STUDIES ON THE EFFECT OF PROCESS PARAMETERS ON MECHANICAL PROPERTIES OF CMT WELDED ALUMINIUM/STEEL JOINT

M.Tech. Thesis

By
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DISCIPLINE OF METALLURGY ENGINEERING AND MATERIALS SCIENCE

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STUDIES ON THE EFFECT OF PROCESS PARAMETERS ON MECHANICAL PROPERTIES OF CMT WELDED ALUMINIUM/STEEL JOINT

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Submitted in partial fulfilment of the
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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled "**STUDIES ON THE EFFECT OF PROCESS PARAMETERS ON MECHANICAL PROPERTIES OF CMT WELDED ALUMINIUM/STEEL JOINTS"** in the partial fulfilment of the requirements for the award of the degree of **MASTER OF TECHNOLOGY** and submitted in the **DISCIPLINE OF METALLURGY ENGINEERING AND MATERIALS SCIENCE**, **Indian Institute of Technology Indore**, is an authentic record of my work carried out during the time period from July 2019 to June 2020 under the supervision of Dr. Jayaprakash Murugesan, Assistant Professor Department of Metallurgical 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.

Ankit Singh
17/06/2020

Signature and name of the student with date
ANKIT KUMAR SINGH

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

M. Jayaprakash

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Dr. Jayaprakash Murugesan, 28.6.2020

ANKIT KUMAR SINGH has successfully given his/her M.Tech. oral examination held on **25 JUNE 2020.**

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Date: 28.06.2020 — Date: 29/06/2020

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Ankit Kumar Singh

CERTIFICATE

It is certified that the above statement made by the students is correct to the best of my knowledge.

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Signature of Guide(s) with dates and their designation

Preface

*This report on "**Studies on the effect of process parameters on mechanical properties of CMT welded Aluminium/Steel joint**" is prepared under the guidance of **Dr. Jayaprakash Murugesan**, Assistant Professor, Dept. of MEMS, IIT Indore.*

Through this report, I have tried to give a detailed description of the study and experiments we have done with different processing parameters and conditions using CMT welding on Aluminium similar and Aluminium-Steel dissimilar, and try to cover every nuance of its properties by getting microstructural and mechanical properties of the weld.

I have tried to the best of our abilities and knowledge to make the report descriptive and self-explanatory.

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ABSTRACT

Abstract:-Cold Metal Transfer (CMT) welding is a modified MIG welding process based on the short-circuiting transfer process. The Cold Metal Transfer machine detects a short circuit which sends a signal that retracts the welding filler material, giving the weld time to cool before each drop is placed, resulting in a drop-by-drop deposit of weld material. However, the technique can be modified or combined with suitable add-ons to give better weld properties such as using supercooling with CMT welding to give better weld properties. In this study, different processing parameters were varied, such as the welding current, cooling rate and feed rate to obtain the best possible weld characteristics like weld bead appearance, microstructure features and mechanical properties named tensile strength and hardness. Aluminium alloy (Al6061) similar and Al6061-Galvanized Steel (Q235) dissimilar were joined using $AlSi_5$ (ER4043) filler wire in CMT welding. Microstructural characterization was done using an optical microscope, and comparing the optimized weld parameters to find the best possible tensile strength and hardness was done. The use of supercooling assisted welding significantly improves the weld properties. This was related to the development of finer grains and a more homogenous distribution of the strengthening particles as supercooling was applied. It also results in the development of grain refinement. This grain refinement led to the increment of hardness and toughness. The results were discussed based on the microstructural features observed and mechanical properties measured. The optimized weld parameters were identified for the maximum improvement in the tensile strength of the joint. Maximum strength for Aluminium similar joint achieved was 154.7MPa at 120A welding current, 8-10mm arc length with welding speed 4.1mm/sec using normal cooling setup. This joint strength was improved by 164.4MPa at 130A welding current using copper cooled backplate. Maximum strength for Al-Steel dissimilar joint achieved was 158.3MPa at 130A welding current, 8-10 mm arc length, 4.1mm/sec welding speed using normal cooling setup.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS

CMT	Cold Metal Transfer
TIG	Tungsten Inert Gas Welding
MIG	Metal Inert Gas Welding
Al	Aluminium
BS	Base Material
F.Z.	Fusion Zone
HAZ	Heat Affected Zone
IMC	Inter Metallic Compound
XRD	X-Ray Diffraction
UTM	Universal Testing Machine

CHAPTER:-1. INTRODUCTION

1.1. Introduction: Cold Metal Transfer welding is a modified MIG welding process based on the short-circuiting transfer process developed by fronius of Austria in 2004. This process mostly works in short circuit (dip transfer) transfer mode which is defined by low current and voltage which signifies low heat input [1]. The important difference of CMT from the conventional GMAW is the full digital control of the welding process. The microcontroller controls the feeding of the wire for the CMT process through the feed motors, no longer dependent on the electrical characteristics [2]. An initial high pulse of current is formed which formed an arc between the advancing electrode and the substrate that melt the electrode tip [3]. The current is reduced following the pulse, as soon as a short circuit is indicated, the voltage reduces, the current is further reducing to a low background value and the wire is retracted, which leads to detachment of the molten droplet [4]. Thus, this process is named CMT due to the metal transfer takes place when the current is very low [5]. Figure 1 shows the different CMT phases. During welding, temperature variation in welds and parent metals have important effects on material characteristics, residual stresses as well as one dimensional and shape accuracy of welded products [6]. There are two main features of the CMT process: one is at the point of short circuit with low current corresponding to low heat input, another is the short circuit occurrence in a stable controlled manner.

The CMT process is characterized by the innovative solution for the weld drop detachment. Unlike in a conventional pulsed arc, the droplet is notched by a current impulse, rather it is a defined rearward motion of the welding wire which brings about controlled droplet detachment as shown in the Figure below.

In Fig. 1. arc represented the different phases that characterize this process:-

(a). During the arcing period, the filler metal moves towards the weld-pool.

(b). When the filler metal dips into the weld-pool, the arc is extinguished. the welding current is lowered.

(c). The rearward movement of the wire assists droplet detachment during the short circuit. The short- circuit current is kept small.

(d). The wire motion is reversed and the process begins all over again.

As mentioned above, Cold Metal Transfer Welding is one of the potential welding processes with low heat input welding. Of course, the term "cold" has to be understood in terms of a welding process: when set against conventional GMAW, CMT-GMAW is indeed a cold process with its characteristic feature of alternating thermal arc pool, i.e. hot when an arc is initiated and cold when the arc is extinguished and the wire is retracted.

Different terms associated with welding:-

- Alternating Current - With alternating current, amplitude and polarity change cyclically. Welding power sources are operated on a single or three-phase alternating current grid and usually supply direct current for welding.
- Arc- The arc burns during welding between the electrode and the workpiece. Due to its high plasma temperatures, it fuses the parent material and melts away the filler metal.
- Arc characteristics - The arc characteristic indicates the relationship between the arc voltage and the arc current.
- Arc length - The arc length refers to the distance between the point where the arc touches the wire electrode until the point of reaching the workpiece. The voltage is a characteristic dimension for the arc length.
- Arc welding - In arc welding, an electric arc (welding arc) burns between the workpiece and electrode. Depending on the welding process, this can melt and act simultaneously as the filler metal or be non- consumable.
- Butt joint - Butt joints are used to join workpieces positioned on the same plane, that is, at an angle of 180 degrees to one another.

- Lap joint- Lap joints are used to join workpieces positioned on the two different parallel plane and workpieces are overlap.
- Cleaning effect - The cleaning effect in aluminium welding means the destruction of the aluminium oxide layer. This process is caused by the positive polarity of the tungsten electrode (during TIG welding).
- CMT - It is a dip transfer welding process where the heat input is kept very low. Due to the reversing wire movement, the CMT process has a completely new type of droplet detachment. This leads to significantly improved dip transfer arc characteristics[1]. CMT Advanced is a variant of the CMT welding process. A cyclical change in polarity of the welding current takes place in the short circuit phase, in conjunction with the reversing wire movement. This additional degree of freedom allows the heat input to be reduced again.
- Cracks - Cracks are weld seam faults that occur under tensile stresses. The two main groups are cold and heat cracks.
- Direct current - Direct current is an electrical current where the amperage and polarity do not change.
- Efficiency - The efficiency describes the relationship between the power input and power output. Examples include the electrical efficiency of a welding system or the thermal efficiency of the arc.
- Electrical current - Electrical current is the directed movement of negatively charged charge carriers (electrons). The unit of measurement is an ampere (A). The formula symbol I describe the quantity of current that flows through a line within a given time period. For the current to be able to flow, it requires an electrical voltage.
- Electrical voltage - The electrical potential difference is referred to as voltage and is between the positive and negative pole.
- Fusion - Fusion indicates the mixture percentage of the parent material with the weld layer applied.
- Gas pre-flow - The gas pre-flow is a way to obtain better shielding gas cover at the start of welding. A fixed period of time is defined here during which the gas solenoid valve should open before welding starts.
- Grounding cable - The grounding cable is the current return cable in the

welding circuit. It is secured to the component.

- Grounding clamp - The grounding clamp is a quick-release mechanical connection between the workpiece and the current-return cable in the welding circuit.
- Heat input - Heat input refers to the energy that is introduced into the component during welding. The heat input is calculated based on the electrical energy input per wield, reduced by the total efficiency.
- Inert Gas - Inert gases are non-reactive noble gases. They are used in metal inert gas welding (MIG) and tungsten inert gas welding (WIG). Inert gases include argon, helium, and mixtures of these.
- Joining - Joining is the permanent connection of two or more materials. Some of the most important joining processes include welding, brazing, bonding, riveting and screwing.
- Lack of fusion - Lack of fusion occurs if there is no secure join between the weld metal and the parent material.
- Mechanical properties - The mechanical properties of parent material or a welded joint act as the basis in the static calculation for supporting structures. They are crucial for choosing the parent material and filler metals to be used. Mechanical properties are hardness, tensile strength, impact energy, toughness, etc.
- Open circuit voltage - This is the voltage that is applied to the welding sockets prior to welding, for example from the ignition of the rod electrode.
- Outgassing - Outgassing refers to the escape of gases from liquid or solid material during the welding process.
- Oxide formation - Surface scaling is called oxide formation. This occurs especially during the manufacturing of Steel or slightly in the case of poor shielding gas cover.
- Penetration - Penetration refers to the depth of the melted zone in the parent material.
- Power source - The function of a welding power source is to convert a

high input voltage into low welding voltage and high welding current. There are different types of models, whereby the controlled type inverters have mostly established themselves.

- Robotic welding - In robotic welding, an industrial robot guides the welding torch within a pre-programmed track.
- Shielding gas - Shielding gas refers to a gas or gas mixture that is designed to suppress the air in the earth's atmosphere during welding. Shielding gases influence the penetration form, penetration, and welding speed and need a corresponding characteristic during CMT welding.
- Thermal conductivity - Thermal conductivity is a material value that describes how well a material conducts heat. Materials with high thermal conductivity are difficult to weld and need a special welding start treatment (eg. Aluminium) or require a high preheating temperature (eg. copper).

1.2.Background:- In similar joining, same material joints together like Aluminium to Aluminium, Steel to Steel, Magnesium to Magnesium. But in dissimilar or hybrid joining two different materials are joined. like Aluminium to Steel, Copper to Steel, Aluminium to copper. Different welding techniques are available for various purpose, some examples are Tungsten Inert Gas (TIG) welding, Metal Inert Gas (MIG) welding, friction stir welding (FSW), Friction welding, Laser welding, Spot welding. All the above welding techniques have their limitations. joining of Aluminium similar and Aluminium to Steel by conventional welding techniques were difficult and also some of the material cannot be joined by conventional welding techniques. Joining of Aluminium to Aluminium similar and Aluminium to Steel are very important mainly in the automobile industry for lightweight design of automobile vehicles for that purpose conventional welding techniques like arc welding, resistance welding, explosive welding, gas welding were not useful because joints of Aluminium Similar and Aluminium-Steel dissimilar did not form with these techniques. Joining of Aluminium and Steel was very difficult because both materials have distinct thermophysical properties like the large difference in melting point, thermal conductivity, coefficient of linear thermal expansion. Also, they form brittle intermetallic at the interface of Al and Steel as both materials have very less solid solubility in each other [4]. Different welding techniques were used to join Al similar and Aluminium and Steel dissimilar materials, which were solid-state welding method, friction stir welding, diffusion bonding and brazing, used to obtain sound and reliable joints of Aluminium Similar and Aluminium-Steel dissimilar. Watanabe et al. obtained good weld bead appearance of friction stir welding Aluminium and Steel joints with tensile strength close to 90% of the Aluminium base material. However, the joint configurations mainly limited to simple geometries, such as butt or overlapping. For diffusion bonding, the connection of Aluminium to Steel by diffusion bonding was obtained with the effect of pressure at high temperatures. Joints of the Aluminium bar to Steel sheet by diffusion bonding, achieved Joint strength 60 MPa. However, this method was limited due to the demand for high pressure and high temperature often need control atmosphere, which adds extra cost. Aluminium and Galvanized steel also joined by Tungsten inert gas welding in lap joint configuration, and tensile strength was obtained 90 MPa [6]. Aluminium and stainless Steel in butt joint configuration were joined by TIG-MIG hybrid welding in which MIG and TIG torch used in the top and bottom position and achieved 70% of base metal strength. Aluminium and austenitic stainless Steel joined by a hybrid process in which first friction stir processing was done on the steel surface and then Aluminium was welded over stainless Steel in lap joint configuration by Cold metal transfer welding technique. In these work effect of coating thickness on joints, tensile strength was investigated.

