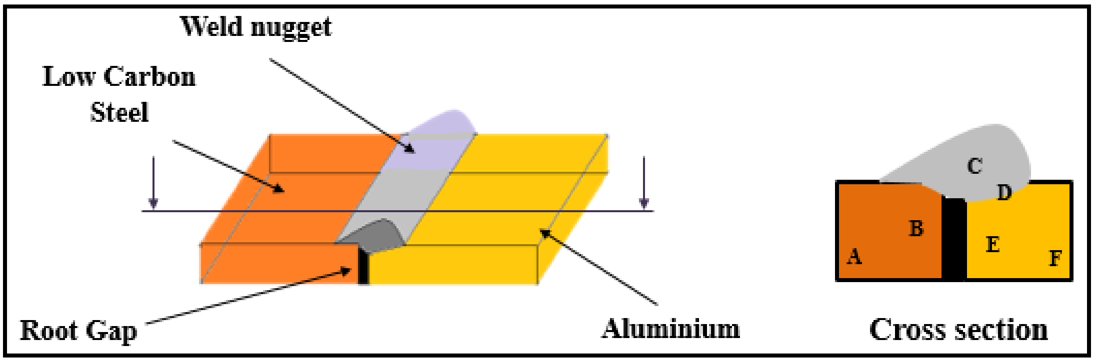


Fig: 4.11 Different locations for microhardness indent.

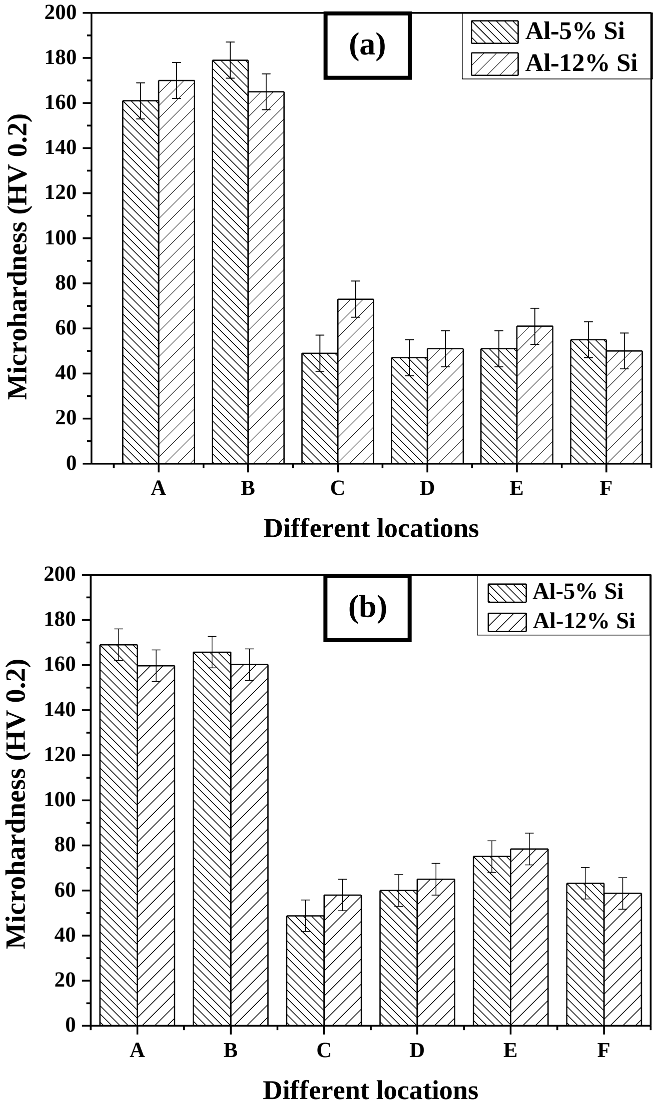


Fig: 4.12 Microhardness results, (a) Results of microhardness test in dry welding condition and (b) Results of microhardness test in wet welding condition.