1.3.Problem Definition:- The growing demand for the CMT joining for lightweight design which provides sufficient strength while remaining light in weight such as in automobiles where fuel consumption can be brought down by decreasing the weight. There is a need to develop new techniques or at least improvement in the existing technologies. Among different material, iron-based and Aluminium-based alloys are the most significant materials which find its applications in various industries.

However, for joining these materials a reliable or a sort of credible welding technique for industrial applications is yet to be established.

CMT welding with very low heat input, wherein heat-affected zone is reduced as compared to conventional MIG welding is ideal for Aluminium joints. Other than that it also has some advantages like stable arc, spatter free, high welding speed, improved weld quality, increase in manufacturing and efficiency. Using CMT welding with additional equipment such as forced cooling and vibrator can further improve the weld quality, which is being investigated in this study.

1.4.Working Principle:- MIG welding joined Al similar and Al-Steel dissimilar but was not produced sound and reliable joints which can directly be used for practical application. The problem encountered in MIG welded joints were joint strength was less, High Heat affected zone, weld spatter and high heat input so this method cannot be utilized for a thin sheet of Al joint and Al-Steel dissimilar joining. The most severe problem of MIG welding during joining of Al and Steel in the Argon gas atmosphere that MIG arc was not stable. So, here we have used modified MIG welding called cold metal transfer (CMT) welding. In this welding techniques CMT arc become stable, less heat input results in the less heat-affected zone(HAZ), high productivity and high strength joints with better weld bead appearance are possible.

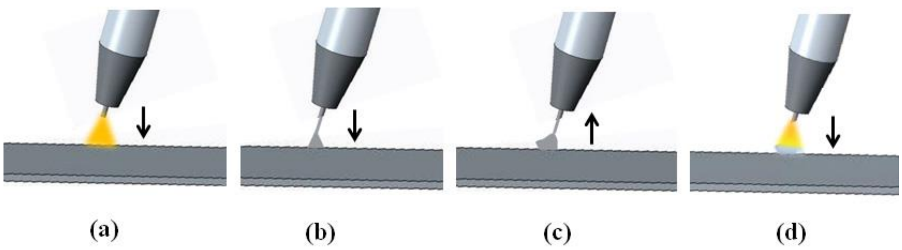


Figure:-1 Schematic of the CMT process (a) represents welding torch moving in the direction of weld pool (b) welding torch dipping the weld pool (c) the upward movement of the welding torch after the droplet is detached during the short circuit (d) the repetition of the process after the wire reversal [2].

1.5. Motivation:-Earlier days automobile industries used Steel alloys to makes the Auto parts, Nowadays Industries are trying to replace it with lightweight materials like Aluminium alloys, Magnesium alloys etc. because it will reduce the weight of the vehicle. The lightweight vehicle will improve fuel efficiency and improve the additional load careering capacity. Less fuel consumption will also decrease greenhouse gas emission to the environment. So, using light material becomes more and more interesting in the automobile industry. Aluminium alloy is one of the best solutions to overcome this problem because it has a high strength to weight ratio and can be recycled. Then the welding of the Aluminium is the key problem to accelerate the use of the Aluminium alloy and guarantee the property of the cars made of Aluminium alloy. Welding of thin Aluminium sheets has many problems, such as burning through and distortion. Conventional MIG welding usually used in Aluminium welding, but when joining thin Aluminium sheets, the lack of control over penetration often limits its use in the field. A short-circuiting metal transfer is a suitable method to join thin Aluminium sheets because of its low heat input characteristics [5]. But the excessive spatter during the welding process also gives the producer a big problem. A recent development in welding technology is the cold metal transfer (CMT) process which is ideally suited to welding Aluminium owing to the no-spatter welding process and low thermal input.

1.6. Research objectives:-

1.6.1. Study on the effect of process parameters on mechanical properties of CMT welded Aluminium joints.

1.6.2. Study on the effect of process parameters on mechanical properties of CMT welded Aluminium-Steel joints.

Process parameters:-

- CMT current.
- Arc length.
- Gas flow rate.
- Welding speed.
- Effect of super/forced cooling by using a water-cooled copper backing plate.

On the following weld joint properties:-

- Weld bead appearance.
- Tensile strength.
- Hardness.
- Microstructure.
- Intermetallic layer thickness (Al-Steel dissimilar joining) and it's relation with heat input.

To achieve these objectives, the research work was carried out as per the research plan is shown in Fig. 2.

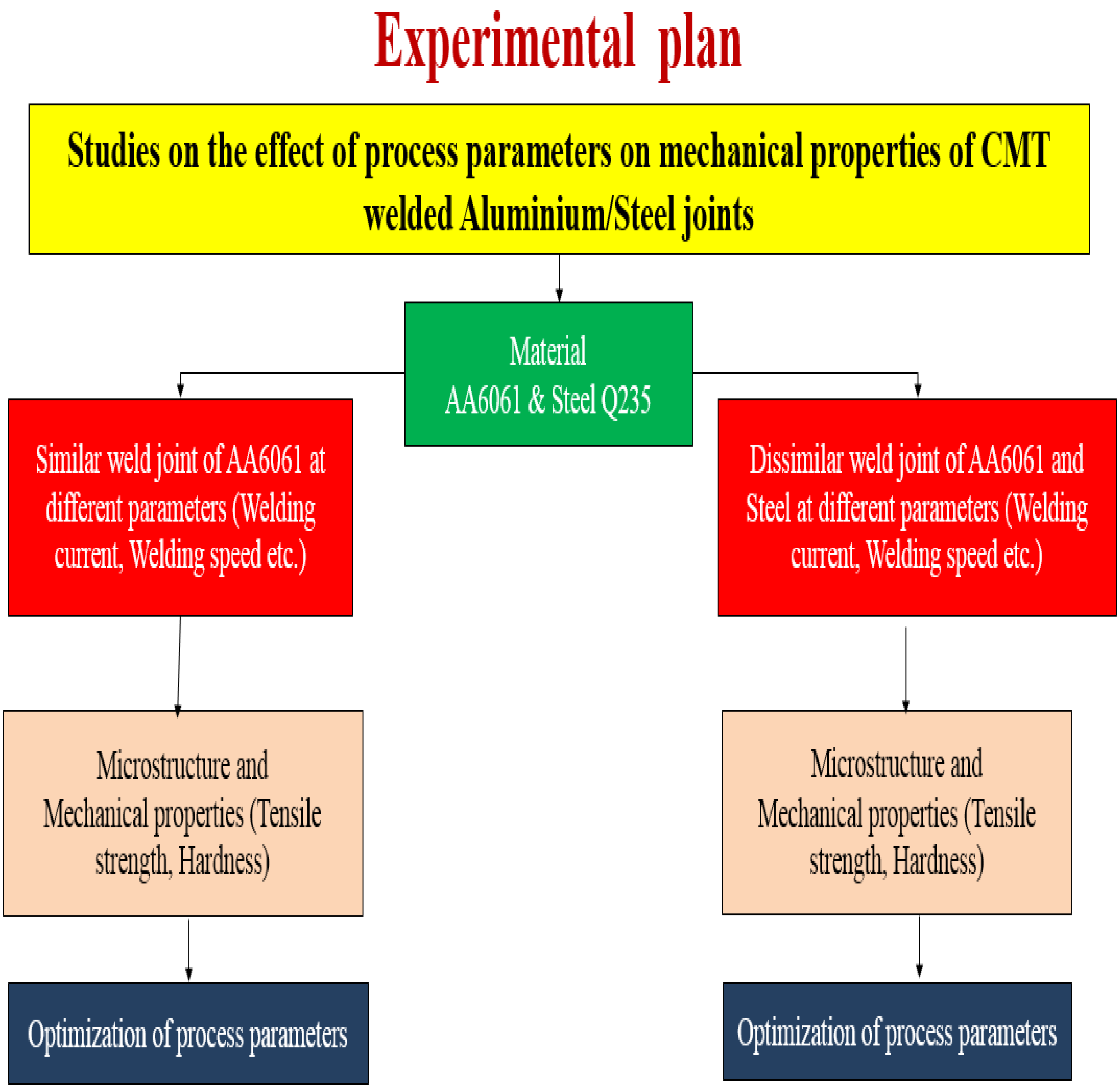


Figure:-2 Research plan flow chart.

CHAPTER 2:- REVIEW OF PAST WORK AND PROBLEM FORMULATION

2.1. Literature review:- This section provides an insight into the current technology available in the field of cold metal transfer welding also highlights various method used by researchers on this topic. Joining of Aluminium similar joint it is a difficult task because of low melting point, oxide formation and poor weld strength. Joining of ammonium steel dissimilar joint is also a difficult task that involves intermetallic formation at the interface of Aluminium and Steel. 30 intermetallic are brittle which reduce the strength of joints. to control the thickness of intimately clear various research and studies already proposed. Intimately thickness is a function of heat input which is used during the welding process heat input is a function of different welding parameters like welding current, arc length, welding speed and gas flow rate.

Hear various method used for joining Aluminium similar and Aluminium steel dissimilar joint to improve the joint strength are briefly described.

Aluminium AA6061 alloy [1]:-When Pavan Kumar et al., welded thin Aluminium alloy sheets using filler, which is of the same composition as of base metal, the weld exhibited a quasi-binary composition. This composition is potentially less susceptible to solidification cracking, controlled fusion line, narrower heat-affected zone (HAZ) and reduced intermetallic phase area. The microstructures for different weld parameters seen in Fig. 3, revealed fine recrystallization at the joints. A uniform distribution of grains and its size in weld HAZ and base metal was distinctly visible.

Aluminium 7075 alloy [1]:- The joints were prepared without spatter, cracks and having very low porosity. The joints exhibited minimum micro-hardness in the weld zone (WZ) depicted in Fig. 4, and a slight hardness decrease in HAZ compared to the Base Metal (B.M.). The comparison of microhardness between WZ and HAZ could be observed in Fig. 5. The joint had mechanical property coefficients of 77%, 60%

and 69% for yield strength, ultimate tensile strength and elongation respectively. The CMT welding performed by Elrefaey was found to produce joints with mechanical characteristics better than the conventional MIG and TIG processes and comparable to FSW and LBW processes.

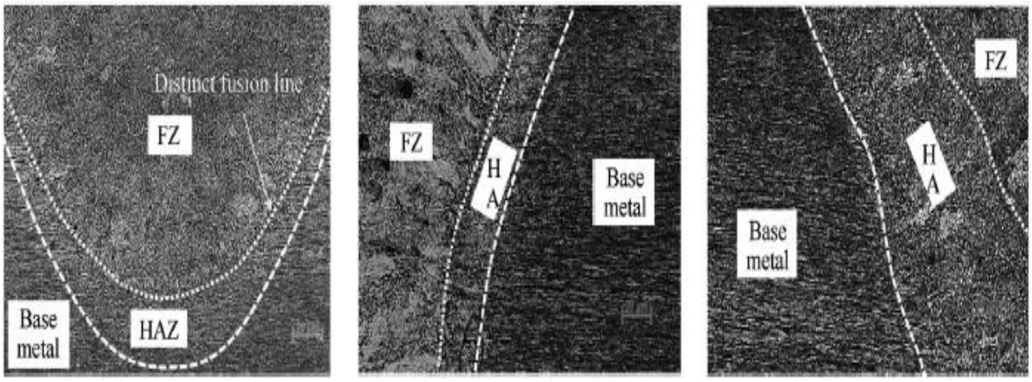


Figure:- 3 Microstructures of AA6061 alloy as seen from optical microscopy [1].

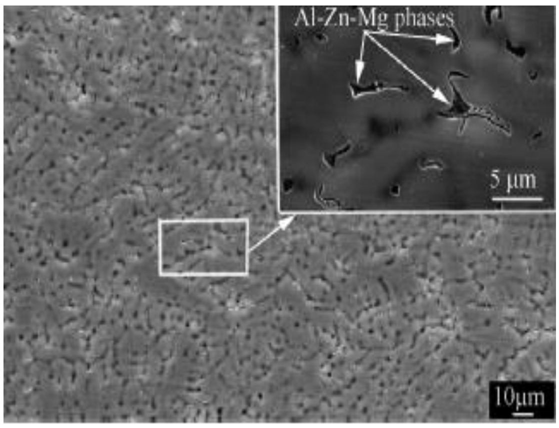


Figure:-4 Weld zone of Al 7075 alloy [1].

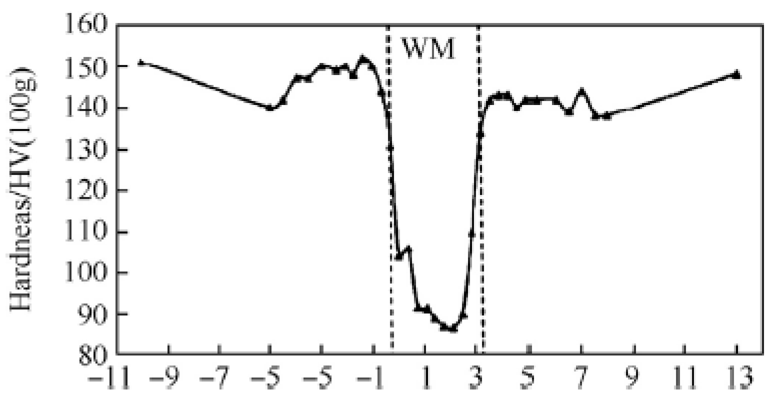


Figure:-5 Microhardness profile at WZ/HAZ interface [1].

Zinc coated steel (Q235) and wrought Aluminium(6061) [1]:- The intermetallic layers formed at the interface between zinc coated steel and wrought Aluminium are predominantly FeAl3 phase. Zhang et al. found that CMT increases the strength of the dissimilar metal lap joint by decreasing the thickness of the brittle intermetallic compound at the interface between Aluminium and Steel. The tooth-like structure as displayed in Fig. 6, predominantly formed during solidification is mainly controlled by the diffusion of Fe and Al atoms at the interface between molten Aluminium and solid Steel.

The CMT welding of Q235 with Al6061 by Cao et al. produced strength equal to CMT welding of Al6061 with Al6061. The joint strength was found to depend on the thickness of the intermetallic layer shown in Fig. 7, and softening of the Aluminium heat-affected zone.

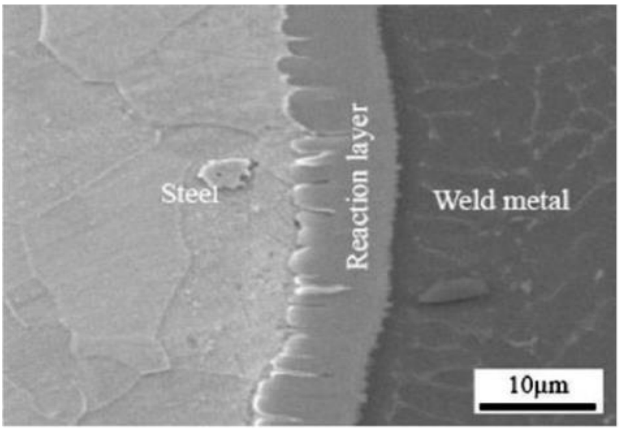


Figure:-6 Interface between weld metal and Steel [1].

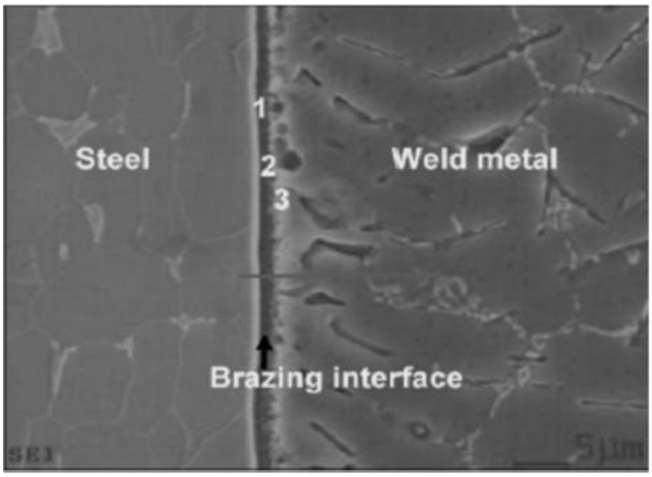


Figure:-7. The microstructure of the brazing interface [1].

Feng Jicai et al.[3]:- Reported that To protect the environment, using light material is becoming more and more interesting in the automobile industry. Because Aluminium alloy is light and strong and can be recycled, new types of car produced from thin Aluminium alloys are under rapid development and some products are already on the market. Then the welding of the thin Aluminium is the key problem to accelerate the use of the Aluminium alloy and guarantee the property of the cars made of Aluminium alloy. Welding of thin Aluminium sheets has many problems, such as burning through and distortion. Conventional MIG welding usually used in Aluminium welding, but when joining thin Aluminium sheets, the lack of control over penetration often limits its use in the field. A short-circuiting metal transfer is a suitable method to join thin Aluminium sheets because of its low heat input characteristics. But the excessive spatter during the welding process also gives the producer a big problem. A recent development in welding technology is the cold metal transfer (CMT) process which is ideally suited to welding Aluminium owing to the no-spatter welding process and low thermal input.

The major aim of this article is to examine the waveform of welding current and voltage and the metal transfer of the CMT process. At the same time, bead-on-plate welding on the pure Aluminium was done to evaluate this process fitness for thin Aluminium sheets welding.

A current and voltage waveforms sensing system and a metal transfer visual sensing system were constructed to examine the process characteristics of the CMT. The results show that the metal transfer process is very stable based on the special wave control features and an assistant back-drawing force. Bead-on-plate tests were done on the thin pure Aluminium sheets, a good appearance can be obtained owing to the no-spatter welding process. Meanwhile, the low heat input of CMT can not only decrease the deflection deformation of the thin sheets when welding pure Aluminium but also promote the gap bridging ability

Kah P. et al.[4]:- Introduced the short-circuiting transfer process named "mechanically assisted droplet deposition" which is applied in controlling short circuit by retracting the wire from short-circuiting. Schierl reported that the droplet compared to the conventional MIG process, so the spatter can decrease. pointed detachment mode of CMT process is without the aid of the electromagnetic force that the CMT process is especially suitable for welding thin Aluminium alloy sheets due to the low heat input and the slight deformation. Additional studies by Zhang et al.. and Cao et al.. concentrated on the application of the process in dissimilar alloys joining owing to the low heat input, which restrains the formation of brittle intermetallic compounds.

Lan zhang et al.[5]:- This paper studied the microstructural and mechanical evolution of friction stir welded (FSW) Aluminium alloy, the influence of notch locations on impact and fatigue crack growth (FCG) behaviour were evaluated. The results show that the grain size, hardness and impact-absorbing the energy of the weld nugget zone (WNZ) was smaller than those of base material and heat-affected zone. Longitudinal residual stresses dominated all the zones of the joint, FSW induced compressive stresses in WNZ. The particles in the Aluminium alloy matrix can impede the propagation of fatigue crack. The microstructural inhomogeneity and crack closure contribute to the fluctuation FCG rate. Failure occurred in the centre of WNZ under tensile loading. Continuous yielding phenomenon occurred in both B.M. and FSW joint, but the mechanical properties changed largely after welding. The joint efficiency reached 72.4%. The typical fatigue fracture surface of stable propagation region was mainly fatigue striations and secondary cracks, some dimples were observed in the rapidly expanding region due to the occurrence of ductile fracture mechanism, dimples dominated the fracture after final unstable failure happened.

H.T. Zhang et al.[6]:- The major aim of this article is to examine the arc characteristics and the metal transfer of the CMT process and use it to join Aluminium and zinc-coated Steel with a lap geometry by a welding–brazing method. The microstructure of the joint and the tensile strength of the joint was investigated to evaluate the process applicability in dissimilar metal joining. The smooth welding seam was made and the zinc coating of the welding back seam can be retained to keep the corrosion resistance. Fig. 8 is the typical cross-section image of the joints.

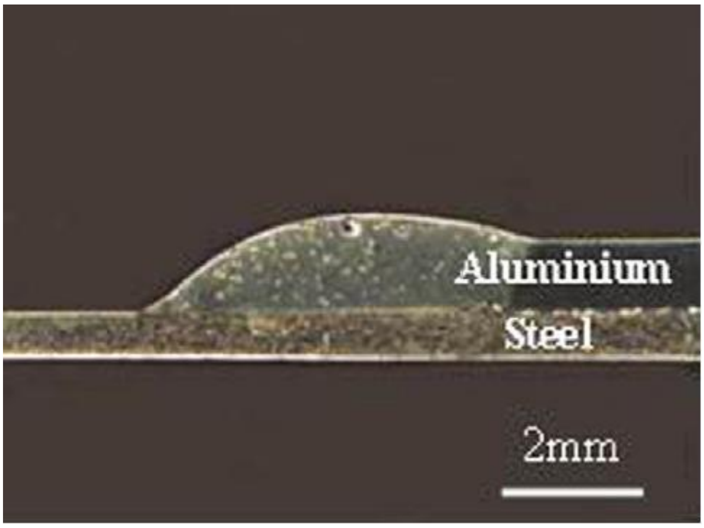


Figure:-8 Cross-sectional optical image of the joints [6].

The scanning electron micrograph shows that a visible intermetallic compound layer between the steel and weld metal has been formed during the welding process as shown in Fig. 9.

The joint was disjoined at the interface between weld metal and Steel. X-ray diffraction was used to determine the phase composition of the compound layer. The results are shown in Fig. 9. The compact layer near the steel side is Fe2Al5 phase and the needle-like compound growing into the weld metal is FeAl3 phase. The maximum thickness of the compound layer in the Aluminium–steel interface is about 4m. The tensile test results show that the bonding strength is about 83MPa, equalled almost to 86% of that of the pure Aluminium and the fracture all occurred in the heat-affected zone of the Aluminium as shown in Fig. 10.

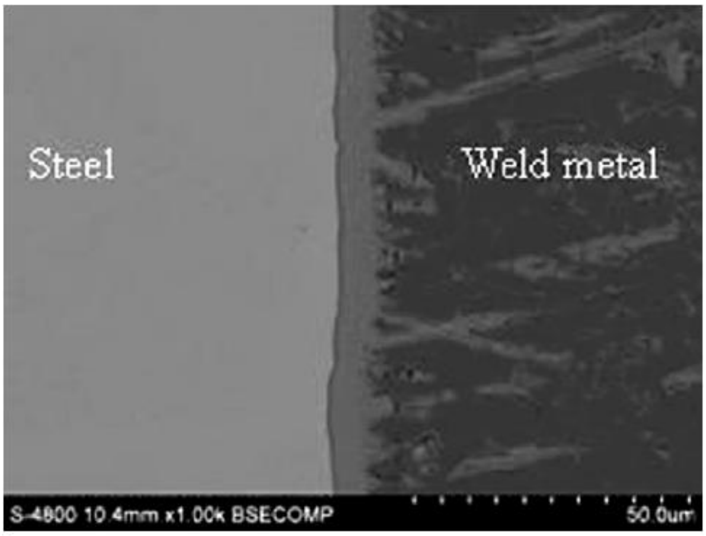


Figure:-9 Microstructures of the interface between Steel and weld metal, obtained by scanning electron microscopy [6].

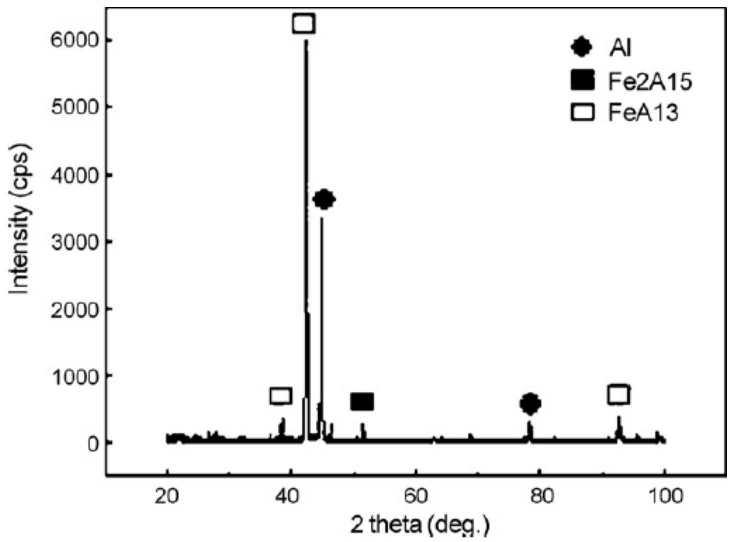


Figure:-10. X-ray diffraction pattern of the fracture plane near the weld metal [6].

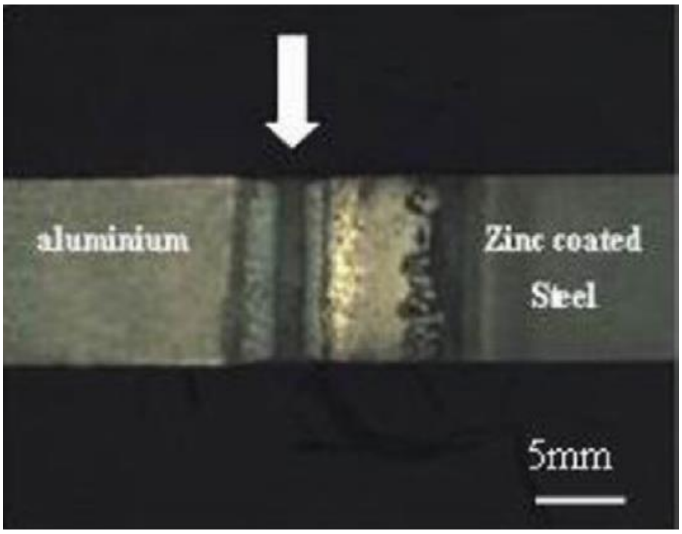


Figure:11 The fracture location of the joint (Designated by white arrow) [6].

The metal transfer process of the CMT is very stable and the arc heating behaviour is changed based on the special wave control features and an assistant back-drawing force. Dissimilar metal joining of Aluminium to zinc-coated steel sheet without cracking by the cold metal transfer process in a lap joint is possible. The compound layer at the interface between Steel and weld metal main consists of Fe2Al5 and FeAl3 phase. The thickness of the intermetallic compound layer can be controlled under 5µm, so the joint strength can be guaranteed. The tensile strength can arrive at 83MPa.