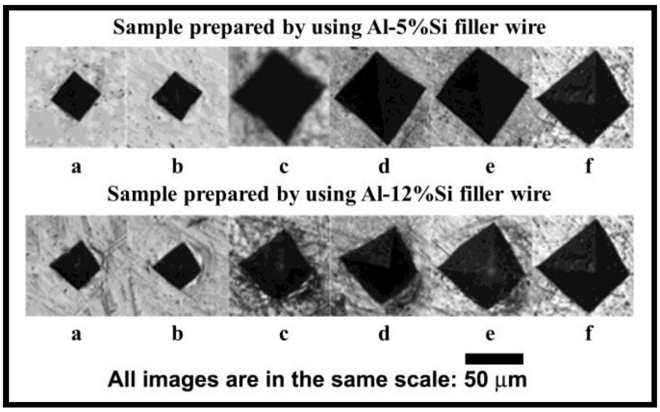


Fig: 4.13 Indent marks obtained in microhardness test for different samples.

Where: a is base material (Steel), b is HAZ in steel, c is weld seam, d is fusion zone, e is HAZ in Al and f is base material (Aluminium).

Chapter 5

CONCLUSIONS AND SCOPE OF FUTURE WORK

This chapter summarises the significant achievements and conclusions from the present work highlighting the extent to which the aims and objectives are met. It also presents the possibilities for future work based on the outcomes of the research.

5.1 Conclusions

Influence of voltage, wire feed rate, filler wire and different welding condition (dry and wet) on the joint strength of 5 mm thick, weld joint of 1050 aluminium alloy and 1018 low carbon steel is studied. The following conclusion can be drawn from the present research work:

1. Use of high welding voltage cause blistering and thermal distortion in aluminium, to avoid these defects the welding voltage is kept in a suitable range and proper clamping is provided.
2. To achieve uniform fusion of workpiece, it is essential that the edges of workpiece are accurately machined and clamping arrangement act as a uniform heat sink. It is also necessary to ensure that the two faces are in perfect contact along the entire length of the joint.
3. All the tensile test specimens are break from the joint of the weld.
4. Filler wire Cu Al-10% Fe is compatible with 1018 low carbon steel but not with 1050 aluminium alloy.
5. In fusion zone, grain refinement is mainly responsible for the increase in the joint strength.

5.1.1 In dry welding condition

1. Reinforcement is more but weld width is less.
2. No significant HAZ is observed in case of low carbon steel resulting no variation in the values of microhardness from the unaffected zone to weld nugget.
3. At same process parameters low penetration found in low carbon steel but high penetration found in aluminium.
4. Ultimate tensile strength of welded joints is 40.2 MPa and 41.5 MPa in case of Al-5% Si and Al-12% Si filler wire respectively.

4. The joint strength of the weld decreases with increase in voltage due to increase in blow holes, thickness of intermetallic compound (IMC) and hot cracks with increase in voltage.
5. Blow holes are less by using Al-12% Si filler wire as compared to Al-5% Si filler wire.

5.1.2 In wet welding condition

1. Reinforcement is less but weld width is more as compared to a dry welding condition due to increase in wetting property of filler wire at higher voltage.
2. Blow holes are less as compared to a dry welding condition.
3. HAZ is more as compared to dry welding condition because working voltage is high.
4. Ultimate tensile strength of resultant joints could reach 43.4 MPa and 45.2 MPa by using Al-5% Si and Al-12% Si filler wire due to ductile Fe-rich β-needles and globular eutectic Si phase present in weld seam.
5. Fe-rich β-needles are formed by using Al-5% Si filler wire and globular eutectic Si region is form by using Al-12% Si filler wire.
6. In HAZ very fine grains are forms by using Al-12% Si filler wire as compared to Al-5% Si filler wire.

5.2 Scope of the future work

- Automated gas metal arc welding (GMAW) setup could be used to achieve higher strength.
- The granular suitable material powder can be used to strengthening weld joint.
- Coated workpiece can be used to improve adhesion property.
- Aspect ratio of bead geometry can be correlated to the joint strength.
- Any other filler wire can be applied, with different alloying element (like Zn, Mg).
- Thermocouple and thermal camera may be used for thermal analysis.
- Gas metal arc welding (GMAW) joining process can be explored for joining even thinner sheets of aluminium and steel.

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