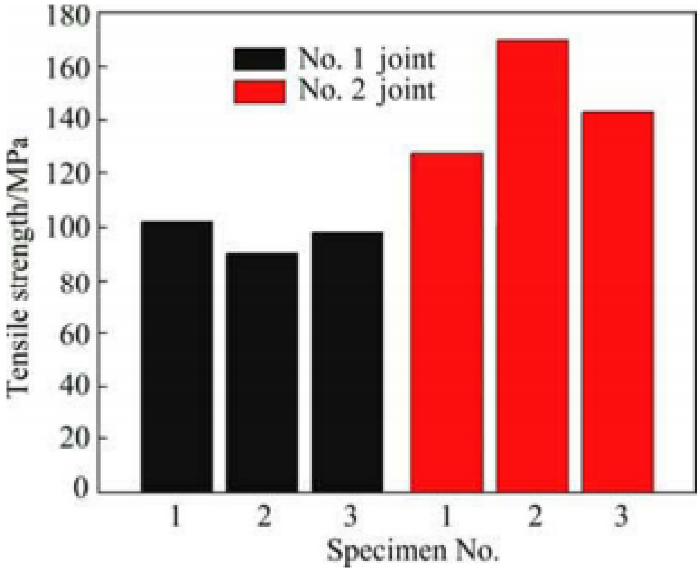
Liu Yibo et al.[7]:- In the present study, an external magnetic field is utilized in the Al-Steel arc welding process. Under a given axial or radial magnetic field, metal fluids are impacted by Lorentz forces produced by currents in the moving fluid that interact with magnetic field lines. This force has been shown to suppress natural convection and homogenize temperature distribution and consequently influence solidification and crystallization processes. In welding, sound weld appearance with refining grain can be obtained by applying a magnetic field during the joining of Aluminium alloy, magnesium alloy and titanium. Previous studies have focused primarily on the joining of homogeneous metals, but typically neglect the effects of magnetic fields on the joining of dissimilar metals. Therefore, Al and Steel are selected and joined by CMT welding under magnetic fields in this study. The weld appearance and molten drop transfer were observed, and the interface microstructure and mechanical properties of Al/steel under the magnetic field are thoroughly investigated.

S. Babu et al.[8]:- In this experiment, they choose cold metal transfer welding to join Aluminium alloy and stainless Steel. Materials used Aluminium alloy Al alloy AA2219 and austenitic stainless steel AISI 321 and Al-Si filler wire AA4047. Before joining stainless Steel with Al alloy, there was pre-processing of stainless Steel by FSW. Pre-processing of stainless Steel involves the coating of Al alloy over stainless steel surface. Reason for doing coating of Al alloy, on stainless Steel because stainless Steel and Al alloy, has very distinct thermo-physical properties which are large difference in melting point, thermal conductivity, heat capacity, thermal expansion, very less solid solubility of Fe in Al cause formation of brittle intermetallic of Fe and Al which reduces strength and reliability of welding joints. By doing the coating of the same material which needs to join with stainless steel sound joints between stainless Steel and Al alloy was produced. For coating of Al alloy on stainless steel surface, friction stir welding was used. In FSW tool use has the same material which needs to deposit over stainless Steel. Different thicknesses coating of Al alloy was done on stainless steel surface at different RPM after doing coating of different thickness Al alloy plate lapped over a stainless steel plate and then welded by CMT welding. Joints formed at different thickness coating were analyzed based on microstructural analysis, tensile test, hardness test, fracture location examination, wettability test. in this research paper, it was reported that by doing Al alloy coating over stainless Steel improve the wettability of melted filler material over, coated stainless steel surface. The controlled intermetallic formation was observed in between coated stainless Steel and Al alloy, which involve FeAl, Fe_4Al_{13} intermetallic. They reported that the optimum dimension of thickness was 0.6 mm thick that joints sustain till load of 260 N/mm. Also reported that at low thickness coating involve the formation of the thicker intermetallic layer, which drastically reduce the tensile strength of joints.

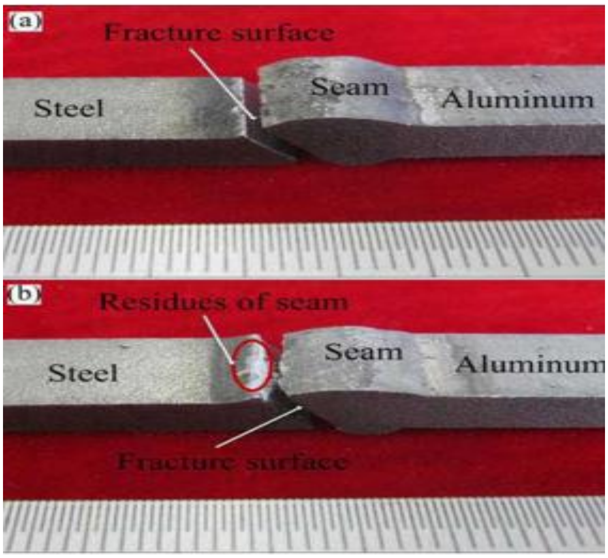
Zheng Ye et al.[9]:- In this experimental study, attempts were made to join dissimilar materials by TIG-MIG hybrid welding having top and bottom configuration of TIG-MIG hybrid welding were used. In that TIG torch was used in the bottom side for preheating purpose MIG torch used in the top side for welding purpose. Materials used in these experimental works were Al alloy 5052 and Q235 steel 3mm thickness. No groove used to join these dissimilar materials. These dissimilar materials were made on different welding parameters. Welding parameters were TIG welding current, TIG welding voltage, MIG welding current, MIG welding voltage, welding speed. Effect on these welding parameters on joint properties was analyzed. Good weld bead appearance both sides of butt joints were obtained. Effect of MIG voltage shows as an increase in voltage heat input increases, which will cause the formation of thicker intermetallic layer and thickness was increased as an increase of MIG welding voltage. Welding speed as increases better weld bead appearance was obtained but after a certain speed material deposition was fewer results poor weld bead appearance. in their study, the calculated tensile strength with and without excess material and also defined joint efficiency formula to compare tensile strength of with and without excess material. after study number of welding parameters, they achieve maximum tensile strength in their experiment watch 70% of the tensile strength of Aluminium alloy 5052, at optimum welding parameters MIG voltage 13V, TIG current 70A, the ratio of MIG/TIG input 1.32 and welding speed 2cm/sec.

Shuhei Kanemaru et al.[10]:- In this experiment, TIG-MIG hybrid welding process was studied in detail. For that purpose, they used the TIG welding setup. Materials used ware 304 stainless steel. Butt joint and lap joints were formed by TIG-MIG hybrid welding process. They analyzed joint based on material transfer and thermal field study around two electrodes. For that purpose they numerical simulation by using the thermal model of ansys software. They also analyzed how much heat gets inputted by using two electrodes simultaneously. In results, they mentioned that the MIG arc was unstable in pure Ar gas atmosphere become stable due to the presence of auxiliary TIG torch. Weld metal toughness also gets improved by using Ar gas instead of CO2 in MIG welding to get a stable arc, they mentioned that TIG welding current should be larger than MIG welding current. By doing the radiography test, their results show no welding defect inside the weld bead, which can reduce weld metal strength; hence, high-quality joints wore produced. Using v-notch, charpy test, weld metal toughness measured and the result shows an increase of toughness of weld joints as compared to TIG-welded sample. Presence of two heating source also reduces the time of welding. They achieved a reduction of time 17-44% by TIG-MIG hybrid welding as compared to TIG welding.

Hong Tao et al.[11]:- In this experiment, the welding process used successfully to join Al alloy and stainless Steel. In the MIG welding process, fusion welding happens in Al side and brazing happen in steel side; they show that less thermal conductivity of steel cause after temperature gradient on steel side additional TIG torch was used.



(a)



(b)

Figure:-12 Tensile strength of butt joints. (a) test results, (b) tested specimens [11].

Thermal gradient exists due to the higher melting temperature of Steel then Al. while the additional TIG arc changes this phenomenon by heating steel side. Use of TIG torch improved the wettability of Al molten metal on steel surface, resulting molten Al metal spread completely over the top and bottom surface of the steel results in sound brazing joint. Increase of Cr and Ni in IMC layer increase quality of

IMC layer and microstructure of IMCs layer also improved, due to sound braze joint bonding between Al and Steel improved and results in an increase of tensile strength of joints. For tensile testing, 10mm width strips were cut from joints, and the tensile strength test was done by UTM. Average tensile strength of TIG-MIG hybrid welded joint-2 obtained was 146.7 MPa which is higher than the average tensile strength obtained by only TIG welding (joint-1) was 96.7 MPa as shown in Fig. 12.

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CHAPTER:-3 EXPERIMENT

3.1.Material details:- Materials used in this experiment were Aluminium alloy Al6061 and hot-dip zinc coated mild Steel (Galvanized Steel) of grade Q235. These materials were joined by Cold metal transfer (CMT) welding by using ER4043 filler wire of 1.2 mm diameter.

Materials composition and filler wire composition is shown in Table 2 and the properties of the materials shown in Table 1.

Table:- 1. Materials properties of the material used:

Material	Tensile strength	Melting point
AA6063	241 MPa	614-654 ^{o}C
Q235	386.MPa	1497 ^{o}C
ER4043 Filler wire	200 MPa	630^{o}C

Table:-2 Composition (wt.%) of the materials used:

Element	Si	Fe	Cu	Mg	Mn	Cr	Zn	Ti	C	S	P	Al
AA6061	0.4-0.8	0-0.7	….	0.8-1,2	0-0.15	0.04-0.35	0-0.25	0-0.15	….	….	….	Bal
Q235	0.3	bal	….	….	0.3	….	….	….	0.12	0.045	0.045	….
ER4043	4.5-6.0	0-0.8	0-0.3	0-0.05	0-0.05	….	0-0.1	….	….	….	….	Bal

3.2.CMT welding:- CMT welding is a modified MIG welding process based on the short-circuiting transfer process. The CMT machine detects a short circuit which sends a signal that retracts the welding filler material, giving the weld time to cool before each drop is placed, resulting in a drop by drop deposit of weld material.

3.2.1. Welding equipment:- In this experiment, the Aluminium alloy to Aluminium alloy and Aluminium alloy to Galvanized Steel were joined using CMT welding machine setup. The CMT torch hold on the KUKA KR 10 R1420 and welding controller FRONIUS TRANSSTEEL 2200 was used shown in Fig. 13.

3.3.Experimental setup:- In this experiment, Al alloy and galvanized Steel were joined using cold metal transfer (CMT) welding. The CMT welding machine Robot used is KUKA KR 10 R1420 and for welding controller fronius Magic wave 190 fronius transsteel 2200 were used respectively, which shown in Fig. 13 and Fig. 14.

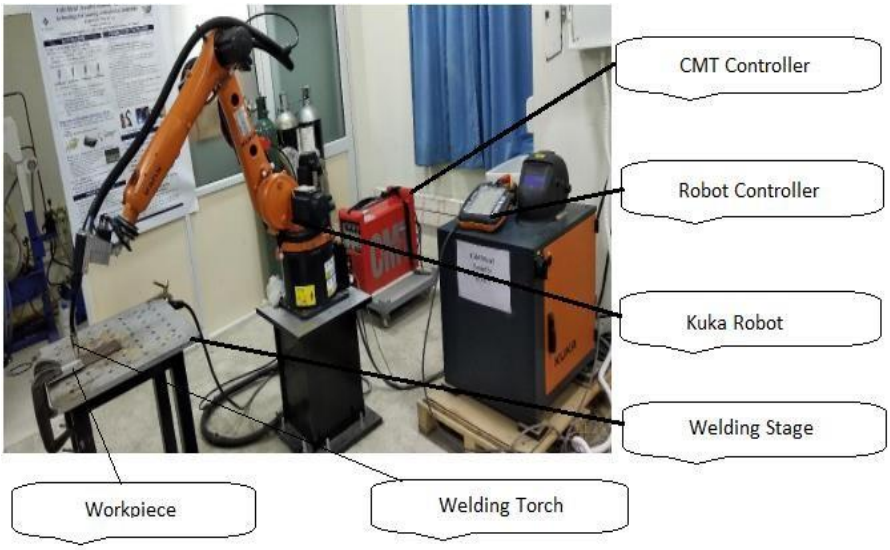

Figure:-13 CMT equipment on a kuka robot.

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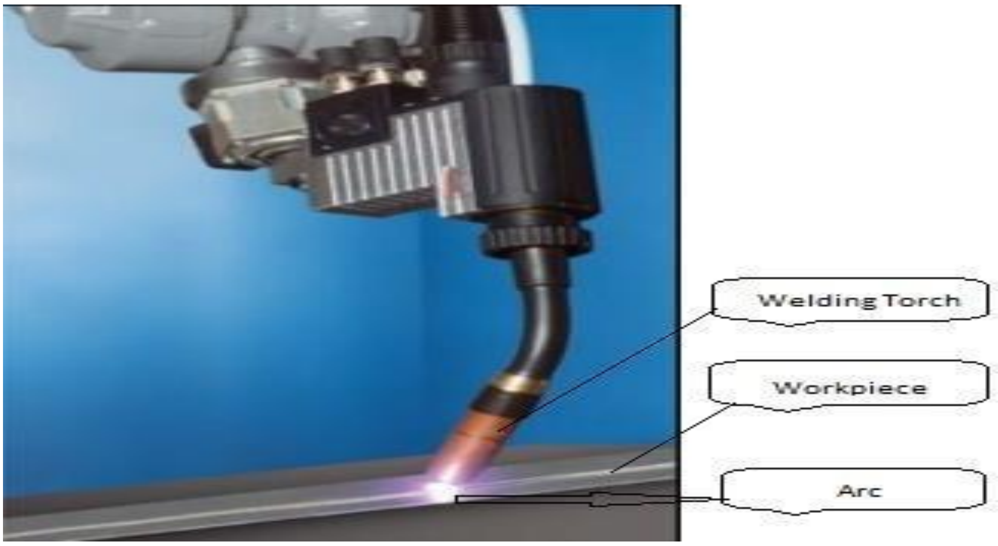

Figure:-14 CMT welding torch

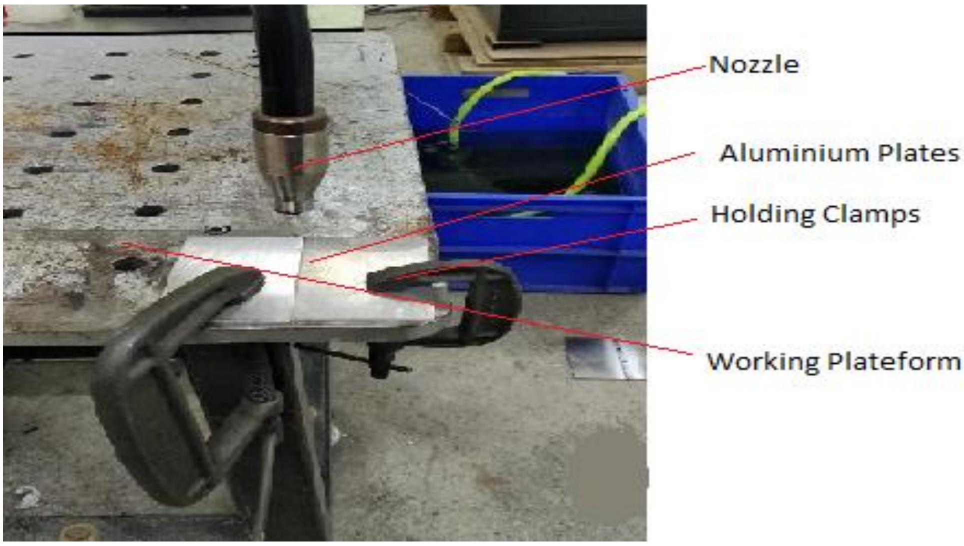

Figure:-15 Normal cooling setup.

In the present study two types of cooling setup were used:-

3.3.1. Normal cooling setup:- In this welding setup requires only a metallic platform on which material to be joined was placed and CMT welding torch attached robot, Ar shielding gas cylinder, welding helmet, welding gloves, welding glasses, welding screen were required. Welding was done using linear programming and letter joints allowed to cool in the air till it comes to room temperature. Arrangements of an air cooling setup shown in Fig. 15.

3.3.2. Super/forced cooling:- In this welding setup arrangements of cooling was done. For that purpose copper block (backing plate) which has continuous water is flowing by two 10mm diameter holes at the rate of 7.5 lit/min. This water-cooled copper backing plate serves as welding platform for welding of Al6061 similar butt joint and Al6061 to Q235 dissimilar lap joint. Materials to be welded placed over the copper backing plate and hold by C-clamps and followed the welding procedure in the same manner as done in normal cooling. The only difference here welding joints cooled by a faster rate due to the presence of water-cooled copper backing plate. Arrangement of copper backing plate with water cooling as shown in Fig. 16.

3.3.3. Water-cooled copper backing plate:- In Fig.17, A setup for CMT welding with a water-cooled copper backing plate is made. First, we cut the solid copper in the shape of a cuboid. Then we drill two holes along the length. Water through holes continuously flows is made. Water is driven by a motor-pump from a water reservoir. Copper is used because of its higher thermal conductivity. The copper plate serves as a welding platform for the welding. Material is placed over the copper plate to provide the cooling effect while welding the materials so that the weld joints are called at a faster rate.

The etchant used in the experiment [12]:- The samples were etched using Keller's solution (190ml water, 2ml H.F., 3ml HCl and 5ml HNO3) for Al alloy and Nital solution (50ml Ethanol and 5ml HNO3) for Steel.

(a)

(b)

Figure:-16 Super/Forced cooling set-up. (a) butt joint configuration. (b) lap joint configuration.

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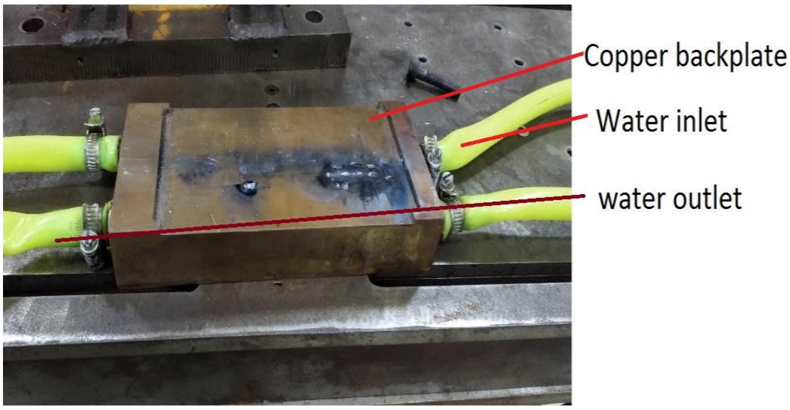


Figure:-17 water-cooled copper backing plate.

3.4. Experimental procedure:- To join Al6061 similar and Al6061-Q235 dissimilar, firstly specimens of dimensions 100mm×55mm×3mm was cut by shear machine From plates of Aluminium alloy Al6061, and Q235 galvanized Steel. These plates of specific dimensions were cleaned by wire brush to remove any thin oxide layer over Al alloy plate and galvanized Steel plate then followed by acetone cleaning to remove any dust particles or any unwanted substance over materials.

Al6061 plates were placed in butt joint configuration for similar joining and welding was done along the 100mm dimension, using the linear program to maintain arc length 8mm at welding speed 4.1 mm/sec.

Finally, CMT welding of the AA6061 with AA6061 was done. In this welding techniques, we used CMT welding, which used filler wire ER4043 of dia 1.2mm. For Al-Steel dissimilar joining, two plates were placed in a lap joint configuration. In lap joint configuration overlapping between plates was 10mm. welding was done along the 100mm dimension using a linear program to maintain arc length 8mm at welding speed 4.1 mm/sec. In this welding techniques, we used CMT welding, which used filler wire ER4043 of dia 1.2mm. The welding torch was normal to the plates throughout the welding. Repetitive welding was performed by changing the various welding parameters on both normal and super/forced cooling setup.

Joints made by CMT welding firstly analyzed based on weld bead appearance. In case of weld bead appearance, things to observed were continuous weld bead formation along the weld length, poor fusion at low current, base material Aluminium melting at high current, surface cracks, arc breakage which leads to the formation of the unwelded area which reduces the strength of joint, weldability, the appearance of joints.

Microstructural characterization was done on the cross-section of the welded sample. The sample's cross-section was cut using EDM. The microstructural characterization includes the use of an inverted optical microscope.

Cross-section of cut from welded joints was first hot mounted and then grind by the abrasive papers of different grades P100, P300, P500, P800, P1000, P1200, P1500, P2000, P2500 followed by Dimond polish then sample eatched by the etchants. For Aluminium alloy Keller's solution was used and for Steel alloy, Nital solution was used.

Composition for Keller's etchant: 50ml of water, 10ml of H.F., 15ml of HCl and 25ml of HNO3 was made and applied for 40-60sec on the polished Aluminium surface [12]. Composition for Nital etchant: 50ml of ethanol, 5ml of HNO3 was made and applied for 15-25 sec on the polished steel surface. And etched samples microstructure studies by optical Microscope and ImageJ software.

Mechanical properties testing involve testing of fracture strength, shear strength and hardness of joints. Fracture strength and shear strength test was done by the tensile testing machine of the standard tensile test samples of ASTM-E8 standard shown in Fig.18 with a crosshead speed of 1mm/min at room temperature.

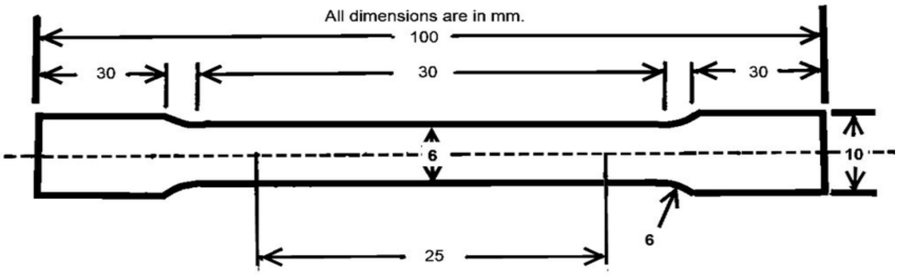


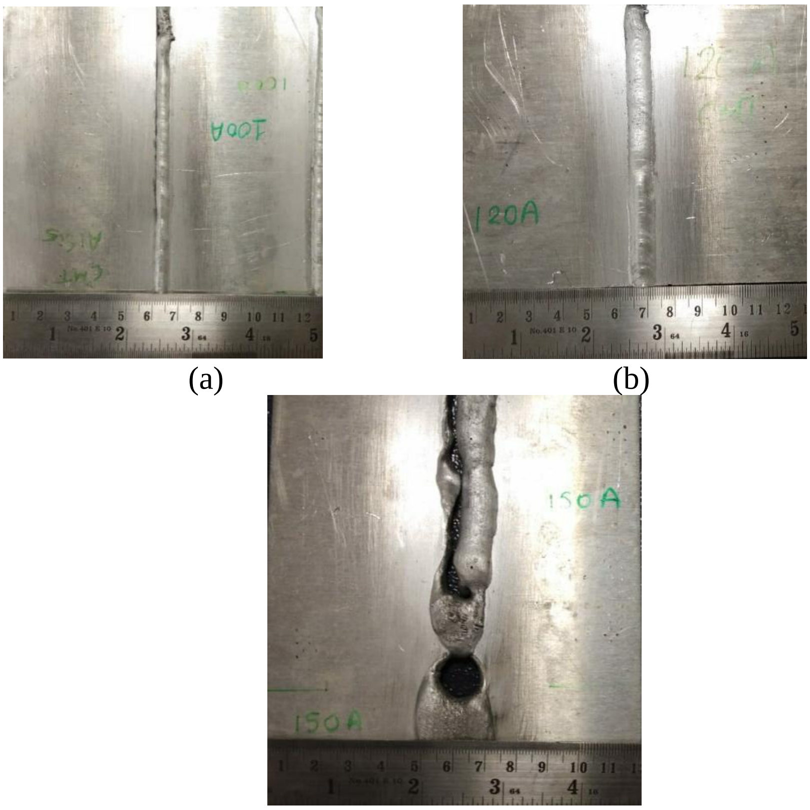
Figure:-18 Tensile specimen subsize of ASTM-E8.

CHAPTER:-4 RESULTS AND DISCUSSIONS

Welded samples were analyzed using different methods. Visual inspection was done for weld bead appearance, the microstructural analysis was done using Optical Microscope and XRD, and mechanical testing was done using Universal Testing Machine (UTM) and Brinnel Hardness number.

4.1. Weld bead appearance:- Comparative study was done to compare weld bead appearance at different CMT welding current with normal cooling and super/forced cooling based on their appearance, wettability, weld coverage and spatter formation.

4.1.1. Weld bead appearance of Al6061 welded joints with normal cooling:-



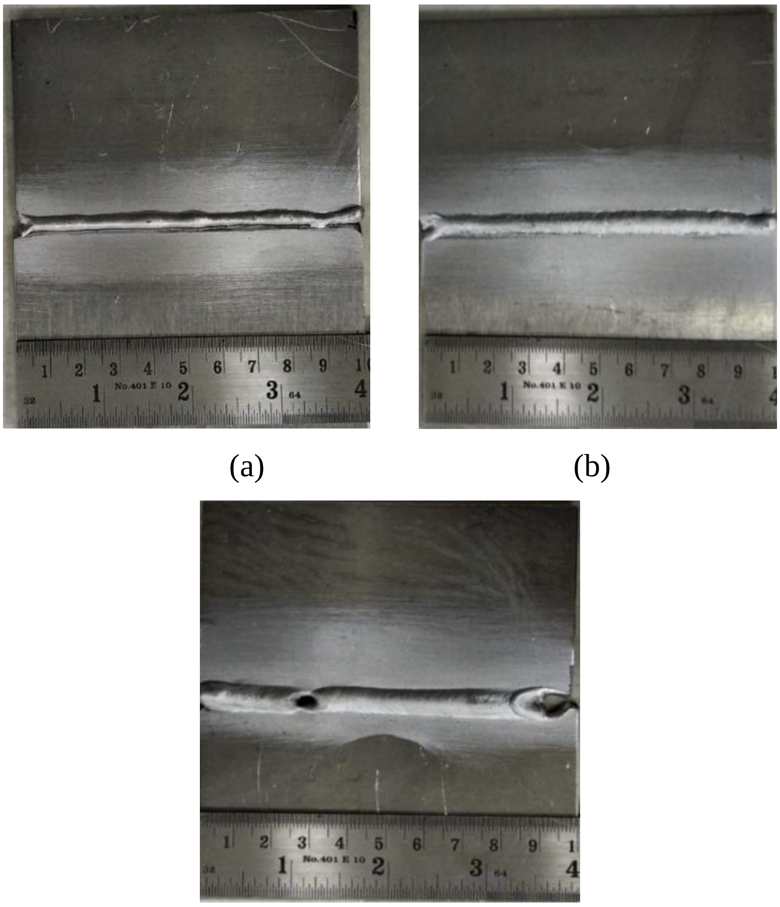
(a) (b)

(c)

Figure:-19 Weld bead appearance of Aluminium similar joints by CMT welding at different welding current with normal cooling. (a) 110A, (b) 120A, (c) 150A welding current.

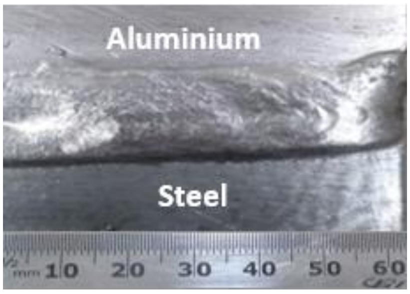
Weld bead appearance obtained by CMT welding with normal cooling is shown in Fig. 19. It is observed from Fig.19, that no spatter formation around the welding area, good weld bead appearance was found at 120A and 130A welding current for Al welded joints and 130A welding current for Al-Steel dissimilar joints with normal cooling setup.

4.1.2. Weld bead appearance of Al6061 welded joints with super/forced cooling:-

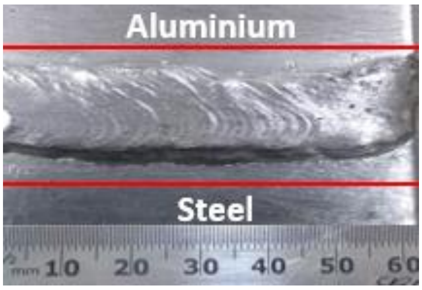


(a) (b) (c)

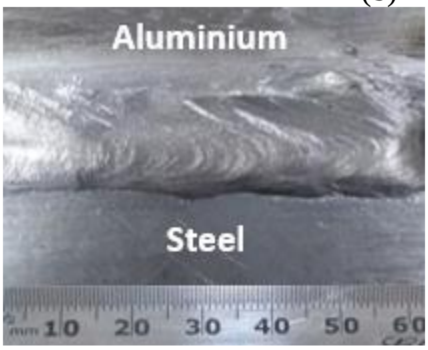
Figure:-20 Weld bead appearance of Aluminium similar joints by CMT welding with forced cooling using a water-cooled copper backing plate at different welding current. (a) 110A, (b) 130A, (c) 150A current.



(a)



(b)



(c)

Figure:-21 Weld bead appearance of Aluminium Steel dissimilar joints by CMT welding at different welding current with normal cooling. (a) 110A, (b) 130A, (c) 150A welding current.

4.1.3. Weld bead appearance of Al-Steel dissimilar welded joints:-

It was observed from the weld bead appearance of CMT welding joints as shown in Fig. 21; uniform weld bead appearance was formed and no spatter formation. At low welding current poor fusion was observed and at a higher value of current base material itself started melting.

From visual inspection of weld images, we can see very less spatter or no spatter at all. As welding current or heat input is increased thickness of weld bead increases as can be seen in the above Fig.20 (c). At 110A welding current, poor fusion takes place and weld coverage is very less in Fig. 20 (a). It can be seen that with an increase in welding current, the weld penetration increases and high deposition is achieved. The best weld bead can be seen at welding current 130A at which desired deposition without pores is obtained. With further increase in welding current extra deposition tends to take place and at 150A the base metal itself starts burning and the metals could not be welded properly.

Similarly, from the above Fig. 21, it can be seen that at lower welding current, improper fusion takes place with very less weld coverage and as the current is increased, the weld penetration increases and high deposition is achieved. The best weld bead can be seen at welding current 130A at which desired deposition without pores is obtained. This can be attributed to the extra heat extraction by a copper plate which leads to faster cooling of the sample. The base metal starts burning at high welding current.

In the above Fig. 20; it can be seen that at lower welding current, improper fusion takes place with very less weld coverage and as the current is increased, the weld penetration increases and high deposition is achieved. Further, the increase in current lead to further increase in heat input and better fusion. Weld pool will have a high temperature in comparison to previous samples. High-temperature weld pool will take more time to get cooled down and due to high fluidity, weld bead will have proper coverage. The best weld bead can be seen at welding current 130A at which desired deposition without pores is obtained. This can be attributed to the extra heat extraction by a copper plate which again is cooled using running water which leads to faster cooling of the sample. Further increase in temperature above optimum value melts the sample.

4.2. Tensile test (fracture strength) results:- Welded joints by CMT welding at different welding current with normal and forced cooling were made. Samples cut from welded joints are subjected to tensile test at a speed of 1mm/min at room temperature. Maximum fracture and shear strength were obtained at their respective best parameters show that supercooling used welded joints had the highest fracture strength. As forced cooling was used results in fine grain structure at the fusion zone and also less heat affected zone in Aluminium similar joints. Due to less heat input and forced cooling we expected less intermetallic layer thickness. The detailed discussions on fracture strength is mentiond in following sections.

4.2.1. Fracture strength test results of Aluminium similar butt joints:- Aluminium alloy Al6061 firstly joined with normal cooling setup. Fusion joints were formed at both Aluminium sides when solidification takes place. The tensile test was carried out for welded joints, which were made on different welding current. From the results of the tensile test, it was observed that heat input at 110A initially was insufficient, which results in inferior quality of joints, which give very low fracture strength of joints. As the increase of welding current fracture strength of joints was increased and achieved a maximum value at a certain value of welding current. Further increase in welding current results decreases in fracture strength, is shown in Fig. 22. And Fig. 24.

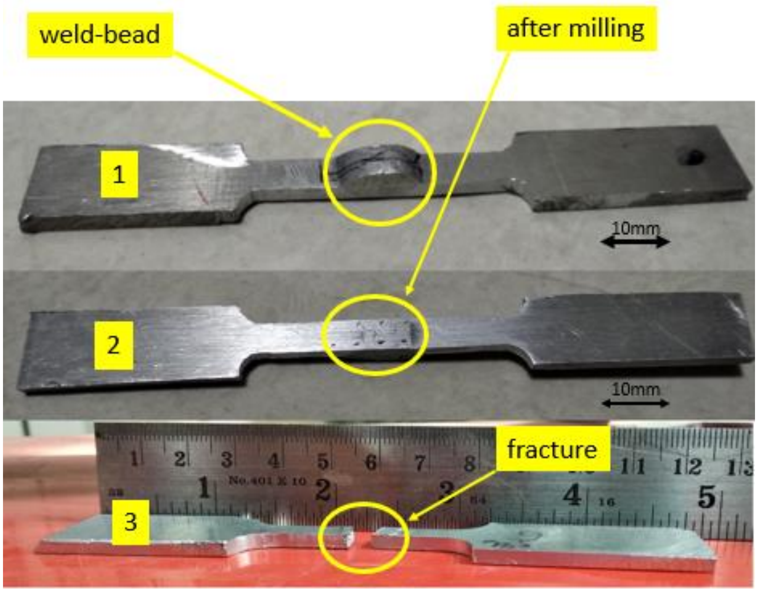


Figure:-22 Tensile test specimen. (a) with reinforcement (b) finished specimen, (c) Fractured specimen after the test.

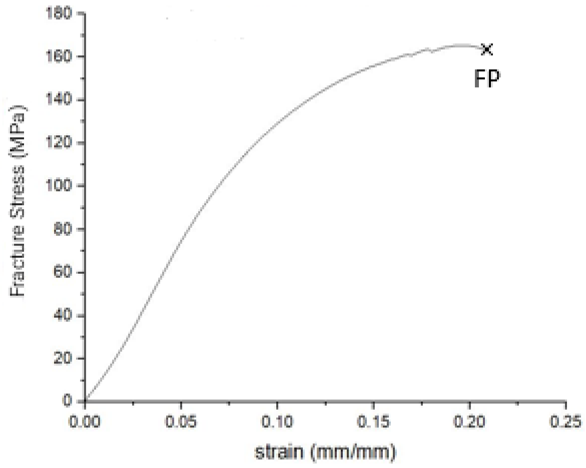


Figure:-23 Fracture strength vs Strain graph of Aluminium welded joint at 120A using CMT welding

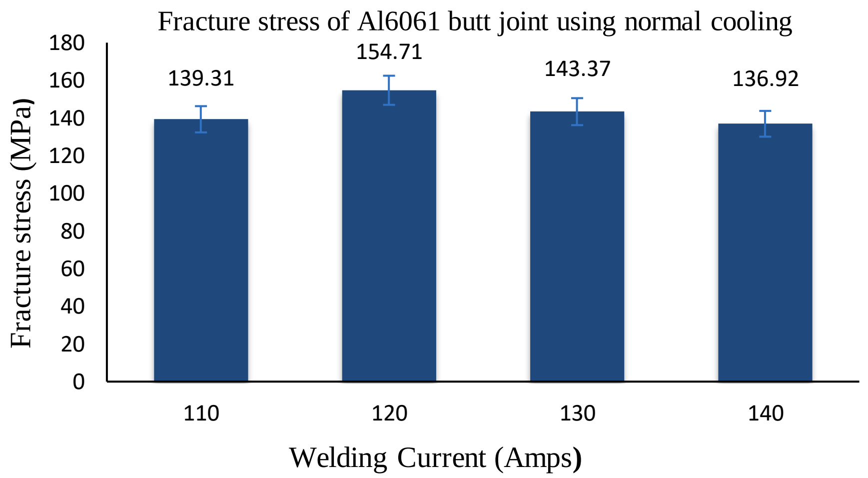


Figure:-24 Fracture stress variation at different welding current of Al6061 butt joints using normal cooling setup.

We observed that during tensile testing, initially, specimens show elastic deformation then reached to the maximum strength (UTS) then the value start decreases than at a certain point specimen failed. .At this failure, point measured strength was fracture strength or fracture point (F.P.) shown in Fig. 23. This F.P., we measured for different welding current using normal and supercooling shown in Fig.24 and Fig. 25.

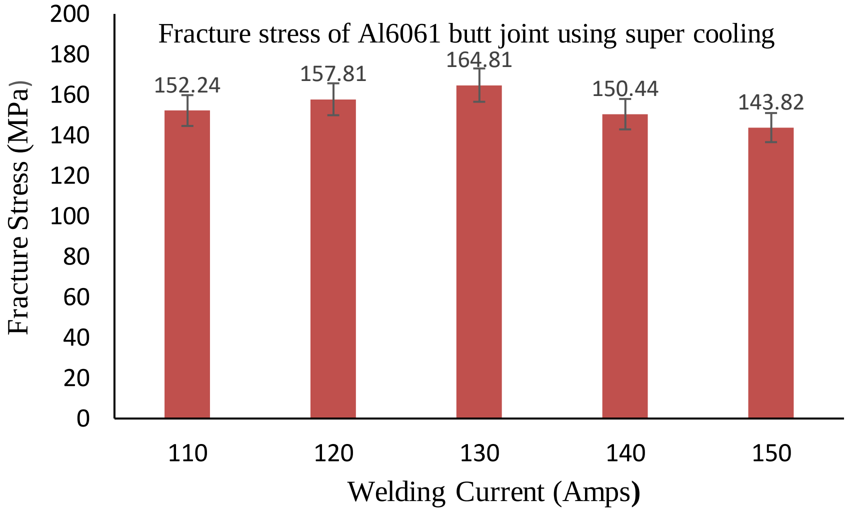


Figure:-25 Fracture strength variation at different welding current of Al6061 butt joints using supercooling setup.

Comparisons of normal and supercooling on the basic of joint strength:- As both setups, normal cooling and supercooling produce similar and dissimilar joints successfully and their tensile test was done. based on the tensile test both the cooling setup used joints compared in Fig. 26; It was observed from the plot that super/forced cooling welded joints have higher strength at each welding current values as compared to normal cooling setup. Although super/forced cooling extracted the more heat from the welded workpieces results in less heat affected zone in Aluminium similar and less intermetallic layer in Aluminium Steel dissimilar joints.

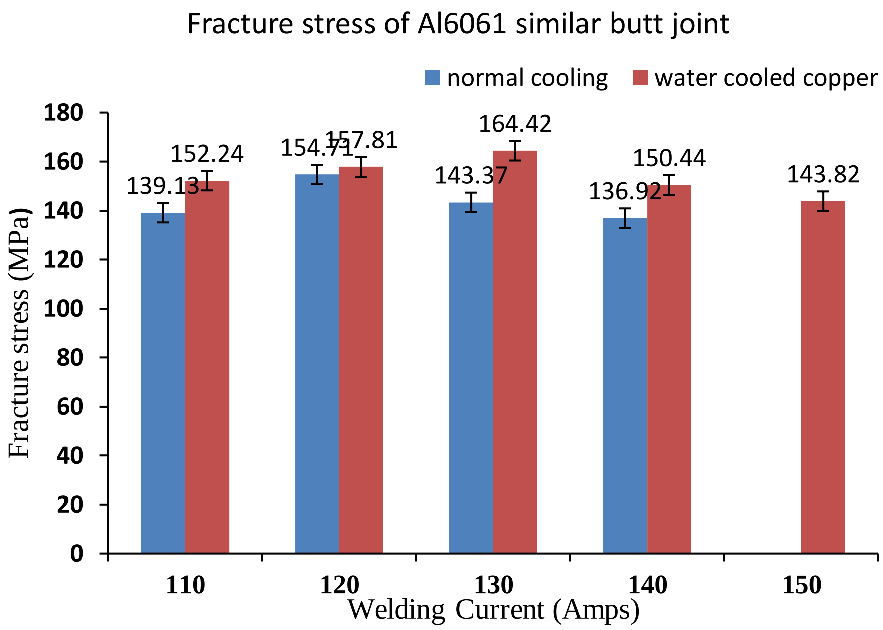


Figure:-26 Comparison of normal and forced cooled Aluminium similar welded joints using CMT.

4.2.2. Fracture (Shear) Stress test results of Aluminium-Steel dissimilar lap joints: - Dissimilar materials Aluminium alloy Al6061 and galvanized steel Q235 joined with both normal and forced cooling setup. The filler wire forms a molten pool which flows over the steel results in a brazing joint at the Steel. The tensile test was carried out for welded joints, which were made on different welding current. From the results of the tensile test, it was observed that heat input at 110A initially was insufficient, which results in inferior quality of joints, which give very low fracture strength of joints. As the increase of welding current shear strength of joints was increased and achieved a maximum value at a certain value of welding current. Further increase in welding current results decreases in shear strength, is shown in Fig. 27. At high heat input, the intermetallic formation leads to a decrease in the shear strength of joints.

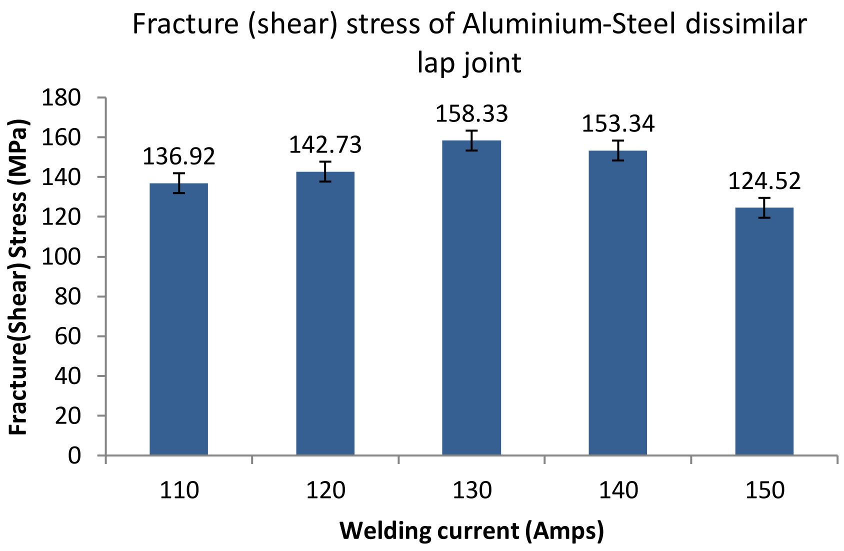


Figure:-27 Fracture (shear) stress variation at different welding current Aluminium-Steel lap joint using normal cooling setup.

4.2.3. Effect of welding parameters on fracture strength of Aluminium similar welded joints:- Cold metal transfer welding has various parameters which need to be controlled to get high strength joints. Some parameters of CMT welding were welding current, arc length, welding speed, gas flow rate and cooling system. These parameters affect joints strength in a different manner. As welding current increases heat input over workpieces also increases if these values are less than required then joints have detected like insufficient fusion, lack of penetration, which drastically reduces joints strength. While more than sufficient values result in the more heat affected zone in Aluminium similar joints a large thickness intermetallic in Aluminium Steel dissimilar joints, which also reduces joints strength. For ensuring sound joints with high Fracture or Shear strength, sufficient welding current to be supplied. For that purpose controlling of heat extraction (cooling rate) from the workpieces during welding is highly important. Other important parameters were arc length and welding speed. As decreases, the welding speed results in high heat input and large heat-affected zone in an Aluminium similar and large thickness of intermetallic in Aluminium Steel dissimilar joints which results in poor joint strength. One more parameter gas flow rate, a sufficient amount of gas flow rate required to get better shielding of the molten pool from the surrounding. Fail to supply a sufficient amount of gas flow reduce the tensile strength of joints due to the formation of brittle oxide inside the weld bead.

4.2.4. Effect of welding current on tensile strength:- In this experiment, CMT welding current varying by keeping other welding parameters welding speed 4.1mm/sec, gas delivery pressure 2kg/sq.cm.constant. It was observed from Fig. 28; that as we increased CMT welding current, joint strength increases and reached maximum value than further increase in current it starts decreasing. Joining of Aluminium similar below 110A was not good due to very less heat input and above 140A heat input was too high similarly in case of Aluminium Steel dissimilar joining. As the welding current increases, heat input increases the fusion and penetration but it also increases the heat-affected zone and the intermetallic formation. This intermetallic layer comprises brittle phases which reduce the joint strength. Joint strength is also affected by the presence of the defect. At high input, fast rate of melting of Aluminium filler wire and base metal can form weld spatter which can deteriorate the surface around the weld zone. Joints formed at 110A, 120A, 130A, 140A and 150A.

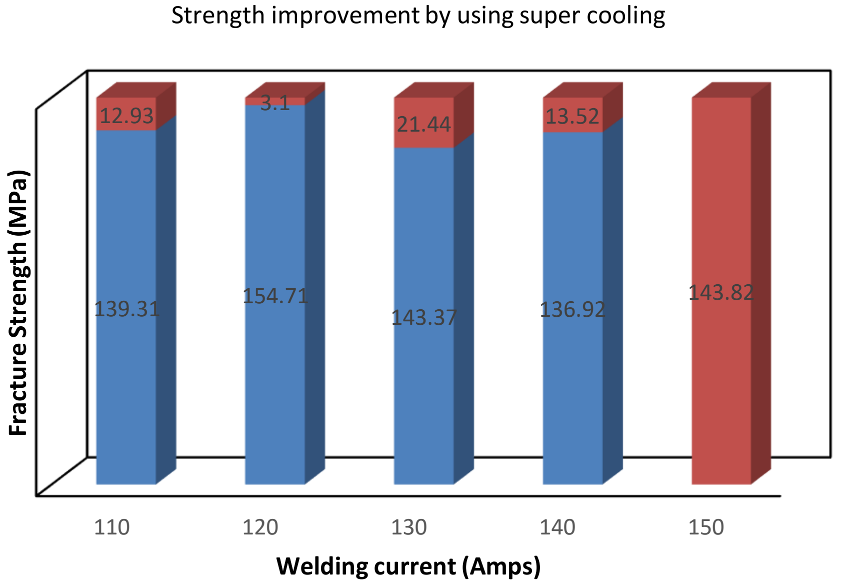


Figure:-29. Improvement in joints Strength using a water-cooled copper backing plate with Aluminium Similar welded joints.

4.2.5. Effect of supercooling using the water-cooled copper backing plate on strength of joints:-From Fig. 26; it was observed that an increase of welding current (up to 120A) joint strength improved and reached maximum value after that it starts decreases due to increases in the heat-affected zone but as compared to normal cooled joints if water-cooled copper backing plate supercooling was used shows joints strength improved. Improvement of fracture strength due to fast heat dissipation rate reduces the heat-affected zone and oxide formation also reduces which is the harder phase which is responsible for brittleness of joints and reduction of strength. The maximum improvement at 130A welding current was 21.44 MPa observed shown in Fig. 29.

4.3. Effect of shielding gas on the strength of welded joints:- In this experiment, we used pure Argon as a shielding gas to protect the weld pool from oxygen and other atmospheric gases. As oxide from inside weld beads results in brittle phases and reduces the strength of joints. Better shielding results in prevention of welded joints from atmospheric interference and leads to the high tensile strength of joins. However, as the gas flow rate from a certain value, tensile strength starts decreasing because, at the high gas flow rate, gas defect tendency increases and welding arc also not stable.

4.4. Fracture locations of welded joints:- The tensile test was done, and fracture location was observed from different CMT welding current with both normal and supercooling setup.

In Aluminium similar joints, CMT welding at low current (110A) failed from the weld bead zone as shown in Fig. 30**;** It might be weaker due to residual shear stresses or defects like incomplete fusion due to insufficient heat input. In other welded joints failed from the heat-affected zone have maximum strength compared to other similar welded joints by normal cooled set up because near the fusion zone base material loses the strength due to oxide formation and heat-affected zones.

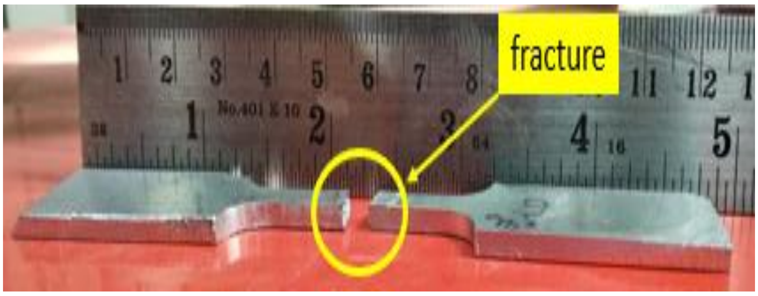


Figure:-30 Fracture locations of aluminium similar welded joints

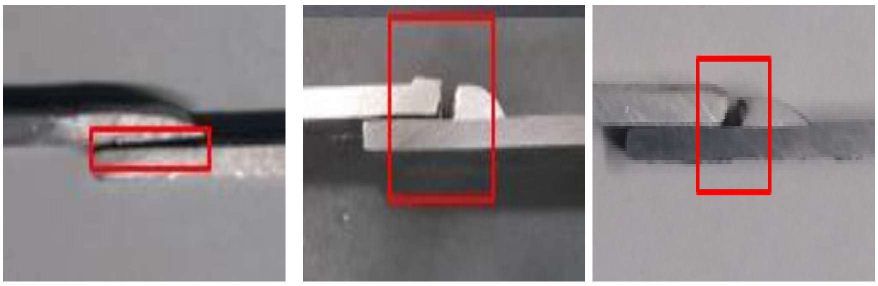


Figure:-31 Fracture location of Al-Steel welded joints. (a) 110A, (b) 130A, (c) 150A welding current.

Two different modes of fracture observed in this experiment as shown in Fig. 31 In Aluminium Steel dissimilar joints, CMT welding at low current(110A) welded sample failed from the interface of Aluminum and steel plate, as shown in Fig. 31(a) because of very less strength of joints and defect like incomplete fusion due to insufficient heat input. In mode 1 material failed from the interface of Aluminum and Steel and gave lower strength as compared to joints which failed by mode 2 failure. In mode 2, failure of material happens from the weld bead in Fig. 31 (b),(c); and gives more strength as compared to failure mode 1.
Mode 1 type of failure in Aluminum steel dissimilar joints were observed due to defect called incomplete fusion. In this case, joints fail from the intermetallic region. As the intermetallic form was brittle, and when we apply the load, the shear load will act on it, and this layer had very less bonding area resulting in the brittle fracture. In this case, failure happens due to the presence of crack inside the intermetallic layer. Crack form inside intermetallic due to internal stresses generated during solidification and due to the formation of brittle intermetallic phases.

Mode 2 type of failure occurred due to wedding defects like heat affected zone, porosity in weld bead and oxide formed in the filler deposited. In the weld zone due to high heat input, these defects happened and it results in the weaker the fusion area and Aluminum alloy near the weld bead. During loading, porous defect and oxide formation had stress start concentrating these areas and then crack start from here and propagate through weld bead and leads to failure of joints.

4.5. Microstructural characterization:-

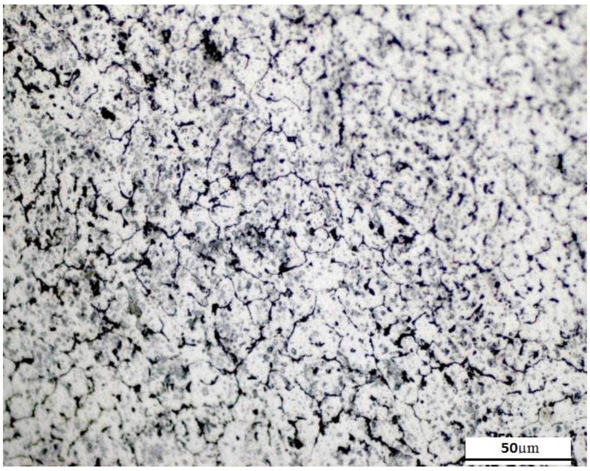
Microstructural characterization was done of cold metal transfer welded joints. For microstructural characterization, we used optical microscopy to observe microstructure. X-ray diffraction technique was used to determine intermetallic phases forming inside joints of CMT welded joints.

4.5.1. Optical microscopy:-The microstructure of welded joints obtain by cutting a cross-section of the welded joint by EDM machine, and then it was hot mounted followed by grinding cross-section of joints by sandpaper of mesh size P100, P200, P400, P600, P800, P1000, P1200, P1500, P2000, P2500 then followed by a diamond polishing with the diamond paste of size 0.25 micron. Then the samples were etched by two different etchants, which were Kellar's solution and Nital solution. Kellar's solution used to etch Aluminium alloy and Nital was used to etch galvanized Steel. Etching time for Aluminium alloy 25-35 sec. and for Steel 15-20 sec. Then microstructures images were taken by an inverted microscope. The microstructure of base materials shown in Fig.32.

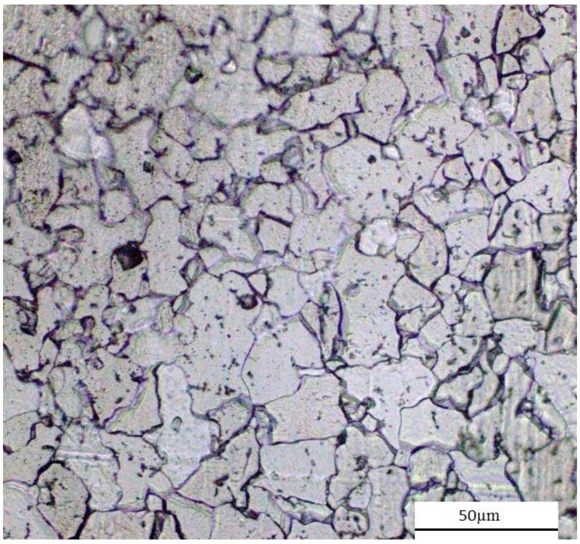
Fig. 33 shows the micrograph of Al6061 similar welded joint using water-cooled copper backing plate setup. Micrograph contain base material Al6061, HAZ, fusion zone of ER4043 filler wire. As we increased the welding current the size of the heat-affected zone and grain size of the fusion zone increases shown in Table 3

Table:-3 HAZ and fusion zone grain size of Aluminium similar welded joints at different welding current using normal cooling:

Welding current (Amps)	110	120	130	140	150
HAZ (μm)	45.23±2.21	52.54±2.05	53.12±2.52	62.33±2.72	Not weld
Fusion zone grain size (μm)	20.46±0.79	22.67±0.92	30.58±0.95	32.96±0.85	



(a)



(b)

Figure:-32 Optical micrograph of the base material (a) Al6061 (b) Q235 galvanized Steel.

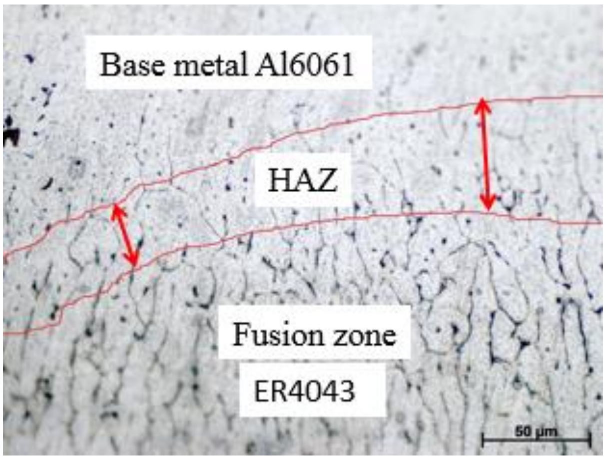


Figure:-33 Al6061 similar welded joint microstructure at 130A welding current with supercooling.

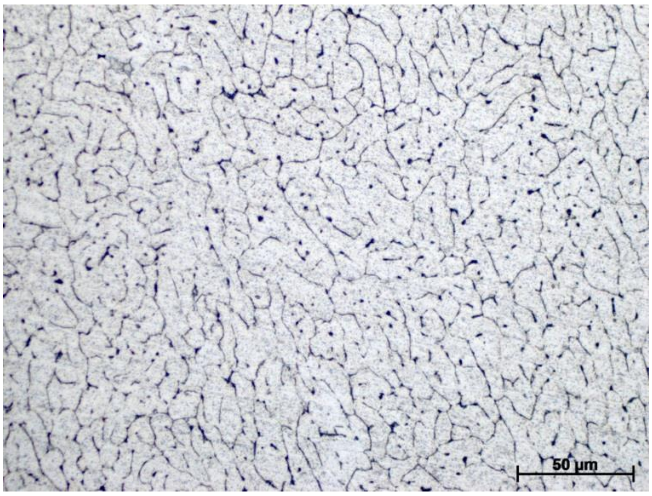


Figure:- 34 Fusion zone microstructure at 130A welding current with supercooling.

Table:-4 HAZ and fusion zone grain size of Aluminium similar welded joints at different welding current using supercooling:

Welding current (A)	110	120	130	140	150
HAZ (μm)	41.82±1.82	42.48±2.51	46.32±1.89	49.79±2.38	51.94±2.33
Fusion zone grain size (μm)	20.22±0.65	20.55±0.82	24.23±1.01	27.33±0.91	28.54±0.81

Similarly, when we used the water-cooled copper backing plate as a supercooling, HAZ and fusion grain size increases with welding current shown in Table 4

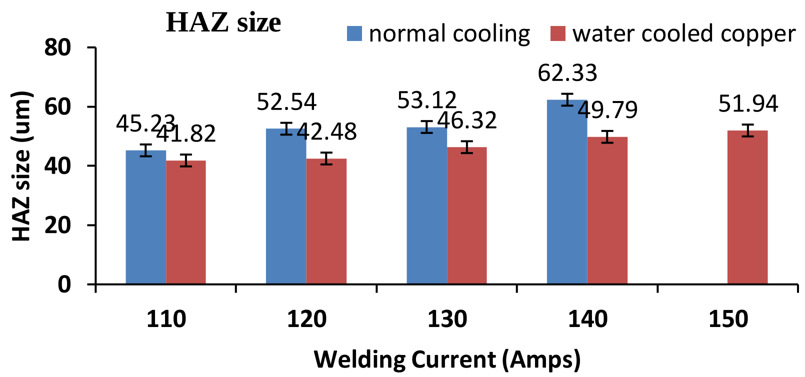


Figure:-35 Comparison in HAZ with welding current using normal and supercooling.

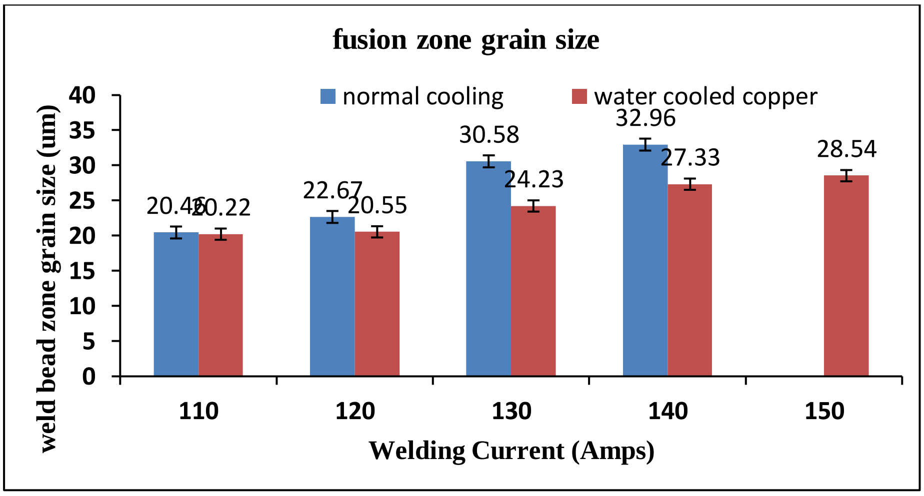


Figure:-36 Comparison in fusion zone grain size with welding current using normal and supercooling.

From Fig. 36. at every welding current values, the HAZ using normal cooling is less compare to supercooling by the water-cooled copper backplate due to more heat extraction during welding.

Similarly, In Fig. 36 at every welding current values, the fusion zone grain size using normal cooling is less compare to supercooling by the water-cooled copper backplate due to more heat extraction during welding give less time to grain growth.

Aluminium-Steel dissimilar welded joint cross-section is shown in Fig. 38**,** has different zones which were fusion zones (F.Z.) which consists of a composition of ER4043 filler wire. Fusion zone completely separated by a fusion line shown by mark 'A' in Fig.37. Marking B and C indicate the intermetallic zone and junction of three materials which was ER4043 filler wire material, Al6061 base material and galvanized Steel.

A fusion line between solid ER4043 filler wire material and Al6061 base material.
B Interface between Al6061 and Q235 galvanized Steel.
C Junction between solidified filler material, Al6061 base material and Steel.
B.M. Base material.
F.Z. Fusion zone.

Figure:-37 Cross-section of Aluminium-Steel welded joint.

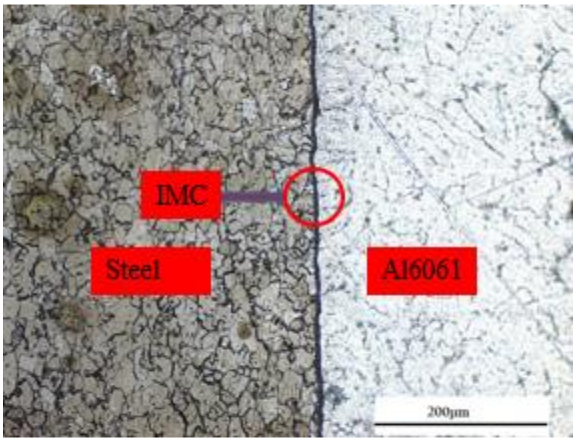


Figure:-38 Aluminium-Steel weld joint microstructure.

Fig. 38 shows the micrograph of Al6061 and Q235 welded joint microstructure. From the micrograph, it was observed that there was the formation of the intermetallic layer between Al6061 and galvanized Steel during solidification. Intermetallic form due to very less solid solubility of Iron in Aluminium. At the steel side, large heat of application affects the microstructure of Steel near the intermetallic region, and the heat-affected zone towards the steel side consists of smaller grain as compared to the unaffected region, which has coarse grain. it was observed that fusion welding happened between ER4043 filler wire material and Al6061 base material due to these there was the formation of heat affected zone which can be seen in micrograph which was separated by fusion line.

4.6. Effect of CMT welding current on intermetallic thickness:- Welding current plays an important role in the formation of the intermetallic layer. It was observed that at the higher welding current. formation of intermetallic layer thickness was more as compared to those at low welding current welded joints. However, it was observed that tensile strength was not maximum either in case of very high welding current or very low welding current. It was maximum at medium (130A) welding current because an optimum thickness of the intermetallic layer is needed to have bonding between two different materials without an intermetallic layer; there was no joint formation between Aluminium alloy and galvanized Steel.

At the higher welding current formation of intermetallic layer thickness was more. Because of the larger thickness and more internal stress inside the intermetallic layer, it will cause the formation of cracks which act as stress concentration points. At low welding current (110A or less) formation of intermetallic layer thickness was very less and it was discontinuous, results in very less bonding area of the intermetallic layer and galvanized Steel. Due to very less bonding area and discontinuous intermetallic layer, it results in a reduction of the tensile strength of joints.

To get sound and reliable joints with high strength welding current, neither high nor low, but it should have optimum value. At optimum value diffusion of Iron from the Steel was less in a molten pool of Aluminium alloy base material and ER4043 filler wire results, less intermetallic compounds.

4.7. XRD analysis of welded joint:- XRD analysis of CMT welded joints were done to detect various intermetallic phases that form at the interface of Al6061 and Q235 galvanized Steel welded joints. Using different parameters joints, it was found that welded joints which were normal cooled form different phases. Based on the literature, we are predicting that various intermetallic phases formed at the Interface of Al6061 and Q235 galvanized Steel. These intermetallic phases are $FeAL_3$ and Fe_2Al_5, out of that Fe_2Al_5 form at high heat input which is very brittle and leads to a decrease of strength of joints. Welded joints at parameters CMT current 130A, welding speed 4.1 mm/sec, arc length 8mm undergo normal cooling forms some intermetallic phases, based on the temprature[6]; It might be Fe_2Al_5 as shown in Fig. 39

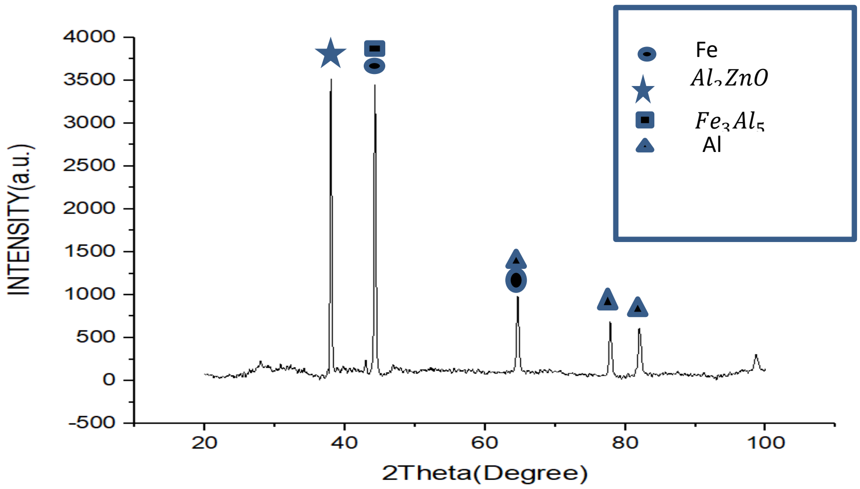


Figure:-39 XRD analysis of Aluminium-Steel welded joint using CMT welding at 130A welding current.

Intermetallic phases are responsible for brittleness of joints, which leads to the reduction of the tensile strength of joints. Once the formation of Fe_2Al_5, which is a very hard phase, it causes a large reduction in the tensile strength of the joint. As it forms its thickness is relatively higher than other phases. Due to the large thickness and hardness of phases, there was the formation of crack as well as it reduces the bonding area, which reduces the tensile strength of joints. Formation of crack inside the intermetallic due to large internal stresses and these crack act as stress concentration centres and crack initiate from these points and propagate and finally fracture happened.

CHAPTER 5:- CONCLUSIONS AND SCOPE FOR FUTURE WORK

In this research work, Aluminum alloy Al6061 similar and Aluminium alloy Al6061 to galvanized steel Q235 dissimilar materials were joined using normal and supercooling setup. Properties of welded joints like weld bead appearance, microstructure feature, tensile properties and hardness were compared. Effect of process parameters which were welding current, welding speed, arc length and Gas flow rate cooling rate was analyzed based on tensile strength of joints. To optimize the welding parameters, joints made at different welding current using supercooling.

From the results following conclusions were drawn:-

Al6061 similar butt joints:-

- Weld bead appearance of welded joints obtain by supercooling set up were better compare to normal cooling setup.
- The grain size of the fusion zone (weld bead) increases gradually in both normal and supercooling setup with increae in weld current.
- Heat affected zone is less using supercooling setup compare to normal cooling setup because of more heat extraction from the workplaces.
- Welded joint obtained maximum fracture strength 154.71 MPa at 120A welding current using normal cooling setup.
- Welded joint obtained highest fracture strength 164.42 MPa at 130A welding current using supercooling setup.
- Optimized welding current 120A and 130A was found for normal cooling and supercooling setup respectively.

Al6061 and Q235 dissimilar lap joints:-

- Initially, shear strength was increased by 15.6% for welding current 110A to 130A then 21% decreases from 130A to 140A in normal cooling set up.
- Optimized welding current 130A was found in normal cooling set up.

Future recommendations:- Due to lack of time (covid-19 pandemic) we did not investigate Aluminium-Steel weld joint using force cooling**.** These experimental work further extended to achieve further improvement in joint strength.

To obtain better joint strength vibration and the effect of cooling rate needs to be investigated in detail.

Fatigue, creep, banding and corrosion properties of weld joint can be studied in details.

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